Handbook of Electrical Engineering

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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Alan L. Sheldrake
Consulting Electrical Engineer, Bangalore, India

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This book is dedicated to my dear wife Ilse who with great patience encouraged me to persevere with the completion of this work.

Contents

Foreword **xix**

Preface **xxi**

Acknowledgements **xxiii**

About the Author **xxv**

1 Estimation of Plant Electrical Load **1**
- 1.1 Preliminary Single-Line Diagrams 1
- 1.2 Load Schedules 2
  - 1.2.1 Worked example 5
- 1.3 Determination of Power Supply Capacity 8
- 1.4 Standby Capacity of Plain Cable Feeders and Transformer Feeders 12
- 1.5 Rating of Generators in Relation to their Prime Movers 13
  - 1.5.1 Operation at low ambient temperatures 13
  - 1.5.2 Upgrading of prime movers 13
- 1.6 Rating of Motors in Relation to their Driven Machines 13
- 1.7 Development of Single-Line Diagrams 14
  - 1.7.1 The key single line diagram 15
  - 1.7.2 Individual switchboards and motor control centres 15
- 1.8 Coordination with other Disciplines 16
  - 1.8.1 Process engineers 16
  - 1.8.2 Mechanical engineers 17
  - 1.8.3 Instrument engineers 17
  - 1.8.4 Communication and safety engineers 18
  - 1.8.5 Facilities and operations engineers 18
  - Reference 18

2 Gas Turbine Driven Generators **19**
- 2.1 Classification of Gas Turbine Engines 19
  - 2.1.1 Aero-derivative gas turbines 19
  - 2.1.2 Light industrial gas turbines 20
  - 2.1.3 Heavy industrial gas turbines 20
  - 2.1.4 Single and two-shaft gas turbines 20
  - 2.1.5 Fuel for gas turbines 23
- 2.2 Energy Obtained from a Gas Turbine 23
  - 2.2.1 Effect of an inefficient compressor and turbine 29
  - 2.2.2 Maximum work done on the generator 30

2.2.3 Variation of specific heat 31
2.2.4 Effect of ducting pressure drop and combustion chamber pressure drop 32
2.2.5 Heat rate and fuel consumption 35
2.3 Power Output from a Gas Turbine 36
2.3.1 Mechanical and electrical power losses 37
2.3.2 Factors to be considered at the design stage of a power plant 37
2.4 Starting Methods for Gas Turbines 39
2.5 Speed Governing of Gas Turbines 39
2.5.1 Open-loop speed-torque characteristic 39
2.5.2 Closed-loop speed-power characteristic 41
2.5.3 Governing systems for gas turbines 43
2.5.4 Load sharing between droop-governed gas turbines 44
2.5.5 Load sharing controllers 50
2.6 Mathematical Modelling of Gas Turbine Speed Governing Systems 52
2.6.1 Modern practice 52
2.6.2 Typical parameter values for speed governing systems 59
References 59
Further Reading 59

3 Synchronous Generators and Motors 61
3.1 Common Aspects Between Generators and Motors 61
3.2 Simplified Theory of Operation of a Generator 61
3.2.1 Steady state armature reaction 62
3.2.2 Transient state armature reaction 63
3.2.3 Sub-transient state armature reaction 63
3.3 Phasor Diagram of Voltages and Currents 64
3.4 The Derived Reactances 65
3.4.1 Sensitivity of x_{md}, x_a, x_f and x_{kd} to changes in physical dimensions 67
3.5 Active and Reactive Power Delivered from a Generator 68
3.5.1 A general case 68
3.5.2 The particular case of a salient pole generator 70
3.5.3 A simpler case of a salient pole generator 71
3.6 The Power Versus Angle Chart of a Salient Pole Generator 72
3.7 Choice of Voltages for Generators 73
3.8 Typical Parameters of Generators 73
3.9 Construction Features of High Voltage Generators and Induction Motors 78
3.9.1 Enclosure 78
3.9.2 Reactances 79
3.9.3 Stator windings 79
3.9.4 Terminal boxes 80
3.9.5 Cooling methods 80
3.9.6 Bearings 80
References 81

4 Automatic Voltage Regulation 83

4.1 Modern Practice 83
  4.1.1 Measurement circuits 83
  4.1.2 Error sensing circuit 84
  4.1.3 Power amplifier 84
  4.1.4 Main exciter 88
4.2 IEEE Standard AVR Models 89
  4.2.1 Worked example 92
  4.2.2 Worked example 92
  4.2.3 Determining of saturation constants 93
  4.2.4 Typical parameter values for AVR systems 97
  Reference 97

5 Induction Motors 99

5.1 Principle of Operation of the Three-Phase Motor 99
5.2 Essential Characteristics 100
  5.2.1 Motor torque versus speed characteristic 100
  5.2.2 Motor starting current versus speed characteristic 107
  5.2.3 Load torque versus speed characteristic 108
  5.2.4 Sensitivity of characteristics to changes in resistances and reactances 109
  5.2.5 Worked example 109
  5.2.6 Typical impedance data for two-pole and four-pole induction motors 114
  5.2.7 Representing the deep-bar effect by two parallel branches 114
5.3 Construction of Induction Motors 119
5.4 Derating Factors 121
5.5 Matching the Motor Rating to the Driven Machine Rating 121
5.6 Effect of the Supply Voltage on Ratings 122
5.7 Effect of the System Fault Level 123
5.8 Cable Volt-drop Considerations 123
5.9 Critical Times for Motors 125
5.10 Methods of Starting Induction Motors 125
  5.10.1 Star-delta method 126
  5.10.2 Korndorfer auto-transformer method 126
  5.10.3 Soft-start power electronics method 127
  5.10.4 Series reactor method 128
  5.10.5 Part winding method 129
  References 129

6 Transformers 131

6.1 Operating Principles 131
6.2 Efficiency of a Transformer 134
6.3 Regulation of a Transformer 135
6.4 Three-Phase Transformer Winding Arrangements 136
6.5 Construction of Transformers 137
  6.5.1 Conservator and sealed type tanks 139

6.6 Transformer Inrush Current 140
References 142

7 Switchgear and Motor Control Centres 143
7.1 Terminology in Common Use 143
7.2 Construction 144
7.2.1 Main busbars 144
7.2.2 Earthing busbars 146
7.2.3 Incoming and busbar section switching device 146
7.2.4 Forms of separation 147
7.2.5 Ambient temperature derating factor 149
7.2.6 Rated normal current 149
7.2.7 Fault making peak current 149
7.2.8 Fundamental AC part 150
7.2.9 DC part 150
7.2.10 Double frequency AC part 150
7.2.11 Fault breaking current 152
7.2.12 Fault withstand duty 153
7.3 Switching Devices 154
7.3.1 Outgoing switching device for switchgear 154
7.3.2 Outgoing switching device for motor control centres 155
7.4 Fuses for Motor Control Centre Outgoing Circuits 156
7.5 Safety Interlocking Devices 157
7.6 Control and Indication Devices 158
7.6.1 Restarting and reaccelerating of motors 158
7.6.2 Micro-computer based systems 159
7.7 Moulded Case Circuit Breakers 162
7.7.1 Comparison with fuses 162
7.7.2 Operating characteristics 163
7.7.3 Cut-off current versus prospective current 164
7.7.4 i-squared-t characteristic 164
7.7.5 Complete and partial coordination of cascaded circuit breakers 165
7.7.6 Worked example for coordination of cascaded circuit breakers 167
7.7.7 Cost and economics 172
References 172

8 Fuses 173
8.1 General Comments 173
8.2 Operation of a Fuse 174
8.3 Influence of the Circuit X-to-R Ratio 174
8.4 The I^2t Characteristic 176
8.4.1 Worked example 179
References 181

9 Cables, Wires and Cable Installation Practices 183
9.1 Electrically Conducting Materials used in the Construction of Cables 183
9.1.1 Copper and aluminium 184
9.1.2 Tin 184
9.1.3 Phosphor bronze 185
9.1.4 Galvanised steel 185
9.1.5 Lead 186
9.2 Electrically Non-Conducting Materials used in the Construction of Cables 187
9.2.1 Definition of basic terminology 187
9.3 Composition of Power and Control Cables 191
9.3.1 Compositional notation 192
9.3.2 Conductor 192
9.3.3 Conductor semiconducting screen 196
9.3.4 Insulation 196
9.3.5 Insulation semiconductor screen 197
9.3.6 Inner sheath 197
9.3.7 Lead sheathing 197
9.3.8 Armouring 198
9.3.9 Outer sheath 198
9.4 Current Ratings of Power Cables 198
9.4.1 Continuous load current 198
9.4.2 Continuous rated current of a cable 199
9.4.3 Volt-drop within a cable 209
9.4.4 Protection against overloading current 242
9.5 Cables with Enhanced Performance 244
9.5.1 Fire retardance 244
9.5.2 Fire resistance 245
9.5.3 Emission of toxic gases and smoke 245
9.5.4 Application of fire retardant and fire resistant cables 246
Reference 247

10 Hazardous Area Classification and the Selection of Equipment 249
10.1 Historical Developments 249
10.2 Present Situation 249
10.3 Elements of Hazardous Area Classification 251
10.3.1 Mixtures of gases, vapours and air 251
10.4 Hazardous Area Zones 253
10.4.1 Non-hazardous area 253
10.4.2 Zone 2 hazardous area 253
10.4.3 Zone 1 hazardous area 253
10.4.4 Zone 0 hazardous area 254
10.4.5 Adjacent hazardous zones 254

10.5 Types of Protection for Hazardous Areas 254
    10.5.1 Type of protection ‘d’ 255
    10.5.2 Type of protection ‘e’ 256
    10.5.3 Type of protection ‘i’ 256
    10.5.4 Type of protection ‘m’ 257
    10.5.5 Type of protection ‘n’ and ‘n’ 257
    10.5.6 Type of protection ‘o’ 258
    10.5.7 Type of protection ‘p’ 258
    10.5.8 Type of protection ‘q’ 259
    10.5.9 Type of protection ‘s’ 259
    10.5.10 Type of protection ‘de’ 259
10.6 Types of Protection for Ingress of Water and Solid Particles 260
    10.6.1 European practice 260
    10.6.2 American practice 261
10.7 Certification of Hazardous Area Equipment 265
10.8 Marking of Equipment Nameplates 266
References 266
Further Reading 266

11 Fault Calculations and Stability Studies 269
11.1 Introduction 269
11.2 Constant Voltage Source – High Voltage 269
11.3 Constant Voltage Source – Low Voltage 271
11.4 Non-Constant Voltage Sources – All Voltage Levels 273
11.5 Calculation of Fault Current due to Faults at the Terminals of a Generator 274
    11.5.1 Pre-fault or initial conditions 274
    11.5.2 Calculation of fault current – rms symmetrical values 276
11.6 Calculate the Sub-Transient symmetrical RMS Fault Current Contributions 279
    11.6.1 Calculate the sub-transient peak fault current contributions 281
11.7 Application of the Doubling Factor to Fault Current I''_{frms} found in 11.6 287
    11.7.1 Worked example 288
    11.7.2 Breaking duty current 291
11.8 Computer Programs for Calculating Fault Currents 292
    11.8.1 Calculation of fault current – rms and peak asymmetrical values 292
    11.8.2 Simplest case 293
    11.8.3 The circuit x-to-r ratio is known 293
    11.8.4 Detailed generator data is available 293
    11.8.5 Motor contribution to fault currents 293
11.9 The use of Reactors 294
    11.9.1 Worked example 297
11.10 Some Comments on the Application of IEC60363 and IEC60909 300
11.11 Stability Studies 300
    11.11.1 Steady state stability 301
    11.11.2 Transient stability 303

References 308
Further Reading 309

12 Protective Relay Coordination 311

- 12.1 Introduction to Overcurrent Coordination 311
  - 12.1.1 Relay notation 313
- 12.2 Generator Protection 313
  - 12.2.1 Main generators 313
  - 12.2.2 Overcurrent 314
  - 12.2.3 Differential stator current relay 318
  - 12.2.4 Field failure relay 319
  - 12.2.5 Reverse active power relay 321
  - 12.2.6 Negative phase sequence relay 322
  - 12.2.7 Stator earth fault relays 322
  - 12.2.8 Over terminal voltage 324
  - 12.2.9 Under terminal voltage 324
  - 12.2.10 Under- and overfrequency 325
- 12.3 Emergency Diesel Generators 325
- 12.4 Feeder Transformer Protection 326
  - 12.4.1 Overcurrent 329
  - 12.4.2 High-set or instantaneous current 330
  - 12.4.3 Characteristics of the upstream source 332
- 12.5 Feeder Cable Protection 332
  - 12.5.1 Overcurrent protection 332
  - 12.5.2 Short-circuit protection 333
  - 12.5.3 Earth fault protection 333
- 12.6 Busbar Protection in Switchboards 334
  - 12.6.1 Busbar zone protection 334
  - 12.6.2 Overcurrent protection 335
  - 12.6.3 Undervoltage protection 335
- 12.7 High Voltage Induction Motor Protection 336
  - 12.7.1 Overloading or thermal image 337
  - 12.7.2 Instantaneous or high-set overcurrent 339
  - 12.7.3 Negative phase sequence 339
  - 12.7.4 Core balance earth fault 340
  - 12.7.5 Differential stator current 340
  - 12.7.6 Stalling current 340
  - 12.7.7 Limitation to the number of successive starts 341
  - 12.7.8 Undercurrent 341
  - 12.7.9 High winding temperature 342
  - 12.7.10 High bearing temperature 342
  - 12.7.11 Excessive vibration 342
- 12.8 Low Voltage Induction Motor Protection 342
  - 12.8.1 Overloading or thermal image 343
  - 12.8.2 Instantaneous or high-set overcurrent 344

12.8.3 Negative phase sequence 344
12.8.4 Core balance earth fault 345
12.8.5 Stalling current 345
12.8.6 Limitation to the number of successive starts 345
12.9 Low Voltage Static Load Protection 345
12.9.1 Time-delayed overcurrent 346
12.9.2 Instantaneous or high-set overcurrent 346
12.9.3 Core balance earth fault 346
12.10 Mathematical Equations for Representing Standard, Very and Extremely Inverse Relays 346
References 349

13 Earthing and Screening 351
13.1 Purpose of Earthing 351
13.1.1 Electric shock 351
13.1.2 Damage to equipment 353
13.1.3 Zero reference potential 353
13.2 Site Locations 353
13.2.1 Steel structures 354
13.2.2 Land-based plants 354
13.2.3 Concrete and brick-built structures 356
13.3 Design of Earthing Systems 356
13.3.1 High voltage systems 356
13.3.2 Low voltage three-phase systems 357
13.3.3 IEC types of earthing systems 360
13.3.4 Earth loop impedance 365
13.3.5 Earthing rods and grids 367
13.4 Construction Details Relating to Earthing 371
13.4.1 Frames, casings and cubicle steelwork 371
13.4.2 Screwed and clearance hole entries 371
13.4.3 Earthing only one end of a cable 372
13.5 Screening and Earthing of Cables used in Electronic Circuits 373
13.5.1 Capacitance and inductance mechanisms 373
13.5.2 Screening against external interference 374
13.5.3 Earthing of screens 379
13.5.4 Screening of high frequencies 380
13.5.5 Power earths, cubicle and clean earths 381
References 383

14 Variable Speed Electrical Drivers 385
14.1 Introduction 385
14.1.1 Environment 386
14.1.2 Power supply 386
14.1.3 Economics 387
14.2 Group 1 Methods 388
14.2.1 Simple variable voltage supplies 388
14.2.2 Pole-changing of the stator winding 389

- 14.2.3 Pole amplitude modulated motors 390
- 14.2.4 Wound rotor induction motors 391

14.3 Group 2 Methods 392
- 14.3.1 Variable voltage constant frequency supply 392
- 14.3.2 Variable frequency variable voltage supply 392

14.4 Variable Speed DC Motors 394

14.5 Electrical Submersible Pumps 394
- 14.5.1 Introduction 394
- 14.5.2 Electrical submersible pump construction 395

14.6 Control Systems for AC Motors 397

References 400

15 Harmonic Voltages and Currents 401

15.1 Introduction 401

15.2 Rectifiers 402
- 15.2.1 Diode bridges 402
- 15.2.2 Thyristor bridges 404
- 15.2.3 Power transistor bridges 407
- 15.2.4 DC motors 407

15.3 Harmonic Content of the Supply Side Currents 413
- 15.3.1 Simplified waveform of a six-pulse bridge 413
- 15.3.2 Simplified commutation delay 414
- 15.3.3 Fourier coefficients of the line current waveform 414
- 15.3.4 Simplified waveform of a 12-pulse bridge 417

15.4 Inverters 421
- 15.4.1 Basic method of operation 421
- 15.4.2 Three-phase power inversion 422
- 15.4.3 Induction motor fed from a voltage source inverter 423

15.5 Filtering of Power Line Harmonics 429

15.6 Protection, Alarms and Indication 433

References 433

16 Computer Based Power Management Systems 435

16.1 Introduction 435

16.2 Typical Configurations 435

16.3 Main Functions 436
- 16.3.1 High-speed load shedding 436
- 16.3.2 Load shedding priority table 439
- 16.3.3 Low-speed load shedding 440
- 16.3.4 Inhibiting the starting of large motors 441
- 16.3.5 VDU display of one-line diagrams 442
- 16.3.6 Active power sharing for generators 443
- 16.3.7 Isochronous control of system frequency 443
- 16.3.8 Reactive power sharing for generators 444
- 16.3.9 Isochronous control of busbar voltage 444
- 16.3.10 Condition monitoring of the gas turbines 444
- 16.3.11 Scheduling the starting up and shutting down of the main generators 445

16.3.12 Control of the reacceleration of motor loads 446
16.3.13 Auto-synchronising of the main generators 447
16.3.14 Data logging, archiving, trending display, alarms, messages and status reporting 448

17 Uninterruptible Power Supplies 449
17.1 AC Uninterruptible Power Supplies 449
17.1.1 The inverter 449
17.1.2 Coordination of the sub-circuit rated current with the inverter rated current 450
17.1.3 Earth fault leakage detection 451
17.2 DC Uninterruptible Power Supplies 451
17.2.1 UPS battery chargers 452
17.2.2 Batteries 455
17.3 Redundancy Configurations 457
References 458

18 Miscellaneous Subjects 459
18.1 Lighting Systems 459
18.1.1 Types of lighting fittings 461
18.1.2 Levels of illumination 461
18.2 Navigation Aids 463
18.2.1 Flashing marker lights 463
18.2.2 White and red flashing lights 464
18.2.3 Navigation buoys 465
18.2.4 Identification panels 465
18.2.5 Aircraft hazard lighting 465
18.2.6 Helicopter landing facilities 466
18.2.7 Radar 466
18.2.8 Radio direction-finder 466
18.2.9 Sonar devices 467
18.3 Cathodic Protection 467
References 468

19 Preparing Equipment Specifications 469
19.1 The Purpose of Specifications 469
19.2 A Typical Format for a Specification 470
19.2.1 Introduction 471
19.2.2 Scope of supply 471
19.2.3 Service and environmental conditions 471
19.2.4 Compliant international standards 471
19.2.5 Definition of technical and non-technical terms 471
19.2.6 Performance or functional requirements 472
19.2.7 Design and construction requirements 473
19.2.8 Inspection and testing 474
19.2.9 Spare parts 475
19.2.10 Documentation 475
19.2.11 Appendices 477

20 Summary of the Generalised Theory of Electrical Machines as Applied to Synchronous Generators and Induction Motors 479

20.1 Introduction 479

20.2 Synchronous Generator 480

20.2.1 Basic mathematical transformations 483

20.3 Some Notes on Induction Motors 490

20.3.1 Derived reactances 491

20.3.2 Application of three-phase short circuit 491

20.3.3 Derived reactances and time constants for an induction motor 493

20.3.4 Derivation of an equivalent circuit 495

20.3.5 ‘Re-iteration or recapitulation’ 496

20.3.6 Contribution of three-phase short-circuit current from induction motor 501

References 504

Further Reading 505

Appendix A Abbreviations Commonly used in Electrical Documents 507

Appendix B A List of Standards Often Used for Designing Electrical Systems and for Specifying Equipment 517

B.1 International Electro-technical Commission (Europe) 517

B.2 Institute of Petroleum (UK) 525

B.3 International Standards Organisation (Worldwide) 526

B.4 British Standards Institution (UK) 526

B.5 American Petroleum Institute (USA) 530

B.6 Counseil International des Grands Reseaux Electriques (France) 530

B.7 Engineering Equipment and Materials Users Association (UK) 530

B.8 Electricity Council (UK) 531

B.9 Verband Deutscher Electrechniker (Germany) 531

B.10 Institute of Electronic and Electrical Engineers Inc. (USA) 531

B.11 Miscellaneous References from the UK 532

Appendix C Numbering System for Protective Devices, Control and Indication Devices for Power Systems 533

C.1 Application of Protective Relays, Control and Alarm Devices for Power System Circuits 533

C.1.1 Notes to sub-section C.1 535

C.2 Electrical Power System Device Numbers and Functions 536

Appendix D Under-Frequency and Over-Temperature Protection of Gas-Turbine Driven Generators 539

Appendix E List of Document Types to be Produced During a Project 545

E.1 Contractors Documents 546

E.1.1 Feasibility studies 546

E.1.2 Conceptual design 546

E.1.3 Detail design 547

E.2 Manufacturers Documents 549
  E.2.1 Feasibility studies 549
  E.2.2 Conceptual design 549
  E.2.3 Detail design 549

Appendix F Worked Example for Calculating the Performance of a Gas Turbine 551
F.1 The Requirements and Data Given 551
F.2 Basic Requirements 551
F.3 Detailed Requirements 552
F.4 Basic Solutions 552
F.5 Detailed Solutions 553

Appendix G Worked Example for the Calculation of Volt-drop in a Circuit Containing an Induction Motor 559
G.1 Introduction 559

Appendix H Worked Example for the Calculation of Earthing Current and Electric Shock Hazard Potential Difference in a Rod and Grid Earthing System 585
H.1 Worked Example 585

Appendix I Conversion Factors for the SI System of Units 597
I.1 Fundamental SI Units 597
I.2 Derived Non-electrical Units 597
I.3 Derived Electrical Units 598
I.4 Conversions 598
  I.4.1 Length 598
  I.4.2 Area 599
  I.4.3 Volume 599
  I.4.4 Mass and density 600
  I.4.5 Velocity and acceleration 600
I.4.6 Force 601
  I.4.7 Torque 601
  I.4.8 Power 601
  I.4.9 Energy and work 601
  I.4.10 Pressure 602
  I.4.11 Moment of inertia and momentum 603
  I.4.12 Illumination 603
  I.4.13 Electricity and magnetism 604
  I.4.14 Miscellaneous quantities 604
I.5 International Standards Organisation (ISO) Conditions 605
I.6 Standard Temperature and Pressure (STP) Conditions 605
I.7 Regularly Used Constants 605
I.8 Regularly Used Prefixes 606
I.9 References 606

Index 607

Foreword

The oil, gas and petrochemical industries depend for safe and efficient operation on their electrical supply and equipment. There have been huge advances in electrical engineering in the last 50 years and thus a need for a comprehensive book on a very sophisticated and complex subject.

When an experienced engineer is considering retirement it is very sad if all his carefully acquired knowledge disappears. I am therefore delighted that Dr Alan Sheldrake has taken the trouble to record his knowledge in this book. He covers both the design of the electrical supply and the specification of the equipment needed in modern oil, gas and petrochemical plants. The book covers generation, supply, protection, utilisation and safety for a site which is brimming with potential hazards and reliability requirements. As a consulting engineer I experienced many of the design problems that are explained here, I only wish this book had been available then for reference with its detailed explanations and specifications.

This is a book that every electrical engineer working in the petrochemical industry should have on his desk. In my time I have read many books on this subject but never one as comprehensive as this. It should be read by every young engineer and dipped into by the more experienced engineer who wants to check their designs. Students will find the theory section useful in their studies.

This book is well laid out for easy reference, contains many worked examples and has a good index for those who do not have not the time to read it from cover to cover.

Dr David A. Jones FREng FIEE FRSA MRI
Past President, Institution of Electrical Engineers
Former Consulting Engineer

Preface

This book can be used as a general handbook for applying electrical engineering to the oil, gas and petrochemical industries. The contents have been developed from a series of lectures on electrical power systems, given to oil company staff and university students, in various countries. The author has condensed many years of his knowledge and practical experience into the book.

The book includes summaries of the necessary theories behind the design of systems together with practical guidance on selecting most types of electrical equipment and systems that are normally encountered with offshore production platforms, drilling rigs, onshore gas plants, pipelines, liquefied natural gas plants, pipeline pumping stations, refineries and chemical plants.

The intention has been to achieve a balance between sufficient mathematical analysis and as much practical material as possible. An emphasis has been put on the 'users' point of view because the user needs to know, or be able to find out quickly, the information that is of immediate application in the design of a plant. The subjects described are those most frequently encountered by electrical engineers in the oil industry. References are frequently made to other texts, published papers and international standards for guidance and as sources of further reading material.

Power systems used in these industries have characteristics significantly different from those found in large-scale power generation and long-distance transmission systems operated by public utility industries. One important difference is the common use of self-contained generating facilities, with little or no reliance upon connections to the public utility. This necessitates special consideration being given to installing spare and reserve equipment and to their interconnection configurations. These systems often have very large induction motors that require being started direct-on-line. Their large size would not be permitted if they were to be supplied from a public utility network. Therefore the system design must ensure that they can be started without unduly disturbing other consumers.

Rule-of-thumb examples are given so that engineers can make quick and practical estimates, before embarking upon the more detailed methods and the use of computer programs. Detailed worked examples are also given to demonstrate the subject with practical parameters and data. Some of these examples may at first seem rather lengthy, but the reasoning behind such detail is explained. In most cases they have been based on actual situations. These worked examples can easily be programmed into a personal computer, and the step-by-step results could be used to check the coding of the programs. Once programmed it is an easy exercise to change the input data to suit the particular problem at hand, and thereby obtain a useful result in a very short period of time.

The chapters have been set out in a sequence that generally represents the approach to engineering and designing a project. The first step is to estimate a total power consumption or load for a plant. Then it is necessary to decide how this load is to be supplied. For example the supply could be from a utility intake, by captive generators or by a combination of both supplies.

Thereafter the problem is to develop a suitable distribution system that will contain a wide variety of equipment and machinery. These equipments and machinery are subsequently covered in the later chapters.

The appendices contain comprehensive listings of abbreviations in common use, international standards that are most relevant, conversion factors for units of measure, detailed worked examples of calculations, the IEEE numbering system for protective and control devices with a commentary pertaining to its use in the oil industry.

All the diagrams and graphs were drawn from a graphics package that was driven by Fortran 77 programs, which were specifically written by the author for this book.

This edition of the book is the first, and the author will be most encouraged to receive any comments, suggestions or additions that could be added to future editions.

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About the Author

The author began his career in the electrical power generating industry in 1960 as an apprentice with UK Central Electricity Generating Board (CEGB), in a coal-burning steam power station. He gained six years' experience in all aspects of the maintenance and operation of the station. He remained with the CEGB until 1975, during which time he worked in the commission, research and development, and planning departments of the CEGB.

Since 1975 he has worked in the oil, gas and petrochemical industries on projects located in many different parts of the world. He has been employed by a series of well-known engineering companies. Most of this work has been in the detailed design and conceptual design of power generating plants for offshore platforms, gas plants, LNG plants, fertiliser plants and refineries. He has held positions as Lead Electrical Engineer and Senior Electrical Engineer, Project Manager of multi-discipline projects, Consultant and Company Director. During these projects he has given lectures on various subjects of power generation and distribution, instrumentation and control and safety to groups of the younger engineers at several oil companies. He has been involved in a conference on hazardous area equipment and postgraduate university seminars.

He gained an MSc degree in power systems in 1968 at Imperial College, London, and a PhD in 1976 on a part-time basis also from Imperial College. He is a Fellow of the Institution of Electrical Engineers in UK, a Senior Member of the Institute of Electronic and Electrical Engineers in the USA, and a Fellow of the Institute of Directors in the UK.

1

Estimation of Plant Electrical Load

One of the earliest tasks for the engineer who is designing a power system is to estimate the normal operating plant load. He is also interested in knowing how much additional margin he should include in the final design. There are no ‘hard and fast’ rules for estimating loads, and various basic questions need to be answered at the beginning of a project, for example,

- Is the plant a new, ‘green field’ plant?
- How long will the plant exist e.g. 10, 20, 30 years?
- Is the plant old and being extended?
- Is the power to be generated on site, or drawn from an external utility, or a combination of both?
- Does the owner have a particular philosophy regarding the ‘sparing’ of equipment?
- Are there any operational or maintenance difficulties to be considered?
- Is the power factor important with regard to importing power from an external source?
- If a generator suddenly shuts down, will this cause a major interruption to the plant production?
- Are there any problems with high fault levels?

1.1 PRELIMINARY SINGLE-LINE DIAGRAMS

In the first few weeks of a new project the engineer will need to roughly draft a key single-line diagram and a set of subsidiary single-line diagrams. The key single-line diagram should show the sources of power e.g. generators, utility intakes, the main switchboard and the interconnections to the subsidiary or secondary switchboards. It should also show important equipment such as power transformers, busbars, busbar section circuit breakers, incoming and interconnecting circuit breakers, large items of equipment such as high voltage induction motors, series reactors for fault current limitation, and connections to old or existing equipment if these are relevant and the main earthing arrangements. The key single-line diagram should show at least, the various voltage levels, system frequency, power or volt-ampere capacity of main items such as generators, motors and transformers, switchboard fault current levels, the vector group for each power transformer and the identification names and unique ‘tag’ numbers of the main equipment.

The set of single-line diagrams forms the basis of all the electrical work carried out in a particular project. They should be regularly reviewed and updated throughout the project and issued

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Table 1.1. Voltages used in different countries for generation, distribution and transmission

Low voltage generation and three-phase consumers (volts)	High voltage generation and distribution (kilovolts)		High voltage transmission less than 75 kV (kilovolts)	
910	18	7.2*	70	24.5
660	16	6.9	69*	24
600*	14.4	6.6*	66*	23
525	13.8*	6.5	65	22
500	13.2*	6.3	60	20
480	12.6	6.24	50	19
460	12.5	6*	46	15
440*	12.47	5.5	45	
420	12.4	5	44	
415*	12	4.8	38	
400*	11.5	4.16*	36	
380*	11.4	4	35	
346	11*	3.3*	34.5*	
277	10.4	3*	33*	
260	10	2.4	31.5	
254**	9	2.3	30	
240**	8.9		27.6	
230**	8.4		27.5	
220**	8.3		27	
208	8		25	
200	7.3		24.9	
190				

Notes* Commonly used voltages in the oil industry.
Notes** Commonly used as single-phase voltages.

in their final form at the completion of the project. They act as a diary and record the development of the work. Single-line diagrams are also called ‘one-line diagrams’.

At this stage the engineer can begin to prepare a load schedule for each subsidiary switchboard and motor control centre, and a master schedule for the main switchboard. The development of the single-line diagrams during the project is discussed in sub-section 1.7.

The master load schedule will give an early estimate of the total power consumption. From this can be decided the number of generators and utility intakes to install. The kW and kVA ratings of each generator or intake will be used to determine the highest voltage to use in the power system. Table 1.1 shows typical voltages used throughout the world for generation, distribution and transmission of power at oil industry plants, see also sub-section 3.7.

1.2 LOAD SCHEDULES

Each switchboard will supply power to each load connected to it and in many cases it will also supply power to switchboards or distribution boards immediately downstream. Hence the input power to a switchboard will have the possibility of two components, one local and one downstream. Hereinafter the term switchboard will also include the term motor control centre, see sub-section 7.1.

Each local load may be classified into several different categories for example, vital, essential and non-essential. Individual oil companies often use their own terminology and terms such as ‘emergency’ and ‘normal’ are frequently encountered. Some processes in an oil installation may handle fluids that are critical to the loss of power e.g. fluids that rapidly solidify and therefore must be kept hot. Other processes such as general cooling water services, air conditioning, sewage pumping may be able to tolerate a loss of supply for several hours without any long-term serious effects.

In general terms there are three ways of considering a load or group of loads and these may be cast in the form of questions. Firstly will the loss of power jeopardise safety of personnel or cause serious damage within the plant? These loads can be called ‘vital’ loads. Secondly will the loss of power cause a degradation or loss of the manufactured product? These loads can be called the ‘essential’ loads. Thirdly does the loss have no effect on safety or production? These can be called the ‘non-essential’ loads.

Vital loads are normally fed from a switchboard that has one or more dedicated generators and one or more incoming feeders from an upstream switchboard. The generators provide power during the emergency when the main source of power fails. Hence these generators are usually called ‘emergency’ generators and are driven by diesel engines. They are designed to automatically start, run-up and be closed onto the switchboard whenever a loss of voltage at the busbars of the switchboard is detected. An undervoltage relay is often used for this purpose. Testing facilities are usually provided so that the generator can be started and run-up to demonstrate that it is ready to respond when required. Automatic and manual synchronising facilities can also be provided so that the generator can be loaded during the tests.

Low voltage diesel generators are typically rated between 100 and 500 kW, and occasionally as large as 1000 kW. High voltage emergency generator ratings are typically between 1000 and 2500 kW. The total amount of vital load is relatively small compared with the normal load and, in many situations, the essential load. Consequently the vital load is fed from uninterruptible power supplies (UPS), as AC or DC depending upon the functions needed. The vital loads are usually fed from a dedicated part of the emergency switchboard. The UPS units themselves are usually provided with dual incoming feeders, as shown in Figure 17.3.

Some of the vital and essential loads are required when the plant is to be started up, and there is no ‘normal’ power available. In this situation the starting up of the plant is called ‘black starting’. The emergency generator must be started from a source of power, which is usually a high capacity storage battery and a DC starter motor, or a fully charged air receiver and a pneumatic starter motor.

In many plants, especially offshore platforms, the vital and essential loads operate at low voltage e.g. 380, 400, 415 volts. Large plants such as LNG refrigeration and storage facilities require substantial amounts of essential power during their start-up and shut-down sequences and so high voltage e.g. 4160, 6600 volts is used. The vital loads would still operate at low voltage. Tables 1.2 and 1.3 shows typical types of loads that can be divided into vital and essential loads.

All of the vital, essential and non-essential loads can be divided into typically three duty categories:

- Continuous duty.
- Intermittent duty.
- Standby duty (those that are not out of service).

Table 1.2. Vital and essential AC loads

Vital AC loads	Essential AC loads
UPS supplies	Diesel fuel transfer pumps
Emergency lighting	Main generator auxiliaries
Emergency generator auxiliaries	Main compressor auxiliaries
Helicopter pad lighting	Main pump auxiliaries
Control room supplies	Diesel fire pump auxiliaries
Vital LV pumps	Electric fire pumps
	Living quarters
	Air compressor
	General service water pumps
	Fresh water pumps
	Equipment room HVAC supplies
	Life boat davits
	Anti-condensation heaters in panels and switchboards
	Security lighting supplies
	Control room supplies
	UPS supplies
	Radio supplies
	Computer supplies
	Battery chargers for engine starting systems
	Instrumentation supplies

Table 1.3. Vital DC loads

Public address system
Plant alarm systems
System shutdown system
Telemetry systems
Emergency radio supplies
Fire and gas detection system
Navigation aids

Hence each switchboard will usually have an amount of all three of these categories. Call these C for continuous duty, I for intermittent duty and S for the standby duty. Let the total amount of each at a particular switchboard j be $C_{j\text{sum}}$, $I_{j\text{sum}}$ and $S_{j\text{sum}}$. Each of these totals will consist of the active power and the corresponding reactive power.

In order to estimate the total consumption for the particular switchboard it is necessary to assign a diversity factor to each total amount. Let these factors be D_{cj} for $C_{\text{sum}j}$, D_{ij} for $I_{\text{sum}j}$ and D_{sj} for $S_{\text{sum}j}$. Oil companies that use this approach have different values for their diversity factors, largely based upon experience gained over many years of designing plants. Different types of plants may warrant different diversity factors. Table 1.4 shows the range of suitable diversity factors. The factors should be chosen in such a manner that the selection of main generators and main feeders from a power utility company are not excessively rated, thereby leading to a poor choice of equipment in terms of economy and operating efficiency.

Table 1.4. Diversity factors for load estimation

Type of project	D_c for C_{sum}	D_i for I_{sum}	D_s for S_{sum}
Conceptual design of a new plant	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Front-end design of a new plant (FEED)	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Detail design in the first half of the design period	1.0 to 1.1	0.5 to 0.6	0.0 to 0.1
Detail design in the second half of the design period	0.9 to 1.0	0.3 to 0.5	0.0 to 0.2
Extensions to existing plants	0.9 to 1.0	0.3 to 0.5	0.0 to 0.2

The above method can be used very effectively for estimating power requirements at the beginning of a new project, when the details of equipment are not known until the manufacturers can offer adequate quotations. Later in a project the details of efficiency, power factor, absorbed power, rated current etc. become well known from the purchase order documentation. A more accurate form of load schedule can then be justified. However, the total power to be supplied will be very similar when both methods are compared.

The total load can be considered in two forms, the total plant running load (TPRL) and the total plant peak load (TPPL), hence,

$$\text{TPRL} = \sum_{j=1}^{n} (D_c C_{\text{sum}j} + D_i I_{\text{sum}j}) \quad \text{kW}$$

$$\text{TPPL} = \sum_{j=1}^{n} (D_c C_{\text{sum}j} + D_i I_{\text{sum}j} + D_s S_{\text{sum}j}) \quad \text{kW}$$

Where n is the number of switchboards.

The installed generators or the main feeders to the plant must be sufficient to supply the TPPL on a continuous basis with a high load factor. This may be required when the production at the plant is near or at its maximum level, as is often the case with a seasonal demand.

Where a plant load is predominantly induction motors it is reasonable to assume the overall power factor of a switchboard to be 0.87 lagging for low voltage and 0.89 lagging for high voltage situations. If the overall power factor is important with regard to payment for imported power, and where a penalty may be imposed on a low power factor, then a detailed calculation of active and reactive powers should be made separately, and the total kVA determined from these two totals. Any necessary power factor improvement can then be calculated from this information.

1.2.1 Worked Example

An offshore production and drilling platform is proposed as a future project, but before the detail design commences it is considered necessary to prepare an estimate of the power consumption. The results of the estimate will be used to determine how many gas-turbine driven generators to install.

Table 1.5. Subsidiary load schedule for the low voltage process switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Production area lighting	2	75	150	0	0
Glycol pumps	4	2	4	0	4
Glycol reboilers	2	75	75	0	75
Glycol transfer pump	1	15	15	0	0
Refrigeration compressor	3	160	320	0	160
Deareator vacuum pumps	2	30	30	0	30
Water injection booster pumps	4	90	270	0	90
Deareator chem. injection pumps	4	2	4	0	4
Sea drain sump pumps	1	10	10	0	0
Water inj. chem. injection pumps	6	2	8	0	4
Reclaim oil pumps	2	37	37	37	0
Treated water pumps	2	132	132	132	0
Oil transfer pumps	4	10	30	10	0
Electric gas heating	2	300	300	0	300
HP gas comp. pre-lube pumps	2	5	5	0	5
2 × HP gas comp. auxiliaries	2	—	35	35	100
LP gas comp. pre-lube pumps	2	5	5	0	5
2 × LP gas comp. auxiliaries	2	—	35	35	100
4 × water inj. pump auxiliaries	4	—	70	70	200
Corrosion inhibitor pumps	1	37	37	0	0
Trace heating	2	40	80	0	0
Sub-totals for the switchboard			1652	319	1077

Normal running load for the switchboard = $(1.0 \times 1652) + (0.5 \times 319) + (0.1 \times 1077) = 1920$ kW

Table 1.6. Subsidiary load schedule for the low voltage utilities switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Utilities area lighting	2	75	150	0	0
Potable water pumps	2	5	5	5	0
Living quarters feeder-A(on)	1	500	300	200	0
Living quarters hot water pumps	2	15	15	15	0
Control room supplies	1	15	15	0	0
Computer supplies	2	15	15	0	15
Radio supplies	2	30	30	0	30
Instrument air compressor	2	90	90	0	90
Instrument air driers	2	10	10	0	10
Plant air compressors	2	90	90	0	90
HVAC fans	16	11	88	0	88
HVAC main air handling unit	1	30	30	0	0
HVAC standby air handling unit	1	10	0	0	10
HVAC refrigeration unit	1	15	15	0	0
Gas turbo-generator auxiliaries	4	—	100	100	300
Trace heating	2	30	60	0	0
Sub-totals for the switchboard			1013	320	600

Normal running load for the switchboard = $(1.0 \times 1013) + (0.5 \times 320) + (0.1 \times 633) = 1236$ kW

This in turn will enable an initial layout of all the facilities and equipment to be proposed. Since this is a new plant and the preliminary data is estimated from process calculations, mechanical calculations and comparisons with similar plants, it is acceptable to use the following diversity factors, $D_c = 1.0$, $D_i = 0.5$ and $D_s = 0.1$.

Tables 1.5, 1.6, 1.7 and 1.8 show the individual loads that are known at the beginning of the project.

The total power is found to be 12,029 kW. At this stage it is not known whether the plant is capable of future expansion. The oil and gas geological reservoir may not have a long life expectation, and the number of wells that can be accommodated on the platform may be limited. The 4000 kW of power consumed by the drilling operations may only be required for a short period of time e.g. one year, and thereafter the demand may be much lower.

Table 1.7. Subsidiary load schedule for the low voltage emergency switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
Emergency lighting	1	75	75	0	0
Chlorine generator	1*	30	30	0	0
Desalination unit	1*	75	75	0	0
Potable water pumps	1	5	5	0	0
Instrument air compressors	1	90	90	0	0
Instrument air driers	1	10	10	0	0
Living quarters feeder-B(off)	1*	500	0	0	0
Living quarters emergency feeder	1	100	50	50	0
Living quarters hot water pumps	1	15	15	0	0
Diesel fuel transfer pump	1	5	5	0	0
Emergency diesel eng. sump heater	1	3	3	0	0
Emergency diesel gen. auxiliaries	1	2	0	0	2
Emergency diesel eng. bat. charger	1	1	0	1	0
Emergency diesel eng. room fans	2	11	11	0	0
Control room fans	2	22	22	0	0
Computer UPS supply	1	5	5	0	0
Emergency radio supplies	1	10	0	0	10
Navigation aids UPS supply	1	10	10	0	0
Life boat davit supplies	2	37	0	50	24
Life boat diesel heater supplies	2	4	4	4	0
Fire pump engine battery chargers	2	22	22	22	0
Seawater washdown pump	1*	37	0	37	0
Anti-condensation swbd heaters	—	25	25	0	0
Anti-condensation motor heaters	—	25	10	15	0
Portable lighting supplies	1	1	1	0	0
Sub-totals for the switchboard			468	179	58

Normal running load for the switchboard = $(1.0 \times 468) + (0.5 \times 179) + (0.1 \times 58) = 563$ kW

For black start delete loads marked (*)

Black start sub-totals for the switchboard = $(1.0 \times 363) + (0.5 \times 142) + (0.1 \times 0) = 434$ kW

Table 1.8. Master load schedule for the high voltage main switchboard

Description of load	No. of units	Nameplate ratings of each unit (kW)	Continuous power consumed (kW)	Intermittent power consumed (kW)	Standby power consumed (kW)
HV motor loads					
Main oil expert pumps	3	650	1300	0	650
Gas compressor	4	500	1500	0	500
Seawater lift pumps	4	450	1350	0	450
LV motor loads					
Feeder to drilling	1	0	2700	2400	1000
Feeder to LV process MCC	2	0	1652	319	1077
Feeder to LV utilities MCC	1	0	1013	320	633
Feeder to LV emergency MCC	1	0	168	179	58
Sub-totals			9983	3218	4368

Totals for the main generator to supply $= (1.0 \times 9983) + (0.5 \times 3218) + (0.1 \times 4368) = 12{,}029$ kW

During the detail design phase of the project the load schedules will be modified and additional loads will inevitably be added. At least 10% extra load should be added to the first estimate i.e. 1203 kW. The total when rounded-up to the nearest 100 kW would be 13,300 kW.

Sufficient generators should be installed such that those that are necessary to run should be loaded to about 80 to 85% of their continuous ratings, at the declared ambient temperature. This subject is discussed in more detail in sub-section 1.3. If four generators are installed on the basis that one is a non-running standby unit, then three must share the load. Hence a reasonable power rating for each generator is between 5216 kW and 5542 kW.

1.3 DETERMINATION OF POWER SUPPLY CAPACITY

After the load has been carefully estimated it is necessary to select the ratings and numbers of generators, or main incoming feeders from a power utility company. Occasionally a plant may require a combination of generators and incoming feeders e.g. refinery, which may operate in isolation or in synchronism with the utility company.

Usually a plant has scope for expansion in the future. This scope may be easy to determine or it may have a high degree of uncertainty. The owner may have strong reasons to economise initially and therefore be only willing to install enough capacity to meet the plant requirements in the first few years of operation. If this is the case then it is prudent to ensure that the switchgear in particular has adequate busbar normal current rating and fault current rating for all future expansion. The main circuit breakers should be rated in a similar manner. If the switchgear is rated properly at the beginning of a project, then all future additions should be relatively easy to achieve in a practical and economical manner. Such an approach also leads to a power system that is easy to start up, operate and shut down.

The supply capacity normally consists of two parts. One part to match the known or initial consumption and a second part to account for keeping a spare generator or feeder ready for service.

Any allowance required for future load growth should be included in the power consumption calculations. This two-part approach is often referred to as the '$N - 1$ philosophy', where N is the number of installed generators or feeders. The philosophy is that under normal operating conditions in a fully load plant $N - 1$ generators or feeders should be sufficient to supply the load at a reasonably high load factor.

Let P_l = power consumption required at the site ambient conditions
P_g = rated power of each generator or feeder at the site ambient conditions
F_o = overload power in % when one generator or feeder is suddenly switched out of service
F_i = load factor in % of each generator or feeder before one is switched out of service
N = number of installed generators or feeders. N is usually between 4 and 6 for an economical design of a generating plant and 2 or 3 for feeders.

P_l and P_g are usually the known variables, with F_i and F_o being the unknown variables. Several feasible ratings of P_g may be available and the value of N may be open to choice. A good choice of P_g and N will ensure that the normally running load factor is high i.e. between 70% and 85%, whilst the post-disturbance overload on the remaining generators or feeders will not be so high that they trip soon after the disturbance, i.e. less than 125%.

The initial load factor can be found as,

$$F_i = \frac{100P_l}{P_g(N-1)}\%$$

The post-disturbance overload can be found as,

$$F_o = \frac{100P_l}{P_g(N-2)}\%$$

If it is required that F_i is chosen for the design such that $F = 100\%$ and no overload occurs then let F be called F_{i100} and so,

$$F_{i100} = \frac{(N-2)100}{N-1} \quad \text{for no overloading.}$$

Table 1.9 shows the values of F_i against N for the no overloading requirement.

Table 1.9. Selecting N and F_{i100} on the basis of $N - 1$ capacity with overloading not tolerated

No. of installed generator or feeders N	Value of F_{i100} to ensure no overloading $F_{i100}\%$
2	Not practical
3	50.0
4	66.67
5	75.00
6	80.00
7	83.33
8	86.71

Table 1.10 shows the values of the load factor F_i and the overload factor F_o for a range of typical power consumptions P_l. The values of P_g are the site requirements and relate approximately to the ratings of gas-turbine generators that are available and used in the oil industry i.e. 2.5 to 40.0 MW.

The table was compiled by constraining F_i and F_o to be within good practical limits,

$$66.7\% \leqslant F_i \leqslant 90.0\%$$

and

$$80 \leqslant F_o \leqslant 125\%$$

Table 1.10. Selecting generator ratings on the basis of $N - 1$ capacity with tolerance of overloading

Power consumption (MW) P_l	Initial load factor (%) F_i	Number of installed generators N	Generator rating at site conditions (MW) P_g	Turbine ISO ratings for a site amb. temp of 40°C (MW) P_{iso40}	Final load factor (%) F_o
10	66.7	4	5.0	5.9	100.0
10	74.1	4	4.5	5.3	111.1
10	83.3	4	4.0	4.7	125.0
10	71.4	5	3.5	4.1	95.2
10	83.3	5	3.0	3.5	111.1
10	66.7	6	3.0	3.5	83.3
10	80.0	6	2.5	2.9	100.0
15	66.7	4	7.5	8.8	100.0
15	75.0	5	5.0	5.9	100.0
15	83.3	5	4.5	5.3	111.1
15	66.7	6	4.5	5.3	83.3
15	75.0	6	4.0	4.7	93.8
15	85.7	6	3.5	4.1	107.1
20	66.7	4	10.0	11.8	100.0
20	66.7	5	7.5	8.8	89.9
20	80.0	6	5.0	5.9	100.0
20	88.9	6	4.5	5.3	111.1
25	69.4	4	12.0	14.1	104.2
25	83.3	4	10.5	11.8	125.0
25	83.3	5	7.5	8.8	111.1
25	66.7	6	7.5	8.8	83.3
30	71.4	4	14.0	16.5	107.1
30	83.3	4	12.0	14.1	125.0
30	75.0	5	10.0	11.8	100.0
30	80.0	6	7.5	8.8	100.0
40	66.7	4	20.0	23.5	100.0
40	74.1	4	18.0	21.2	111.1
40	83.3	4	16.0	18.8	125.0
40	71.4	5	14.0	16.5	95.2
40	83.3	5	12.0	14.1	111.1
40	66.7	6	12.0	14.1	83.3

Table 1.10. (*continued*)

Power consumption (MW) P_l	Initial load factor (%) F_i	Number of installed generators N	Generator rating at site conditions (MW) P_g	Turbine ISO ratings for a site amb. temp of 40°C (MW) P_{iso40}	Final load factor (%) F_o
40	80.0	6	10.0	11.8	100.0
60	66.7	4	30.0	35.3	100.0
60	72.7	4	27.5	32.4	109.1
60	80.0	4	25.0	29.4	120.0
60	66.7	5	22.5	26.5	88.9
60	75.0	5	20.0	23.5	100.0
60	83.3	5	18.0	21.2	111.1
60	66.7	6	18.0	21.2	83.3
60	75.0	6	16.0	18.8	93.8
60	85.7	6	14.0	16.5	107.1
80	66.7	4	40.0	47.1	100.0
80	76.2	4	35.0	41.2	114.3
80	66.7	5	30.0	35.3	88.9
80	72.7	5	27.5	32.4	97.0
80	80.0	5	25.0	29.4	106.7
80	88.9	5	22.5	26.5	118.5
80	71.1	6	22.5	26.5	88.9
80	80.0	6	20.0	23.5	100.0
80	88.9	6	18.0	21.2	111.1
100	83.3	4	40.0	47.1	125.0
100	71.4	5	35.0	41.2	95.2
100	83.3	5	30.0	35.3	111.1
100	66.7	6	30.0	35.3	83.3
100	72.7	6	27.5	32.4	91.9
100	80.0	6	25.0	29.4	100.0
100	88.9	6	22.5	26.5	111.1

In practice if F_i is too high the operator of the plant will become nervous and will often switch into service the spare generator. If F_i is too low then there will be too many generators in service and it should be possible to withdraw one. Gas turbines have poor fuel economy when they are lightly loaded.

High values of F_o should be avoided because of the risk of cascade tripping by the gas turbines. The margin of overload that a gas turbine can tolerate is relatively small and varies with the turbine design. The higher the normal combustion temperature within the turbine, the lower the tolerance is usually found to be available. A high overload will also be accompanied by a significant fall in electrical system frequency, caused by the slowing down of the power turbine and the relatively long time taken by the speed governing system to respond. Many power systems that use gas-turbine generators are provided with underfrequency and overfrequency protective relays, and these may be set to trip the generator when a high overload occurs. The initial rate of decline in frequency is determined by the moment of inertia of the power turbine, plus the generator rotor, and the magnitude of the power change seen at the terminals of the generator. See Reference 1. This subject is discussed and illustrated in sub-section 12.2.10 and Appendix D.

If F_o is designed to be less than approximately 105% then the generators will be able to absorb the overload until some corrective action by an operator is taken e.g. puts the spare generator into service.

However, it is also possible to introduce a high-speed load shedding scheme into the power system when F_o is found to be above 105%. Such a scheme will compute in an anticipatory manner how much consumption should be deleted in the event of a loss of one generator. The designer will be able to predetermine enough low priority consumers to achieve the necessary corrective action. See Chapter 16.

The application of the $N - 1$ philosophy is less complicated with incoming feeders e.g. underground cables, overhead lines. N is usually chosen as 2 because it is not usually economical to use three or more feeders for one switchboard. Both feeders are usually in service and so the 'spare' does not usually exist. However, each feeder is rated to carry the full demand of the switchboard. Therefore with both in service each one carries half of the demand, and can rapidly take the full demand if one is switched out of service. This approach also enables a feeder to be taken out service for periodic maintenance, without disturbing the consumers.

1.4 STANDBY CAPACITY OF PLAIN CABLE FEEDERS AND TRANSFORMER FEEDERS

In sub-section 1.2 the three ways of considering consumers were discussed, and the terms, vital, essential and non-essential were introduced. Because of the sensitive nature of the vital and essential consumers with regard to personnel safety and production continuity, it is established practice to supply their associated switchboards with dual, or occasionally triple, feeders. For non-essential switchboards it may be practical to use only one feeder.

For switchboards other than those for the generator or intake feeders it is established practice to add some margin in power capacity of their feeders so that some future growth can be accommodated. The margin is often chosen to be 25% above the TPPL.

If the feeders are plain cables or overhead lines then it is a simple matter to choose their cross-sectional areas to match the current at the 125% duty.

For transformer feeders there are two choices that are normally available. Most power transformers can be fitted with external cooling fans, provided the attachments for these fans are included in the original purchase order. It is common practice to order transformers initially without fans and operate them as ONAN until the demand increases to justify the fan cooling. Thereafter the transformer is operated as ONAF, see sub-section 6.5. Adding fans can increase the capacity of the transformer by 25% to 35%, depending upon the particular design and ambient conditions. The alternative choice is simply to rate the ONAN transformer for the 125% duty, and initially operate it at a lower level. The decision is often a matter of economics and an uncertainty about the future growth.

When standby or future capacity is required for transformers it is necessary to rate the secondary cables or busbars correctly at the design stage of the project. Likewise the secondary circuit breakers and switchgear busbars need to be appropriately rated for the future demand. The decision to over-rate the primary cables or lines may be made at the beginning of the project or later when demand increases. Again this is a matter of economics and forecasting demand.

1.5 RATING OF GENERATORS IN RELATION TO THEIR PRIME MOVERS

1.5.1 Operation at Low Ambient Temperatures

In some countries the ambient temperature can vary significantly over a 24-hour period, and its average daily value can also vary widely over a 12-month period. The power plant designer should therefore ascertain the minimum and maximum ambient temperatures that apply to the plant. The maximum value will be used frequently in the sizing and specification of equipment. The minimum value will seldom be used, but it is very important when the sizing of generators and their prime movers are being examined.

Prime movers will produce more output power at their shafts when the ambient temperature is low. The combustion air in the prime mover is taken in at the ambient temperature. Gas turbines are more sensitive to the ambient air temperature than are piston engines.

If the ambient temperature is low for long periods of time then the power plant can generate its highest output, which can be beneficial to the plant especially if a seasonal peak demand occurs during this period of low temperature. In some situations a generator may be able to be taken out of service, and hence save on wear and tear, and fuel.

With this in mind the generator rating should exceed that of the prime mover when power is required at the low ambient temperature. A margin of between 5% and 10% should be added to the prime mover output to obtain a suitable rating for the generator. It should be noted that when the output of a prime mover is being considered, it should be the output from the main gearbox if one is used. Gearbox losses can amount to 1% to 2% of rated output power.

1.5.2 Upgrading of Prime Movers

Some prime movers, especially new designs, are conservatively rated by their manufacturer. As the years pass some designs are upgraded to produce more power. As much as 10% to 15% can be increased in this manner. If the power system designer is aware of this potential increase in rating then the generator rating should be chosen initially to allow for this benefit. At the same time the cables and switchgear should be rated accordingly.

Situations occur, especially with offshore platforms, where no physical space is available to install an extra generator and its associated equipment. Sometimes the main switchrooms cannot accept any more switchgear, not even one more generator circuit breaker. Therefore the potential for upgrading a prime mover without having to make major changes to the electrical system is an option that should be considered seriously at the beginning of a project.

1.6 RATING OF MOTORS IN RELATION TO THEIR DRIVEN MACHINES

The rating of a motor should exceed that of its driven machine by a suitable margin. The selection of this margin is often made by the manufacturer of the driven machine, unless advised otherwise. The actual choice depends on various factors e.g.

Table 1.11. Ratio of motor rating to the driven machine rating

Approximate rating of the motor or machine (kW)	Margin of the motor rating above the machine rating (%)
Up to 15	125
16.0 to 55	115
Above 55	110

- The absolute rating of either the motor or the driven machine i.e. small or large machines.
- The function of the driven machine e.g. pump, compressor, fan, crane, conveyor.
- Expected operating level e.g. often near to maximum performance, short-term overloading permitted.
- Shape of the operating characteristic of the machine e.g. pressure (head) versus liquid flow rate in a pump.
- Change in energy conversion efficiency of the machine over its working range.
- Machine is driven at nearly constant speed.
- Machine is driven by a variable speed motor.
- Harmonic currents will be present in the motor.
- The nearest standard kW rating available of the motor.
- Ambient temperature.

Some rule-of-thumb methods are often stated in the purchasing specifications of the motor–machine unit, see for example Table 1.11, which applies to low voltage three-phase induction motors.

Where the driven machine is a centrifugal type i.e. pump or compressor, the shaft power may be taken as that which occurs at the ‘end of curve’ operating point. This rule-of-thumb point is defined as being 125% of the power required at the maximum operating efficiency point on the designed curve of pressure (head) versus fluid flow rate, at the rated shaft speed.

These rule-of-thumb methods can be used to check the declared performance and ratings from a machine manufacturer.

1.7 DEVELOPMENT OF SINGLE-LINE DIAGRAMS

Single-line diagrams are the most essential documents that are developed during the detail design phase of a project. They identify almost all the main items of power equipment and their associated ancillaries. Initially they define the starting point of a project. Finally they are a concise record of the design, from which all the design and purchasing work evolved.

The final single-line diagrams should contain at least the following information. Complicated power systems may require the single-line diagrams to be sub-divided into several companion diagrams, in which aspects such as protection, interlocking and earthing are treated separately. This ensures that the diagrams are not overly congested with information. The end results should be unambiguous and be easily read and understood by the recipient.

1.7.1 The Key Single Line Diagram

Switchboards and motor control centres:

- All switchboards and motor control centre names, bus-section numbers, line voltages, number of phases, number of wires, frequency, busbar continuous current rating.
- Identification of main incoming, bus-section, outgoing and interconnecting circuit breakers, including spare and unequipped cubicles.
- Some diagrams show the cable tag number of the principal cables.

Generators:

- Names and tag numbers.
- Nominal ratings in MVA or kVA and power factor.
- D-axis synchronous reactance in per-unit.
- D-axis transient reactance in per-unit.
- D-axis sub-transient reactance in per-unit.
- Neutral earthing arrangements, e.g. solid, with a neutral earthing resistance (NER), with a common busbar, switches or circuit breakers for isolation.
- Current and time rating of the NER if used, and the voltage ratio of the earthing transformer if used.

Transformer feeders:

- Names and tag numbers.
- Nominal ratings in MVA or kVA.
- Leakage impedance in per-unit.
- Symbolic winding arrangement of the primary and secondary.
- Line voltage ratio.

High voltage and large low voltage motors:

- Names and tag numbers.
- Nominal ratings in kW.

General notes column or box:

Usually several notes are added to the diagram to explain unusual or particular features, such as interlocking, limitations on impedance values for fault currents or voltdrop.

1.7.2 Individual Switchboards and Motor Control Centres

- Switchboards and motor control centre name and tag number.
- Bus-section numbers or letters.
- Cubicle numbers or letters.

- Line voltage, number of phases, number of wires, frequency, busbar continuous current rating.
- Busbar nominal fault breaking capacity in kA at 1 or 3 seconds.
- Identification of all circuit breakers, fuse-contactor units, and their nominal current ratings.
- Neutral earthing arrangements, e.g. connections to the incomers.
- Protective devices of all incomers, bus-section circuit breakers, busbars, and outgoing circuits.
- Interlocking systems in schematic form.
- Local and remote indication facilities.
- Details of special devices such as transducers, automatic voltage regulators, synchronising schemes, fault limiting reactors, reduced voltage motor starters, busbar trunking.
- Rating, ratio and accuracy class of current and voltage transformers.
- Identification of spare and unequipped cubicles.
- References to other drawing numbers, e.g. continuation of a switchboard, associated switchgear, drawing in the same series, legend drawing, cables schedule and protective relay schedule.
- Column or box for detailed notes.
- Column or box for legend of symbols.

1.8 COORDINATION WITH OTHER DISCIPLINES

At the earliest practical time in a project the engineers will need to identify areas of engineering and design where interfaces are necessary. An efficient system of communication and exchange of information should be established and implemented at regular intervals. Meetings should be arranged to discuss problem areas and short-falls in information. The following generally summarises what is needed, particularly during the feasibility and conceptual stage of a project.

In order to be able to engineer an economical and efficient power system it is desirable for the electrical engineer to have:

- A basic understanding of the hydrocarbon and chemical processes and their supporting utilities e.g. compression, pumping, control and operation, cooling arrangements.
- A procedure for regular communication with engineers of other disciplines, e.g. instrument, process, mechanical, safety, telecommunications, facilities, operations and maintenance.
- An appreciation of the technical and economical benefits and shortcomings of the various electrical engineering options that may be available for a particular project.
- The technical flexibility to enable the final design to be kept simple, easy to operate and easy to maintain.

1.8.1 Process Engineers

The process engineers should be able to inform the electrical engineers on matters relating to the production processes and supporting utilities e.g.:

- Oil, gas, condensate and product compositions and rates, and their method of delivery to and from a plant.
- Variation of production rates with time over the anticipated lifetime of the plant.

- Fuel availability, rates and calorific values, pollution components e.g. sulphur, carbon dioxide, alkali contaminants, particle size and filtration.
- Electrical heating and refrigeration loads, trace heating of vessels and piping.
- Make available process flow diagrams, process and instrumentation diagrams, utilities and instrumentation diagrams.

1.8.2 Mechanical Engineers

The mechanical engineers will normally need to advise on power consumption data for rotating machines, e.g. pumps, compressors, fans, conveyors, and cranes. They will also advise the power output options available for the different types and models of prime movers for generators, e.g. gas turbines, diesel engines, gas engines.

In all cases the electrical engineer needs to know the shaft power at the coupling of the electrical machine. He is then able to calculate or check that the electrical power consumption is appropriate for the rating of the motor, or the power output is adequate for the generator.

The mechanical engineer will also advise on the necessary duplication of machinery, e.g. continuous duty, maximum short-time duty, standby duty and out-of-service spare machines. He will also give some advice on the proposed method of operation and control of rotating machines, and this may influence the choice of cooling media, construction materials, types of bearings, ducting systems, sources of fresh air, hazardous area suitability, etc.

The electrical engineer should keep in close ‘contact’ with the progress of machinery selection during the early stages of a project up to the procurement stage in particular, so that he is sure the electrical machines and their associated equipment are correctly specified. Likewise after the purchase orders are placed he should ensure that he receives all the latest manufacturers’ data relating to the electrical aspects, e.g. data sheets, drawings, changes, hazardous area information. See also Chapter 19 and Appendix E.

1.8.3 Instrument Engineers

The process and instrument engineers will generally develop the operation and control philosophies for individual equipments and overall schemes. The electrical engineer should then interface to enable the following to be understood:

- Interlocking and controls that affect motor control centres and switchboards, generator controls, control panels, local and remote stations, mimic panels, SCADA, computer networking, displays in the CCR and other locations.
- Cabling specifications and requirements, e.g. screening, numbers of cores, materials, earthing, routing, segregation and racking of cables.
- Power supplies for control systems, AC and DC, UPS requirements, battery systems.
- Symbolic notation, e.g. tag numbers, equipment names and labels, cable and core numbering systems.

1.8.4 Communication and Safety Engineers

The communication and safety engineers will be able to advise on power supply requirements for:

- Radar, radio, telecommunications and public address.
- Aids to navigation, e.g. lamps, beacons, foghorns, sirens; also alarms, lifeboat davits, etc.
- Emergency routing and exit lighting systems.
- Supplies for emergency shut-down systems.

1.8.5 Facilities and Operations Engineers

These engineers do not normally contribute any power consumption data, but their input to the work of the electrical engineer is to advise on subjects such as equipment layout, access to equipment, maintainability, maintenance lay-down space, emergency exit routing, operational philosophies of plant and systems, hazardous area classification.

REFERENCE

1. J. L. Blackburn, *Applied protective relaying*. Westinghouse Electric Corporation (1976). Newark, NJ 07101, USA. Library of Congress Card No. 76-8060.

2

Gas Turbine Driven Generators

2.1 CLASSIFICATION OF GAS TURBINE ENGINES

For an individual generator that is rated above 1000 kW, and is to be used in the oil industry, it is usual practice to use a gas turbine as the driving machine (also called the prime mover). Below 1000 kW a diesel engine is normally preferred, usually because it is an emergency generator running on diesel oil fuel.

Gas turbines can be classified in several ways, common forms are:-

- Aero-derivative gas turbines.
- Light industrial gas turbines.
- Heavy industrial gas turbines.

2.1.1 Aero-derivative Gas Turbines

Aircraft engines are used as ‘gas generators’, i.e. as a source of hot, high velocity gas. This gas is then directed into a power turbine, which is placed close up to the exhaust of the gas generator. The power turbine drives the generator. The benefits of this arrangement are:-

- Easy maintenance since the gas generator can be removed as a single, simple module. This can be achieved very quickly when compared with other systems.
- High power-to-weight ratio, which is very beneficial in an offshore situation.
- Can be easily designed for single lift modular installations.
- Easy to operate.
- They use the minimum of floor area.

The main disadvantages are:-

- Relatively high costs of maintenance due to short running times between overhauls.
- Fuel economy is usually lower than other types of gas turbines.
- The gas generators are expensive to replace.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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Aero-derivative generators are available in single unit form for power outputs from about 8 MW up to about 25 MW. These outputs fall conveniently into the typical power outputs required in the oil and gas production industry, such as those on offshore platforms.

2.1.2 Light Industrial Gas Turbines

Some manufacturers utilize certain of the advantages of the aero-derivative machines, i.e. high power-to-weight ratio and easy maintenance. The high power-to-weight ratios are achieved by running the machines with high combustion and exhaust temperatures and by operating the primary air compressors at reasonably high compression ratios i.e. above 7. A minimum of metal is used and so a more frequent maintenance programme is needed. Easier maintenance is achieved by designing the combustion chambers, the gas generator and compressor turbine section to be easily removable as a single modular type of unit. The ratings of machines in this category are limited to about 10 MW.

2.1.3 Heavy Industrial Gas Turbines

Heavy industrial gas turbines are usually to be found in refineries, chemical plants and power utilities. They are chosen mainly because of their long and reliable running times between major maintenance overhauls. They are also capable of burning most types of liquid and gaseous fuel, even the heavier crude oils. They also tend to tolerate a higher level of impurities in the fuels. Heavy industrial machines are unsuitable for offshore applications because:-

- Their poor power-to-weight ratio means that the structures supporting them would need to be much larger and stronger.
- Maintenance shutdown time is usually much longer and is inconvenient because the machine must be disassembled into many separate components. A modular concept is not possible in the design of these heavy industrial machines.
- The thermodynamic performance is usually poorer than that of the light and medium machines. This is partly due to the need for low compression ratios in the compressor.

They do, however, lend themselves to various methods of heat energy recovery e.g. exhaust heat exchangers, recuperators on the inlet air.

Figures 2.1 and 2.2 show the relative costs and weights for these types of machines.

2.1.4 Single and Two-shaft Gas Turbines

There are basically two gas turbine driving methods, known as ‘single-shaft’ and ‘two (or twin) shaft’ drives. In a single-shaft gas turbine, all the rotating elements share a common shaft. The common elements are the air compressor, the compressor turbine and the power turbine. The power turbine drives the generator.

In some gas turbines, the compressor turbine and the power turbine are an integral component. This tends to be the case with heavy-duty machines.

The basic arrangement is shown in Figure 2.3.

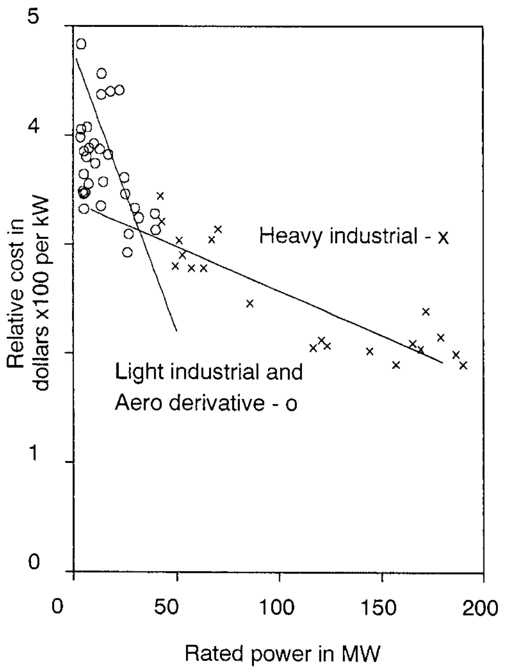

Figure 2.1 Relative cost of gas turbo-generators versus power rating.

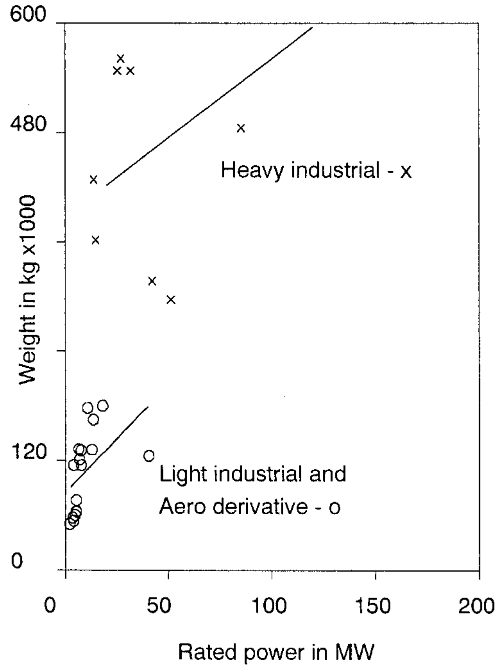

Figure 2.2 Weight of gas turbo-generators versus power rating.

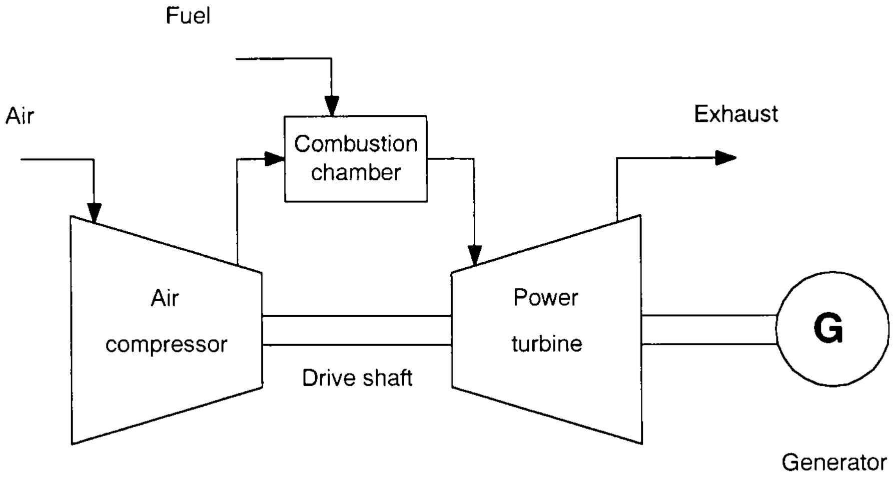

Figure 2.3 Single-shaft gas turbine.

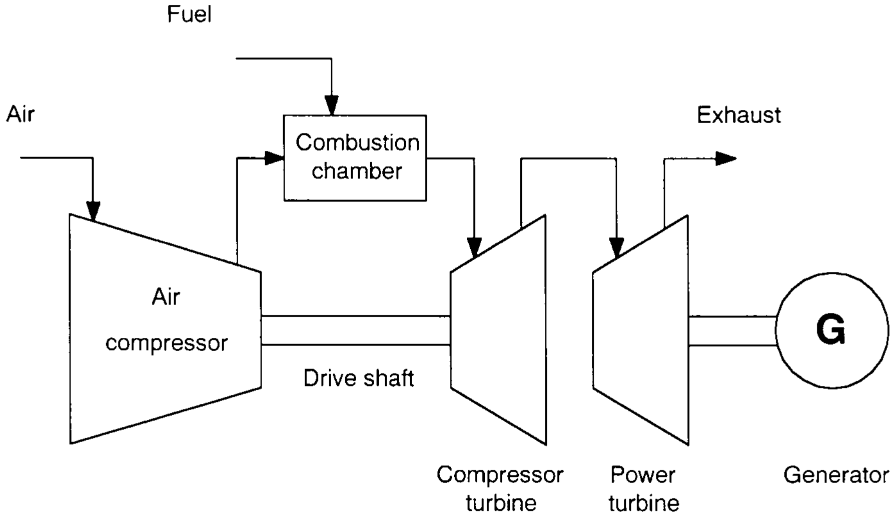

Figure 2.4 Two-shaft gas turbine.

In a two-shaft gas turbine the compressor is driven by a high pressure turbine called the compressor turbine, and the generator is driven separately by a low pressure turbine called the power turbine.

The basic arrangement is shown in Figure 2.4.

Two-shaft systems are generally those which use aero-derivative engines as 'gas generators', i.e. they produce hot, high velocity, high pressure gas which is directed into the power turbine. Some light industrial gas turbines have been designed for either type of drive. This is achieved by fitting a removable coupling shaft between the two turbines. Some points to consider with regard to the two types of driver are:-

a) High speed of rotation tends to improve the compressor and turbine efficiency. Hence, with two separate shafts, the best thermodynamic performance from both turbines and the compressor is obtainable.
b) Using aero-derivative machines means that a simple ‘add on’ power turbine can be fitted in the exhaust streams of the aero engine. This enables many manufacturers to design a simple power turbine and to use a particular aero engine.
c) Two-shaft machines are often criticised as electrical generators because of their slower response to power demands in comparison with the single-shaft machines. This can be a problem when a two-shaft machine may have to operate in synchronism with other single-shaft machines or steam turbine generators. Sometimes the slower response may affect the power system performance during the starting period of large motors. A power system computerised stability study should be carried out to investigate these types of problem.

Some of the recent aero engines could be called ‘three-shaft’ arrangements because within the gas generator there are two compressor turbines and two compressors.

2.1.5 Fuel for Gas Turbines

The fuels usually consumed in gas turbines are either in liquid or dry gas forms and, in most cases, are hydrocarbons. In special cases non-hydrocarbon fuels may be used, but the machines may then need to be specially modified to handle the combustion temperatures and the chemical composition of the fuel and its combustion products.

Gas turbine internal components such as blades, vanes, combustors, seals and fuel gas valves are sensitive to corrosive components present in the fuel or its combustion products such as carbon dioxide, sulphur, sodium or alkali contaminants, see also sub-section 2.2.5.

The fuel can generally be divided into several classifications:-

- Low heating value gas.
- Natural gas.
- High heating value gas.
- Distillate oils.
- Crude oil.
- Residual oil.

2.2 ENERGY OBTAINED FROM A GAS TURBINE

A gas turbine functions as a heat engine using the thermodynamic Joule cycle, as explained in many textbooks, see for example References 1 to 5. Most gas turbines used in the oil industry use the

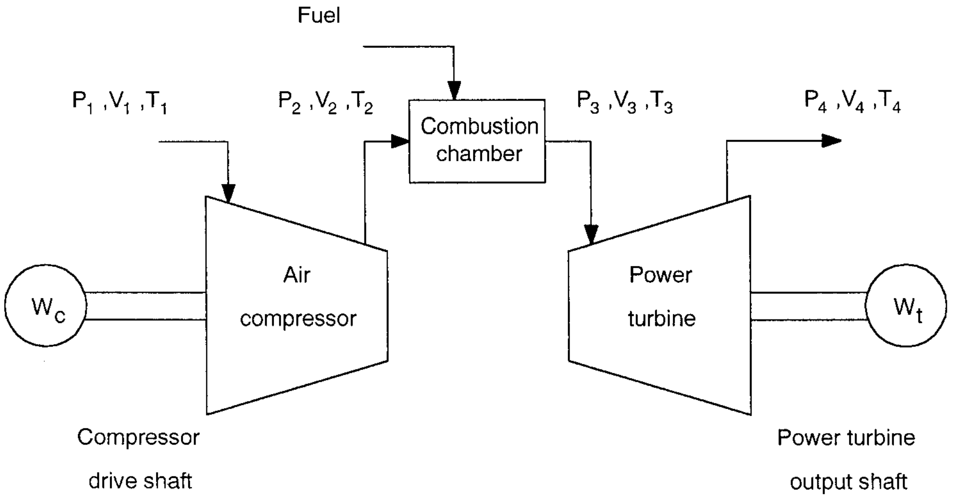

Figure 2.5 Gas turbine thermodynamic cycle. Simple-cycle gas turbine.

'simple-cycle' version of the Joule cycle. The main components of the gas turbine are shown in Figure 2.5.

The thermodynamic relationships used to describe the operation of the gas turbine are the pressure (P) versus volume (V) characteristic in Figure 2.6 and the temperature (T) versus entropy (S) characteristic in Figure 2.7. These figures also show the effect of practical inefficiencies that occur both in the air compressor and the turbine.

Air is drawn into the compressor at atmospheric pressure P_1 (in practice slightly lower due to the inlet silencer, filter and ducting) and atmospheric temperature T_1, and compressed adiabatically to a higher pressure P_2 to reduce its volume to V_2 and raise its temperature to T_2. The adiabatic compression is given by the following equations; see standard textbooks e.g. References 1 to 5.

$$\frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1} = \text{constant} \tag{2.1}$$

$$P_2 V_2{}^{\gamma} = P_1 V_1{}^{\gamma} = \text{constant} \tag{2.2}$$

The work done in the compressor per kg of fluid U_c is,

$$U_c = \frac{\gamma}{\gamma - 1}(P_2 V_2 - P_1 V_1) \tag{2.3}$$

The following standard relationships apply,

$$P_1 V_1 = RT_1 \tag{2.4}$$

$$P_2 V_2 = RT_2 \tag{2.5}$$

$$C_p - C_v = R \tag{2.6}$$

$$\frac{C_p}{C_v} = \gamma \tag{2.7}$$

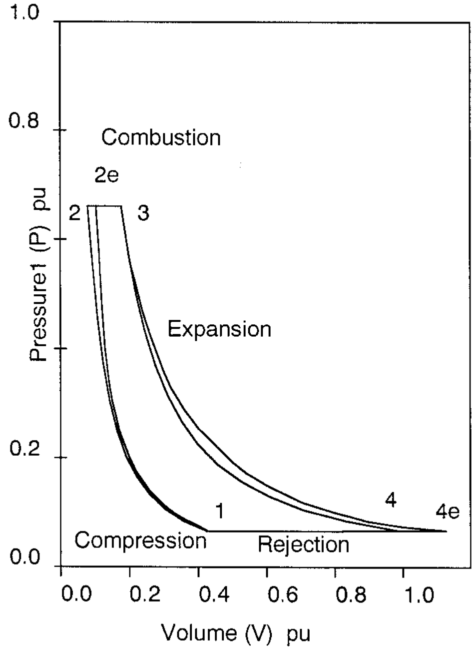

Figure 2.6 Pressure versus volume in the thermodynamic cycle.

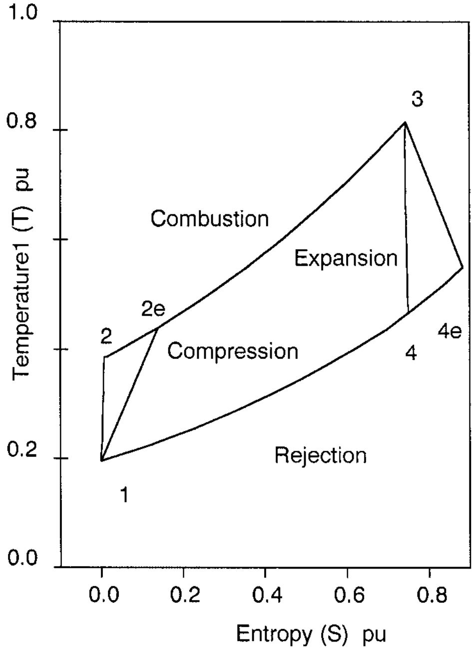

Figure 2.7 Temperature versus entropy in the thermodynamic cycle.

Where, C_p is the specific heat of the air at constant pressure, kcal/kg K $\simeq 1.005$
C_v is the specific heat of the air at constant volume, kcal/kg K $\simeq 0.718$
R is the particular gas constant for air, kJ/kg K $\simeq 0.287$
γ is the ratio of specific heats $\simeq 1.4$

From (2.3) and (2.7),

$$\frac{\gamma}{\gamma - 1} = \frac{C_p}{R} \tag{2.8}$$

Substitute (2.4, 2.5 and 2.8) into (2.1),

$$U_c = C_p(T_2 - T_1) \text{ kJ/kg} \tag{2.9}$$

The air leaving the compressor at pressure P_2 passes into the combustion chamber where its temperature is raised to T_3, at constant pressure.

The hot air–fuel mixture burns and the gaseous products of combustion pass into the turbine where the pressure falls to the atmospheric pressure $P_4 = P_1$ (in practice slightly higher due to the resistance or ‘back pressure’ of the exhaust silencer and ducting). The exhaust gas temperature is T_4 and is lower than the combustion temperature T_3. (The ducting systems should be arranged so that the exhaust gas is discharged at a point far enough away from the inlet ducting entrance that no interaction occurs i.e. T_4 does not influence T_1.)

The turbine expansion process can be described by similar equations to (2.1) through (2.7), with T_3 replacing T_2 and T_4 replacing T_1. Hence the work done by the turbine (U_t) is,

$$U_t = C_p(T_3 - T_4) \text{ kJ/kg} \tag{2.10}$$

The heat supplied by the fuel is C_p $(T_3 - T_2)$.

In a conventional gas turbine the turbine supplies power to drive its compressor and so the power available to drive a generator is the net power available from the turbine. Neglecting inefficiencies in the compressor and the turbine, the work done on the generator at the coupling of the gas turbine is U_{out},

$$U_{\text{out}} = U_t - U_c = C_p(T_3 - T_4 - T_2 + T_1) \text{ kJ/kg} \tag{2.11}$$

The ideal cycle efficiency η_i of the gas turbine is:

$$\begin{aligned}\eta_i &= \frac{C_p(T_3 - T_4 - T_2 + T_1)}{C_p(T_3 - T_2)} = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2}\right) \\ &= 1 - \frac{\text{Rejection temperature difference}}{\text{Combustion temperature difference}}\end{aligned} \tag{2.12}$$

From (2.1), raise to the power γ,

$$\left(\frac{P_2 V_2}{T_2}\right)^{\gamma} = \left(\frac{P_1 V_1}{T_1}\right)^{\gamma} \tag{2.13}$$

From here onwards the following substitutions will be used in order to keep the presentation of the equations in a simpler format.

$$\beta = \frac{\gamma - 1}{\gamma}, \quad \beta_c = \frac{\gamma_c - 1}{\gamma_c}, \quad \beta_t = \frac{\gamma_t - 1}{\gamma_t}$$

$$\delta = \frac{1 - \gamma}{\gamma}, \quad \delta_c = \frac{1 - \gamma_c}{\gamma_c}, \quad \delta_t = \frac{1 - \gamma_t}{\gamma_t}$$

Where subscript 'c' refers to the compressor and 't' to the turbine, the absence of a subscript means a general case.

Divide (2.2) by (2.13) to obtain an expression for the compressor,

$$\left(\frac{P_2}{P_1}\right)^{\delta} = \frac{T_1}{T_2} \tag{2.14}$$

Similarly for the turbine,

$$\left(\frac{P_3}{P_4}\right)^{\delta} = \frac{T_4}{T_3} \tag{2.15}$$

It is of interest to determine the work done on the generator in terms of the ambient temperature T_1 and the combustion temperature T_3.

From (2.14),

$$T_2 = T_1 {r_p}^{\beta}$$

And from (2.15),

$$T_4 = T_3 {r_p}^{\delta}$$

Therefore (2.11) becomes,

$$\begin{aligned} U_{\text{out}} &= C_p(T_3 - T_3 {r_p}^{\delta} - T_1 {r_p}^{\beta} + T_1) \\ &= C_p T_3(1 - {r_p}^{\delta}) - C_p T_1({r_p}^{\beta} - 1) \end{aligned} \tag{2.16}$$

The ideal cycle efficiency η_i can also be expressed in terms of T_1 and T_3.

$$\eta_i = 1 - \left(\frac{T_3 {r_p}^{\delta} - T_1}{T_3 - T_1 {r_p}^{\beta}}\right) \tag{2.17}$$

The specific heat C_p is assumed to be constant and equal for both compression and expansion. In practice these assumptions are not valid because the specific heat C_p is a function of temperature. The average temperature in the turbine is about twice that in the compressor. Also the products of combustion i.e. water vapour and carbon dioxide, slightly increase the specific heat of air–gas mixture in the turbine. Figures 2.8 and 2.9 show the spread of values for the pressure ratio and exhaust temperature for a range of gas turbines from 1 MW to approximately 75 MW.

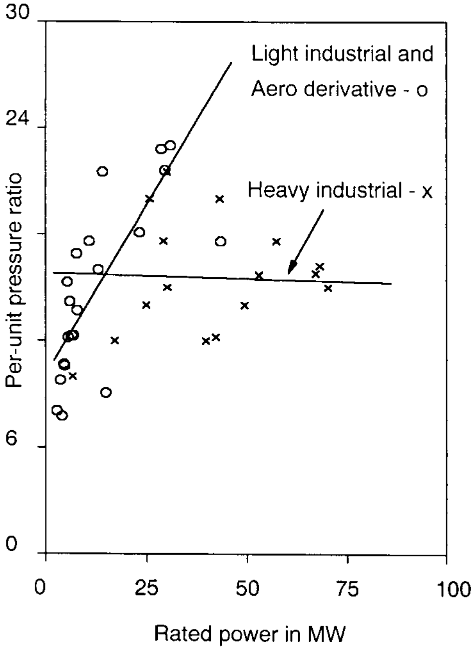

Figure 2.8 Per-unit pressure ratio versus power rating.

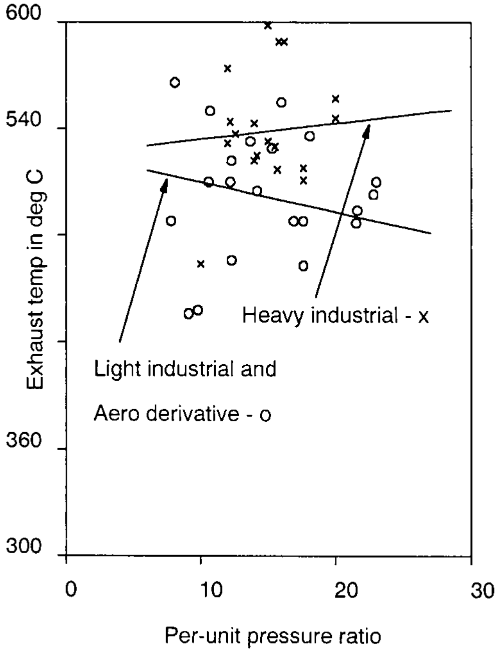

Figure 2.9 Exhaust temperature versus pressure ratio.

2.2.1 Effect of an Inefficient Compressor and Turbine

Frictional losses in the compressor raise the output temperature. Similarly the losses in the turbine raise the exhaust temperature. These losses are quantified by modifying the temperatures T_2 and T_4 to account for their increases.

The compression ratio (P_2/P_1) of the compressor is usually given by the manufacturer and therefore the temperature of the air leaving the compressor is easily found from (2.13). If the efficiency of compression η_c is known e.g. 90% and that of the turbine η_t is known e.g. 85% then a better estimate of the output energy can be calculated. In this situation T_2 becomes T_{2e} and T_4 becomes T_{4e}, as follows:-

$$T_{2e} = \frac{T_2}{\eta_c} + \left(1 - \frac{1}{\eta_c}\right) T_1 \quad \text{and} \quad T_{4e} = T_4\eta_t + (1 - \eta_t)T_3 \tag{2.18}$$

These would be the temperatures measurable in practice. In (2.14) and (2.15) the pressure ratios are theoretically equal, and in practice nearly equal, hence:

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = r_p{}^{\beta} \tag{2.19}$$

Where r_p is the pressure ratio $\dfrac{P_2}{P_1}$ or $\dfrac{P_3}{P_4}$

In practice the temperatures T_1 and T_3 are known from the manufacturer or from measuring instruments installed on the machine. The pressure ratio r_p is also known. The ratio of specific heats is also known or can be taken as 1.4 for air. If the compressor and turbine efficiencies are taken into account then the practical cycle efficiency η_p of the gas turbine can be expressed as:

$$\eta_p = \frac{T_3(1 - r_p{}^{\delta})\eta_c\eta_t - T_1(r_p{}^{\beta} - 1)}{T_3\eta_c - T_1(r_p - 1 + \eta_c)} \tag{2.20}$$

which has a similar form to (2.17) for comparison.

2.2.1.1 *Worked example*

A light industrial gas turbine operates at an ambient temperature T_1 of 25°C and the combustion temperature T_3 is 950°C. The pressure ratio r_p is 10.

If the overall efficiency is 32% find the efficiency of the compressor assuming the turbine efficiency to be 86%.

From (2.20),

$$T_1 = 273 + 25 = 298^\circ\text{K}$$

$$T_3 = 273 + 950 = 1223^\circ\text{K}$$

$$r_p{}^{\delta} = 10^{-0.2857} = 0.51796 \quad \text{and} \quad r_p{}^{\beta} = 10^{+0.2857} = 1.93063$$

Therefore,

$$\eta_p = 0.32 = \frac{1223(1.0 - 0.51796)\eta_c(0.86) - 298(1.93063 - 1.0)}{1223\eta_c - 298(1.93063 - 1.0 + \eta_c)}$$

Transposing for η_c results in $\eta_c = 0.894$. Hence the compressor efficiency would be 89.4%.

2.2.2 Maximum Work Done on the Generator

If the temperatures T_{2e} and T_{4e} are used in (2.11) to compensate for the efficiencies of the compressor and turbine, then it is possible to determine the maximum power output that can be obtained as a function of the pressure ratio r_p.

The revised turbine work done U_{te} is,

$$U_{te} = C_p(T_3 - T_4)\eta_t \text{ kJ/kg} \tag{2.21}$$

The revised compressor work done U_{ce} is,

$$U_{ce} = C_p(T_2 - T_1)\frac{1}{\eta_c} \text{ kJ/kg} \tag{2.22}$$

The revised heat input from the fuel U_{fe} is,

$$U_{fe} = C_p(T_3 - T_{2e}) \text{ kJ/kg} \tag{2.23}$$

where,

$$T_{2e} = T_1\left(\frac{r_p{}^{\beta} - 1 + \eta_c}{\eta_c}\right)$$

From (2.19),

$$T_4 = T_3 r_p{}^{\delta} \tag{2.24}$$

and

$$T_2 = T_1 r_p{}^{\beta} \tag{2.25}$$

Substituting for T_2, T_{2e} and T_4 gives the resulting output work done U_{oute} to be,

$$U_{\text{oute}} = U_{te} - U_{ce} = C_p(T_3 - T_3 r_p{}^{\delta})\eta_t - C_p\left(\frac{T_1 r_p{}^{\beta} - T_1}{\eta_c}\right)$$

$$= C_p\left[T_3(1 - r^{\delta})\eta t - \frac{T_1}{\eta_c}(r_p{}^{\beta} - 1)\right] \text{kJ/kg} \tag{2.26}$$

To find the maximum value of U_{oute} differentiate U_{oute} with respect to γ_p and equate the result to zero. The optimum value of γ_p to give the maximum value of U_{oute} is,

$$r_{p\max} = \left(\frac{T_1}{T_3\eta_c\eta_t}\right)^{d} \tag{2.27}$$

Where

$$d = \frac{1}{2\delta}$$

which when substituted in (2.26) gives the maximum work done U_{outemax}.

2.2.2.1 *Worked example*

Find $r_{p\max}$ for the worked example in sub-section 2.2.1.1.

Given that,

$$T_1 = 298\ K, T_3 = 1223^{\circ}\text{C},$$

$$r = 1.4, \eta_t = 0.86 \text{ and } \eta_c = 0.894$$

$$d = \frac{\gamma}{2(1-\gamma)} = \frac{1.4}{2(1.0-1.4)} = -1.75$$

$$r_{p\max} = \left[\frac{298}{1223(0.894)(0.86)}\right]^{-1.75}$$

$$= 0.3169^{-1.75} = 7.4$$

2.2.3 Variation of Specific Heat

As mentioned in sub-section 2.2 the specific heat C_p changes with temperature. From Reference 4, Figure 4.4, an approximate cubic equation can be used to describe C_p in the range of temperature 300 K to 1300 K when the fuel-to-air ratio by mass is 0.01, and for the air alone for compression, as shown in Table 2.1. The specific heat for the compressor can be denoted as C_{pc} and for the turbine C_{pt}. The appropriate values of C_{pc} and C_{pt} can be found iteratively from the cubic expression and equations (2.24) and (2.25). At each iteration the average of T_1 and T_2 can be used to recalculate C_{pc}, and T_3 and T_4 to recalculate C_{pt}. The initial value of γ can be taken as 1.4 in both cases, and C_v can be assumed constant at 0.24/1.4 = 0.171 kcal/kg K. The pressure ratio is constant. Having found suitable values of C_{pc} and C_{pt} it is now possible to revise the equations for thermal efficiency η_{pa} and output energy U_{outea}, where the suffix 'a' is added to note the inclusion of variations in specific heat C_p.

Table 2.1. Specific heat C_p as a cubic function of absolute temperature K in the range 373 K to 1273 K $C_p = a + bT + cT^2 + dT^3$

Fuel-air ratio	Cubic equation constants			
	$a \times 10^0$	$b \times 10^{-4}$	$c \times 10^{-7}$	$d \times 10^{-10}$
0.0	0.99653	−1.6117	+5.4984	−2.4164
0.01	1.0011	−1.4117	+5.4973	−2.4691
0.02	1.0057	−1.2117	+5.4962	−2.5218

The energy equations for the compressor and turbine become,

$$U_{cea} = C_{pc}(T_2 - T_1)\left(\frac{1}{\eta_c}\right) \text{ kJ/kg} \tag{2.28}$$

and

$$U_{tea} = C_{pt}(T_3 - T_4)\left(\frac{1}{\eta_t}\right) \text{ kJ/kg} \tag{2.29}$$

Also assume that the specific heat C_{pf} of the fuel–air mixture is the value corresponding to the average value of T_2 and T_3, see Reference 4, sub-section 4.7.1, (2.23).

Hence the fuel energy equation becomes, from (2.23),

$$U_{fea} = C_{pf}(T_3 - T_{2ea}) \text{ kJ/kg} \tag{2.30}$$

Where

$$T_{2ea} = \frac{T_1({r_p}^{\beta_c} - 1 + \eta_c)}{\eta_c} \tag{2.31}$$

Where r_c and r_t apply to the compressor and turbine and are found from C_{pc}, C_{pt} and C_v.

The work done on the generator is now,

$$U_{\text{outea}} = C_{pt}\ T_3(1 - {r_p}^{\delta_t})\eta_t - \frac{C_{pc}T_1}{\eta_c}({r_p}^{\beta_t} - 1) \tag{2.32}$$

and

$$T_{4ea} = T_3(\eta_t {r_p}^{\delta_c} + 1 - \eta_t)$$

From U_{fea} and U_{outea} the thermal efficiency η_{pa} can be found as,

$$\eta_{pa} = \frac{U_{\text{outea}}}{U_{fea}} \tag{2.33}$$

2.2.4 Effect of Ducting Pressure Drop and Combustion Chamber Pressure Drop

Practical gas turbines are fitted with inlet and exhaust silencing and ducting systems to enable the incoming air to be taken from a convenient source and the outgoing gas to be discharged to a second convenient location. These systems can be long enough to create significant pressure drops at the inlet and outlet of the gas turbine itself. The inlet system reduces the pressure at the entry to the compressor, by an amount $\Delta P_{1.}$ The exhaust system increases the pressure at the exit of the power turbine, by an amount ΔP_4.

Between the outlet of the compressor and the inlet to the turbine there is a small pressure drop caused by the presence of the combustion chamber and the throttling effect of its casing. Let this pressure drop be ΔP_{23}.

The effects of ΔP_1, ΔP_{23} and ΔP_4 can be found by modifying their corresponding pressure ratios, r_{pc} for the compressor and r_{pt} for the turbine, and using the binomial theorem to simplify the results. ΔP_{23} and ΔP_4 apply to the turbine pressure ratio.

After a gas turbine has been operating for a long time the inlet filter pressure drop may become high enough to indicate that the filter needs cleaning. The drop in pressure across silencers will remain almost constant; the effect of ingress of particles or development of soot can be neglected.

The pressure ratio terms in (2.31) and (2.32) are of the general form,

$$y + \Delta y = \left(\frac{x + \Delta x}{w + \Delta w}\right)^n \tag{2.34}$$

and,

$$y = \left(\frac{x}{w}\right)^n \tag{2.35}$$

which upon expanding becomes,

$$yw^n + nyw^{n-1}\Delta w + w^n\Delta y = x^n + nx^{n-1}\Delta x \tag{2.36}$$

Where the second and higher orders of Δ are neglected. If the initial values are deducted then the expression relating the small changes becomes,

$$nyw^{n-1}\Delta w + w^n\Delta y = nx^{n-1}\Delta x \tag{2.37}$$

Hence the change in y becomes,

$$\Delta y = \frac{nx^{n-1}}{w^n}\Delta x - \frac{ny}{w}\Delta w \tag{2.38}$$

For the compressor it is assumed that the inlet pressure is increased by ΔP_1. The pressure ratio remains unchanged and so the change in output pressure is,

$$\Delta P_2 = r_p\Delta P_1$$

Since the pressure ratio is unchanged the output temperature will be unchanged at T_2.

The heat from the fuel is a function of T_2 and therefore it will also be unchanged.

For the turbine there are three pressure drops to consider. One for the compressor discharge ΔP_2, one for the practical throttling effect in the combustion chamber ΔP_{23} and one for the turbine exhaust pressure due to ducting ΔP_4. The two pressure drops at the inlet to the turbine can be combined as,

$$\Delta P_{223} = \Delta P_2 + \Delta P_{23} \tag{2.39}$$

In (2.34) Δx is ΔP_{223} and Δ_w is ΔP_4. Hence their effect on the turbine pressure ratio is $\Delta \mathrm{r}_{pt}{}^{nt}$,

$$\Delta r_{pt}{}^{nt} = \frac{n_t P_3{}^{nt-1}}{P_4{}^{nt}}\Delta P_{223} - \frac{n_t r_{pt}{}^{nt}}{P_4}\Delta P_4 \tag{2.40}$$

The turbine energy changes from U_{tea} to $U_{tea} + \Delta U_{tea}$. Substitute (2.40) into (2.29),

$$
\begin{aligned}
U_{tea} + \Delta U_{tea} &= C_{pt} T_3 (1 - (r_{pt} + \Delta r_{pt})^{nt}) \eta_t \\
&= C_{pt} T_3 \eta_t \left[1 - \left(r_{pt}{}^{n} + \frac{n_t P_3{}^{nt-1}}{P_4{}^{nt}} \Delta P_{223} - \frac{n_t r_{pt}{}^{nt}}{P_4} \Delta P_4 \right) \right]
\end{aligned}
$$

from which,

$$\Delta U_{tea} = +n_t \eta_t C_{pt} T_3 r_{pt}{}^{nt-1} \left[\frac{r_{pt} \Delta P_4 - r_{pt} \Delta P_1 - \Delta P_{23}}{P_4} \right] \tag{2.41}$$

The change in efficiency η_{pa} in (2.33) is,

$$\eta_{pa} + \Delta \eta_{pa} = \frac{U_{tea} + \Delta U_{tea} - U_{cea} - \Delta U_{cea}}{U_{fea} + \Delta U_{fea}} \tag{2.42}$$

from which, by substituting for ΔU_{tea}, $\Delta U_{cea} = 0.0$ and $\Delta U_{fea} = 0.0$ and deducting the initial conditions gives,

$$\Delta \eta_{pa} = \frac{\Delta U_{tea}}{U_{fea}} \tag{2.43}$$

The change in work done on the generator

$$\Delta U_{\text{outea}} = \Delta U_{tea} \text{ kJ/kg} \tag{2.44}$$

Note that in the above analysis the signs of the practical changes are,

ΔP_1 is negative

ΔP_{23} is negative

and ΔP_4 is positive

The pressure drops ΔP_1 and ΔP_4 are dependent upon the layout of the gas turbine generator, the dimensions of the ducting systems and the specification of silencers and filters. ΔP_{23} is fixed by the design of the combustion system and cannot be changed by external factors such as ducting systems.

2.2.4.1 Typical values of pressure drop losses

A newly installed gas turbine generator can be taken to have the typical losses given in Table 2.2.

Table 2.2. Typical pressure drop losses in gas turbine

Inlet or exhaust	Pressure drop		% change in	
	Bar	Inches of water	Power output	Heat rate
Inlet	0.01245	5.0	−2.00	+0.75
Exhaust	0.006227	2.5	−0.50	+0.40

2.2.5 Heat Rate and Fuel Consumption

The heat rate is the ratio of heat given up by the fuel, in terms of its lower calorific or heating value (LHV), to the power available at the gas turbine coupling to its generator. It has the SI units of kJ/kWh. The lower heating value of typical fuels is given in Table 2.3.

The heat rate for a particular gas turbine will be given by its manufacturer at ISO conditions, and at various ambient temperatures. The typical variation of heat rate and power output, in relation to their ISO values, are shown in Figure 2.10. For a definition of ISO conditions see sub-section 2.3.2.

Table 2.3. Lower heating values of fuels

Fuel	Lower heating value (LHV) MJ/m^3 for gases MJ/kg for liquids	Btu/ft^3 for gases Btu/lb for liquids
GASES		
Natural gas	35.40 to 39.12	950 to 1050
Methane	33.94	911
Ethane	60.77	1,631
Propane	87.67	2,353
Butane	115.54	3,101
Hydrogen	10.17	273
Hydrogen sulphide	23.14	621
LIQUIDS		
Diesel oil	45.36	19,500
Kerosene	41.87	18,000
Distillate	44.89	19,300
Crude oil	44.66	19,200

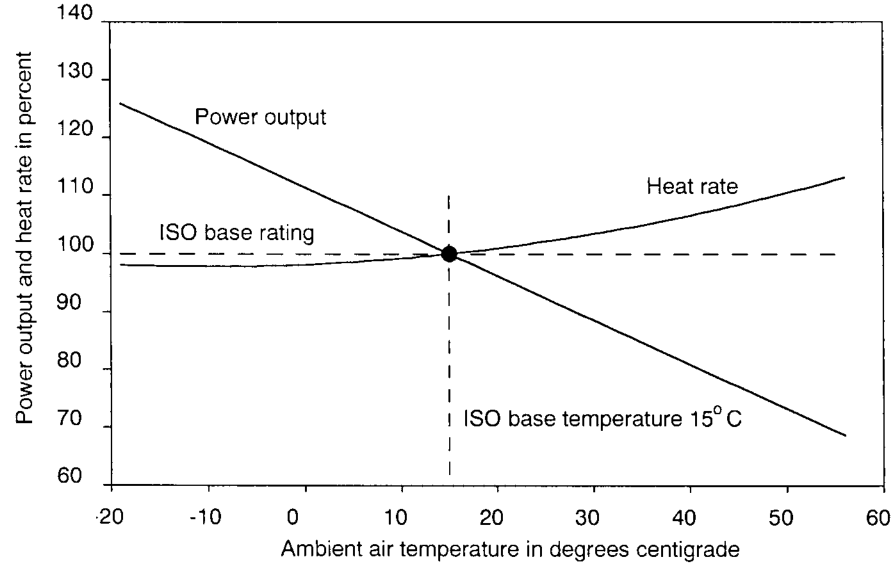

Figure 2.10 Power output and heat rate versus ambient air temperature.

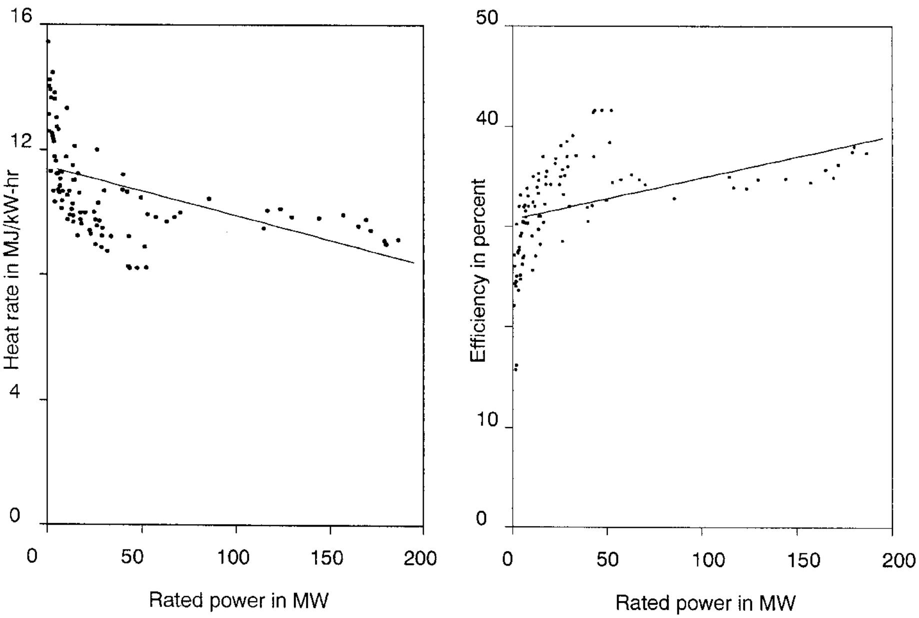

Figure 2.11 Heat rate and efficiency versus power rating.

The reduction in output power is typically 0.5 to 0.8%/°C.

The fuel consumption can be calculated approximately from,

$$\text{Fuel consumption} = \frac{\text{Power output} \times \text{Heat rate}}{\text{Fuel LHV}} \ \text{m}^3/\text{h (or kg/h)}$$

For situations where there is a mixture of gases it is advisable to consult the manufacturer of the gas turbine, since he will have a data bank containing all kinds of fuel compositions and heating values.

The heat rate and overall thermal efficiencies for typical modern gas turbines in the range of ISO power ratings 1 MW to 200 MW are shown in Figure 2.11. The data were derived from Reference 6.

2.3 POWER OUTPUT FROM A GAS TURBINE

In sub-section 2.2 the performance of a gas turbine was determined as the energy obtainable at the output shaft coupling. The energy equations are based on a unit of mass flow, 1.0 kg/s, of the fluid passing through the gas turbine i.e. from the air intake to the exhaust aperture.

The mass flow through the turbine is about 1% higher than that through the compressor because of the presence of the burnt fuel. Hence the mass flow rate (m) to produce the output power is,

$$m = \frac{\text{Output power to the generator}}{\text{Output energy per unit mass}} \ \text{kg/s}$$

$$= \frac{W_{\text{out}}}{U_{\text{out}}} \qquad \left(\frac{\text{kW kg}}{\text{kj}} = \text{kg/s}\right)$$

Therefore it is a simple matter to predetermine the required output power and divide this by the specific energy available to the generator. The result is then the mass flow rate.

2.3.1 Mechanical and Electrical Power Losses

The power and specific energy available to drive the generator determined in the previous sub-section are those at the output shaft of the gas turbine. In most situations in the oil industry, where these machines seldom are rated above 40 MW, a speed-reducing gearbox is placed between the turbine and the generator. The generators are usually 4-pole machines that operate at 1500 or 1800 rev/min. The power loss in a typical gearbox is about 1.5% of the rated output power. Let the gearbox efficiency be η_{gb}.

The efficiency (η_{gen}) of electromechanical conversion in the generator can be defined as,

$$\eta_{\text{gen}} = \frac{\text{Power output at the terminals}}{\text{Power input to the shaft coupling}} \quad \text{pu}$$

Most rotating electrical machines above about 500 kW have efficiencies above 95%, which increases to about 98% for large machines in the hundreds of megawatts range. Their losses are due to windage between the rotor and the stator, friction in the bearings and seals, iron and copper electrical losses.

In some situations, such as ‘packaged’ gas turbine generators, all the necessary auxiliary electrical power consumers are supplied from the terminals of the generator through a transformer and a small motor control centre (or switchboard). These auxiliaries include lubricating oil pumps, fuel pumps, filter drive motors, cooling fans, purging air fans, local lighting, and sump heaters. Some of these operate continuously while others are intermittent. A rule-of-thumb estimate of the consumed power of these auxiliaries is between 1% and 5% of the rated power of the generator.

Care needs to be taken when referring to the efficiency of a gas-turbine generator set. See the worked example in Appendix F. The power system engineer is concerned with the power output from the terminals of the generator that is obtainable from the fuel consumed. Hence he considers the practical efficiency η_{pa} of the gas turbine, and the conversion efficiency through the gearbox η_{gb} and generator η_{gen}. Hence the Overall Thermal Efficiency η_{pao} would be:-

$$\eta_{\text{pao}} = \eta_{\text{pa}} \times \eta_g \times \eta_{\text{gen}}$$

2.3.2 Factors to be Considered at the Design Stage of a Power Plant

The electrical engineer should take full account of the site location and environmental conditions that a gas turbine generator will need to endure. These conditions can seriously effect the electrical power output that will be achievable from the machine. The starting point when considering the possible output is the ISO rating. This is the declared rating of the machine for the following conditions:-

- Sea level elevation.
- 15°C (59°F) ambient temperature.
- Basic engine, no losses for inlet or exhaust systems, no losses for gearbox and mechanical transmission.
- Clean engine, as delivered from the factory.

The gas turbine manufacturer provides a standardised mechanical output power versus ambient temperature characteristic, e.g., Figure 2.10. (Some manufacturers also give the electrical output power versus ambient temperature characteristic. Therefore care must be exercised to be sure exactly which data are to be given and used.)

The following derating factors should be used in the estimation of the continuous site rating for the complete machine:

- ISO to a higher site ambient temperature, typically 0.5 to 0.8% per °C.
- Altitude, usually not necessary for most oil industry plants since they are near sea level.
- Dirty engine losses and the ageing of the gas turbine, assume 5%.
- Fuel composition and heating value losses, discuss with the manufacturer.
- Silencer, filter and ducting losses, assume 2 to 5%.
- Gearbox loss, typically 1 to 2%.
- Generator electromechanical inefficiency, typically 2 to 4%.
- Auxiliary loads connected to the generator, typically 1 to 5%.

2.3.2.1 Dirty engine losses

Consideration should be given to the fact that engines become contaminated with the combustion deposits, the lubrication oil becomes less efficient, blades erode and lose their thermodynamic efficiency and air filters become less efficient due to the presence of filtered particles. These effects combine to reduce the output of the machine. A rule-of-thumb figure for derating a gas turbine for dirty engine operation is 5%. This depends upon the type of fuel, the type of engine, the environment and how long the engine operates between clean-up maintenance periods. Individual manufacturers can advise suitable data for their engines operating in particular conditions. Dirty engine conditions should be considered, otherwise embarrassment will follow later once the machine is in regular service.

2.3.2.2 Fuel composition and heating value losses

The chemical composition and quality of the fuel will to some extent influence the power output. However, it is usually the case that more or less fuel has to be supplied by the fuel control valve for a given throughput of combustion air. Hence it is usually possible to obtain the declared normal rating from the machine, but attention has to be given to the supply of the fuel. In extreme cases the profile of the fuel control valve may require modification so that adequate feedback control is maintained over the full range of power output. The appropriate derating factor is usually 100%, i.e. no derating.

2.3.2.3 Silencer, filter and ducting losses

The amount of silencing and filtering of the inlet combustion air depends upon the site environment and the operational considerations.

Site environmental conditions may be particularly bad, e.g. deserts where sand storms are frequent; offshore where rain storms are frequent and long lasting. The more filtering that is required, the more will be the pressure lost across the filters, both during clean and dirty operation. This pressure drop causes a loss of power output from the machine.

The amount of inlet and exhaust noise silencing will depend upon, the location of machine with respect to people in say offices or control rooms, how many machines will be in one group since this affects the maintenance staff and total noise level permitted by international or national standards. The effects of a silencer are similar to a filter since the silencing elements cause a pressure drop.

With offshore platforms it is not always practical to locate the main generators in a good place regarding the position and routing of the inlet and exhaust ducting. Long runs of ducting are sometimes unavoidable. It is then necessary to allow a derating factor for the pressure drop that will occur. The manufacturer should be consulted for advice on this aspect. For a typical offshore or onshore situation with a reasonable degree of silencing a rule-of-thumb derating factor would be 98%. In a poor location assume 95%.

2.4 STARTING METHODS FOR GAS TURBINES

Gas turbines are usually started by a DC motor or an air motor. Either system is available for most turbines up to about 20 MW. Occasionally AC motors are used. Beyond 20 MW, when heavy industrial machines tend to be used, it becomes more practical to use air motors or even diesel engine starters. DC motors require a powerful battery system. The DC motor and battery systems tend to be more reliable and less space consuming, which is important for offshore systems. Air motors require air receivers and compressors. The compressors require AC motors or diesel engines. Air start and diesel start systems are more popular for onshore plants especially remote plants, e.g. in the desert. This is partly due to the fact that batteries tend to suffer from poor maintenance in hot, dry locations. Air systems require regular maintenance and must be kept fully charged in readiness for a quick start. Air system receivers can become very large if more than three successive starting attempts are required. More starts can probably be obtained by a battery system that occupies the same physical space.

Occasionally process gas can be used instead of air to drive the air/gas starter motor. This eliminates the need for receivers and compressors. However, there should always be a reliable source of gas available. The exhaust gas from the starter motor should be safely discharged e.g. into a ventilating pipeline.

2.5 SPEED GOVERNING OF GAS TURBINES

2.5.1 Open-loop Speed-torque Characteristic

The ungoverned or open-loop speed-torque characteristic of a gas turbine has a very steep negative slope and is unsuitable for regulating the power output of the generator. The open-loop characteristic is explicitly determined by the thermodynamic design of the gas turbine, together with the mechanical inertial and frictional characteristics of the rotating masses. Without closed-loop feedback control action the initial decline in speed in response to an increase in shaft torque would be mainly determined by the shaft inertia. Let T, ω and P be the torque, speed and shaft power respectively in per-unit terms. The expression relating these variables is,

$$P = T\omega \tag{2.45}$$

The open-loop speed-torque function may be expressed as,

$$\omega = f(T) \tag{2.46}$$

which may be represented by a simple linear function,

$$\omega = \omega_o - kT \tag{2.47}$$

where k is a positive number in the order of 1.0 pu equal to the open-loop slope, and ω_o is the shaft speed at no-load.

Reference 7 discusses the slope k in Chapter 2, Section 2.3.1.

Assume that the turbine is designed to deliver unit torque at unit speed, therefore,

$$1.0 = \omega_o - k(1.0) = \omega_o - k \tag{2.48}$$

From which $\omega_o = 1 + k$ and so (2.47) becomes,

$$\omega = 1 + k - kT \text{ or } T = \frac{1 + k - \omega}{k} \tag{2.49}$$

The speed can now be related to the shaft power rather than the torque,

$$P = \left(\frac{1 + k - \omega}{k}\right)\omega \tag{2.50}$$

Or in the form of a quadratic equation,

$$0 = \omega^2 - (1 + k)\omega + kP \tag{2.51}$$

The two roots of which are,

$$\omega_{1,2} = \frac{1 + k}{2} \pm \left(\frac{(1 + k)^2 - 4kP}{2}\right)^{1/2} \tag{2.52}$$

The positive root applies to the stable operating region, whilst the negative root applies to the unstable region after stalling occurs.

For example assume $k = 1.5$. Table 2.4 shows the values of the two roots for an increase in shaft power.

Table 2.4. Open-loop steady state speed-power characteristic of a gas turbine ($k = 1.5$)

Shaft power P (per unit)	Shaft speed ω (per unit)	
	Positive root	Negative root
0.0	2.5	0.0
0.5	2.151	0.349
0.75	1.911	0.589
1.00	1.500	1.000
1.04	1.250	1.250
1.04 + (unstable)		

Table 2.5. Open-loop steady state speed-power characteristic of a gas turbine ($k = 0.1$)

Shaft power P (per unit)	Shaft speed ω (per unit)	
	Positive root	Negative root
0.0	1.10	0.0
0.5	1.0525	0.0475
0.75	1.027	0.073
1.00	1.000	0.100
1.04	0.9955	0.1045
1.50	0.9405	0.1550
2.00	0.8700	0.2300
3.00	0.6000	0.5000
3.025	0.5500	0.0

At $P = 1.0$ the torque corresponding to the positive root is $T = 0.667$ pu, whilst that for the negative root is $T = 1.00$ pu. Hence the torque at full-load power is less than unity (due to the speed being higher than unity). The above example illustrates the impractical nature of the open-loop speed-torque and speed-power characteristics.

Suppose the design of the engine could be substantially improved such that k could be reduced to say 0.1 (approaching a value for a typical closed-loop feedback controlled system). Table 2.5 shows comparable results to those given in Table 2.4.

It can be seen that unit power is obtained at unit speed in the stable region, and that the stalling point is at a power much greater than unity. The above illustrates more desirable open-loop speed-torque and speed-power characteristics. Unfortunately reducing k to values between say 0.01 and 0.1 by thermodynamic design is not practical. Consequently a closed-loop feedback control system is necessary. Figure 2.12 shows the open-loop speed-power responses for different values of k. The transient response of the gas turbine just after a disturbance in the shaft power is of interest when underfrequency protective relays are to be used to protect the power system from overloading, see sub-section 12.2.10.

2.5.2 Closed-loop Speed-power Characteristic

All prime-moves used for driving electrical generators are equipped with closed-loop speed governors. Their main purpose is to reduce the variation in shaft speed to a small amount over the full range of shaft power. Deviations in speed are measured and amplified. The amplified signal is used to operate the fuel value in such a manner as to reduce the deviation in speed. It may be assumed that a linear relationship exists between the amplified signal received at the value and the shaft power created by the fuel passed through the valve orifice. The fuel valve may be regarded as a regulating device for power available at the shaft. It may therefore be assumed that the output of the valve is the shaft power P, whilst its inputs are a reference power P_{ref} and the amplified speed error P_e.

Therefore,

$$P = P_{\text{ref}} - P_e \tag{2.53}$$

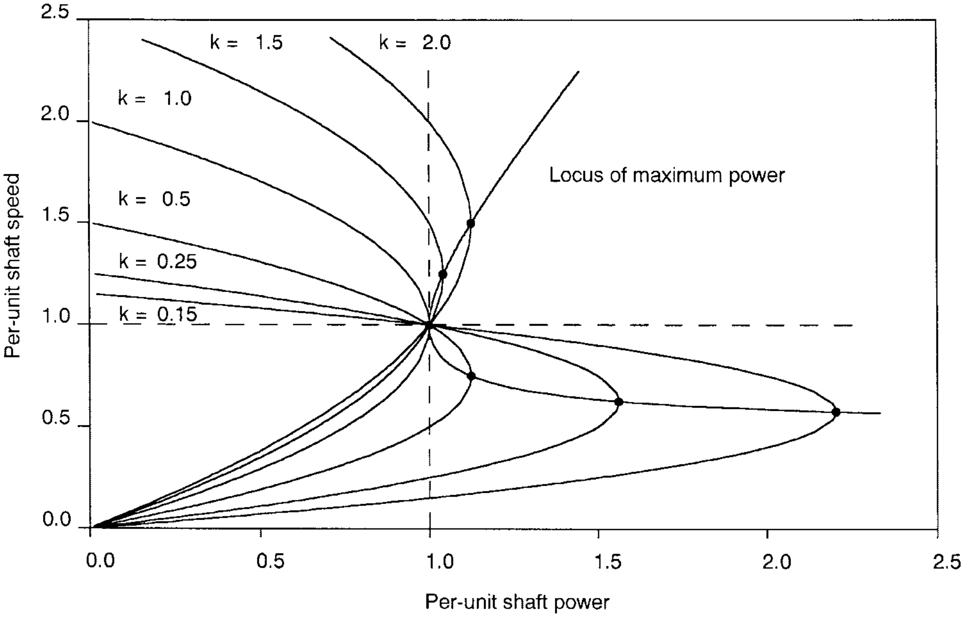

Figure 2.12 Open-loop speed regulation of a gas turbine.

where

$$P_e = F(\omega_o - \omega) \tag{2.54}$$

and ω_o is the nominal shaft speed, and F is the feedback gain.

Hence the closed-loop control system for steady state conditions may be described by the forward transfer function of (2.52), using the positive root, and the feedback transfer function of (2.54). In order to establish suitable relationships between k and F it is necessary to consider small changes in the variables and by so doing linearise the equations using a two-term Taylor's series. Transpose and square the positive root of (2.52).

$$\left(\omega - \frac{1+k}{2}\right)^2 = \frac{1}{4}\left((1+k)^2 - 4\,kP\right) \tag{2.55}$$

Let ω be increased by $\Delta\omega$ as the power P is increased by ΔP.

Equation (2.55) becomes,

$$\begin{aligned} 2\omega\Delta\omega - \Delta\omega(1+k) + \omega^2 - \omega(1+k) + \left(\frac{1+k}{4}\right)^2 \\ = \left(\frac{1+k}{4}\right)^2 - kP - k\Delta P \end{aligned} \tag{2.56}$$

Subtract the predisturbance state,

$$\frac{\Delta\omega}{\Delta P} = \frac{-k}{4(2\omega - 1 - k)} \tag{2.57}$$

In (2.53) and (2.54) let ω be increased by $\Delta\omega$ and P by ΔP, and subtract the predisturbance state,

Hence, $$\Delta P_e = F\Delta\omega$$

or $$\frac{\Delta\omega}{\Delta P_e} = \frac{1}{F} \tag{2.58}$$

and $$\Delta P = \Delta P_{\text{ref}} - \Delta P_e \tag{2.59}$$

A change in the demand for shaft power ΔP_d may be added to the summing point of ΔP_{ref} and ΔP_e, and ΔP_{ref} assumed to be zero. Hence the overall closed-loop transfer function gain G_c at the speed ω is found to be,

$$\begin{aligned} G_c = \frac{\Delta\omega}{\Delta P_d} &= \frac{\text{Forward gain}}{1 + (\text{Forward gain})(\text{Feedback gain})} \\ &= \frac{\dfrac{-k}{4(2\omega - 1 - k)}}{1 - \dfrac{kF}{4(2\omega - 1 - k)}} \\ &= \frac{k}{kF - 4(2\omega - 1 - k)} \end{aligned} \tag{2.60}$$

For typical power system applications the transfer function gain has the per-unit value of 0.04, and the operating shaft speed ω is within a small range centred around the rated speed. The rated speed corresponds to the nominal frequency of the power system. Hence the term $4(2\omega - 1 - k)$ may be neglected since k is typically in the range of 1.0 to 2.0.

The transfer function simplifies to become,

$$G_c = \frac{1}{F} \quad \text{where F is typically 25 per unit} \tag{2.61}$$

The transfer function gain is also called the 'droop' characteristic of the gas turbine.

2.5.3 Governing Systems for Gas Turbines

The following discussions outline the important principles behind the governing of gas turbines. In all power systems the requirement is that the steady state speed deviation, and hence frequency, is kept small for incremental changes in power demand, even if these power increments are quite large – 20%, for example.

There are two main methods used for speed governing gas turbines,

a) Droop governing.

b) Isochronous governing.

Droop governing requires a steady state error in speed to create the necessary feedback control of the fuel value. ‘Droop’ means that a fall in shaft speed (and hence generator electrical frequency) will occur as load is increased. It is customary that a droop of about 4% should occur when 100% load is applied. Droop governing provides the simplest method of sharing load between a group of generators connected to the same power system.

In control theory terminology this action is called ‘proportional control’. This method of governing is the one most commonly used in power systems because it provides a reasonably accurate load sharing capability between groups of generators.

Isochronous governing causes the steady state speed error to become zero, thereby producing a constant speed at the shaft and a constant frequency for the power system. Isochronous governing is also a form of ‘integral control’. This method is best suited to a power system that is supplied by one generator. This type of power system has very limited application. However, there are situations where one isochronously governed generator can operate in parallel with one or more droop-governed generators. The droop-governed generators will each have a fixed amount of power assigned to them for the particular system frequency. This is achieved by adjusting their set points. As the demand on the whole system changes, positively or negatively, the isochronously governed generator will take up or reject these changes, and the steady state frequency will remain constant. This hybrid type of load sharing is seldom used in the oil industry.

Accurate power sharing and constant speed control can be obtained by using a specially designed controller. This controller incorporates load measurement of each generator, measurement of common system frequency and a sub-system to reduce the power mismatches of each generator to zero. The controller regularly or even continuously trims the speed set points of each gas turbine to maintain zero mismatches. A slowly operating integrator can be superimposed onto these set points to adjust them simultaneously so that the frequency is kept constant. This is a form of ‘proportional-integral’ control. See also Chapter 16 for a further discussion of these subjects.

The basic control system of most gas turbine generator systems is shown in Figure 2.13.

Where ω = shaft speed
ω_{ref} = reference speed
P_e = electrical power at the generator shaft
P_m = mechanical output power of the gas turbine
P_a = accelerating power
P_f = friction and windage power

2.5.4 Load Sharing between Droop-governed Gas Turbines

Consider a number of generators connected to the same busbars. For the purpose of generality it will be assumed that each of the generators has a different power rating, and that each governor has a different droop. The droop characteristic for the i_{th} gas turbine is,

$$f = f_{zi} - \frac{D_i P_i f_o}{G_i} \tag{2.62}$$

Where f_o = the nominal system frequency in Hz

f = the actual system frequency in Hz

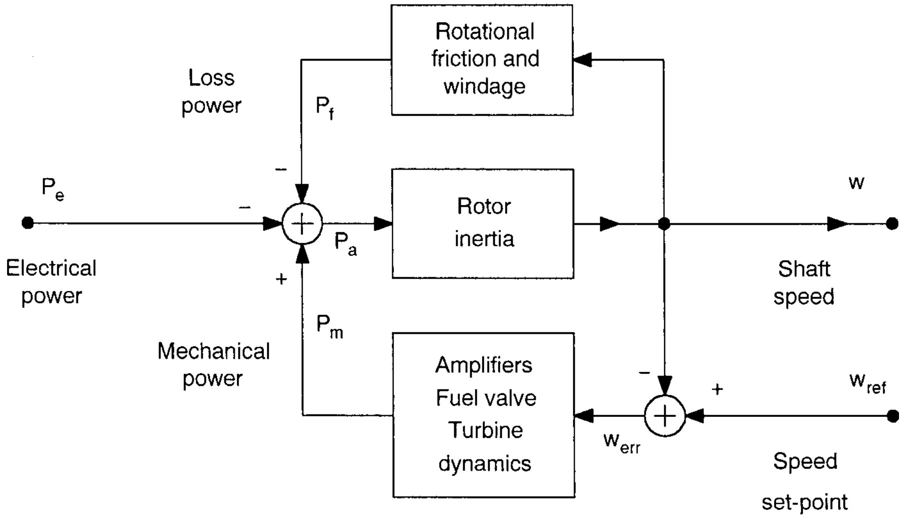

Figure 2.13 Basic control system block diagram of a gas turbine. The diagram represents the main elements of the equation of motion.

f_{zi} = frequency set-point of the i_{th} governor in Hz

D_i = governor droop in per unit of the i_{th} governor

P_i = electrical load of the i_{th} generator in kW

G_i = electrical power rating of the i_{th} generator in kW

Transpose (2.62) to find P_i,

$$P_i = (f_{zi} - f)\frac{G_i}{D_i f_o} \tag{2.63}$$

The total power demand P for n generators is,

$$P = \sum_{i=1}^{i=n} P_i \tag{2.64}$$

$$= \frac{1}{f_o}\sum_{i=1}^{i=n}\frac{f_{zi}G_i}{D_i} - \frac{f}{f_o}\sum_{i=1}^{i=n}\frac{G_i}{D_I} \tag{2.65}$$

Which is of the simple form,

$$P = a - bf \tag{2.66}$$

where

$$a = \frac{1}{f_o}\sum_{i=1}^{i=n}\frac{f_{zi}G_i}{D_i} \text{ is a constant} \tag{2.67}$$

and

$$b = \frac{1}{f_o} \sum_{i=1}^{i=n} \frac{G_i}{D_i} \text{ is also a constant} \tag{2.68}$$

(2.65) and (2.66) represent the overall droop characteristic of the power system.

The application of (2.63) and (2.64) can be demonstrated graphically for a system in which two generators are sharing a common load.

Consider two gas turbine generators, called Gen.1 and Gen.2, of the same size are sharing a common load. Assume Gen.1 takes 60% and Gen.2 the remaining 40%. Let the system frequency be 60 Hz at full load and the droop of each machine be 4%.

The speed (frequency) versus load sharing situations can be shown graphically as in Figure 2.14 where point 'A' is the initial situation.

Now, supposing it is necessary to equalise the load shared by the two machines, then one or both of the speed settings will need to be adjusted depending upon the final common speed (frequency) required by the machines. It can be seen that unless the speed settings are changed, the load taken by each machine cannot change. There are several methods by which this may be done, by changing the speed setting of Gen.1 or Gen.2 or both.

Method 1. Change the speed setting of Gen.1 only:

The droop characteristic line 1A-A must be lowered to the new position ID-D so that it crosses the line 2A-D of Gen.2 at point 'D' for 50% sharing of load. Thus the speed

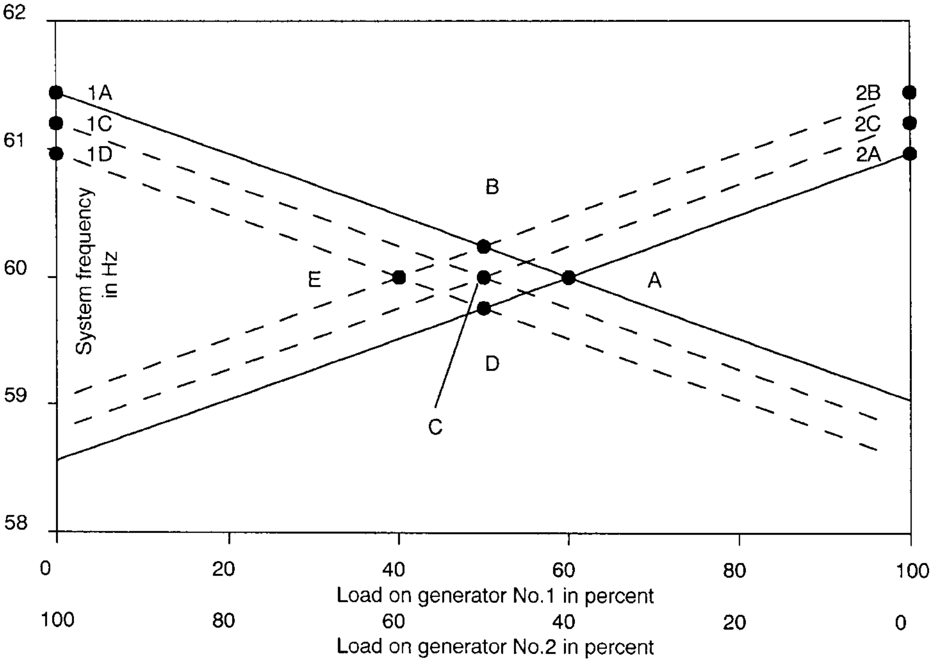

Figure 2.14 Frequency droop governing and load sharing of two gas turbines.

setting must be reduced from 102.4% (61.44 Hz) to 101.6% (60.96 Hz) i.e. the same as that of Gen.2. The common new frequency will be at point 'D' as 99.6% (59.76 Hz).

Method 2. Change the speed setting of Gen.2 only:

The droop characteristic line 2A-A must be raised to the new position 2B-B so that it crosses the line 1A-B of Gen.1 at point 'B' for 50% sharing of load. Thus the speed setting must be raised from 101.6% (60.96 Hz) to 102.4% (61.44 Hz) i.e. the same as that of Gen.1. The new frequency will be at point 'B' as 100.4% (60.24 Hz).

Method 3. Change the speed setting of Gen.1 and Gen.2.

In order to recover the frequency to 100% (60 Hz) both speed settings will need to be changed.

Gen.1 speed setting will be reduced to 102% (61.2 Hz).

Gen.2 speed setting will be raised to 102%.

The operating point will be 'C'.

The droop lines will be 1C-C and 2C-C.

2.5.4.1 Worked example

Three generators have different ratings and operate in a power system that has a nominal frequency of 60 Hz. Each generator is partially loaded and the total load is 25 MW.

a) Find the loading of each generator and the system frequency if the total load increases to 40.5 MW, whilst their set points remain unchanged.
b) Also find the changes required for the set points that will cause the system frequency to be restored to 60 Hz. The initial loads on each generator and their droop values are, shown in Table 2.6.
c) Find the changes in the set points that will enable the generators to be equally loaded at the new total load, with the system frequency found in a).
d) Find the additional changes in the set points that will enable the frequency to be recovered to 60 Hz.

Step 1. Find the initial set points f_{zi} before the load is increased. Transpose (2.62) to find f_{zi}

$$f_{zi} = f + \frac{D_i P_i f_o}{G_i} \tag{2.69}$$

For generator No. 1,

$$f_{z1} = 60.0 + \frac{0.03 \times 60.0 \times 10.0}{20} = 60.9 \text{ Hz}$$

Table 2.6. Data and initial conditions of three generators

Generator rating (MW)	Initial loading (MW)	Drop in per unit
20	10	0.03
15	10	0.04
10	5	0.05

Similarly for generators Nos. 2 and 3,

$$f_{z2} = 61.6 \text{ Hz and } f_{z3} = 61.5 \text{ Hz}$$

Step 2. The common system frequency after the load increases is found from (2.66), (2.67) and (2.68).

$$\begin{aligned} a &= \frac{1}{60.0}\left(\frac{60.9 \times 20.0}{0.03} + \frac{61.6 \times 15.0}{0.04} + \frac{61.5 \times 10.0}{0.05}\right) = 1266.67 \\ b &= \frac{1}{60}\left(\frac{20.0}{0.03} + \frac{15.0}{0.04} + \frac{10.0}{0.05}\right) = 20.6945 \\ f &= \frac{a - P}{b} = \frac{1266.67 - 40.5}{20.6945} \\ &= 59.25101 \text{ Hz} \end{aligned}$$

Step 3. Find the new load on each generator

$$\begin{aligned} P_1 &= (f_{z1} - f)\frac{G_1}{D_1 f_o} = (60.9 - 59.25101)\frac{20.0}{0.03 \times 60.0} \\ &= 18.3221 \text{ MW } (91.61\%) \end{aligned}$$

Similarly for generators Nos. 2 and 3,

$$P_2 = 14.6819 \text{ MW } (97.88\%) \text{ and } P_3 = 7.4966 \text{ MW } (74.97\%)$$

Note,

$$\begin{aligned} P_{\text{new}} &= P_1 + P_2 + P_3 = 18.3221 + 14.6819 + 7.4966 \\ &= 40.5 \text{ MW as required.} \end{aligned}$$

Step 4. Find the new set points that will recover the frequency to 60 Hz.

If a change ΔP_i in P_i is added to the (2.69) then the change in the set point will be,

$$\Delta f_{zi} = \frac{D_i \Delta P_i f_o}{G_I} \text{ (or } 60.0 - f)$$

For generator No. 1,

$$\Delta f_{z1} = \frac{0.03 \times (18.3221 - 10.0)60.0}{20} = 0.74899$$

And so the new set-point is $f_{z1} + \Delta f_{z1} = 61.6489$ Hz

Similarly for generators Nos. 2 and 3

$$f_{z2} + \Delta f_{z2} = 62.3491 \text{ Hz, and } f_{z3} + \Delta f_{z3} = 62.2489 \text{ Hz}$$

Step 5. Find the set points that will enable the generators to be equally loaded.

For generator No. 1, the ratio K_1 of its new load to its rating is,

$$\frac{P_1 + \Delta P_1}{G_1} = K_1$$

Similarly for generators Nos. 2 and 3,

$$\frac{P_2 + \Delta P_2}{G_2} = K_2 \text{ and } \frac{P_3 + \Delta P_3}{G_3} = K_3$$

For the generators to be equally loaded $K_1 = K_2 = K_3 =$K.

In addition the ratio of the total load to the total of the generator ratings must be the same as for each generator,

Hence,

$$K = \frac{P_1 + \Delta P_1 + P_2 + \Delta P_2 + P_3 + \Delta P_3}{G_1 + G_2 + G_3}$$

$$K = \frac{40.5}{20 + 15 + 10} = 0.9$$

Therefore since

$$\frac{P_1 + \Delta P_1}{G_1} = 0.9$$

$$\Delta P_1 = (0.9 \times 20) - 10.0 = 8.00 \text{ MW}$$

so that

$$P_1 + \Delta P_1 = 18.00 \text{ MW } (90\%)$$

and

$$\Delta P_2 = (0.9 \times 15) - 10.0 = 3.5 \text{ MW}$$

so that

$$P_2 + \Delta P_2 = 10.0 + 3.5 = 13.5 \text{ MW } (90\%)$$

and

$$\Delta P_3 = (0.9 \times 10) - 5.0 = 4.0 \text{ MW}$$

so that

$$P_3 + \Delta P_3 = 5.0 + 4.0 = 9.0 \text{ MW } (90\%)$$

Step 6. Find the new set points.

From (2.62), for generator No. 1, using the original frequency of 59.25101 Hz, found in Step 2,

$$\begin{aligned} f_{z1} &= 59.25101 + \frac{0.03 \times 18.00 \times 60.0}{20.0} \\ &= 60.871 \text{ Hz} \end{aligned}$$

Similarly for generators Nos. 2 and 3,

$$f_{z2} = 61.411 \text{ Hz and } f_{z3} = 61.951 \text{ Hz}$$

Step 7. Find the new set points that will recover the frequency to 60 Hz whilst maintaining equally loaded generators.

Let the desired frequency of 60 Hz be denoted at f_d. In order to reach this frequency all the set points need to be increased by the difference between f_d and f, which is,

$$\Delta f = f_d - f = 60.0 - 59.25101 = 0.749 \text{ Hz}$$

Therefore,

$$f_{z1} = 60.871 + 0.749 = 61.62 \text{ Hz}$$

$$f_{z2} = 61.411 + 0.749 = 62.16 \text{ Hz}$$

and

$$f_{z3} = 61.951 + 0.749 = 62.70 \text{ Hz}$$

Check that f has now the correct value, by using (2.62),

$$\begin{aligned} f &= f_{z1} - \frac{D_1 P_1 f_o}{G_1} = 61.62 - \frac{0.03 \times 18.0 \times 60}{20} \\ &= 61.62 - 1.62 = 60.0 \text{ Hz} \\ f &= f_{z2} - \frac{D_2 P_2 f_o}{G_2} = 62.16 - \frac{0.04 \times 13.5 \times 60}{15} \\ &= 62.16 - 2.16 = 60.0 \text{ Hz} \end{aligned}$$

and,

$$\begin{aligned} f &= f_{z3} - \frac{D_3 P_3 f_o}{G_3} = 62.70 - \frac{0.05 \times 9.0 \times 60}{10} \\ &= 62.70 - 2.70 = 60.0 \text{ Hz} \end{aligned}$$

2.5.5 Load Sharing Controllers

The above worked example illustrates the combination of droop governing with an overall isochronous control function. In a practical control scheme the following variables can be easily measured by suitable transducers,

f = the system frequency.
P_i = the electrical power at the terminals of the generator (the generator losses and gearbox losses can be ignored).
f_{zi} = the governor set point within the controller that drives the fuel valve. A suitable potentiometer can be used to derive the signal.

The constants D_i, G_i and f_o can be incorporated into the controller as potentiometer adjustments, or in a program if a programmable computing type of controller is used.

The control action can be made continuous or intermittent, i.e. control signals dispatched at regular intervals.

2.5.5.1 Simulation of gas turbine generators

As described in sub-section 2.1.4 there are two main methods of transferring power from the gas turbine to the generator, i.e., single-shaft and two-shaft driving systems. Established practice has a preference for single-shaft machines for generator duty, but only where the ratings are available. There is a reluctance to have both types on a common self-contained power system, such as those used with offshore platforms or isolated land-based plants. It is generally considered that a single-shaft machine has a superior speed performance when sudden changes in electrical power occur. The deviation in shaft speed and frequency are lower and the recovery time is faster. In a two-shaft machine there is a finite delay caused by the fact that the compressor responds before the power turbine can respond.

The block diagrams for these two driving arrangements are different, the two-shaft arrangement being slightly more complicated. Figure 2.13 can be rearranged as Figure 2.15 to show the reference speed signal on the left-hand side as the main input to the system. The main output of interest is the shaft speed. The rotational friction and windage block can be ignored since its influence on the performance of the control system is very small. The complexity of these diagrams depends upon what data are available from the manufacturer and the nature of the study being performed. The diagrams from manufacturers sometimes show features, which are not usually needed for stability studies, for example overspeed safety loops. Therefore some reasonable simplification is usually acceptable.

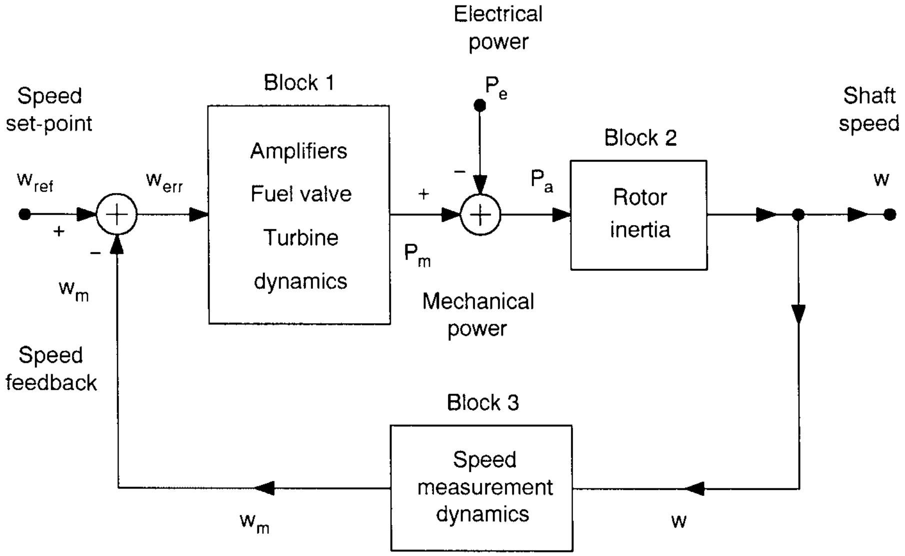

Figure 2.15 Simplified equation of motion of a gas turbine.

Block 1 in Figure 2.15 contains most of the main control and turbine functions, such as,

a) Governor gain.
b) Governor lead and lag compensating dynamics.
c) Derivative damping term for the speed signal.
d) Fuel valve gain, limits and dynamic terms.
e) Combustion system lag dynamic term.
f) Combustion system limits.
g) Power turbine dynamics.
h) Compressor dynamics.
i) Compressor protection system.
j) Turbine temperature measurement dynamics and limit or reference level.

The functions h), i) and j) are used when a two-shaft drive system needs to be simulated. When applied they usually require a special signal selection block to be incorporated just before the fuel valve or governor. The purpose of this signal selector is to automatically choose the lowest value or its two input signals, so that the least fuel is passed to the combustion system. This contributes to the slower response of a two-shaft machine.

The data supplied by the manufacturer is often given in physical units such as, the position of the fuel valve in angular degrees, shaft speed in revolutions per minute, power output in kilowatts, combustion temperature in degrees Kelvin. In most power system computer programs these data need to be converted into a compatible per-unit form. This can be a little difficult to achieve and a source of numerical errors, which can lead to incorrect results from the program. Manufacturers may also provide a per-unit form of the block diagram, if requested to do so. The time constants used in these diagrams vary significantly from one type and rating of gas turbine to another. It is difficult to generalise their values. The rotor inertia of the turbine should include the inertia of the gearbox and the rotor of the generator. The speed measurement block usually contains the governing lead and lag compensation time constants. These time constants and the derivative damping gain have a strong influence on the speed response to a change in electrical power, and should therefore be chosen or calculated carefully.

2.6 MATHEMATICAL MODELLING OF GAS TURBINE SPEED GOVERNING SYSTEMS

2.6.1 Modern Practice

Control systems used for the speed governing of gas turbines have become highly involved in electronic circuitry. Electromechanical fuel value control has largely replaced methods based on hydraulic control. The reliability of electronic and electrical devices has improved to such a level that they are generally preferred to hydraulic and mechanical devices, where their use is appropriate.

Most computer programs used for dynamic studies of power systems are capable of representing control systems and machinery dynamics to a reasonably high level of detail. Manufacturers of

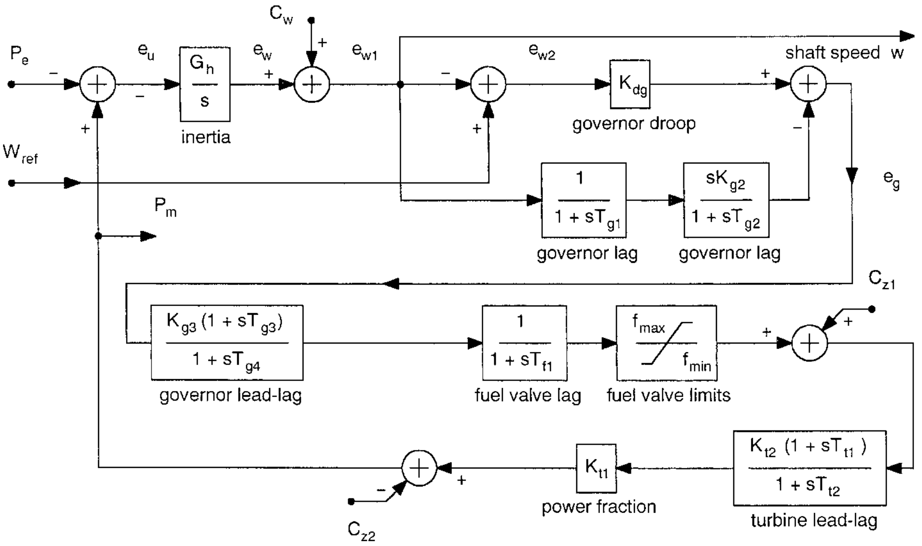

Figure 2.16 Control system for the speed governing of a single-shaft gas turbine.

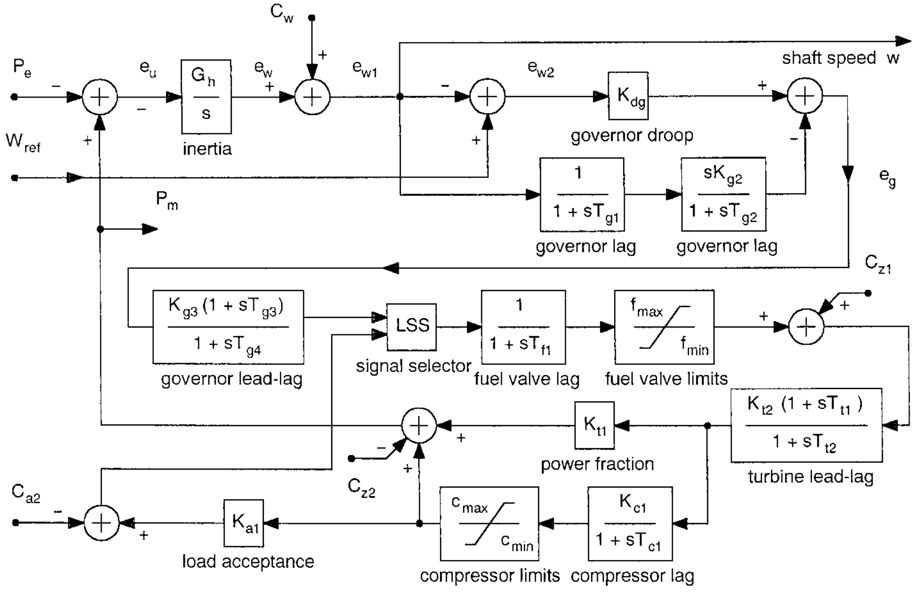

Figure 2.17 Control system for the speed governing of a two-shaft gas turbine.

gas turbines are normally able to provide detailed mathematical models of the machines and their control systems.

The modelling of the complete gas turbine including its control system and its interaction with the driven generator can be divided into several main functions. See Figures 2.16 and 2.17. Figure 2.16 represents a single-shaft gas turbine whilst Figure 2.17 represents a two-shaft machine.

The main functions are:-

- Summation of electrical and mechanical power.
- Acceleration of the rotating mass.
- Speed error sensing circuit to compare the shaft speed with a set or reference value.
- A power amplifier to amplify the error signal and to provide sufficient power to supply the fuel valve actuator.
- Fuel value limits and dynamics.
- Division of power between the power turbine and the compressor turbine.

Often the data to be used in a computer program are provided in actual physical units based on the SI or English thermodynamic systems of measurement. Most programs require the data in a per unit format. Care needs to be taken in converting the data into a suitable per unit format, especially the constants, scaling factors and controller limits. Figures 2.16 and 2.17 have therefore been drawn using per unit quantities.

2.6.1.1 Summation of electrical and mechanical power

The electrical power P_e input comes from the generator equations, which are usually presented in their two-axis form. This power is the power demand at the shaft coupling of the generator. This is derived from the transient or sub-transient equations of the generator, as described in sub-section 3.4. The choice depends upon the mathematical model used for the generator. For studies using practical data that are subject to tolerances of typically ±15%, and often approximations, the differences in the results obtained from a sub-transient or a transient model are small enough to ignore.

The mechanical output power P_m is the net power produced by the turbines of the gas turbine. This is the total power converted to mechanical power less the amount consumed by the compressor. In some models factors are given that show the proportion of power consumed by the compressor to that delivered to the power output turbine, as shown in Figure 2.17. The sum of two factors equals unity.

2.6.1.2 Acceleration of the rotating mass

The rotating mass considered in this part of the model is the total of the masses that form parts of the power turbine, its couplings, the gearbox rotating elements and the rotor of the generator (complete with its attachments such as the main exciter). It is customary to convert all the rotating polar moments of inertia into their 'inertia constants' and to use their total value in the model. Usually the turbine manufacturer will be able to advise the total polar inertia of the turbine plus the generator. However, the units used may be given in for example, SI (kgm^2), TM (kgfm^2) or English (Ibft^2) units. The TM system of units is commonly used in Europe, especially in Germany although it is being superseded by the SI system. A discussion of this aspect can be found in Chapter 1, Table 22 of Reference 8. If the polar moment of inertia is given in TM units of kgfm^2 then the equivalent quantity in SI units is 0.25 kgm^2, due to a fundamental difference in the definition of the radius of gyration. A possible source of error by a factor of four could result from simply ignoring the subscript 'f' in kgfm^2 and assuming it is the same as kgm^2.

The ‘inertia constant *H*’ is a constant used in electrical engineering to relate the actual moment of inertia of mechanical rotating components to a base of electrical volt-amperes. It was developed specifically for use in solving differential equations that describe the transient speed changes of generator shafts. Subsequently it has been used more widely in motor dynamic analysis. Two early references to the definitions of inertia constants are a report by Evans in 1937 (Reference 9), and a paper by Wagner and Evans in 1928 (Reference 10). The inertia constant H is defined as the energy stored in the rotating mass divided by the volt-ampere rating of the generator (or motor), which gives.

$$\begin{aligned} H &= \frac{\text{kilo-joules}}{\text{kVA}} \quad \text{or} \quad \frac{\text{kWsec}}{\text{kVA}} \\ &= \frac{2J{\omega_o}^2}{Sp^2} \text{ seconds} \end{aligned}$$

where J is the polar moment of inertia
ω_o is the synchronous speed
S is the VA rating of the machine
p is the number of poles of the machine

In English units,

$$H = \frac{0.231JN^2 \times 10^{-6}}{S} \text{ seconds}$$

with J in Lbft^2
N in revs/min
S in kVA

In SI units,

$$H = \frac{J\pi^2N^2 \times 10^{-3}}{1800S} \text{ seconds}$$

with J in kgm^2
N in revs/min
S in kVA

It should be noted that H is a function of the synchronous speed of the machine. If the speed should vary over a wide range then the variation of H with speed should be included in the mathematical simulation. For small excursions in speed about the synchronous speed, the error in using a constant value of H is negligible. This point is discussed in Reference 11.

2.6.1.3 Speed error sensing circuit

The output from the inertia block is the speed change e_ω due to integration of the mismatch in power between P_e and P_m.

The governor responds to the actual speed of the shaft and so the speed change needs to be added to the 1.0 pu base speed C_ω. The actual shaft speed is compared to the reference or set-point speed resulting in the error $e_{\omega 2}$.

2.6.1.4 Power amplifier

Power amplification is necessary in order to develop sufficient power to drive the fuel value open or closed. The amplifier incorporates,

- The droop constant K_{d1}.
- The lag term time constants T_{g1} and T_{g2} which are inherently present in the electronic circuits.
- The derivative damping gain K_{g2} which is often made adjustable.

2.6.1.5 Governor compensation

In order to improve the speed of response a lag-lead compensation circuit is employed in some governor control systems. It contains a gain term K_{g3}, a lag time constant T_{g4} and a lead time constant T_{g3}. If data are not available for these they may be assumed to be $K_{g3} = 1.0$ and $T_{g3} = T_{g4} = 0$.

2.6.1.6 Fuel valve mechanism lag

The fuel valve actuator and its mechanism may have sufficient inductance or inertia to introduce a perceptible lag in the valve stem response to its input signal. The equivalent time constant is T_{f1}.

2.6.1.7 Fuel valve limits

The fuel valve naturally has an upper and lower physical limit of the 'hard' type, i.e. a limit that is suddenly reached by the moving part. (A 'soft' limit is one in which the moving part reaches a region of increasing resistance before it eventually comes to rest. An electrical analogy would be magnetic saturation in an exciter, see sub-section 4.2.) The two hard limits are $f_{\min}$ and $f_{\max}$ where $f_{\min}$ is usually set at zero. Occasionally $f_{\min}$ has a negative value to artificially account for the no-load turbine power needed to drive the compressor. Hence at no load on the gas-turbine coupling the valve would be represented as having its position set to zero, whereas in practice it would open to about 15% of its travel.

Some fuel valves are driven by constant speed servomechanisms such as stepper motors. When they move the stem from one position to another the initial acceleration to constant speed is rapid, and likewise when the final position is reached. Feedback is applied in the valve controller to accurately relate the stem position to the magnitude of the control signal. Often this type of device is not modelled in computer programs, and so some form of approximation should be used to account for the lag in time between the receipt of the signal and the valve stem reaching its correct position. The constant speed motion of the valve actuator is also called 'slewing' and the 'slewing rate' is the measure of the rate of change of position during the constant speed motion.

An exponential approximation of slewing is now considered. Assume that the valve can move from its zero position to its 100% position in T_{100} seconds, at a constant rate, when a step input signal is applied at $t = 0$ seconds. Assume that an equivalent exponential lag term responds to the same step input over the same period of T_{100} seconds. Figure 2.18 shows the two responses referred to a common base of time. A good 'measure of fit' can be made by choosing the time constant T_{fa} such that the area represented by the lower part (A) equals that represented by the upper area (B). This is determined by equating these two areas. The areas are found by integration. Area (A) is found by

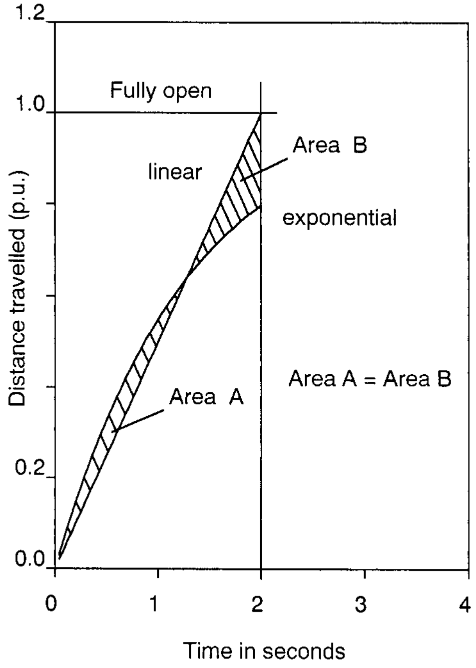

Figure 2.18 Simulation of slewing of the fuel valve by using an exponential approximation.

integrating between $t_1 = 0$ and $t_2 = T_e$, whilst area (B) is found by integrating between $t_1 = T_e$ and $t_2 = T_{100}$. If R is the slewing rate in per unit movement per second, then the solution for the best measure of fit is,

$$\frac{1}{2R} = (1 - e^{-f})T_{fa} \text{ seconds}$$

Where,

$$f = \frac{-1}{RT_{fa}}$$

Hence a unique value of T_{fa} can be found for each value of slewing rate R. The ratio of $1.0/T_{fa}$ to R that satisfies the above equation for all non-zero R is,

$$\frac{1}{RT_{fa}} = 1.5932, \text{ which may be rounded up to } 1.6$$

If for example the slewing rate is 3 per-unit travel/second then $1.0/R = 0.333$ and $T_{fa} = 0.333/1.6 = 0.208$ seconds.

If this approximation is made then an additional lag term should be inserted in the denominator of the ‘fuel valve lag’ block described in sub section 2.6.1.7 and the hard limits simply applied to the output of the block.

2.6.1.8 Combustion and turbine dynamics

After the fuel valve moves from one position to another the flow rate of the fuel delivered to the combustors changes, but a delay due to the inertia of the fuel occurs. The fuel enters the combustor and burns along its length at a finite burning rate. Completion of the combustion takes time and adds a further delay to the energy conversion process. A finite time is required for the burnt gas to pass through the power turbine and transfer part of its energy to the turbine. The 'turbine lead-lag' block approximates these conversion processes. The number of lead and lag terms varies from one gas turbine type to another.

In a single-shaft gas turbine the turbine lead-lag block represents the amount of energy or power that is convertible to mechanical power for accelerating the output shaft masses and to balance the electrical power demand.

In a two-shaft gas turbine the situation is slightly more complicated. Part of the convertible power is required to drive the separate compressor. The compressor has its own dynamic response and is shown as a parallel branch in Figure 2.17. This illustrates the fact that the resulting mechanical

Table 2.7. Typical data for simulating gas-turbine control systems

Parameter	Low	Values Typical	High
H note i)	1.2	1.5	2.0
G_h	0.25	0.33	0.42
C_w	1.0	1.0	1.0
K_{g1}	1.0	1.0	1.0
T_{g1}	0.05	0.01	0.015
K_{g2} note ii)	10.0	20.0	40.0
T_{g2}	0.02	0.04	0.15
K_{dg}	0.02	0.04	0.08
T_{g3}	0.25	0.50	0.75
T_{g4}	1.0	1.50	1.75
T_{f1}	0.01	0.02	0.05
f_{max}	1.2	1.35	1.5
f_{min}	−0.2	−0.15	0
K_{t1}	1.0	1.0	1.0
T_{t1}	0.3	0.6	0.9
T_{t2}	1.2	1.4	2.0
K_{t2}	0.4 (1.0)	0.5 (1.0)	06 (1.0)
K_{c1}	0.4 (0)	0.5 (0)	0.6 (0)
T_{c1}	Tt_2 (0)	Tt_2 (0)	Tt_2 (0)
C_{max}	1.1 (0)	1.2 (0)	1.3 (0)
C_{min}	0	0	0
K_{a1}	2.0 (0)	2.5 (0)	3.0 (0)
C_{a2}	0.38 (0)	0.4 (0)	0.42 (0)
C_{z1}	0.38 (0)	0.4 (0)	0.42 (0)
C_{z2}	0.48 (0)	0.5 (0)	0.52 (0)

Notes:

i) $G_h = \dfrac{1.0}{2H}$

ii) $K_{g1} x K_{g2} \simeq$ a constant value

iii) Data in brackets ( ) apply to the single-shaft mathematical model.

power has a part that is delayed when a disturbance occurs. It is generally considered that two-shaft gas turbines have a slower response characteristic to disturbances in electrical power, and that this gives rise to greater excursion in shaft speed. The delay due to the compressor being on a separate shaft accounts for this inferior performance.

With a two-shaft system the compressor is free to accelerate since it is not constrained by the heavy mass of the driven generator. In order to avoid excessive acceleration of the compressor a suitable signal is derived and passed through a safety control loop, often called the load schedule or acceleration control. The signal is compared with the output of the governor power amplifier and the least of these two signals is selected and sent to the fuel valve. The 'least signal selector' block carries out this comparison, as shown in Figure 2.17. Where the compressor loop is given with a slewing block, with upper and lower limits, the approximation of the slewing may be considered in the same manner as for the fuel valve actuator and its limits.

2.6.2 Typical Parameter Values for Speed Governing Systems

Table 2.7 shows typical per-unit values for the gains, limits and time constants used in the speed governing control systems for gas turbines having ratings up to approximately 25 MW.

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3

Synchronous Generators and Motors

3.1 COMMON ASPECTS BETWEEN GENERATORS AND MOTORS

The theoretical operation of synchronous generators and synchronous motors is almost the same. The main differences are the direction of stator current and the flow of power through these machines. The theory of operation of these machines is dealt with in great detail in most standard textbooks on electrical machines, e.g. References 1 to 6.

The construction of generators and motors, of the same kW ratings, used in the oil and gas industry is very similar, as discussed in sub-section 3.9. Variations that are noticeable from the external appearance exist mainly due to the location of the machine and its surrounding environment. It is uncommon for generators to be placed in hazardous areas, whereas it is occasionally necessary to use a synchronous motor in a hazardous area, e.g. driving a large gas compressor. Large induction motors are often used for driving oil pumps and gas compressors that need to operate in hazardous areas.

The rotor of generators may be either ‘cylindrical’ or ‘salient’ in construction. Synchronous motors nearly always have salient pole rotors. Machines with four or more poles are always of the salient pole rotor type. Cylindrical pole rotors are used for two-pole generators, and these generators are usually driven by steam or gas turbines at 3600 rpm for 60 Hz or 3000 rpm for 50 Hz operation and have power output ratings above 30 megawatts.

The methods of cooling and the types of bearings are generally the same.

The remaining discussion in this chapter, up to sub-section 3.9, will concentrate on salient pole machines with an emphasis on generators.

3.2 SIMPLIFIED THEORY OF OPERATION OF A GENERATOR

The stator, also called the armature, carries the three-phase AC winding. The rotor, also called the field, carries the DC excitation or field winding. The field winding therefore rotates at the shaft speed and sets up the main magnetic flux in the machine.

The fundamental magnetic action between the stator and rotor is one of tangential pulling. In a generator, the rotor pole pulls the corresponding stator pole flux around with it. In a motor, the stator pole pulls the rotor pole flux around with it. The action is analogous to stretching a spring, the greater the power developed, the greater the pull and greater the corresponding distance that is created between the rotor and stator flux axes.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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When a machine is not connected to the three-phase supply but is running at rated speed and with rated terminal voltage at the stator, there exists rated flux in the iron circuit and across the air gap. This flux cuts the stator winding and induces rated emf in winding and hence rated voltage at the main terminals. Consider what happens in a generator. Let the generator be connected to a load, or the live switchboard busbars. Stator current is caused to flow. The current in the stator winding causes a stator flux to be created which tends to counteract the air-gap flux that is produced by the excitation. This reduction of air-gap flux causes the terminal voltage to fall. The terminal voltage can be restored by increasing the rotor excitation current and hence the flux. So the demagnetising effect of the stator current can be compensated by increasing the field excitation current. This demagnetising effect of the stator current is called 'armature reaction' and gives rise to what is known as the synchronous reactance, which is also called a 'derived' reactance as described in sub-section 3.4.

The subject of armature reaction in the steady and transient states is explained very well in Reference 7. A brief description is given below.

3.2.1 Steady State Armature Reaction

The rotating field in the air gap of a synchronous machine is generally considered to be free of space harmonics, when the basic operation of the machine is being considered. In an actual machine there are space harmonics present in the air gap, more in salient pole machines than a cylindrical rotor machine, see for example References 4 and 6. It is acceptable to ignore the effects of space harmonics when considering armature reaction and the associated reactances. Therefore the flux wave produced by the rotating field winding can be assumed to be distributed sinusoidally in space around the poles of the rotor and across the air gap.

If the stator winding, which consists of many coils that are basically connected as a series circuit, is not connected to a load then the resulting emf from all the coils is the open circuit emf of the phase winding. Closing the circuit on to a load causes a steady state current to flow in the stator coils. Each coil creates a flux and their total flux opposes the field flux from the rotor. The resulting flux in the air gap is reduced. The emf corresponding to the air-gap flux drives the stator current through the leakage reactance and conductor resistance of the stator coils. The voltage dropped across this winding impedance is small in relation to the air-gap voltage. Deducting this voltage drop from the air-gap voltage gives the terminal voltage of the loaded generator. In the circumstance described thus far the reduction in air-gap flux is called armature reaction and the resulting flux is much smaller than its value when the stator is open circuit. Restoring air gap and terminal voltage requires the field current to be increased, which is the necessary function of the automatic voltage regulator and the exciter.

When the rotor pole axis coincides with the axis of the stator coils the magnetic circuit seen by the stator has minimum reluctance. The reactance corresponding to the armature reaction in this rotor position is called the 'direct axis synchronous reactance X_{sd}'. If the stator winding leakage reactance, X_a, is deducted from X_{sd} the resulting reactance is called the 'direct axis reactance X_d'.

A similar situation occurs when the rotor pole axis is at right angles to the axis of the stator coils. Here the magnetic reluctance is at its maximum value due to the widest part of the air gap facing the stator coils. The complete reactance in this position is called the 'quadrature axis synchronous reactance X_{sq}'. Deducting X_a results in the 'quadrature axis reactance X_q'.

3.2.2 Transient State Armature Reaction

Assume the generator is loaded and operating in a steady state. If the peak-to-peak or rms value of the stator current changes in magnitude then its corresponding change in magneto-motive force (mmf) will try to change the air-gap flux by armature reaction. Relatively slow changes will allow the change in flux to penetrate into the rotor. When this occurs an emf is induced in the field winding. This emf drives a transient current around a circuit consisting of the field winding itself and the exciter that is supplying the winding. The induction of current is by transformer action. An increase in stator current will be matched by an increase in field current during the transient state. A voltage drop will occur in the machine due to the armature reaction and the reduction in air-gap flux. Reactances are associated with this type of armature reaction.

When the rotor poles are coincident with the stator coils axis the armature reaction is a maximum and the reactance is called the 'direct axis transient reactance X'_d'.

The situation is different when the rotor poles are at right angles to the stator coils. There is no induction in the field circuit and the reluctance is high, being almost the same as for the steady state condition. In this situation the corresponding quadrature axis transient reactance X'_q approximately equals the reactance X_q. Cylindrical rotors of two-pole high speed generators have a nearly uniform rotor diameter and almost constant air gap all around the periphery. Hence the reactance X'_q is almost equal to X'_d.

3.2.3 Sub-Transient State Armature Reaction

Again assume that the generator is loaded and operating in a steady state. In this situation the magnitude of the stator current is allowed to change rapidly, as in the case of a short circuit in the stator circuit. The additional flux produced by the stator winding will try to penetrate the surface of the rotor poles. Most oil industry generators are provided with damper bars to reduce the excursions in rotor speed during major disturbances. The bars are made of copper or copper alloy and placed longitudinally in the face of the rotor poles. They function in a manner similar to a squirrel cage induction motor when there is a transient change in rotor speed relative to the synchronous speed. As soon as the additional flux passes through the pole faces it will induce currents in the damper bars and the solid pole tips, by the process of transformer induction. These induced currents will set up flux in opposition in order to maintain constant flux linkages with the stator.

During this transient condition, or more appropriately called a sub-transient condition, the additional flux is forced to occupy a region consisting of air and the surface of the rotor poles. This is a high reluctance condition which gives rise to reactances of low values.

Some generators have the damper bars connected to a ring at either end of the pole structure, which provides some damping action from the quadrature axis. This provides a set of short-circuited coils in the quadrature axis, which are air cored and able to repel the flux that is attempting to enter their region.

By the same reasoning as for the 'transient' reactances so the 'sub-transient' reactances are derived, and are called the 'direct axis sub-transient reactance X''_d' and the 'quadrature axis sub-transient reactance X''_q'.

3.3 PHASOR DIAGRAM OF VOLTAGES AND CURRENTS

The following points apply to the drawing of phasor diagrams of generators and motors:-

- The terminal voltage V is the reference phasor and is drawn horizontally.
- The emf E lies along the pole axis of the rotor.
- The current in the stator can be resolved into two components, its direct component along the 'direct or d-axis' and its quadrature component along the 'quadrature or q-axis'.

The emf E leads the voltage V in an anti-clockwise direction when the machine is a generator.

Each reactance and resistance in the machine has a volt drop associated with it due to the stator current flowing through it. Consider a generator. The following currents and voltages can be shown in a phasor diagram for both the steady and the dynamic states.

- E the emf produced by the field current I_f.
- V the terminal voltage.
- V_d the component of V along the d-axis.
- V_q the component of V along the q-axis.

- I the stator current.
- I_d the component of I along the d-axis.
- I_q the component of I along the q-axis.
- IR_a the volt drop due to the armature or stator current.
- $I_d R_a$ the component of IR_a along the d-axis.
- $I_q R_a$ the component of IR_a along the q-axis.

- $I_d X_d$ the volt drop due to the d-axis synchronous reactance.
- $I_d X_d'$ the volt drop due to the d-axis transient reactance.
- $I_d X_d''$ the volt drop due to the d-axis sub-transient reactance.
- $I_q X_q$ the volt drop due to the q-axis synchronous reactance.
- $I_q X_q'$ the volt drop due to the q-axis transient reactance (normally taken as $I_q X_q$).
- $I_q X_q''$ the volt drop due to the q-axis sub-transient reactance.
- E' the emf behind the transient impedance.
- E'' the emf behind the sub-transient impedance.

Explanations of the two-axis, or d-q, theory are given in Reference 1, Chapter 17 and in more detail in References 2 and 3.

Figure 3.1 has been drawn for a 15 MW generator operating at full-load and a power factor of 0.8 lagging.

The following per-unit data were used:-

$$E = 2.098$$

$$V = 1.0, \quad V_d = 0.423, \quad V_q = 0.906$$

$$I = 1.0, \quad I_d = 0.882, \quad I_q = 0.472$$

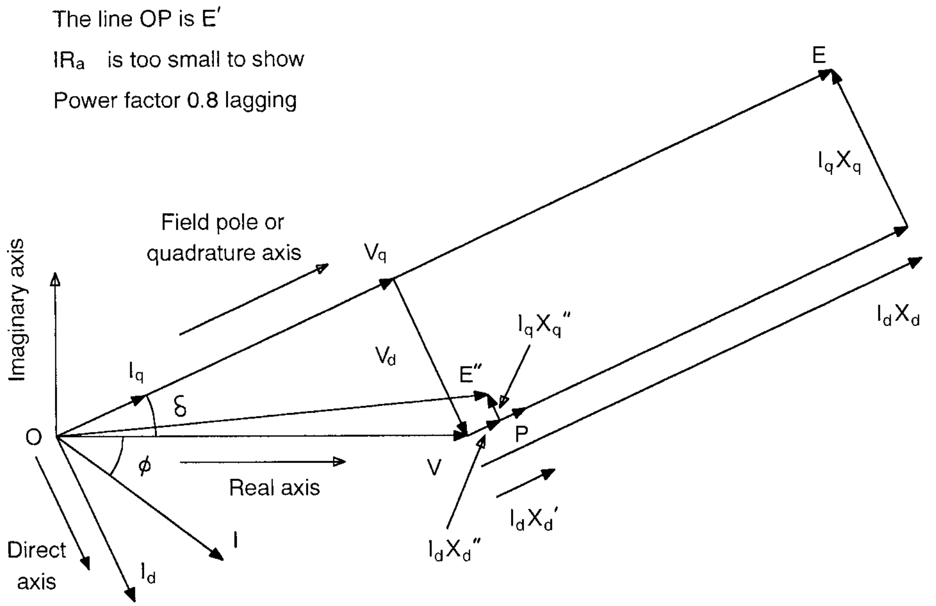

Figure 3.1 Phasor diagram of a two-axis salient pole generator.

$R_a = 0.002$

$X_d = 2.5 \quad X_q = 0.9$

$X_d' = 0.18 \quad X_q' = X_q$

$X_d'' = 0.1 \quad X_q'' = 0.15$

3.4 THE DERIVED REACTANCES

The derived reactances were described in sub-section 3.2 in relation to their effect on armature reaction. They are derived from the actual winding reactances by the standard equations, for example References 8 and 9.

Direct axis:

$$X_d = X_a + X_{md} \tag{3.1}$$

$$X_d' = X_a + \frac{X_{md}X_f}{X_{md} + X_f} \simeq X_a + X_f \tag{3.2}$$

$$X_d'' = X_a + \frac{X_{md}X_fX_{kd}}{X_{md}X_f + X_{md}X_{kd} + X_fX_{kd}} \tag{3.3}$$

$$\simeq X_a + \frac{X_fX_{kd}}{X_f + X_{kd}}$$

Quadrative axis:

$$X_q = X_a + X_{mq} \tag{3.4}$$

$$X''_q = X_a + \frac{X_{mq}X_{kd}}{X_{mq} + X_{kd}} \simeq X_a + X_{kd} \tag{3.5}$$

Where X_{md} and X_{mq} are much larger than any of the other reactances.

These equations can be transposed to find X_f, X_{kd} and X_{kq} in terms of X'_d, X''_d and X''_q in particular. The purchaser may require certain limits to X'_d and X''_d because of constraints on fault currents and volt drop. Consequently the machine designer is faced with finding physical dimensions to satisfy the resulting X_{md}, X_f and X_{kd}. The purchaser is not usually too concerned about the quadrature parameters. Transposing (3.1), (3.2) and (3.3) gives the designer the following:-

$$X_{md} = X_d - X_a \tag{3.6}$$

$$X_f = \frac{X_{md}(X'_d - X_a)}{X_{md} - X'_d + X_a} \tag{3.7}$$

$$X_{kd} = \frac{X_{md}X_f(X''_d - X_a)}{X_{md}(X_f + X_a) + X_aX_f - X''_d(X_{md} + X_f)} \tag{3.8}$$

Where X_a is kept as small as is practically reasonable.

Figures 3.2 and 3.3 show the variations of X'_d and X''_d with X_f for a family of X_{md} and X_{kd} values.

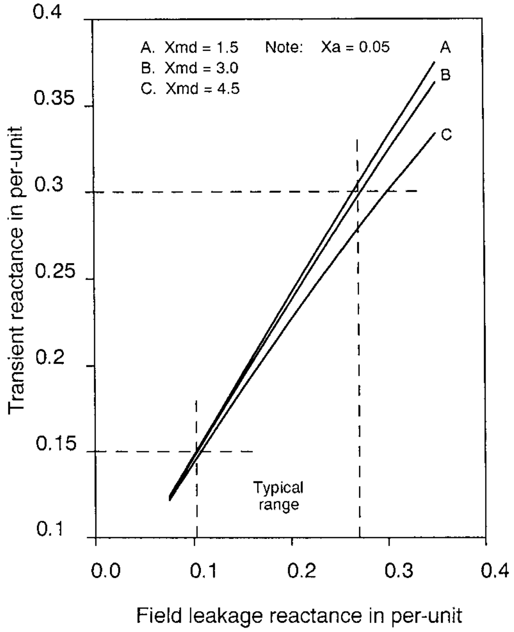

Figure 3.2 D-axis transient reactance versus field leakage reactance.

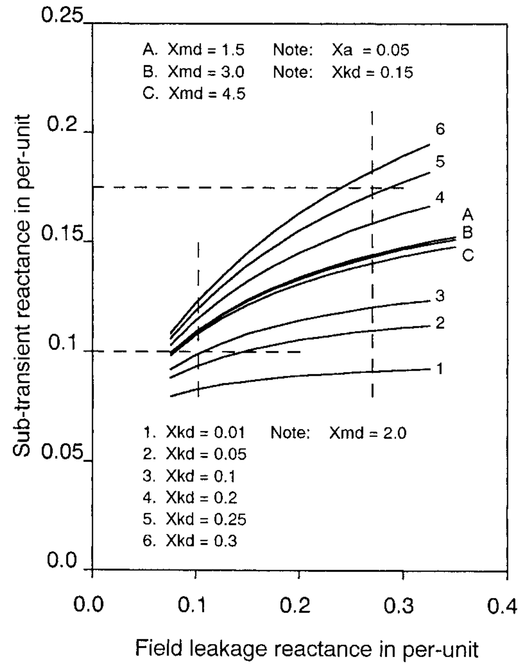

Figure 3.3 *D*-axis sub-transient reactance versus field leakage reactance.

3.4.1 Sensitivity of X_{md}, X_a, X_f and X_{kd} to Changes in Physical Dimensions

Assume a particular machine has a given rotor length and diameter, and radial depth of stator core. Allow other dimensions to vary.

The mutual coupling X_{md} between the rotor and the stator is much influenced by the radial length of the air gap.

A large air gap gives rise to a high reluctance path and a small mutual reactance X_{md}. Large air gaps facilitate the efficient removal of heat from the rotor and stator surfaces. Unfortunately a large air gap also results in more ampere-turns being needed in the rotor to fully excite the machine. This requires more volume in the rotor and for a given air gaps a larger mean diameter of the stator, hence a heavier and more expensive machine. As the kW rating of a machine increases so do its synchronous reactances, see sub-section 3.8.

$$X_{md} \propto \frac{\text{diameter of rotor} \times \text{length of rotor}}{\text{air-gap radial distance}}$$

A low armature leakage reactance X_a requires the number of stator slots per phase to be kept small, and a high utilisation of conductors per slot. Double layer slots are most often used for high voltage machines.

The armature leakage reactance is very much dependent upon the stator slot dimensions. It can be shown that:

$$X_a \propto \frac{\text{axial length of slots} \times \text{depth of slots}}{\text{width of slots}}$$

The field leakage reactance is dependent on the shape of the pole yoke,

$$X_f \propto \frac{\text{circumference of the yoke}}{\text{radial length of the yoke}}$$

Therefore a low value of X_f is obtained by having a radially long yoke of small cross-sectional area. Hence the overall diameter of the rotor tends to increase as the reactance decreases.

The damper bars or winding act in a manner very similar to an induction motor and provide a breaking torque against the transient disturbances in shaft speed. To be effective the damper needs to have a steep torque versus slip characteristic in the region near synchronous speed. The equivalent impedance of the damper requires a low resistance and a high reactance. High conductivity copper bars are embedded into the pole face to provide a low reluctance path for the leakage flux.

The variation in X_{kd} with slot dimensions is similar to the armature leakage,

$$X_{kd} \propto \frac{\text{axial length of slots} \times \text{depth of slots}}{\text{width of slots}}$$

Increasing X_{kd} tends to slightly increase the overall diameter of the rotor.

Reference 10 gives a full description of the physical design of electrical machines.

3.5 ACTIVE AND REACTIVE POWER DELIVERED FROM A GENERATOR

3.5.1 A General Case

If the steady state, transient and sub-transient phasors in Figure 3.1 are considered separately, then there is seen to be a similar structure. The terminal voltage V is resolved into its two-axis components V_d and V_q. The emfs E, E' and E'' can also be resolved into their components; E_d, E_q, E'_d, E'_q, E''_d and E''_q. In practical machines E_d does not exist (except for an interesting prototype built for the CEGB in approximately 1970, called the Divided Winding Rotor generator, see References 12 and 13). E_d would require a second exciter to produce it.

The variables can be regarded as ‘sending-end’ and ‘receiving-end’ variables. The sending-end variables are the emfs E, E_d and E_q, whilst the receiving-end ones are V, V_d and V_q. The current I, resolved into I_d and I_q, is common to both ends. The emfs, voltages and volt drops along each axis can be equated as,

For the d-axis

$$E_d = V_d + I_d R_d - I_q X_q \tag{3.9}$$

For the q-axis

$$E_q = V_q + I_q R_q + I_d X_d \tag{3.10}$$

Where R_d and R_q are the resistances present in their respective axis, usually both are equal to R_a the armature resistance.

To distinguish between the sending-end and the receiving-end the subscripts 's' and 'r' are introduced for the δ angles between E and E_q, and V and V_q respectively. Hence their components are:-

$$\begin{aligned}
V_d &= V\sin\delta_r\\
V_q &= V\cos\delta_r\\
E_d &= E\sin\delta_s\\
E_q &= E\cos\delta_s\\
I_d &= -I\sin(\emptyset+\delta_r)\\
I_q &= I\cos(\emptyset+\delta_r)
\end{aligned}$$

Equations (3.9) and (3.10) can be transposed to find I_d and I_q,

$$I_d = \frac{(E_q - V_q)X_q + (E_d - V_d)R_q}{X_dX_q + R_dR_q}$$

And

$$I_q = \frac{(E_q - V_q)R_d - (E_d - V_d)X_d}{X_dX_q + R_dR_q}$$

Active and reactive power leaving the terminals of the 'receiving-end' and received by the load are,

$$P_r = \frac{P_{r1} + P_{r2}}{\text{DEN}}$$

$$Q_r = \frac{Q_{r1} + Q_{r2}}{\text{DEN}}$$

Where,

$$\begin{aligned}
P_{r1} &= V\sin\delta_r(E_qX_q + E_dR_q) + \frac{V^2}{2}\sin 2\delta_r(X_d - X_q)\\
P_{r2} &= V\cos\delta_r(E_qR_d - E_dX_d) - V^2(R_q\sin\delta_r + R_d\cos^2\delta_r)\\
Q_{r1} &= V\cos\delta_r(E_qX_q + E_dR_q) + \frac{V^2}{2}\sin 2\delta_r(R_d - R_q)\\
Q_{r2} &= V\sin\delta_r(E_dX_d - E_qR_d) - V^2(X_d\sin^2\delta_r + X_q\cos^2\delta_r)\\
\text{DEN} &= X_dX_q + R_dR_q
\end{aligned}$$

Also the active and reactive power leaving the shaft and the exciter are,

$$\begin{aligned}
P_s &= \text{Real part of (EI}^*)\\
&= I\left(E_q\cos(\delta_r + \emptyset) + E_d\sin(\delta_r + \emptyset)\right)
\end{aligned}$$

Where I* denotes the conjugate of the phasor I.

$$\begin{aligned} Q_s &= \text{Imaginary part of (EI}^*\text{)} \\ &= I\left(E_q \sin(\delta_r + \emptyset) - E_d \cos(\delta_r + \emptyset)\right) \end{aligned}$$

The active and reactive power losses are,

$$P_{\text{loss}} = {I_d}^2 R_d + {I_q}^2 R_q$$
$$Q_{\text{loss}} = {I_d}^2 X_d + {I_q}^2 X_q$$

From which the summations of powers are,

$$P_S = P_r + P_{\text{loss}}$$
$$Q_S = Q_r + Q_{\text{loss}}$$

The equations above are shown for the steady state. However they apply equally well for the transient and sub-transient states provided the substitutions for E'_d, E'_q, E''_d, E''_q, X'_d, X'_q, X''_d and X''_q are made systematically. Such substitutions are necessary in the digital computation of transient disturbances in power systems, those that are often called 'transient stability studies'.

3.5.2 The Particular Case of a Salient Pole Generator

The first simplification is to assume $R_d = R_q = R_a$ which is very practical. In addition the steady state variables E_d and δ_r can be assumed to be zero. Hence the equations in sub-section 3.5.1 become.

$$V_d = V \sin\delta$$
$$V_q = V \cos\delta$$
$$E_d = 0$$
$$E_q = E$$
$$I_d = -I \sin(\phi + \delta)$$
$$I_q = I \cos(\phi + \delta)$$
$$I_d = \frac{(E_q - V_q)X_q - V_d R_a}{X_d X_q + {R_a}^2}$$
$$I_q = \frac{(E_q - V_q)R_a - V_d X_d}{X_d X_q + {R_a}^2}$$
$$P_r = \frac{P_{r1} + P_{r2}}{\text{DEN}}$$
$$Q_r = \frac{Q_{r1} + Q_{r2}}{\text{DEN}}$$

Where,

$$\begin{aligned}
P_{r1} &= V\sin\delta(E_q X_q) + \frac{V^2}{2}\sin 2\delta(X_d - X_q)\\
P_{r2} &= V\cos\delta(E_q R_a) - V^2 R_a\\
Q_{r1} &= V\cos\delta(E_q X_q)\\
Q_{r2} &= V\sin\delta(-E_q R_a) - V^2(X_d\sin^2\delta + X_q\cos^2\delta)\\
\mathrm{DEN} &= X_d X_q + {R_a}^2
\end{aligned}$$

The sending-end variables become,

$$\begin{aligned}
P_S &= I\ E_q\cos(\delta+\phi)\\
Q_S &= I\ E_q\sin(\delta+\phi)
\end{aligned}$$

3.5.3 A Simpler Case of a Salient Pole Generator

Most practical generators have an armature resistance R_a that is much less in value than the synchronous reactances X_d and X_q. Consequently the equations in sub-section 3.5.2 can be further simplified without incurring a noticeable error. They become,

$$\begin{aligned}
V_d &= V\sin\delta\\
V_q &= V\cos\delta\\
E_q &= E\\
I_d &= -I\sin(\phi+\delta)\\
I_q &= I\cos(\phi+\delta)\\
I_d &= \frac{E_q - V_q}{X_d}\\
I_q &= \frac{V_d}{X_q}\\
P_r &= \frac{P_{r1}+P_{r2}}{\mathrm{DEN}}\\
Q_r &= \frac{Q_{r1}+Q_{r2}}{\mathrm{DEN}}
\end{aligned}$$

Where,

$$\begin{aligned}
P_{r1} &= V\sin\delta(E_q X_q) + \frac{V^2}{2}\sin^2\delta(X_d - X_q)\\
P_{r2} &= 0\\
Q_{r1} &= V\cos\delta(E_q X_q)
\end{aligned}$$

$$Q_{r2} = -V^2(X_d \sin^2 \delta + X_q \cos^2 \delta)$$

$$\text{DEN} = X_d X_q$$

The sending-end variables remain the same. These equations are of the same form as those found in most textbooks that cover this subject.

3.6 THE POWER VERSUS ANGLE CHART OF A SALIENT POLE GENERATOR

Manufacturers of synchronous generators will usually provide a power-angle chart of the form shown in Figure 3.4, which was drawn using typical data. Let the volt drop $I_q X_q$ in Figure 3.1 be extended at its intersection with E to a value $I_q X_d$, and then divide all the variables by X_d. Figure 3.4 is the resulting power angle diagram, derived in the manner recommended in Reference 11, which incidentally has not changed since then. The line AB represents the kVA of the generator and OB the excitation emf.

Power-angle charts are normally used where a generator feeds into a utility grid rather than a local captive load as with 'island mode' operation. When a generator feeds into a grid its operating condition is not only determined by the overall load on the grid but also by the reactive power requirements of the overhead lines at and near to the generator. For example at night-time the active power demand tends to be lower than in the day-time but since the transmission system is still connected it requires compensation to counteract the excessive capacitance charging current that is

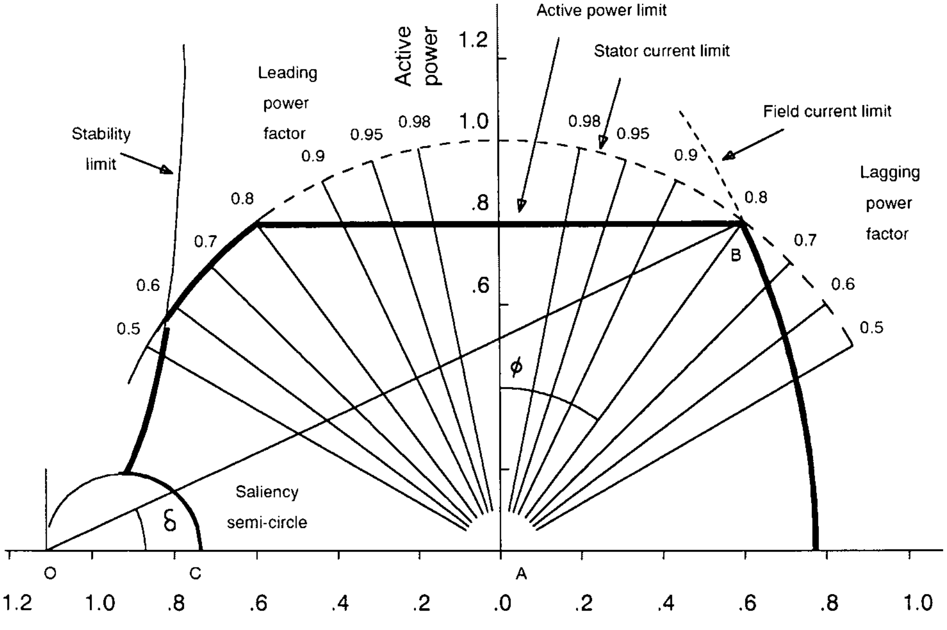

Figure 3.4 Operating chart of a two-axis salient pole generator.

Table 3.1. Preferred rated voltages of generators

Generator rating (kVA)	Approximate voltage rating (volts)	
	Min.	Max.
100	200	450
200	200	800
500	300	3,000
1,000	400	7,500
2,000	600	15,000
5,000	2,000	15,000
10,000	5,000	15,000
20,000	10,000	15,000
30,000	15,000	15,000

present. This can only be achieved by under-exciting the generator, thereby causing it to operate near or in its leading power factor region.

The above situation cannot normally occur with a self-contained power plant such as those on marine installations, unless they are interconnected by submarine cables to other installations that also have running generators. Even with interconnections of typically 20 km the amount of capacitance charging current is not sufficient to cause generators to operate in their leading power factor regions. It is possible under abnormal operating conditions, but these are too rare to consider. Oil industry power plants operate with a lagging power factor at or near to 0.9.

In conclusion it can be seen that the use and benefit of power-angle charts are minimal for most oil industry power plants.

3.7 CHOICE OF VOLTAGES FOR GENERATORS

The rated voltage of generators tends to increase in steps as the power rating increases. The most preferred voltages are given as a guide in Table 3.1. See also IEC60038.

3.8 TYPICAL PARAMETERS OF GENERATORS

Often at the beginning of a design project it is necessary to carry out some basic calculations and studies. For example, estimating the maximum fault current at the main generator switchboard and a preliminary stability assessment. At this stage equipment will not have been fully specified and so definitive data are not available from the chosen manufacturers. Typical data need to be used. Figures 3.5 through 3.12 show typical reactances and time constants for generators in the range 1.0 to 40 MVA drawn from a modest sample of generators. In each figure it can be seen that there is a spread of points about the average line. This is partly due to the data being taken from some generators that have had constraints placed on them for minimum fault currents and volt drops. Other generators were closer to the standard or preferred design of the manufacturer. For preliminary studies and calculations the data taken from the average (or trend) lines would give reasonable results. If worst-case situations are to be considered then a value either side of the trend line within the range

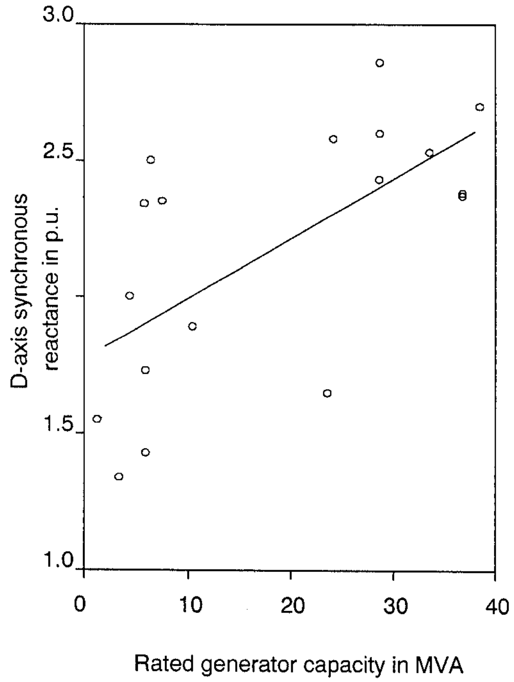

Figure 3.5 *D*-axis synchronous reactance versus generator MVA rating.

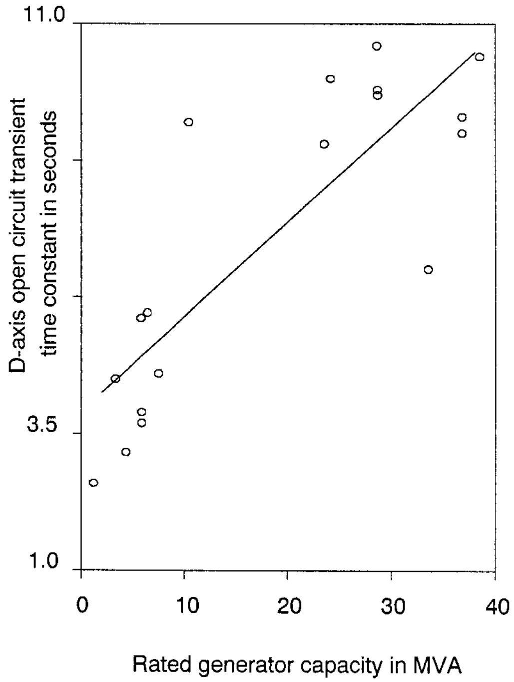

Figure 3.6 *D*-axis open circuit time constant versus generator MVA rating.

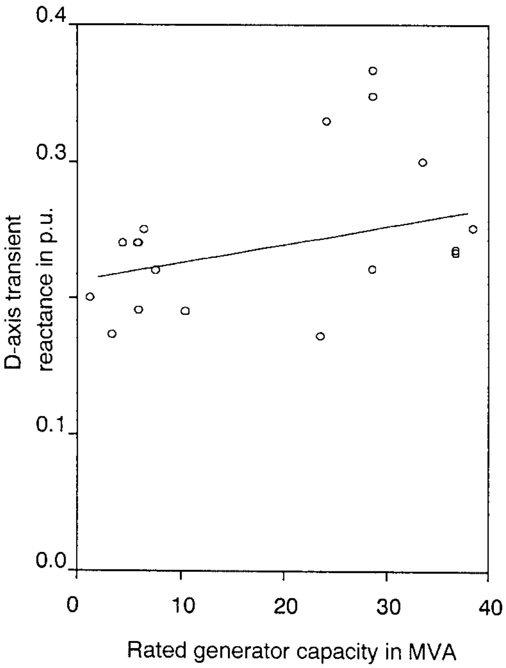

Figure 3.7 *D*-axis transient reactance versus generator MVA rating.

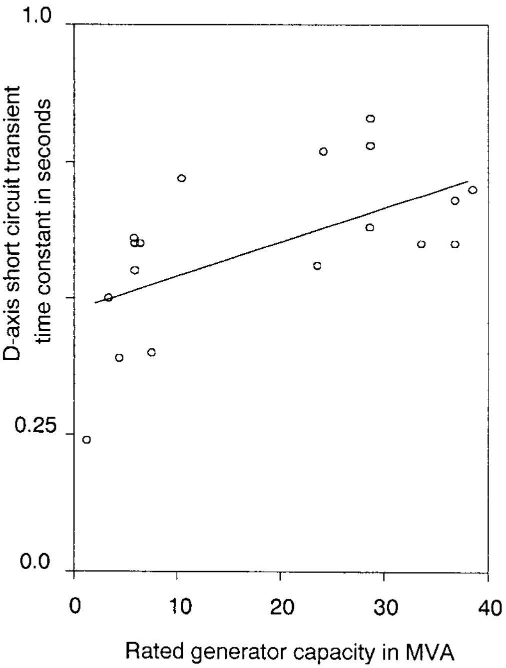

Figure 3.8 *D*-axis short circuit transient time constant versus generator MVA rating.

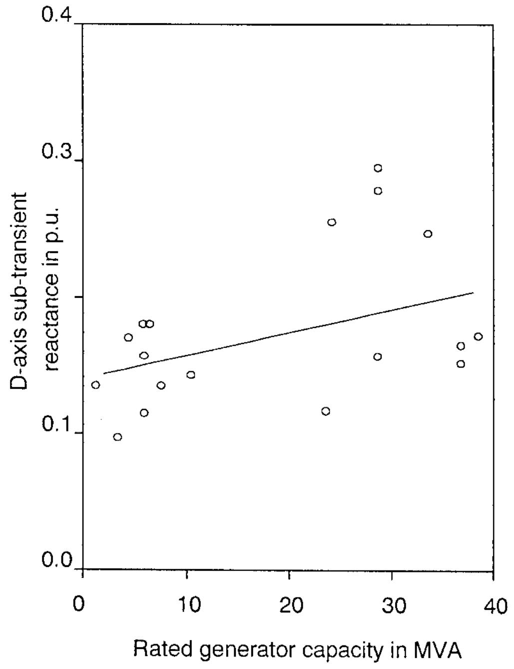

Figure 3.9 *D*-axis sub-transient reactance versus generator MVA rating.

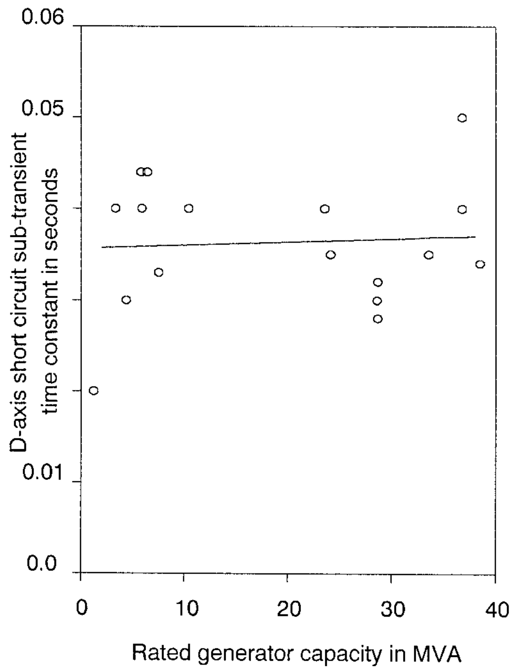

Figure 3.10 *D*-axis short circuit sub-transient time constant versus generator MVA rating.

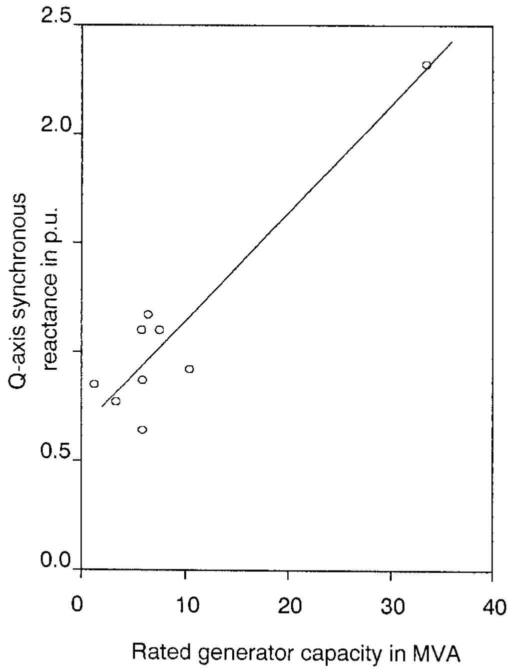

Figure 3.11 Q-axis synchronous reactance versus generator MVA rating.

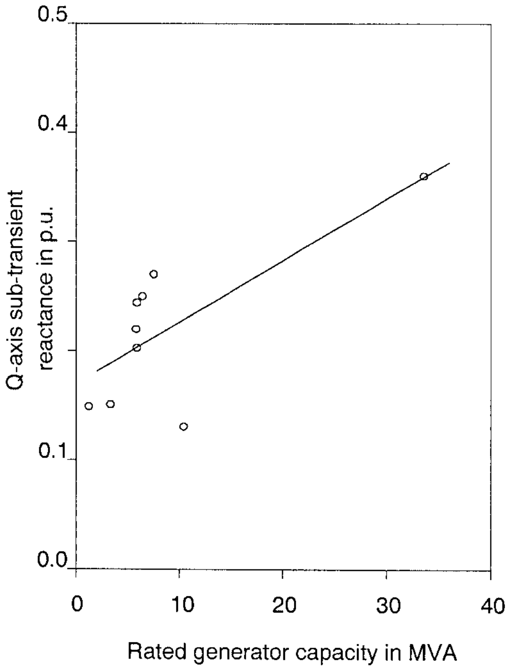

Figure 3.12 Q-axis sub-transient reactance generator MVA rating.

of the spread would also give realistic results. It should be remembered that manufacturers normally quote data with a tolerance of plus and minus 15%.

The inertia constant H for four pole machines varies from about 1.2 MW seconds/MVA for a 1 MVA generator to about 2.5 for a 40 MVA generator.

3.9 CONSTRUCTION FEATURES OF HIGH VOLTAGE GENERATORS AND INDUCTION MOTORS

From outward appearances a high voltage generator will look very similar to a high voltage motor. The first noticeable difference will be the presence of the exciter at the non-drive end of the generator. Less noticeable is the rotor. Synchronous machines will have wound rotors fed with DC current from an exciter. Induction motors will invariably have caged rotor bars and no external excitation to the rotor. (There are special designs of induction motors that have external connections to the rotor, but these are outside the scope of this book.)

3.9.1 Enclosure

The enclosure or casing of the machine needs to withstand the ingress of liquids and dust that become present at oil industry sites. For outdoor locations the environment can range from cold and stormy marine conditions to hot and dry desert conditions. In offshore locations the machines are usually, but not always, placed indoors in a room or module. This protects them from heavy rain and saltwater spray. Even inside the room or module they need to withstand firewater spray, if used, and hosing down with water. The environment in land-based plants can also be hostile and the machine needs protection against ingress from, for example, coastal weather, desert sand storms, smoke pollution.

The IEC60529 standard describes in detail the ingress protection to be achieved, see also section 10.6 herein. For indoor locations machines of megawatt ratings may be specified for IP44 or, for extra protection, IP54. Machines with ratings below approximately 2000 kW, and which are of standard ‘off-the-shelf’ designs, the protection may be IP54, IP55 or IP56. The cost differences may not be significant for standard machines.

Outdoor locations require a more rigorous protection and IP54 would be the minimum for the larger machines. For ‘off-the-shelf’ designs again IP55 or IP56 would be acceptable.

In all outdoor and indoor situations it is common practice to specify IP55 for the main and auxiliary terminal boxes.

Generators should not be located in classified hazardous areas. Whereas it is often unavoidable to locate a high voltage motor in a Zone 2 or Zone 1 hazardous area. The lower ratings of motors are generally available in at least Ex ‘d’ certification for use in Zone 2 and Zone 1 locations. Large motors are difficult and expensive to manufacture with Ex ‘d’ enclosures. It is therefore common practice to require an Ex ‘n’ enclosure design and purge the interior with air or nitrogen from a safe source. This design of motor would then be certified as an Ex ‘p’ machine. The terminal boxes for such a motor would be specified as Ex ‘de’ with ingress protection IP55 as a minimum. This subject is covered in more detail in Chapter 10.

3.9.2 Reactances

Where possible it is most economical to accept the design values of reactances offered by manufacturers. However, in the design of the power system as a whole certain constraints may arise. For example the plant load may be predominantly induction motors, of which a large proportion may be at high voltage. This situation will impose two main constraints:

i) A high contribution of sub-transient fault current at the inception of a major fault.

ii) Potentially high volt drop at the main switchboard if the high voltage motors are to be started 'direct-on-line'.

Constraint i) will need the sub-transient reactances of the generators to be higher than for a standard design. It may also require the starting impedance of the motors to be higher than normal in order to reduce their sub-transient currents.

Constraint ii) requires the transient reactances of the generator to be kept as small as practically possible. At the same time the starting current of the motors should be kept as low as possible, without unduly increasing their run-up time.

These two constraints counteract in the design of the generator, because the physical dimensions of items such as rotor and stator conductor slots affect the sub-transient and transient reactances differently. In general fixing one of these reactances will limit the choice available for the other.

3.9.3 Stator Windings

Modern switchgear is fast acting in the interruption of current, which happens near to a current zero. The sharp cut-off of a current which is not at zero gives rise to a high induced emf in the windings of motors. In addition to the high magnitude of the emf, its rate of rise is also high which imposes stress on the winding insulation. Earlier designs of motors that were switched by vacuum contactors suffered damage to their insulation and it became an established practice to install surge diverters on the feeder cables, either at the switchboard or in the motor terminal box. Modern motors do not suffer from this problem as much as their older designs. Improvements have been made to insulating materials and to the reduction of voltage stressing within the windings, for example as the winding coils emerge from their slots.

Modern machines are connected to power systems that often have relatively high prospective fault levels and so the generators and motors need to have their windings and terminations robustly braced to avoid movement during a major fault. General-purpose industrial machines may not be robust enough for such high fault level service.

The winding insulation temperature rise criteria are often specified to be Class F design but the performance limited to Class B. This results in a conservative design and potentially longer mean time before failure of the insulation. The class of insulation is common to several international standards e.g. IEC60085. The choice of Class B operating temperature rise will tend to slightly increase the volume of material used to build the machine. The insulating materials are often vacuum impregnated to render them resistant to the absorption of moisture, which is necessary for coastal, marine and tropical installations.

3.9.4 Terminal Boxes

Motors and generators should be provided with properly designed terminal boxes. They should be capable of withstanding a full three-phase fault without destruction and with the minimum of subsequent repair work and materials being needed. The duration of the fault would be typical of the relay or fuse protection provided in the switchboard. With a generator the limitation of damage by the corrective action of the switchgear protective devices is not as effective as for a motor. The switchgear in feed to the terminal box fault can be isolated by the relays in the circuit breaker. However, unless the exciter can be shut down or the machine brought to rest there is a possibility that the generator will feed its own fault. These events are rare but possible, and when they do occur they are very disruptive to the production from the plant.

Large high voltage machines are usually protected by differential stator current (87) relays and earth fault (51G) and (64) relays. These systems require current transformers to be fitted close to the winding terminals. It is very desirable to mount these transformers inside the main terminal box. Frequently it is necessary to have two main terminal boxes, one for the high-tension transformers and cable connections, and one for the star point transformers and NER cable connection. It is also preferable to fit the transformers in the star point ends of the windings because these are at almost zero potential for the majority of the life-time of the machine. This minimizes the problems in designing adequate space at the high-tension ends of the windings to locate these items. The usual alternative is to fit them at the switchgear end of the feeder cable or bus-ducting which also has the advantage of including these in the zone of protection.

3.9.5 Cooling Methods

The majority of motors are cooled by a simple shaft mounted fan which is attached to the non-drive end and blows air across ribs or channels in the outer surface of the enclosure. This method is satisfactory with machines rated up to about 1000 kW, thereafter a more elaborate system of air-to-air (CACA) or air-to-water (CACW) heat exchangers is necessary. In all cases the main enclosure should be totally enclosed and sealed from the surrounding atmosphere by machined faces and shaft seals. This concept is also called ‘totally enclosed fan cooled or TEFC’, where the fan referred to is generally the internal fan which circulates the enclosed air along the air gap and amongst the windings. IEC60034 Part 6 and the NEMA standard MG1 give details of motor and generator enclosures.

Externally mounted fans on the shaft or in the heat exchangers should be made of a material that cannot produce a spark if the blades happen to touch their surrounding metalwork. See also sub-section 5.1.8 for further comments on the construction of induction motors.

3.9.6 Bearings

Machines rated up to about 150 kW generally use rolling element bearings, one of which usually acts as the centralising and thrust-carrying element for the shaft. The lubricating medium is grease. Some driven machines impart a longitudinal thrust on to the shaft of motors (150 kW is also near the limit for the use of low voltage machines when direct-on-line starting is to be used). The above limit may be extended to 500 kW for high voltage machines. Above 500 kW the practice is to use sleeve bearings with or without forced lubrication. As the ratings increase the use of forced lubrication becomes necessary, and with it the need for a cooling system for the lubricant.

The rotating metal components such as the shaft itself, the rotor poles and the laminations move in space relative to the magnetic fields that are present in the air gap and in the vicinity of the stator end windings. These magnetic fields contain small levels of harmonic components due to slotting and the sharp corners of the iron circuits near the end windings. As the metal components pass through these complex field patterns they induce small levels of harmonic emfs. This subject is discussed in Reference 7 in relation to induction motors. The induced emfs are capable of driving currents around a conductive metal circuit, which can be the rotor body, the shaft, the bearing surfaces, the stator frame and enclosure. If the stationary parts of the bearings are not insulated from their housings then a low conductivity circuit is available for the induced currents, which are called ‘circulating currents’. Motors and generators are usually specified to have their non-drive and bearing housing or pedestal insulated so that the presence of circulating currents is minimised. If these currents are allowed to pass across the shaft-bearing interface, then there is always a risk that some sparking will occur that will rapidly lead to serious damage to the bearing surfaces.

The insulation should not be applied only to the drive end because the driven machine will act as a short circuit across the insulation, and thereby put the bearing surfaces of the driven machine also at risk. Some purchasers specify that both bearings are insulated.

The level of induced voltage that is typically deemed acceptable is between 200 and 500 mV, measurable as the root-mean-square value when the insulation is present. Rolling element bearings cannot tolerate the higher voltage that can be accepted for sleeve bearings.

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4

Automatic Voltage Regulation

4.1 MODERN PRACTICE

Most modern synchronous generators are furnished with a self-contained voltage regulation system, in that it does not require a power supply from an external switchboard. The complete system consists of:-

- Circuits to measure the current and voltage of the generator stator windings.
- A voltage error sensing circuit to compare the terminal voltage at the generator with a set or reference value.
- A power amplifier to amplify the error signal and to provide sufficient power to energise the field winding of the exciter.
- An auxiliary AC generator, called the exciter, to further amplify the signal power to a sufficient level to energise the field winding of the main generator.

Figure 4.1 shows the control system as a block diagram, and scaled into a per unit form that is suitable for computer studies and analysis.

4.1.1 Measurement Circuits

The terminal voltage of the main generator is measured by the use of a voltage transformer connected across two of the stator lines, e.g. L1 and L2. The signal is then rectified and smoothed in the automatic voltage regulator (AVR), by a circuit that incurs a small time constant T_{r1}.

Most modern generators are required to operate in parallel with other generators on the same busbars, which requires them to share the reactive power in proportion to their individual ratings. This sharing process is determined by using a proportional feedback signal. This signal is derived from a circuit that creates the reactive power component from the sinusoidal terminal voltage and sinusoidal current of the main generator stator winding. The voltage is the same as that taken above from the voltage transformer connected to lines L1 and L2. A current transformer is connected in the third line L3. The voltage and current signals are fed into a multiplier that creates a DC signal equivalent to the reactive power. The unsmoothed signal also contains sinusoidal components, which are subsequently smoothed out by a suitable filter. The smoothing circuit incurs a small time constant T_{r2}, of similar magnitude to T_{r1}.

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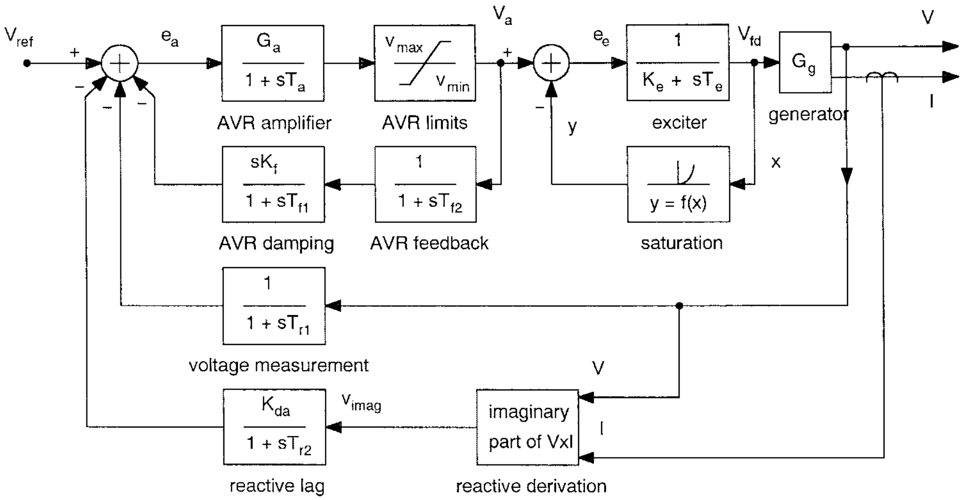

Figure 4.1 Control system for the automatic voltage regulation of a synchronous generator.

The proportional gain of the reactive power is called the 'droop' constant K_{da} in Figure 4.1 and is usually set on the range of 3 to 6% of the rated MVA of the generator.

4.1.2 Error Sensing Circuit

The reference voltage V_{ref} for the AVR is usually taken from the moving brush of a potentiometer that is driven by a small servomotor inside the AVR controller. The servomotor receives 'raise' and 'lower' signals from control switches mounted locally on the AVR controller, remotely at the main generator switchgear or at a control room.

The terminal voltage signal V is compared with the reference signal V_{ref}. In addition the reactive droop signal is deducted from V_{ref} so that the terminal voltage falls slightly with an increase in reactive loading on the generator.

The automatic voltage regulation is stabilised by the use of derivative feedback. The source of the feedback is the output of the power amplifier. The output from the derivative, or damping, circuit is deducted from the reference voltage at the summing junction. The damping is mainly determined by the factor K_f. The two time constants T_{f1} and T_{f2} result from the components in the feedback measurement and smoothing circuits.

4.1.3 Power Amplifier

The power amplifier raises the signal level from a few volts and few milliamps to tens of volts and tens of amps that are required by the field winding of the exciter. The amplification is shown as the gain G_a that is typically in the range 200 to 500 per unit (see example below).

The design of the AVR system is such that, without the droop being enabled, the regulation of the terminal voltage of the generator should be approximately 0.5%. This occurs when the generator is loaded from zero to full-load at rated power factor. In order to achieve this low level of regulation the gain G_a needs to be high.

The power amplifier has a practical lower limit of zero and an upper limit of typically 10.0 per unit. The upper limit should be high enough to ensure that the full output of the exciter can be obtained during field forcing of the main generator, e.g. during short circuits that are at or near to the generator.

4.1.3.1 Worked example

Find the value of the gain G_a for an AVR fitted to a generator that has a synchronous reactance of 2.0 pu. Assume the full-load has a power factor of 0.8 lagging and a terminal voltage V of 0.995 pu i.e. (0.5% regulation)

Step 1. Find the equivalent series impedance Z that can represent the load. The full volt-ampere load on the generator is S,

$$S = P + jQ \quad \text{pu} \quad \text{MVA}$$

When the terminal voltage is $V < 1.0$, the load impedance Z is,

$$Z = R + jX = \frac{VV^*}{S^*}$$

Where $*$ denotes a conjugate quantity.

Hence

$$Z = \frac{0.995^2}{0.8 - j0.6} = 0.792 + j0.594 \quad \text{pu}$$

Step 2. Find the emf in the generator

The emf feeds a series circuit consisting of the load plus the synchronous reactance X_s. It can be shown that the emf E is,

$$E = \frac{V}{Z^2}\left[(Z^2 + X.X_s) + jR.X_s\right]$$

Hence

$$|E| = \frac{V}{Z^2}\sqrt{(Z^2 + X.X_s)^2 + (R.X_s)^2} \tag{4.1}$$

Now

$$\begin{aligned} Z^2 &= R^2 + X^2 = 0.9801 \text{ pu} \\ |E| &= \frac{0.995}{0.9801}\sqrt{(0.9801 + (0.594)(2.0))^2 \times ((0.792)(2.0))^2} \\ &= 2.7259 \end{aligned}$$

Hence the gain G_g of the generator in its full-load steady state is,

$$G_g = \frac{|V|}{|E|} = \frac{0.995}{2.7259} = 0.365 \text{ pu} \tag{4.2}$$

Step 3. Derive the steady state conditions of the AVR for no load and full-load on the generator.

Step 3a) No load

From Figure 4.1 it can be seen that at no load $V = 1.0$. Assuming that the exciter is not saturated,

$$e_e = V_{fd} = V = 1.0, \quad \text{since at no load } G_g = 1.0$$

Let

$$V_o = V \text{ at no load}$$

Hence,

$$e_a = \frac{e_e}{G_a} \text{ and } V_{\text{ref}} = e_a + V_o$$

And so,

$$V_o = G_a(V_{\text{ref}} - V_o) \tag{4.3}$$

Step 3b) Full-load

From Figure 4.1 it can be seen that at full-load, $V = 0.995$, $V_{fd} = 2.7259$ from equation (4.1) and therefore $G_g = 0.365$.

Again assume that the exciter is not saturated and so,

$$e_e = V_{fd} = |E| = 2.7259 \text{ pu}$$

Let

$$V_1 = V \text{ at full-load}$$

Hence,

$$e_a = \frac{e_e}{G_a} \text{ and } V_{\text{ref}} = e_a + V_1$$

And so,

$$V_1 = G_a\ G_g(V_{\text{ref}} - V_1) \tag{4.4}$$

Step 4. Find V_{ref} and G_a

There are two equations, equations (4.3) and (4.4), containing two unknowns V_{ref} and G_a. Divide (4.4) by V_1 and rearrange to give,

$$G_a\left(G_g\frac{V_{\text{ref}}}{V_1} - G_g\right) = 1.0 \tag{4.5}$$

In (4.3) the voltage $V_o = 1.0$, and so,

$$G_a(V_{\text{ref}} - 1.0) = 1.0 \tag{4.6}$$

Equate the bracketed terms in (4.5) and (4.6)

$$G_g \frac{V_{\text{ref}}}{V_1} - G_g = V_{\text{ref}} - 1.0$$

Hence,

$$V_{\text{ref}} = \frac{(G_g - 1.0)V_1}{G_g - V_1} \tag{4.7}$$

Inserting the data gives $V_{\text{ref}} = 1.002897$ pu

Substitute V_{ref} into (4.6) to find G_a,

$$G_a = \frac{G_g - V_1}{G_g(V_1 - 1.0)} \tag{4.8}$$

Inserting the data gives $G_a = 345.205$ pu, which is of the correct order for an AVR.

The solution to the example can be found by using equations (4.1), (4.2) and (4.8) V_{ref} can be found from (4.7).

4.1.3.2 Variation of G_a with X_s

If the above sequence is repeated for different values of synchronous reactance then appropriate values of the AVR gain G_a can be found, as shown in Table 4.1.

In practice the value of G_a may be higher than those given in Table 4.1, in which case a regulation better than 0.5% would be obtained. In general the higher the value of G_a that is used, the

Table 4.1. AVR gain G_a as a function of the synchronous reactance X_s

Synchronous reactance X_s (pu)	Generator gain G_g (pu)	AVR gain G_a (pu)
1.5	0.442	250.0
1.6	0.424	268.9
1.7	0.408	287.8
1.8	0.393	306.9
1.9	0.378	326.0
2.0	0.365	345.2
2.1	0.353	364.4
2.2	0.341	383.7
2.3	0.330	403.1
2.4	0.320	422.5
2.5	0.310	442.0
2.6	0.301	461.5
2.7	0.292	481.0
2.8	0.284	500.5
2.9	0.276	520.1
3.0	0.269	539.7

more damping feedback will be required. Hence the values of K_f and T_{f2} will tend towards their higher values, see Table 4.3.

4.1.4 Main Exciter

The exciter (sometimes called the main exciter) is a synchronous generator that has its stator and rotor windings inverted. Its field winding is fixed in the stator, and the rotor carries the armature or AC windings. In addition the rotor carries the semiconductor bridge rectifier that converts the armature voltages to a two-wire DC voltage system. The AC voltages and currents in the armature are often alternating at a higher frequency than those in the main generator, e.g. 400 Hz. The higher frequency improves the speed of response of the exciter. The DC power circuit is coupled to the field of the main generator by the use of insulated conductors that pass coaxially inside the rotor of the exciter and the rotor of the main generator. This eliminates the use of slip rings, which were traditionally used before shaft mounted rectifiers were developed. A slight disadvantage of this technique is that the derivative feedback cannot be taken from the output of the exciter. However, with modern electronic devices used throughout the AVR, this can be regarded as an insignificant disadvantage.

The time constant T_e of the exciter is mainly related to its field winding.

The saturation block in Figure 4.1 accounts for the magnetic saturation of the iron core of the exciter, and it is important to represent this because the expected range of the performance of the exciter is wide. Its terminal voltage may have a value of typically 3.0 per unit when the generator is fully loaded. This may increase to about 6.5 per unit when the generator needs to maintain a full short circuit at or near to its terminals. The maximum excitation voltage is called the ‘ceiling voltage’ of the exciter.

4.1.4.1 Pilot exciter

The AVR system requires a source of power for its amplifier, its reference voltage and other electronic circuits that may be involved e.g. alarms. There are several methods of obtaining this necessary power,

- An external power supply.
- Self-excitation.
- Pilot exciter.

An external supply could be an uninterrupted power supply (UPS) that is dedicated to the generator. Although this is feasible it is not a method that is used, the main reason being that it departs from the requirement of self-containment. The equipment involved would require external cables and switchgear, both of which add a factor of unreliability to the scheme.

The self-excitation method relies upon the residual magnetism in the iron core of the main generator that remains in the core after the generator is shut down. When the generator is started again and run up to speed a small emf is generated by the residual magnetism. A special circuit detects the residual emf at the main terminals and amplifies it to a predetermined level. This amplified voltage is rendered insensitive to a wide range of emf values and has sufficient power to feed all the auxiliary requirements of the AVR. The advantage of this method is its low cost compared with using a pilot exciter. Its main disadvantage is an inferior performance when a short circuit occurs at or near the main generator. The detected emf, or terminal voltage, when the generator is connected to the busbars, falls to near zero when the short circuit exists. The AVR may loose its supply during this period or perform in an unpredictable manner. The excitation of the generator may collapse, which is not desirable.

The pilot exciter method is highly reliable and has a fully predictable performance. A small alternator is mounted on the same shaft, and often within the same frame, as the main exciter. It receives its excitation from a shaft mounted permanent magnet rotor system. Hence its level of excitation is constant and dependable. The AC output from the pilot exciter is rectified and smoothed by components within the AVR cubicle. It can be seen that this method is completely independent of the conditions existing in the main generator. This is the method usually specified in the oil industry.

4.2 IEEE STANDARD AVR MODELS

In order to standardise the modelling of AVR systems for computer analysis the IEEE, see Reference 1, has derived a set of block diagrams for the purpose. The model described above is called the Type 2 and is the most frequently used. If a slip-ring connected main exciter is used then a Type 1 is appropriate.

In Figure 4.1 the block representing the generator shows a function G_g. This function is a complicated combination of the dynamic variables and time constants within the generator equations. However, in the steady state the numerical value of G_g as a gain term varies from 1.0 at no-load where V is equal to V_{fd}, to typically 0.365 at full-load and rated power factor. This variation G_g needs to be taken into account when the value of the AVR gain G_a is established to give an overall voltage regulation of 0.5% and zero reactive drop.

The saturation function for the main exciter is approximated by a simple exponential function of the form, $y = Ae^{Bx}$, where x is the output voltage V_{fd} of the exciter and y is the error e_e leaving the summing junction.

The constant A is usually a small number typically in the range 0.07 and 0.1 per unit so that when the generator is at or near no load the exciter is either not saturated or is only just beginning to become saturated. The constant B takes account of the extent of saturation that occurs as the exciter field voltage is increased. It has a typical value in the range of 0.4 to 0.6 per unit.

Figures 4.2 and 4.3 show the open-circuit curves for a wider range of values for A and B in order to show more clearly the effect that they have on the shape of the curve.

The two constants A and B can be found from data given by the manufacturer for the exciter open-circuit voltage V_{fd} and the excitation voltage (or current) V_a. The data are usually given in graphical form as actual quantities, i.e. volts and amps. These should first be converted into their equivalent per unit form by dividing by their values that correspond to the no-load condition of the main generator. When this conversion is made unit output voltage of the exciter produces unit terminal voltage at the main generator.

Since there are two unknown constants their solution will require two equations. Hence any two pairs of data points can be used from the open-circuit voltage curve of the exciter. Using the notation in Figure 4.2 or 4.3 let these pairs of points be,

$$V_{a1} \text{ with } V_{fd1} \text{ and } V_{a2} \text{ with } V_{fd2}$$

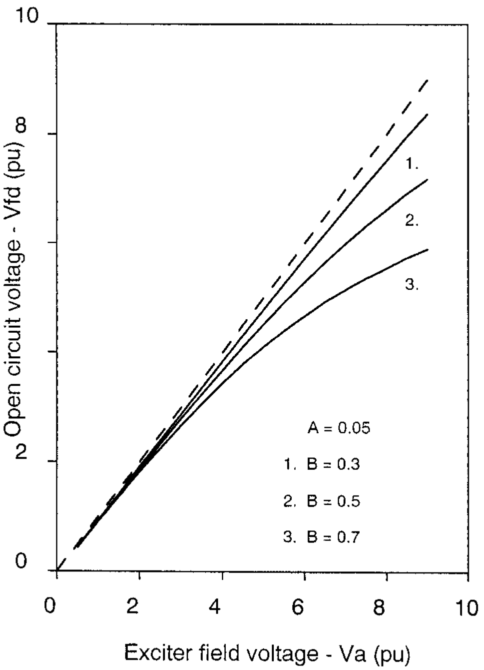

Figure 4.2 Open circuit voltage versus exciter field voltage. The graph shows the effect on the saturation curvature caused by changing the constant B over a wide range with the constant A fixed at 0.05.

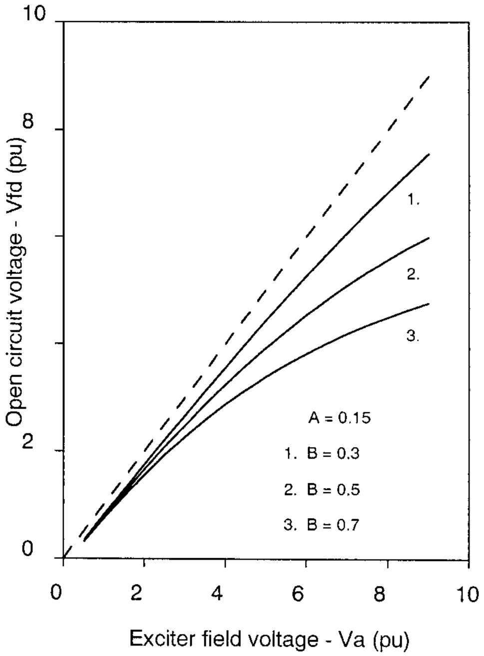

Figure 4.3 Open circuit voltage versus exciter field voltage. The graph shows the effect on the saturation curvature caused by changing the constant B over a wide range with the constant A fixed at 0.15.

The output signals from the saturation block are therefore,

$$V_{a1} - V_{fd1} = Ae^{BVfd1} \tag{4.9}$$

And

$$V_{a2} - V_{fd2} = Ae^{BVfd2} \tag{4.10}$$

Taking natural logarithms of both sides of equations (4.9) and (4.10) gives,

$$\log_e(V_{a1} - V_{fd1}) = \log_e A + BV_{fd1}$$

And

$$\log_e(V_{a2} - V_{fd2}) = \log_e A + BV_{fd2}$$

Eliminating $\log_e$ A by subtraction gives

$$B = \frac{\log_e(V_{a1} - V_{fd1}) - \log_e(V_{a2} - V_{fd2})}{V_{fd1} - V_{fd2}}$$

$$B = \frac{\log_e\left(\dfrac{V_{a1} - V_{fd1}}{V_{a2} - V_{fd2}}\right)}{V_{fd1} - V_{fd2}} \tag{4.11}$$

And therefore from (4.9) and (4.10)

$$A = \frac{V_{a1} - V_{fd1}}{e^{BVfd1}} \quad \text{or} \quad \frac{V_{a2} - V_{fd2}}{e^{BVfd2}} \tag{4.12}$$

It has become the custom to choose the two pairs of data at the 100% and 75% excitation levels of the exciter. The purpose being to suit computer simulation programs that require these specific data points.

The 100% pairs are those at the ceiling output voltage of the exciter whilst the 75% pair are at 75% of the ceiling output voltage. The saturation level can be described by dividing the difference in V_a that is needed above that required on the linear non-saturated line, by the non-saturated value of V_a. Hence at V_{fd100} the value of V_a is V_{a100S} from the saturated curve and V_{a100U} from the straight line. Similarly at the reduced output voltage V_{fd75} the two values of V_a are V_{a75S} and V_{a75U}. The two saturation levels S_{E100} and S_{E75} are given by,

$$S_{E100} = \frac{V_{a100S} - V_{a100U}}{V_{a100U}} \qquad \text{per unit}$$

And

$$S_{E75} = \frac{V_{a75S} - V_{a75U}}{V_{a75U}} \qquad \text{per unit}$$

From the data for the exciter V_{fd100} and V_{a100S} should be available together with V_{a75S}. The manufacturer may also provide S_{E100} and S_{E75}. V_{fd75} is easily calculated from V_{fd100}.

4.2.1 Worked Example

An exciter has an open-circuit curve which has the following two pairs of data points.

$$V_{a1} = 2.0 \quad V_{fd1} = 1.853$$
$$V_{a2} = 4.0 \quad V_{fd2} = 3.693$$

Find the constants A and B in the exponential function that describes the saturation characteristic of the exciter,

$$\frac{V_{a1} - V_{fd1}}{V_{a2} - V_{fd2}} = \frac{2.0 - 1.853}{4.0 - 3.693} = \frac{0.1470}{0.3070} = 0.478827$$
$$V_{fd1} - V_{fd2} = 1.853 - 3.693 = -1.840$$
$$B = \frac{\log_e 0.478827}{-1.840} = 0.400226$$
$$A = \frac{V_{a1} - V_{fd1}}{e^{BVfd1}} = \frac{0.1470}{e^{0.741618}} = 0.070022$$

4.2.2 Worked Example

Repeat the example of 4.2.1 but assume the data are less accurate due to visual rounding errors in V_{fd}. Assume the data are,

$$V_{a1} = 2.0 \qquad V_{fd1} = 1.85 \text{ instead of } 1.853$$
$$V_{a2} = 4.0 \qquad V_{fd2} = 3.70 \text{ instead of } 3.693$$
$$\frac{V_{a1} - V_{fd1}}{V_{a2} - V_{fd2}} = \frac{2.0 - 1.85}{4.0 - 3.70} = \frac{0.15}{0.30} = 0.5$$
$$V_{fd1} - V_{fd2} = 1.85 - 3.70 = -1.85$$
$$B = \frac{\log_e 0.5}{-1.85} = 0.374674$$
$$A = \frac{V_{a1} - V_{fd1}}{e^{BVfd1}} = \frac{0.15}{e^{0.6931}} = 0.075$$

or

$$A = \frac{V_{a2} - V_{fd2}}{e^{BVfd2}} = \frac{0.15}{e^{0.6931}} = 0.075$$

Hence an average error in V_{fd} of 0.176% causes an error in B of 6.38% and an error in A of 7.11%. It is therefore important to carefully extract the data from the open-circuit curves to at least the third decimal place.

4.2.3 Determining of Saturation Constants

Saturation data for exciters and main generators can be described in an approximate manner by an exponential function of the form,

$$S = Ae^{BVfd}$$

In order to find A and B it is necessary to be given two values of S. In practice these two values are usually called S_{E75} and S_{E100}, which will be discussed at the conclusion of this subsection. The following procedure is applicable to both exciters and main generators and shows how any two values of S can be used, and why S_{E75} and S_{E100} are preferred.

Figure 4.4 shows the open-circuit curve for an exciter in actual volts and amps. Figure 4.5 shows the same curve converted into its per-unit form. Three points are chosen on the linear characteristic that has been extrapolated over the range excitation voltage. Call these V_{fd1}, V_{fd2} and V_{fd3}. Their corresponding excitation voltages are called V_{a12}, V_{a22} and V_{a32} for a non-saturating exciter. At each V_{fd} point a horizontal line is drawn to intercept the saturated or actual characteristic, and call these V_{a11}, V_{a21} and V_{a31} respectively.

Define three saturation functions as,

$$S_1 = \frac{V_{a11} - V_{a12}}{V_{a12}} \tag{4.13}$$

$$S_2 = \frac{V_{a21} - V_{a22}}{V_{a22}} \tag{4.14}$$

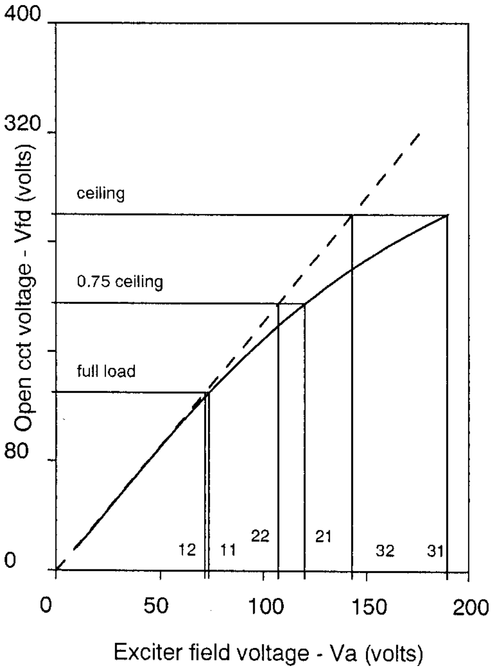

Figure 4.4 Open-circuit voltage in volts versus exciter field voltage in volts. For use in determining the SE75 and SE100 parameters of the exciter.

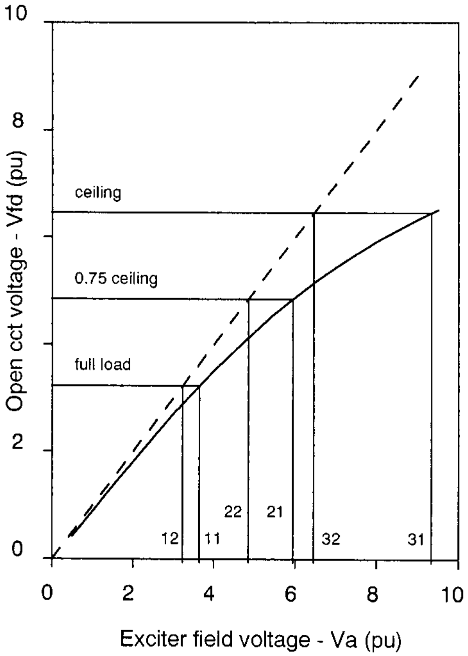

Figure 4.5 Open-circuit voltage in per unit versus exciter field voltage in per unit. For use in determining the SE75 and SE100 parameters of the exciter.

$$S_3 = \frac{V_{a31} - V_{a32}}{V_{a32}} \tag{4.15}$$

Use V_{fd1} as the reference output voltage and convert V_{fd3} into a per unit factor of V_{fd1}, denoted as $V_{fd3\text{pu}}$.

$$V_{fd3\text{pu}} = \frac{V_{fd3}}{V_{fd1}} \tag{4.16}$$

By simple proportions,

$$V_{a32} = V_{a12}.V_{fd3\text{pu}} \tag{4.17}$$

Choose a factor $u > 1$, such that,

$$u = \frac{V_{a32}}{V_{a22}} = \frac{V_{a12}.V_{fd3\text{pu}}}{V_{a22}} \tag{4.18}$$

Therefore,

$$V_{a22} = \frac{V_{a12}.V_{fd3\text{pu}}}{u} \tag{4.19}$$

Substitute (4.19) into (4.14), and (4.17) into (4.15),

$$S_2 = \left(\frac{V_{a21} - V_{a22}}{V_{a12}V_{fd3\text{pu}}}\right)u = Ae^{BVfd2} \tag{4.20}$$

And,

$$S_3 = \left(\frac{V_{a31} - V_{a32}}{V_{a12} V_{fd3\text{pu}}}\right) u = Ae^{BVfd3} \tag{4.21}$$

Divide (4.21) by (4.20)

$$\frac{S_3}{S_2} = e^{B(Vfd3 - Vfd2)}$$

From which,

$$B = \frac{\log_e \left(\dfrac{S_3}{S_2}\right)}{V_{fd3} - V_{fd2}} \tag{4.22}$$

Also,

$$\frac{S_3}{S_2} = \frac{(V_{a31} - V_{a32})}{(V_{a21} - V_{a22})u}$$

Since

$$u = \frac{V_{fd3}}{V_{fd2}} \quad \text{by proportion from (4.18)}$$

$$S_3 = A\ e^{Bu\ Vfd2}$$

$$S_2 = A\ e^{B\ Vfd2}$$

Hence,

$$\log_e S_3 = \log_e A + uBV_{fd2} \tag{4.23}$$

And,

$$\log_e S_2 = \log_e A + BV_{fd2} \tag{4.24}$$

Multiply (4.24) by u, and subtract from (4.23),

$$\begin{aligned} \log_e S_3 - u \log_e S_2 &= \log_e A - u \log_e A \\ &= (1 - u) \log_e A \end{aligned}$$

Therefore,

$$A^{1-u} = \frac{S_3}{{S_2}^u}$$

Hence,

$$A = \frac{{S_3}^{1/(1-u)}}{{S_2}^{u/(1-u)}}$$

Returning to (4.22) and substituting u,

$$V_{fd3} - V_{fd2} = \left(\frac{u-1}{u}\right) V_{fd3}$$

And so,

$$B = \frac{1}{V_{fd3}} \left(\frac{u}{u-1}\right) \log_e \left(\frac{S_3}{S_2}\right)$$

If u is chosen as a quotient of integer numbers, one greater than the other, such that the result is greater than unity, then the quotient is,

$$u = \frac{m+1}{m}$$

From which,

$$\frac{1}{1-u} = -m, \quad \frac{u}{1-u} = -m-1, \quad \text{and} \quad \frac{u}{u-1} = m+1$$

Therefore,

$$A = \frac{{S_2}^{m+1}}{{S_3}^{m}}$$

And

$$B = \frac{1}{V_{fd3}} (m+1) \log_e \left(\frac{S_3}{S_2}\right)$$

Table 4.2 shows the various coefficients and subscripts of S_2 and S_3 for different choices of m.

For an exciter the customary choices of S_2 and S_3 are S_{E75} and S_{E100} because the excursions of V_a and V_{fd} above their full-load values are large. However, such excursions in a main generator are smaller and the data given covers a smaller range of values. In this situation a larger value of m is more suitable, e.g. $m = 4$ or 5, which requires S_2 to be S_{E80} or S_{E83}.

Since computer programs usually require per unit data, the calculation of S_2, S_3, A and B should be carried out after the open-circuit data has been converted into per unit values.

Table 4.2. Saturation function S_2 and S_3 as functions of integer m

m	u	$m+1$	S_2	S_3
1	2.0	2	SE50	SE100
2	1.5	3	SE67	SE100
3	1.333	4	SE75	SE100
4	1.25	5	SE80	SE100
5	1.20	6	SE83	SE100

Table 4.3. Typical data for AVR control systems

Parameter	Low	Values Typical	High
G_a	250	500	1500
T_a	0.01	0.04	0.1
K_f	0.02	0.06	0.1
T_{f1}	0.1	0.4	0.6
T_{f2}	0.3	1.5	2.5
$V_{\max}$	5.0	15.0	20.0
$V_{\min}$	0.0	0.0	0.0
K_e	1.0	1.0	1.0
T_e	0.05	0.4	1.2
S_{E75}	0.45	0.75	0.96
S_{E100}	0.80	0.90	0.96
A	0.07	0.08	0.1
B	0.4	0.5	0.6
G_g	0.3	0.35	0.4
T_{r1}	0.01	0.02	0.03
T_{r2}	0.01	0.02	0.03
K_{da}	0.03	0.04	0.06

4.2.4 Typical Parameter Values for AVR Systems

Table 4.3 shows typical per unit values for the gains, limits and time constants used in the automatic voltage regulation systems for generators having ratings up to 50 MW.

REFERENCE

1. *Computer representation of excitation systems*. IEEE Transactions, PAS 87, No.6, June 1968.

5

Induction Motors

5.1 PRINCIPLE OF OPERATION OF THE THREE-PHASE MOTOR

In the form used for industrial drives, induction motors have two main components, the stator and the rotor. The stator carries a three-phase winding that receives power from the supply. The rotor carries a winding that is in the form of a set of single-bar conductors placed in slots just below the surface of the rotor. The slots have a narrow opening at the surface of the rotor, which serves to lock the conductor bars in position. Each end of each bar conductor is connected to a short-circuiting ring, one at each end of the rotor. The stator winding is a conventional type as found in three-phase generators and synchronous motors.

The three-phase stator winding produces a rotating field of constant magnitude, which rotates at the speed corresponding to the frequency of the supply and the number of poles in the motor. The higher the number of poles the lower the speed of the rotation. Assume that the rotor is stationary and the motor has just been energised. The magnetic flux produced by the stator passes through the rotor and in so doing cuts the rotor conductors as it rotates. Since the flux has a sinusoidal distribution in space its rotation causes a sinusoidal emf to be induced into the rotor conductors. Hence currents are caused to flow in the rotor conductors due to the emfs that are induced. The emfs are induced in the rotor by transformer action, which is why the machine is called an ‘induction’ motor. Since currents now flow in both the stator and the rotor, the rotor conductors will set up local fluxes which interact with the excitation flux from the stator. This interaction causes a torque to be developed on the rotor. If this torque exceeds the torque required by the mechanical load the shaft will begin to rotate and accelerate until these two torques are equal. The rotation will be in the direction of the stator flux since the rotor conductors are being driven by the stator flux.

Initially the speed is much less than that of the stator field, although it is increasing. Consequently the rate at which the stator flux cuts the rotor conductors reduces as the shaft speed increases. The frequency and magnitude of the induced rotor emfs therefore decrease as the shaft accelerates. The local flux produced by the rotor conductors therefore rotates at a slower speed relative to the rotor surface. However, since the rotor body is rotating at a slow speed, the combined effect of the body speed plus the rotational speed of the local rotor flux causes the resulting rotor flux to rotate at the same speed as the stator field.

The rotor currents are limited by the short-circuit impedance of the rotor circuit. This circuit contains resistance and reactance. The inductive reactance is directly proportional to the frequency of the induced emfs in the rotor. As the rotor accelerates two effects take place:-

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a) The rotor impedance increases.

b) The rotor emf reduces.

These effects result in the supply current is being nearly constant during most of the run-up period.

The rotor speed cannot reach the same speed as that of the stator field, otherwise there would be no induced emfs and currents in the rotor, and no torque would be developed. Consequently when the rotor speed is near to the synchronous speed the torque begins to decrease rapidly until it matches that of the load and rotational friction and windage losses. When this balance is achieved the speed will remain constant.

5.2 ESSENTIAL CHARACTERISTICS

The most significant design characteristics of interest to power system engineers in the oil industry are:-

- Torque versus speed.
- Stator current versus speed.

Characteristics such as efficiency and power factor at running conditions have traditionally been of secondary importance, but nowadays with an emphasis on energy conservation more attention is being paid to efficiency in particular. The main objectives in the choice of a motor are that:-

- It creates plenty of torque during the whole run-up period.
- It can be started easily using simple switching methods.
- It is a 'standard' design from a manufacturer.

5.2.1 Motor Torque versus Speed Characteristic

Many of the electrical engineering textbooks that include the subject of motors in their contents describe the equivalent circuit of an induction motor as a series and parallel combination of resistances and reactances, see References 1 to 8. The equivalent circuit usually defines the situation for one of the three phases and so care needs to be taken to ensure that the final results obtained apply to the complete motor. Care is also necessary in using the ohmic data from manufacturers, they may have either star winding values or delta winding values and the choice may not be obvious. The equivalent circuit of most practical use is shown in Figure 5.1 for one star connected winding, where:-

$$s = \text{slip} = \frac{\text{stator frequency} - \text{rotor frequency}}{\text{stator frequency}} \quad \text{per unit}$$

$$= \frac{(f \text{ or } \omega) - (f_r \text{ or } \omega_r)}{(f \text{ or } \omega)} \quad \text{per unit}$$

V_s = supply voltage per phase.

I_1 = supply and stator current per phase.

I_2 = rotor current per phase.

R_c = resistance representing the iron core eddy current loss. In some situations the manufacturer may add to this a component to represent friction and windage

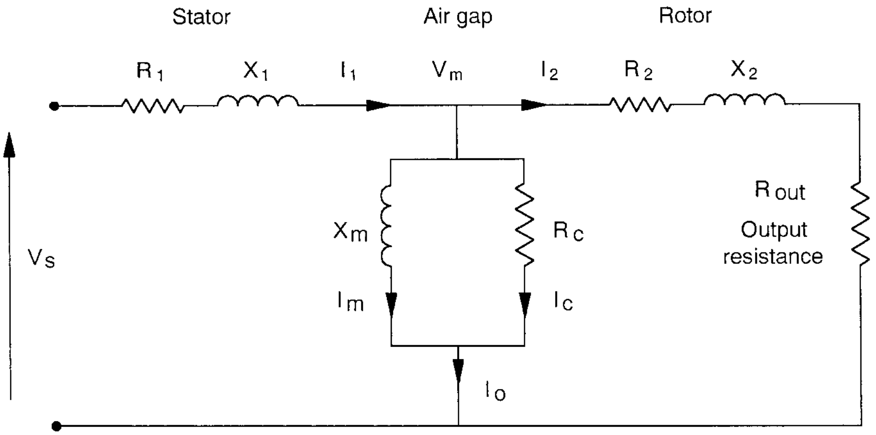


Figure 5.1 Commonly used equivalent circuit of an induction motor.

so that the calculated efficiency and power factor more closely match their measured values when the motor is tested in the factory.

X_m = magnetising reactance of the complete iron core, which represents the flux that passes across the air gap between the stator and the rotor.
R_1 = stator winding resistance.
X_1 = stator winding reactance.
R_2 = rotor winding resistance.
X_2 = rotor winding reactance.
R_{out} = rotor resistance that represents the power delivered to the shaft.
f = supply frequency in Hz.
ω = supply frequency in radians per second.
f_r = rotor frequency in Hz.
ω_r = rotor frequency in radians per second.

This equivalent circuit takes account of the turns ratio between the stator and the rotor if all the rotor resistances and reactance are given in the data as 'referred to the stator' values. The circuit can be used with actual quantities such as ohms, amps and volts, or in their 'per-unit' equivalent values which is often more convenient. This approach is customary since it easily corresponds to measurements that can be made in practice when tests are carried out in the factory.

The resistance R_2 and reactance X_2 are designed by the manufacturer to be functions of slip, so that they take advantage of what is called the 'deep-bar' effect. If the rotor bars are set deep into the surface of the rotor then the rotor resistance R_2 is not so influenced by surface eddy currents, and the rotor leakage reactance X_2 is relatively high due to the depth of the slot which gives a low reluctance path across the slot sides for the flux produced by the bars. Conversely if the conductors are set near to the surface then R_2 becomes high and X_2 becomes low for a given slip. Some special motors actually have two separate cages in their rotors. These are called 'double-cage' motors and are used for driving loads that have high and almost constant torques, such as conveyor belts and cranes. Modern motors utilise the principle of deep bars by designing bars that are shaped rather than simple round bars. The shapes, or cross-sectional areas, are arranged to be narrower at the surface than at their bases. Manufacturers tend to have their own preferences for the shapes and geometries of the rotor bars.

The functions $R_2(s)$ and $X_2(s)$ can be approximated by the following simple linear expressions:-

$$R_2(s) = (R_{21} - R_{20})s + R_{20}$$

and

$$X_2(s) = (X_{21} - X_{20})s + X_{20}$$

Where the suffix 1 refers to the standstill value, and suffix 0 to the full-load value.

The ratio of the standstill values of $R_2(s)$ and $X_2(s)$ to their full-load values are called the 'deep-bar factors' which are:-

$$\text{Deep-bar resistance factor} = u_{r2} = \frac{R_{21}}{R_{20}} > 1.0$$

$$\text{Deep-bar reactance factor} = u_{x2} = \frac{X_{21}}{X_{20}} < 1.0$$

The values of these factors vary with the kW rating and number of poles for the motor, and from one manufacturer to another. Figures 5.2 and 5.3 show the variations in the deep-bar factors for a range of motor ratings from 11 kW to 11 MW, taken from a small sample of typical oil industry two-pole and four-pole motors.

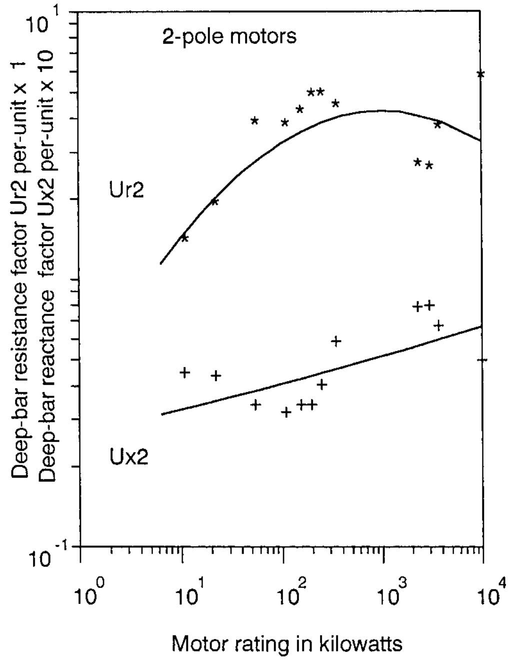


Figure 5.2 Approximate deep-bar resistance and reactance factor curves for two-pole motors rated from 10 kW to 10 MW.

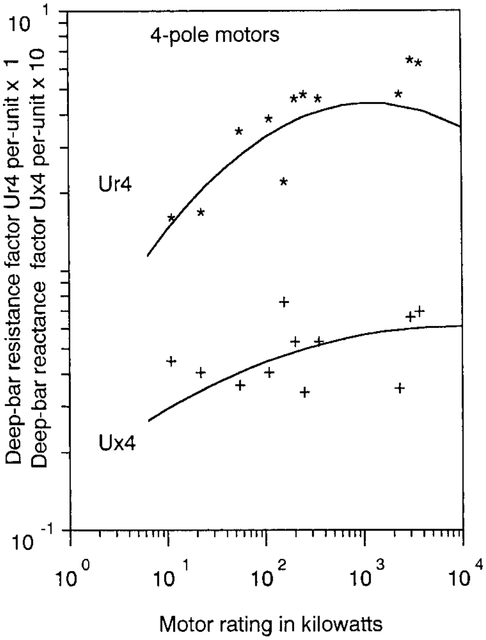


Figure 5.3 Approximate deep-bar resistance reactance curves for four-pole motors rated from 10 kW to 10 MW.

The torque T_e developed in the rotor shaft can be expressed as a function of the air-gap voltage V_m:-

$$T_e = \frac{sR_2{V_m}^2}{{R_2}^2 + (sX_2)^2} \quad \text{Newton metres}$$

Where R_2 and X_2 are both functions of the slip s as explained above. The air-gap voltage can be found from the supply voltage V_s by noting that a voltage divider circuit exists which consists of the series components of the stator and the parallel combination of the magnetising branch and the rotor circuit. Hence V_m becomes:-

$$V_m = \frac{V_s Z_{2m}}{Z_1 + Z_{2m}}$$

where

$$Z_1 = R_1 + jX_1$$

and

$$Z_{2m} = \frac{1}{\dfrac{1}{R_c} + \dfrac{1}{jX_m} + \dfrac{1}{R_2 + R_{\text{out}} + jX_2}}$$

but

$$R_2 + R_{\text{out}} = \frac{R_2}{s}$$

and

$$R_{\text{out}} = \frac{R_2(1-s)}{s}$$

A reasonable and practical approximation can be made for Z_{2m}, which is that the magnitudes of R_c and X_m are each much greater than the magnitude of R_2 and X_2. (For a more precise analysis see Reference 1, Chapter 12.) Hence Z_{2m} reduces to:-

$$Z_{2m} = \frac{R_2}{s} + jX_2$$

And so V_m becomes:-

$$V_m = \frac{V_s(R_2 + jsX_2)}{sR_1 + R_2 + jsX_{12}} \qquad \text{where } X_{12} = X_1 + X_2$$

And so V_m^2 becomes:-

$${V_m}^2 = \frac{{V_s}^2({R_2}^2 + js^2{X_2}^2)}{(sR_1 + R_2)^2 + s^2{X_{12}}^2}$$

Hence the torque becomes:-

$$T_e = \frac{sR_2{V_s}^2}{(sR_1 + R_2)^2 + s^2{X_{12}}^2} \tag{5.1}$$

There are three important conditions to consider from the torque equation:

a) The starting condition in which the slip is unity.

b) The full-load condition in which the slip is small, i.e. 0.005 to 0.05 per-unit.

c) The value and location of the maximum torque $T_{\max}$.

a) The starting condition.

When the slip s equals unity the starting torque T_1 can be found from equation (5.1) as:

$$T_1 = \frac{R_2{V_s}^2}{{R_{12}}^2 + {X_{12}}^2} \tag{5.2}$$

Where,

$$R_{12} = R_1 + R_2$$

The starting torque is very dependent upon R_2 because for typical parameters the total reactance X_{12} is significantly larger than the total resistance R_{12}. During the starting process the denominator remains fairly constant until the slip approaches a value that creates the maximum torque, which is typically a value between 0.05 and 0.2 per-unit, as seen in Figures 5.4 and 5.5 for two ratings of low voltage motors. The higher value of slip generally applies to the lower kW rated motors.

b) The full-load condition

Full-load is obtained when the slip is typically in the range 0.005 to 0.05 per-unit. The higher values apply to the lower kW rated motors. The full-load torque T_0 can be approximated as:-

$$T_0 \approx \frac{s{V_s}^2}{R_2} \tag{5.3}$$

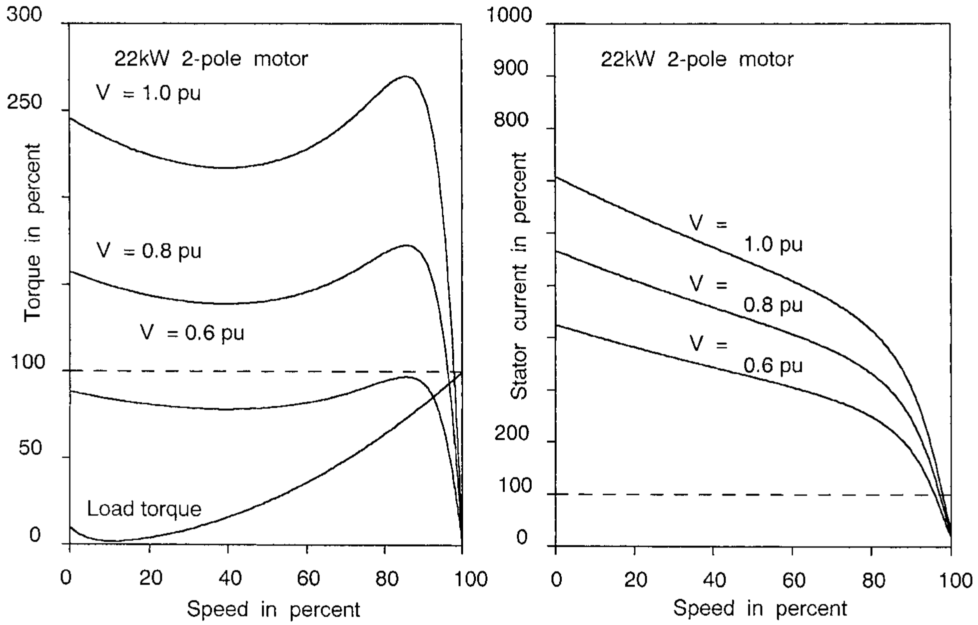


Figure 5.4 Torque and current versus speed curves 22 kW two-pole motor, for different values of applied voltage. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

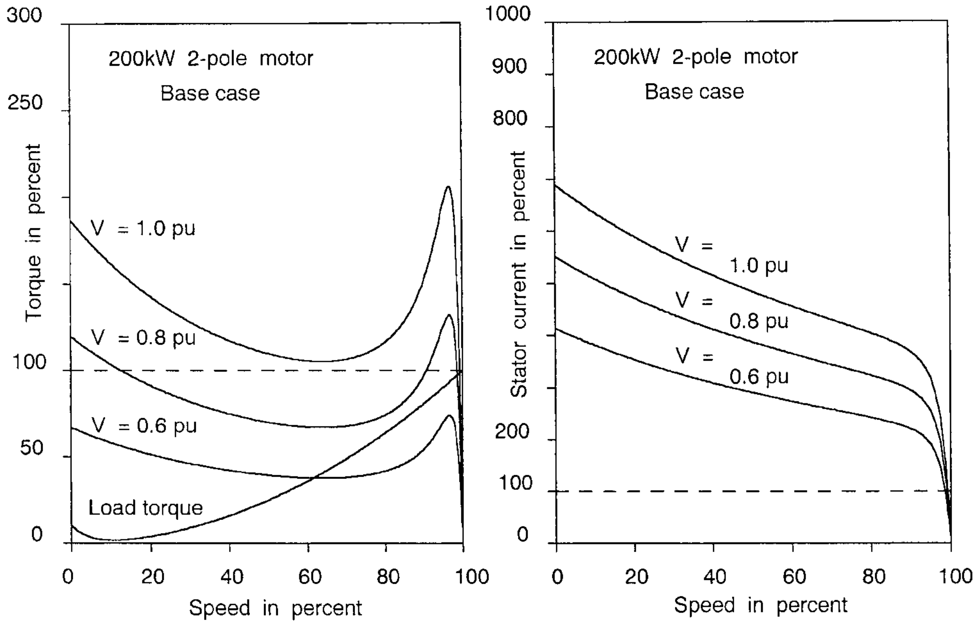


Figure 5.5 Torque and current versus speed curves 200 kW two-pole motor, for different values of applied voltage. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

Hence the torque-slip curve has a steep straight-line section near to the region of zero slip. Small changes in slip cause large changes in torque. If the value of R_2 is increased to raise the starting torque then the slope of the full-load straight-line section is reduced, and the speed regulation for changes in load torque becomes poor. The efficiency at and near full-load also falls with increasing values of R_2.

c) The condition for maximum torque.

The maximum torque T_{max} can be found by differentiating the torque with respect to the slip and equating the derivative to zero. The torque occurs at a particular slip s_{max}, which is found to be:-

$$s_{max} = \frac{R_2}{\sqrt{{R_1}^2 + {X_{12}}^2}} \tag{5.4}$$

The torque T_{max} is found by substituting s_{max} into (5.1):-

$$T_{max} = \frac{s_{max} R_2 {V_s}^2}{(s_{max} R_1 + R_2)^2 + (s_{max} X_{12})^2} \tag{5.5}$$

For actual motors chosen for oil company applications the value of s_{max} is very small when compared with unity. Therefore some approximations can be made. In the denominator the resistive term can be simplified as:-

$$(s_{max} R_1 + R_2)^2 \simeq {R_2}^2$$

The reactive component approaches zero in value for small values of slip. Therefore the maximum torque can be expressed as:-

$$T_{max} \approx \frac{{V_s}^2}{\sqrt{{R_1}^2 + {X_{12}}^2}} \quad \text{or} \quad \frac{s_{max} {V_s}^2}{R_2} \tag{5.6}$$

In practice R_1 is much smaller than X_{12} and so the maximum torque is very dependent upon the value of the leakage reactances, especially the rotor leakage reactance X_2. The maximum torque is also called the ‘breakdown’ torque.

Motors are usually started ‘direct-on-line’ with no series impedance added or starting transformers inserted between the supply and the stator terminals of the motor. The starting current is therefore high and an associated volt-drop occurs in the feeder cable to the motor. It is normally a requirement in motor specifications that the motor should start and run up to speed whilst the terminal voltage is reduced to 80% of its rated value. This is an allowance for the volt-drop in the feeder cable. The torque produced by the motor varies with the square of the terminal voltage. Consequently at 80% voltage the torque is reduced to 64% of its value at any slip in the range of zero to unity. This is shown in Figure 5.4 for a 22 kW motor and in Figure 5.5 for a 200 kW low voltage motor. For most designs of motors the ability to start at a voltage of 80% is assured if the motor drives a centrifugal machine. If the voltage falls much lower e.g. 70% or less, then the motor may not develop enough torque to accelerate the load to its full speed. In practice the motor would accelerate the load up to some intermediate speed and then remain at that speed. It would draw a high current and eventually fail from overheating, or be shut down by the protective devices in the switchgear. It is also important that the motor develops a sufficient minimum torque during the run-up period. This torque is often called the ‘pull-up’ torque and it must not fall below the load torque at the associated slip. This is shown in Figure 5.5 for a voltage of 75%, where the rotor would settle at a speed of about 85% and a current of about 230%.

5.2.2 Motor Starting Current versus Speed Characteristic

Once it is established that the motor will produce sufficient torque throughout the speed range then the next considerations are the starting and run-up currents. By examining typical motor impedance values or data from manufacturers, it can be seen that the starting current for typical motors varies between 3.5 times full-load current for large high voltage motors and about 7 times for small low voltage motors. For oil industry applications it is often required that the starting current of the motor should be kept to a low value for direct-on-line starting. The oil industry standard EEMUA132, 1988, gives recommended reduced ratios of starting current to full-load current (I_s/I_n) for ratings above 40 kW, see clauses 5.2 and 5.3 therein. These clauses refer to ‘Design N’ and ‘Design D’ motors, which are described in BS4999 part 112 and IEC60034 part 12. Both designs are for direct-on-line starting. Design N provides for general purpose motors, whereas Design D requires the motor to have reduced starting current. These standards have several tables which state the limiting values of ‘locked rotor apparent power’, which is synonymous with starting current and takes account of the power factor at starting. There are also tables that give limiting values for the starting torque, pull-up torque and breakdown torque for these two types of designs. American practice is covered by NEMA publication MG1 which gives comprehensive tables and data for many different ‘designs’ and ‘codes’ for induction motors.

The starting current can be calculated from the equivalent circuit with the value of slip set equal to zero. Once the starting current has been calculated then the starting kVA and power factor can easily be found. The variation of starting current over the full range of slip values is shown in Figure 5.4 for a 22 kW motor and in Figure 5.5 for a 200 kW low voltage motor. The engineer is usually given the following data by a manufacturer for full-load operation of the motor:-

- Rated line-to-line voltage V in volts.
- Rated line current I in amps.
- Rated output power P_0 in kilowatts.
- Rated power factor $\cos\phi$ in per-unit.
- Rated efficiency η in per-unit or percent
- Rated slip in per-unit or percent

These variables are related by the following expressions:-

$$\text{Rated kVA} \qquad S_0 = \frac{\sqrt{3}VI}{1000}$$

$$\text{Rated input power} \qquad P_i = \frac{P_0}{\eta} = S_0 \cos\phi$$

$$\text{Rated input current} \qquad I = \frac{S}{\sqrt{3}V} = \frac{P_0}{\sqrt{3}V\eta\cos\phi}$$

5.2.3 Load Torque versus Speed Characteristic

Most mechanical loads in the oil industry may be classified into two groups:-

- Quadratic torque versus speed.
- Constant torque versus speed.

A quadratic characteristic is typical of centrifugal pumps, centrifugal compressors, screw and axial compressors, fans and turbo-machinery. The characteristic generally consists of two parts, a static part and a dynamic part. The static part accounts for the initial torque that is required at zero and very low speeds. When the driven shaft is stationary, or is rotating slowly, the lubrication between the shaft surface or journal and its bearing is poor. About 5% to 15% of the full-load torque is required to move the shaft. This initial torque is occasionally called 'stiction'. As the shaft begins to rotate this torque declines as the lubrication improves. Once the speed is above about 10% the static torque can be ignored, since the shaft is well supported in its bearings by the lubricant. The dynamic part of the torque is associated with the energy required to compress the fluid in the machine and deliver it from its discharge port. The dynamic characteristic can be expressed in the form:-

$$T_{\text{dynamic}} = KN^2 \quad \text{where } N \text{ is the shaft speed}$$

Most large centrifugal pumps and compressors are started in a 'no-load' state. This means that the suction valve is open and the discharge valve is closed. The machine is filled with fluid but there is little or no throughput of the fluid. The machine therefore requires the minimum energy and torque from the motor. The full-speed torque for 'no-load' operation is between 40% and 60% of the full-load operating torque. When the driven machine reaches full speed the discharge valve is opened and the machine becomes fully loaded. The driven machine should not be allowed to operate continuously in its start-up mode because the energy transmitted to the fluid will be rapidly converted into heat. The machine could be thereby damaged. Small centrifugal pumps and compressors may be started in a partly or fully loaded state. Starting the machine in a no-load state gives the advantage of allowing the motor to create significantly more torque than the machine requires. The surplus torque is able to accelerate the machine in the shortest possible time. The conventional induction motor has only one rotor winding and has the torque characteristic already outlined. Such a motor is usually adequate for driving centrifugal machinery. Figures 5.4, 5.5 and 5.6 show the complete curve for the load torque of a centrifugal machine.

A constant torque versus speed characteristic is typical of reciprocating pumps, reciprocating compressors, conveyors, lifting and cranage equipment and crushers. From zero to full speed the torque is usually almost constant. In addition to high frictional and load torque, these systems may also require a substantial accelerating torque due a high inertia being present. This type of machinery may therefore be difficult to start and run up to full speed. The motor has to be carefully selected and what is called a 'double-cage' motor may prove necessary. A double-cage motor has a rotor which has two rotor windings, one on the outer surface as normal and one set deeper in the same or a separate set of slots. The deeper winding is called the 'inner winding'. By choosing different X-to-R ratios for these two windings or cages it is possible for the motor to develop two torque characteristics simultaneously for a particular slip. The combined torque can be almost constant during the run-up period. However, it is still necessary to ensure that the motor develops adequate surplus torque to accelerate the load when the terminal voltage is depressed.

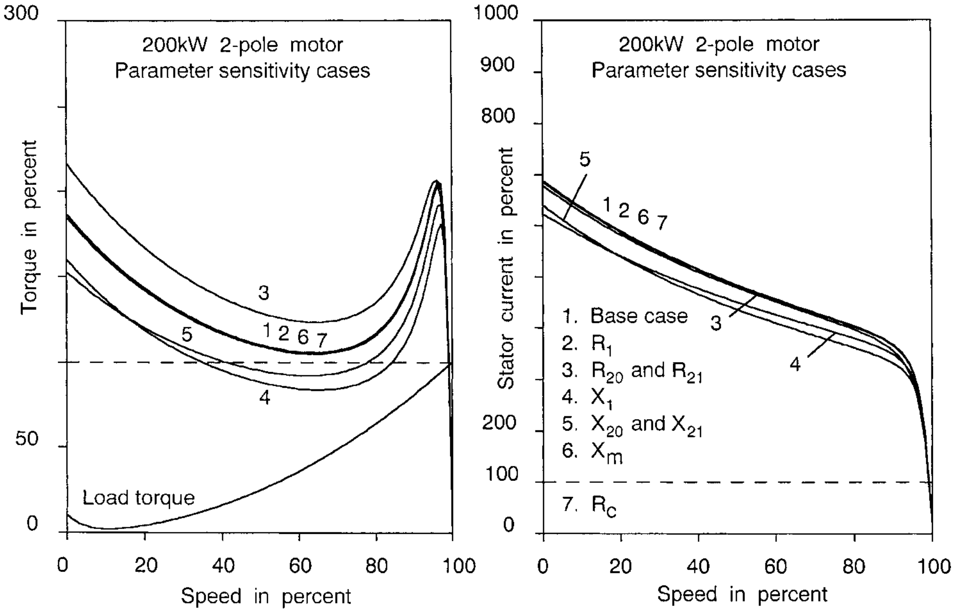


Figure 5.6 Sensitivity of the torque and current versus speed curves to a 20% increase in the nominal value of the resistance or reactance for a 200 kW two-pole motor.

5.2.4 Sensitivity of Characteristics to Changes in Resistances and Reactances

The international standards set recommended limits on the variations of the parameters given by manufacturers. These limits are given as percentage tolerances, and their recommended values are generally not too difficult to achieve. IEC60034 part 1 describes the requirements for duty (as S1 to S9), ratings, operating conditions, temperature rise, tolerances and the like for rotating electrical machines. Regarding tolerances its section 9, Table VIII, gives values for the performance parameters such as losses, running power factor, slip, locked rotor current, locked rotor torque, breakdown torque, pull-up torque and moment of inertia. The standard does not set tolerances on the particular resistances and reactances of the equivalent circuit. In order to show how sensitive the torque–speed and stator current–speed curves are to changes in impedance values, Figure 5.6 was prepared for a typical 200 kW two-pole motor of the Design D type. The six components R_1, X_1, R_2, X_2, R_c and X_m were individually increased by 20% from their nominal values and the appropriate slip recalculated so that the nominal shaft output power was re-established. The following can be seen:-

- Changes in R_1, R_c and X_m have little effect.
- Changes in R_{20} and R_{21} increase the starting and run-up torque, but only change the current by a small amount.
- Changes in X_1, X_{20} and X_{21} reduce both the torque and the current.

5.2.5 Worked Example

A 22 kW two-pole motor drives a water pump and is supplied from a 415 V, 50 Hz power system. Assume that there is no voltage dropped between the supply and the motor. The full-load slip is

0.02208 per-unit. The following ohmic values apply at 415 V for an equivalent star-wound stator:-

$$\begin{array}{llll} R_1 & = 0.179 & X_1 & = 0.438 \\ R_{20} & = 0.0145 & X_{20} & = 0.8230 \\ R_{21} & = 0.253 & X_{21} & = 0.333 \\ R_c & = 115.0 & X_m & = 17.0 \end{array}$$

Calculate the following:-

- Full-load current from the supply.
- Full-load power factor.
- Full-load efficiency.
- Full-load torque.

- Starting current from the supply.
- Starting power factor.
- Starting torque.

Figure 5.1 is the appropriate equivalent circuit for the calculations.

a) Solution for full-load.

The applied voltage per phase V_p is:-

$$V_p = \frac{415.0}{\sqrt{3}} = 239.6 \text{ volts}$$

The rotor resistance R_2 and reactance X_2 are:-

$$R_2 = (0.253 - 0.145) \times 0.02208 + 0.145 = 0.1474 \text{ ohms}$$

$$X_2 = (0.333 - 0.823) \times 0.02208 + 0.823 = 0.8122 \text{ ohms}$$

The rotor 'output power' resistance R_{out} at the given slip is:-

$$R_{\text{out}} = R_2 \left(\frac{1 - s}{s}\right) = 0.1474 \left(\frac{1 - 0.02208}{0.02208}\right) = 6.5273 \text{ ohms}$$

The total rotor impedance Z_{22} is:-

$$\begin{aligned} Z_{22} &= R_2 + jX_2 + R_{\text{out}} = 0.1474 + j0.8122 + 6.5273 \\ &= 6.6747 + j0.8122 \end{aligned}$$

The shunt components at the air gap are combined in parallel as:-

$$Z_{mc} = \frac{R_c\, jX_m}{R_c + jX_m} = \frac{115.0 \times j17.0}{115.0 + j17.0}$$
$$= 2.4593 + j16.6365 \text{ ohms}$$

The total air-gap impedance Z_{m22} is:-

$$Z_{m22} = \frac{Z_{mc} Z_{22}}{Z_{mc} + Z_{22}} = \frac{(2.4593 + j16.6365) \times (6.6747 + j0.8122)}{2.4593 + j16.6365 + 6.6747 + j0.8122}$$
$$= 5.1534 + j2.5313 \text{ ohms}$$

The total motor impedance Z_{mot} is:-

$$Z_{\text{mot}} = R_1 + jX_1 + Z_{m22} = 0.179 + j0.438 + 5.1534 + j2.5313$$
$$= 5.3324 + j2.9693 \text{ ohms, which has a magnitude of 6.1033 ohms.}$$

The stator current per phase I_1 is:-

$$I_1 = \frac{V_p}{Z_{\text{mot}}} = \frac{239.6 + j0.0}{5.3324 + j2.9693} = 34.2982 - j19.0987 \text{ amps,}$$

which has a magnitude of 39.257 amps.

The air-gap voltage V_m is:-

$$V_m = V_p - I_1 Z_1 = (239.6 + j0.0) - (34.2982 - j19.0987)(0.179 + j0.438)$$
$$= 225.096 - j11.604 \text{ volts, which has a magnitude of 225.395 volts.}$$

The rotor current per phase I_2 is:-

$$I_2 = \frac{V_m}{Z_{22}} = \frac{225.06 - j11.604}{6.6747 + j0.8122} = 33.0235 - j5.7569 \text{ amps,}$$
$$R_c + jX_m = 115.0 + j17.0$$

which has a magnitude of 33.5215 amps.

The output power P_{out} is:-

$$P_{\text{out}} = 3 \times {I_2}^2 \times R_{\text{out}} = 3 \times 1123.691 \times 6.5273 = 22.004 \text{ kW}$$

The magnetising current per phase I_m is:-

$$I_m = \frac{V_m}{jX_m} = \frac{225.06 - j11.604}{j17.0} = 0.6826 - j13.241 \text{ amps}$$

The core loss current per phase I_c is:-

$$I_c = \frac{V_m}{R_c} = \frac{225.06 - j11.604}{115.0} = 1.9574 - j0.1009 \text{ amps}$$

Therefore the total shunt current I_o at the air gap is:-

$$I_o = I_m + I_c = 2.6400 - j13.342 \text{ amps}$$

The input kVA S_{in} is:-

$$S_{\text{in}} = \frac{3 \times I_1{}^* \times V_p}{1000} = \frac{3}{1000}(34.2982 + j19.0987)(239.6 + j0.0)$$
$$= 24.653 + j13.728 \text{ kVA, which has a magnitude of } 28.218 \text{ kVA.}$$

Hence the input active power P_{in} in kW and input reactive power Q_{in} in kVAr are:-

$$P_{\text{in}} = 24.653 \text{ kW and } Q_{\text{in}} = 13.728 \text{ kVAr}$$

The input power factor PF_{in} of the stator current is:-

$$PF_{\text{in}} = \frac{P_{\text{in}}}{S_{\text{in}}} = \frac{24.653}{28.218} = 0.8737 \text{ pu lagging}$$

The efficiency η of the motor at full-load is:-

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{22.004}{24.653} = 0.8925 \text{ pu}$$

The full-load torque T_e is:-

$$T_e = \frac{3sR_2V_m{}^2}{R_2{}^2 + s^2X_2{}^2} = \frac{3 \times 0.02208 \times (0.1474 \times 225.395)^2}{0.1474^2 + (0.02208 \times 0.8122)^2} = 22524.2 \text{ nm}$$

b) Solution for starting.

The same sequence of calculations can be followed for the starting condition as was used for the full-load condition, but with the slip set to unity. The results of each step are summarised below:-

$$R_2 = R_{21} = 0.253 \text{ ohms and } X_2 = X_{21} = 0.333 \text{ ohms}$$

The rotor ‘output power’ resistance R_{out} is zero.

The total rotor impedance Z_{22} is:-

$$Z_{22} = R_2 + jX_2 + 0.0 = 0.253 + j0.333 \text{ ohms}$$

The shunt components at the air gap are combined in parallel as:-

$$Z_{mc} = \frac{R_c jX_m}{R_c + jX_m} = \frac{115.0 \times j17.0}{115.0 + j17.0} = 2.4593 + j16.6365 \text{ ohms}$$

The total air-gap impedance Z_{m22} is:-

$$Z_{m22} = \frac{Z_{mc} Z_{22}}{Z_{mc} + Z_{22}} = 0.2437 + j0.3288 \text{ ohms}$$

The total motor impedance Z_{mot} is:-

$$Z_{\text{mot}} = R_1 + jX_1 + Z_{m22} = 0.4227 + j0.7668 \text{ ohms}$$

The stator current per phase I_1 is:-

$$I_1 = \frac{V_p}{Z_{\text{mot}}} = 132.124 - j239.64 \text{ amps},$$

which has a magnitude of 273.65 amps, which is 6.97 times the full-load value.

The air-gap voltage V_m is:-

$$\begin{aligned} V_m &= V_p - I_1 Z_1 \\ &= 110.988 - j14.9748 \text{ volts, which has a magnitude of 111.994 volts.} \end{aligned}$$

The rotor current per phase I_2 is:-

$$I_2 = \frac{V_m}{Z_{22}} = \frac{110.988 - j14.9748}{0.253 + j0.333} = 132.039 - j232.98 \text{ amps},$$

which has a magnitude of 267.795 amps.

The output power P_{out} is zero.

The total shunt current I_o at the air gap is:-

$$I_m = \frac{V_m}{\dfrac{R_c j\ X_m}{R_c + j\ X_m}} = 0.0842 - j\ 6.6589 \text{ amps}$$

The input kVA S_{in} is:-

$$\begin{aligned} S_{\text{in}} &= \frac{3 \times I_1{}^* \times V_p}{1000} \\ &= 94.971 + j\ 172.253 \text{ kVA, which has a magnitude of 196.699 kVA.} \end{aligned}$$

Hence the input active power P_{in} in kW and input reactive power Q_{in} in kVAr are:-

$$P_{\text{in}1} = 94.971 \text{ kW and } Q_{in1} = 172.253 \text{ kVAr}$$

The input power factor PF_{in} of the stator current is:-

$$PF_{\text{in}} = \frac{P_{\text{in}1}}{S_{\text{in}1}} = \frac{94.971}{196.699} = 0.4828 \text{ pu lagging}$$

The efficiency η of the motor at starting is zero.

The starting torque T_{e1} is:-

$$T_{e1} = \frac{3\ R_2\ {V_m}^2}{{R_2}^2 + {X_2}^2} = \frac{3 \times 0.253 \times 111.994^2}{0.253^2 + 0.333^2} = 54431.0 \text{ nm}$$

which is 2.417 times the full-load value.

5.2.6 Typical Impedance Data for two-Pole and four-Pole Induction Motors

Tables 5.1–5.4 show the approximate resistance and reactance values in per-unit for two-pole and four-pole low voltage induction motors that are generally of the Design D type. Tables 5.5–5.8 show the approximate resistance and reactance values in per-unit for two-pole and four-pole high voltage induction motors that are of the reduced starting current type. In the absence of exact data from a manufacturer these data can be used for system studies such as starting motors, transient stability and fault current contribution. The data from a manufacturer should be used for calculations and system studies that are to be carried out during the detailed design phase of a project.

5.2.7 Representing the Deep-Bar Effect by Two Parallel Branches

Consider a series connection of resistance and inductive reactance, denoted as $R_n + jX_n$. Any number, n, of these branches can be connected in parallel. The sum of these parallel branches can also be

Table 5.1. Per-unit resistances and starting-to-full-load current ratio for LV two-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
11	0.0433	0.0437	0.0323	0.0398	15.44	6.29
15	0.0355	0.0377	0.0270	0.0411	16.69	6.42
22	0.0282	0.0312	0.0218	0.0421	18.35	6.55
30	0.0237	0.0268	0.0186	0.0425	19.81	6.65
37	0.0216	0.0241	0.0167	0.0425	20.85	6.70
45	0.0191	0.0219	0.0152	0.0423	21.86	6.74
55	0.0173	0.0197	0.0138	0.0419	22.95	6.78
75	0.0150	0.0168	0.0120	0.0410	24.73	6.83
90	0.0138	0.0153	0.0111	0.0403	25.83	6.85
110	0.0126	0.0138	0.0103	0.0393	27.09	6.86
132	0.0117	0.0125	0.00955	0.0384	28.28	6.87
160	0.0108	0.0113	0.00888	0.0372	29.59	6.87
200	0.00995	0.0100	0.00820	0.0357	31.17	6.85
250	0.00917	0.00887	0.00759	0.0341	32.83	6.83
315	0.00846	0.00782	0.00705	0.0323	34.63	6.79

Table 5.2. Per-unit reactances and starting-to-full-load torque ratio for LV two-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
11	0.0433	0.0840	0.114	0.0531	2.317	1.50
15	0.0355	0.0833	0.124	0.0528	2.503	1.61
22	0.0282	0.0825	0.137	0.0527	2.752	1.73
30	0.0237	0.0819	0.147	0.0529	2.970	1.80
37	0.0216	0.0815	0.153	0.0532	3.126	1.84
45	0.0191	0.0812	0.159	0.0536	3.278	1.86
55	0.0173	0.0809	0.165	0.0541	3.442	1.86
75	0.0150	0.0804	0.173	0.0551	3.708	1.85
90	0.0138	0.0802	0.178	0.0558	3.874	1.83
110	0.0126	0.0799	0.182	0.0567	4.064	1.80
132	0.0117	0.0797	0.186	0.0576	4.244	1.76
160	0.0108	0.0795	0.189	0.0587	4.442	1.70
200	0.00995	0.0793	0.193	0.0601	4.682	1.63
250	0.00917	0.0791	0.196	0.0617	4.934	1.55
315	0.00846	0.0790	0.198	0.0635	5.207	1.45

Table 5.3. Per-unit resistances and starting-to-full-load current ratio for LV four-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
11	0.0527	0.0405	0.0379	0.0497	14.92	6.01
15	0.0436	0.0361	0.0319	0.0488	16.06	6.03
22	0.0352	0.0311	0.0261	0.0478	17.41	6.06
30	0.0299	0.0275	0.0225	0.0471	18.43	6.08
37	0.0270	0.0252	0.0204	0.0468	19.07	6.10
45	0.0246	0.0232	0.0187	0.0464	19.63	6.13
55	0.0225	0.0213	0.0172	0.0462	20.16	6.16
75	0.0197	0.0186	0.0152	0.0458	20.86	6.22
90	0.0183	0.0171	0.0142	0.0456	21.22	6.26
110	0.0170	0.0156	0.0132	0.0455	21.55	6.31
132	0.0159	0.0144	0.0124	0.0454	21.79	6.37
160	0.0148	0.0131	0.0117	0.0453	21.99	6.43
200	0.0138	0.0118	0.0109	0.0453	22.14	6.52
250	0.0129	0.0106	0.0102	0.0453	22.21	6.62
315	0.0121	0.00942	0.00965	0.0454	22.19	6.74

represented by a series circuit of the $R + jX$ type. This approach can be used to represent the deep-bar effect in the rotor of an induction motor. It has the effect of splitting the rotor bars into a set of outer bars and a set of inner bars, both sets then being independent of each other. In addition the resistances become simple reciprocal functions of slip, whilst the inductive reactances remain constant as the slip varies.

Let the outer bars be represented by the series branch $R_{22}/s + jX_{22}$ and the inner bars by the branch $R_{33}/s + jX_{33}$, where s is the slip. Let the sum of the two branches be $R_{23}/s + jX_{23}$. It is

Table 5.4. Per-unit reactances and starting-to-full-load torque ratio for LV four-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
11	0.0527	0.0813	0.149	0.0610	2.245	1.69
15	0.0436	0.0810	0.160	0.0638	2.416	1.67
22	0.0352	0.0806	0.173	0.0668	2.617	1.66
30	0.0299	0.0801	0.183	0.0687	2.768	1.65
37	0.0270	0.0797	0.188	0.0697	2.863	1.65
45	0.0246	0.0793	0.193	0.0705	2.946	1.65
55	0.0225	0.0788	0.197	0.0710	3.023	1.66
75	0.0197	0.0780	0.203	0.0715	3.127	1.68
90	0.0183	0.0775	0.205	0.0715	3.178	1.70
110	0.0170	0.0769	0.207	0.0712	3.226	1.73
132	0.0159	0.0763	0.208	0.0708	3.262	1.76
160	0.0148	0.0756	0.209	0.0702	3.290	1.79
200	0.0138	0.0748	0.208	0.0693	3.311	1.84
250	0.0129	0.0739	0.207	0.0681	3.319	1.90
315	0.0121	0.0730	0.205	0.0666	3.313	1.97

Table 5.5. Per-unit resistances and starting-to-full-load current ratio for HV two-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_M	I_s/I_n
630	0.00887	0.00627	0.00771	0.0183	44.16	6.24
800	0.00896	0.00648	0.00776	0.0175	45.20	6.02
1100	0.00901	0.00667	0.00777	0.0172	46.17	5.71
2500	0.00883	0.00662	0.00740	0.0205	46.24	4.85
5000	0.00842	0.00600	0.00672	0.0303	43.63	4.11

Table 5.6. Per-unit reactances and starting-to-full-load torque ratio for HV two-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
630	0.00887	0.112	0.0961	0.0471	4.134	0.694
800	0.00896	0.118	0.0935	0.0470	4.313	0.620
1100	0.00901	0.126	0.0912	0.0477	4.518	0.550
2500	0.00883	0.151	0.0917	0.0537	4.817	0.472
5000	0.00842	0.176	0.0991	0.0651	4.781	0.497

required to find unique values for R_{22}, X_{22}, R_{33} and X_{33} that give the required values of R_{23} and X_{23}. (The double suffices are chosen so as not to cause confusion with the single suffices used for example in sub-section 5.2.1.) This can only be achieved if two values of slip are used, which for convenience are the standstill and full-load values. This choice yields four equations in four unknown variables. Hence a unique solution should be achievable. The equations are not linear and so transposing them into a simple algebraic form is not possible, therefore an iterative method needs to be used to find the solution. The four equations are found as follows.

Table 5.7. Per-unit resistances and starting-to-full-load current ratio for HV four-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
630	0.00828	0.00809	0.00688	0.0285	39.01	5.84
800	0.00932	0.00804	0.00764	0.0288	45.16	5.45
1,100	0.01050	0.00780	0.00844	0.0287	52.88	5.00
1,500	0.01120	0.00742	0.00889	0.0280	59.20	4.66
2,500	0.01120	0.00650	0.00878	0.0256	65.29	4.35
5,000	0.00895	0.00495	0.00713	0.0207	62.59	4.40
6,300	0.00785	0.00441	0.00633	0.0189	59.01	4.53
8,000	0.00667	0.00386	0.00545	0.0169	54.24	4.71
11,000	0.00515	0.00308	0.00450	0.0143	53.06	5.02

Table 5.8. Per-unit reactances and starting-to-full-load torque ratio for HV four-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
630	0.00828	0.109	0.120	0.0594	3.213	0.934
800	0.00932	0.126	0.112	0.0546	3.403	0.828
1,100	0.01050	0.147	0.104	0.0501	3.635	0.697
1,500	0.01120	0.165	0.0996	0.0474	3.834	0.593
2,500	0.01120	0.182	0.0976	0.0460	4.085	0.473
5,000	0.00895	0.177	0.106	0.0498	4.242	0.391
6,300	0.00785	0.173	0.111	0.0528	4.243	0.377
8,000	0.00667	0.155	0.119	0.0570	4.217	0.365
11,000	0.00515	0.135	0.134	0.0647	4.145	0.350

At standstill the slip is 1, therefore the equivalent impedance is,

$$Z_{231} = R_{231} + jX_{231} = \frac{(R_{22} + jX_{22})(R_{33} + jX_{33})}{R_{22} + jX_{22} + R_{33} + jX_{33}} \tag{5.7}$$

At full-load the slip is s, therefore the equivalent impedance is,

$$Z_{230} = R_{230}/s + jX_{230} = \frac{(R_{22}/s + jX_{22})(R_{33}/s + jX_{33})}{R_{22}/s + jX_{22} + R_{33}/s + jX_{33}} \tag{5.8}$$

Taking the real and imaginary parts of each equation separately yields the four equations required for the solution. The given values are R_{230}, X_{230}, R_{231}, X_{231} and the full-load slip s. The solution is the set of values R_{22}, X_{22}, R_{33}, and X_{33}.

The iterative solution can be carried out by one of various algorithms, for example Newton's approximation to find roots, steepest descent to find a minimum quadratic error, rough search, successive substitution. Newton's method in four dimensions works reasonably well, although instability can set in if the incremental changes are allowed to be too large. Hence some 'deceleration' is required to stabilise the algorithm. The method of successive substitution is more efficient, but also requires stabilising with a 'deceleration' factor. Equation (5.7) for slip = 1 can be expanded to yield the following equation,

$$Z_{231} = R_{231} + jX_{231} = \frac{C_1E_1 + D_1F_1}{G_1} + \frac{j(D_1E_1 - C_1F_1)}{G_1} \tag{5.9}$$

Similarly (5.8) for slip = s can be expanded to yield the following equation,

$$Z_{230} = R_{230} + jX_{230} = \frac{C_0E_0 + D_0F_0}{G_0} + \frac{j(D_0E_0 - C_0F_0)}{G_0} \tag{5.10}$$

From (5.9) a new value of R_{22} can be found as R_{22N},

$$R_{22N} = \frac{G_1R_{231} - D_1F_1}{E_1R_{33}} + \frac{X_{22}X_{33}}{R_{33}} \tag{5.11}$$

Also from (5.9) a new value of X_{22} can found be as X_{22N},

$$X_{22N} = \frac{G_1X_{231} + C_1F_1}{E_1R_{33}} - \frac{R_{22}\ X_{33}}{R_{33}} \tag{5.12}$$

From (5.10) a new value of R_{33} can be found as R_{33N},

$$R_{33N} = \frac{G_0R_{230} - D_0F_0}{U^2E_0R_{22}} + \frac{X_{22}\ X_{33}}{U^2R_{22}} \tag{5.11}$$

Also from (5.10) a new value of X_{33} can be found as X_{33N},

$$X_{33N} = \frac{G_0X_{230} + C_0F_0}{UE_0R_{22}} - \frac{X_{22}\ R_{33}}{R_{22}} \tag{5.12}$$

Where $U = 1/\text{slip} = 1/s$
$C_1 = R_{22}R_{33} - X_{22}X_{33}$
$D_1 = R_{22}X_{33} + X_{22}R_{33}$
$E_1 = R_{22} + R_{33}$
$F_1 = X_{22} + X_{33}$
$G_1 = {E_1}^2 + {F_1}^2$

and $C_0 = U^2R_{22}R_{33} - X_{22}X_{33}$
$D_0 = UR_{22}X_{33} + X_{22}R_{33}$
$E_0 = U(R_{22} + R_{33})$
$F_0 = X_{22} + X_{33}$
$G_0 = U^2{E_0}^2 + {F_0}^2$

The calculation process is simple and convergent provided some deceleration 'k' is applied. An initial guess is required for R_{22}, X_{22}, R_{33} and X_{33}, which may require a little trial and error experimentation to find suitable values. These values are used in the equations to yield a new set of

$R_{22\mathrm{N}}$, $X_{22\mathrm{N}}$, $R_{33\mathrm{N}}$ and $X_{33\mathrm{N}}$. The cycle is repeated using the 'old' values (call these $R_{22\mathrm{O}}$, $X_{22\mathrm{O}}$, $R_{33\mathrm{O}}$ and $X_{33\mathrm{O}}$) plus a small amount of the error between the 'new' and 'old' values, i.e.,

$$R_{22} = R_{22\mathrm{O}} + k(R_{22\mathrm{N}} - R_{22\mathrm{O}})$$

$$X_{22} = X_{22\mathrm{O}} + k(X_{22\mathrm{N}} - X_{22\mathrm{O}})$$

$$R_{33} = R_{33\mathrm{O}} + k(R_{33\mathrm{N}} - R_{33\mathrm{O}})$$

$$X_{33} = X_{33\mathrm{O}} + k(X_{33\mathrm{N}} - X_{33\mathrm{O}})$$

The value of 'k' should be chosen to be between +0.001 and +0.01 to ensure stability. The process is stopped once the absolute error in each of the parameters has fallen below a suitably small value, e.g. 0.001 per-unit of its absolute value. Tables 5.9 and 5.10 for two-pole induction motors were complied from Tables 5.1, 5.2, 5.5 and 5.6, to show the results of the method.

5.3 CONSTRUCTION OF INDUCTION MOTORS

The physical construction of an induction motor is greatly influenced by the environment and ambient conditions. The environmental conditions include considerations for explosion, corrosion, dampness, ingress of dust and solid particles, proximity to human operators, cost and economics. Ambient conditions relate to surface temperature, methods of cooling, fan design and appropriate derating factors.

Table 5.9. Per-unit resistances for equivalent double-cage two-pole motors

Rated power (kW)	Slip (pu)	R_{20}	R_{21}	R_{22}	R_{33}
LV	—	—	—	—	—
11	0.0433	0.0323	0.0398	0.0434	0.11308
15	0.0355	0.0270	0.0411	0.05127	0.05491
22	0.0282	0.0218	0.0421	0.05865	0.03391
30	0.0237	0.0186	0.0425	0.06165	0.02619
37	0.0216	0.0167	0.0425	0.06342	0.02232
45	0.0191	0.0152	0.0423	0.06389	0.01967
55	0.0173	0.0138	0.0419	0.06402	0.01737
75	0.0150	0.0120	0.0410	0.06378	0.01461
90	0.0138	0.0111	0.0403	0.06312	0.01332
110	0.0126	0.0103	0.0393	0.06210	0.01222
132	0.0117	0.00955	0.0384	0.06119	0.01120
160	0.0108	0.00888	0.0372	0.06007	0.01032
200	0.00995	0.00820	0.0357	0.05840	0.00945
250	0.00917	0.00759	0.0341	0.05685	0.00868
315	0.00846	0.00705	0.0323	0.05485	0.00802
HV	—	—	—	—	—
630	0.00887	0.00771	0.0183	0.03660	0.00920
800	0.00896	0.00776	0.0175	0.03491	0.00995
1100	0.00901	0.00777	0.0172	0.03587	0.00989
2500	0.00883	0.00740	0.0205	0.06099	0.00841
5000	0.00842	0.00672	0.0303	0.12957	0.00709

Table 5.10. Per-unit reactances for equivalent double-cage two-pole motors

Rated power (kW)	Slip (pu)	X_{20}	X_{21}	X_{22}	X_{33}
LV	—	—	—	—	—
11	0.0433	0.114	0.0531	0.05442	1.1944
15	0.0355	0.124	0.0528	0.05573	0.4755
22	0.0282	0.137	0.0527	0.05619	0.3236
30	0.0237	0.147	0.0529	0.05571	0.2899
37	0.0216	0.153	0.0532	0.05596	0.2741
45	0.0191	0.159	0.0536	0.05640	0.2678
55	0.0173	0.165	0.0541	0.05716	0.2635
75	0.0150	0.173	0.0551	0.05882	0.2591
90	0.0138	0.178	0.0558	0.06012	0.2591
110	0.0126	0.182	0.0567	0.06195	0.2590
132	0.0117	0.186	0.0576	0.06357	0.2590
160	0.0108	0.189	0.0587	0.06601	0.2582
200	0.00995	0.193	0.0601	0.06892	0.2594
250	0.00917	0.196	0.0617	0.07223	0.2593
315	0.00846	0.198	0.0635	0.07597	0.2586
HV	—	—	—	—	—
630	0.00887	0.0961	0.0471	0.07070	0.1413
800	0.00896	0.0935	0.0470	0.06432	0.1493
1100	0.00901	0.0912	0.0477	0.06695	0.1433
2500	0.00883	0.0917	0.0537	0.08472	0.1173
5000	0.00842	0.0991	0.0651	0.08768	0.1101

The stator design is more affected by these factors than that of the rotor but the rotor needs to be designed so that efficient fan cooling can be achieved. The stator winding and magnetic iron circuit are part of the enclosure. The enclosure is the frame and casing which anchors the windings and provides the fixing structure of the motor, e.g. bed-plate, flange mounting. The enclosure may be of an 'open' or 'closed' type. The simplest and cheapest motors use an open enclosure. All the windings are exposed to the surrounding air by virtue of deliberately placed windows or openings at the 'drive' and 'non-drive' ends of the enclosure. The surrounding air is drawn through these windows by a simple shaft-mounted fan which is used to cool the rotor and the stator materials. The air is drawn along the air gap and discharged at the outlet end. An example of such a simple construction is a modern domestic washing machine or vacuum cleaner, but in an industrial situation this design would be deemed unsafe to human operators and would be exposed to any kind of pollution present in the cooling air, e.g. moisture, dust, chemicals, flammable gas. There are several forms of open-type motors as defined in American documentation. For example NEMA standard MG1 classifies those appropriate for general non-hazardous use. Not all open-type motors can be used in oil industry plants.

The oil industry normally specifies closed or enclosed type motors. Industrial motors are designed so that their windings and bearings are given the least exposure to poor quality air and, to this end, a 'totally enclosed' (TE) construction is used. In a TE design the bearings, rotor and stator windings are surrounded by an enclosed air atmosphere. The enclosed air is circulated by one or two shaft-mounted fans. The NEMA MG1 standard also classifies those that are appropriate for both hazardous and non-hazardous area installations. IEC60034 part 5, IEC60079 and NEC articles

500 to 516 give recommendations for the use of motors in hazardous areas and different types of environment, see also Chapter 10. Air is arranged to pass along the air gap to absorb the rotor heat and along and between the stator windings to absorb the stator heat. The heat is radiated from the outer surface of the stator frame. The design of the fans and the air paths is a complicated subject and has to be optimised for each type of motor and its rated speed.

As the motors become larger the removal of heat becomes more difficult to achieve and hence more elaborate means need to be employed. To rely solely on simple surface radiation from the stator would not be a sufficient means for motors above about 50 kW. A second air circuit is created by mounting an external fan on the non-drive end of the rotor. This fan draws in cool air from the non-drive end face, under a cowling, and blows it over the stator surface. The stator surface may be ribbed to increase the surface area or be fitted with longitudinal air tubes. These methods are satisfactory for motors up to about 500 kW. Beyond 500 kW the methods of fan cooling can become very elaborate, involving large air-to-air heat exchangers or even air-to-water exchangers.

Ingress of water and particles is defined in various international standards as outlined in Chapters 3 and 10.

5.4 DERATING FACTORS

In common with other power system equipment, motors need to be derated to suit a high ambient temperature. Equipment that is manufactured in America, UK and Europe is usually based on a maximum design temperature of 40°C. For higher ambient temperatures, e.g. 50°C as found in the Middle East and Far East, the continuous duty output power and supply current would need to be reduced. The continuous duty is that as defined as type S1 in IEC60034 part 1. International standards recommend performance and design criteria suitable for 40°C. Although most of these standard requirements will apply to ambient temperatures above 40°C there may be some addition restrictions to apply. In particular aspects of full-load current, duty, radiation of heat loss and outer surface temperature will need to be considered, see for example IEC60034 part 1 clauses 11 and 16.3. Some countries that experience high ambient temperatures and who enjoy a substantial ‘home market’ for their own products, such as India, use national standards that set the ambient temperature to a higher value such as 45°C, which is more practical in their circumstances. When a purchase specification is being prepared it is recommended that this aspect of operating a motor continuously at or near its full-load rating in a high ambient temperature is highlighted.

IEC60085 and IEC60034 part 1 describe the limitations placed on materials used inside motors (and other electrical equipment). Most electrical machines with air or gas as the cooling medium use Class B or F solid insulation material. Where the environment is harsh, and high ambient temperatures occur, then it is advisable to specify Class F insulation materials but with a restriction of Class B temperature rise. Such a specification will inherently increase the mean time to failure of the materials since they will be less stressed.

5.5 MATCHING THE MOTOR RATING TO THE DRIVEN MACHINE RATING

The importance of having sufficient motor torque for all speeds has been described earlier. For general guidance it is possible to choose the kW rating of the motor on a ‘rule-of-thumb’ basis by using Table 5.11 below.

Table 5.11. Margin of motor rating above the machine rating

Driven machine power rating (kW)	Margin multiplier (per-unit)
Up to 15	1.25
16 to 55	1.15
56 and above	1.10

When considering centrifugal machines it is important to base the motor rating on the 'end of curve' condition of the driven machine, because in practice the machine may need to run at this extreme condition for a reasonably long period of time. This condition is generally defined as 125% of the capacity of the machine at the maximum working efficiency point on the 'head-flow' curve for the designed shaft speed.

For belt-driven loads the margin factor should be a little larger than for direct in-line driven machines due to the lower transmission efficiency of belt drives. Let an additional multiplying factor be used to that given in Table 5.11. This factor should be approximately 1.2 for the smaller motors to 1.4 for the larger motors. It is also advisable to obtain advice from the manufacturers of both the driven machine and the motor.

In addition to overcoming the static torque of the load at all speeds the motor must be capable of accelerating the inertia of the load. If the inertia is too high the motor will take an excessive length of time to reach the desired speed. In the worst case it may not be able to accelerate at all. In both cases the motor will overheat and possibly suffer damage. The international standards recommend a maximum polar moment of inertia (J) in $\mathrm{kg\,m^2}$ units of the load. This information is given for a wide range of kW ratings and numbers of poles in the motor. For example Table III of IEC60034 part 12 gives inertia values for 2, 4, 6 and 8 pole motors rated up to 630 kW. Table 5 also gives formulae that can be used for higher ratings. This subject is also addressed in IEC60034 part 1 clause 6 in connection with the nine different 'duty types, S1 to S9'. If a load has an inertia higher than the limit for a motor matched by other criteria, then the rating of the motor will need to be increased until the inertia criterion is met. This will result in a motor that will run continuously at a continuous power appreciably less than its rated power. Some attention may need to be given to the choice of the protective overload relay and its settings in such a circumstance.

5.6 EFFECT OF THE SUPPLY VOLTAGE ON RATINGS

Since the torque at any speed is a function of the supply voltage squared it is important that the voltage at the terminals of the motor does not fall too far during the starting period or during predictable system disturbances. As a general guide or 'rule-of-thumb' the motor should operate satisfactorily and accelerate the load quickly even when the terminal voltage remains as low as 80% of its rated value for a long period of time. Hence the torque will be 64% of its value during this situation. This amount of torque should be at least 15% above the load torque at the worst-case slip.

As the motor kW ratings increase the supply voltage becomes limited and a higher voltage will be needed. This is because large currents cannot be carried in the stator windings. The design and fabrication of the slots, windings and end connections become physically very difficult when the

Table 5.12. Limits to motor ratings due to system voltage

Motor power rating (kW)	Appropriate system line voltage (volts)
Up to 250	LV e.g. 380 to 440
150 to 3000	HV e.g. 2400 to 4160
200 to 3000	HV e.g. 3300 to 7200
1000 to 15,000	HV e.g. 6600 to 13,800

cross-sectional area of the conductors becomes large. The typical kW limits for various voltages are given in Table 5.12, see also IEC60034 part 1 clause 29.

5.7 EFFECT OF THE SYSTEM FAULT LEVEL

Motors are controlled by circuit breakers or contactors. With high voltage motors it is necessary to ensure that the main terminal box and the terminals inside can withstand the effects of a major three-phase fault inside the box. This applies especially to motors that are to be used in a hazardous area. As a guide to the level of safeguard, Table 5.13 may be used.

When contactors are backed up by fuses it is possible to reduce the fault levels considerations. The current versus let-through-time characteristics of the fuses need to be studied if the above fault levels are to be reduced.

5.8 CABLE VOLT-DROP CONSIDERATIONS

The conductor size and length of the motor feeder cable need to be chosen carefully and the following points should be considered:-

- Normal running current.
- Starting current.
- Ambient temperature.
- Laying cables in air or buried in the ground.
- Laying cables vertically or horizontally.
- Derating factors for grouping cables.

Table 5.13. Correspondence between system voltage and fault level at the motor terminals

System line voltage (volts)	System peak fault current (kA_{pk})	System fault level (MVA)
3300 to 4160	85 to 110	150 to 250
6600 to 7200	70 to 110	350 to 500
11,000 to 13,800	65 to 80	500 to 750

- Motor power rating relative to the power supply capacity.
- Fault withstand capacity of the cable for a major fault at the motor.

Assuming 100% voltage at the switchboard or motor control centre, the volt-drop at the motor terminals should not exceed the following guidelines:-

- LV cable volt-drop at starting 20%.
- LV cable volt-drop when running at full-load 2.5% to 5.0%.
- HV cable volt-drop at starting 15%.
- HV cable volt-drop when running at full-load 1.5% to 3.0%.

The cable conductor area will need to be increased if the ambient temperature is greater than 20°C (or the standard temperature given by the cable manufacturer). The derating that will be necessary depends upon the construction and the design offered by the manufacturers, see Chapter 9. If the cables are grouped together on racks, in concrete trenches or directly buried then various derating factors must be applied. When cables are to be buried in the ground the soil conditions need to be known since the heat dissipated from the cable outer surface must be absorbed by the soil in a stable manner. The efficiency of the heat absorption varies greatly with the type of soil. For example the soil may be sandy, predominantly composed of clay or rocks, or it may be dry or wet. References 8 and 9 give recommended derating factors for grouping and burying cables. See also Chapter 10.

Where the power system has self-contained generation, the maximum size of the motor that can be started direct-on-line becomes limited, as is discussed later in this chapter. For example if a 15% volt-drop is permitted at the motor during starting then the motor kW rating should not exceed about 1/6, as a 'rule-of-thumb' guide, of the kW rating of the minimum generation that will be available. If a power system has, say three 20 MW generators then the largest direct-on-line starting of a motor will be about 3.5 MW, since it may need to be started when only one generator is operating. Detailed studies and calculations will be needed to determine exactly the maximum motor rating. In such a case full details of parameters from the chosen manufacturers will be required, together with the tolerances for each parameter. The worst-case situation should be used.

When high voltage motors are being considered, it is usually found that the minimum conductor size of the cable is determined by the let-through fault withstand capability rather than the full-load or starting current. Cable manufacturers provide graphical data for fault withstand capabilities of their cables, which are based on practical tests. These aspects are also associated with the protection system used for the motor, e.g. a contactor-fuse combination, a circuit breaker, the protective relay characteristics (thermal, inverse time with or without instantaneous or earth fault elements).

Appendix G gives detailed calculations of cable volt-drops for the starting and full-load running conditions of a 500 kW induction motor that is to be started direct-on-line in a power system that is fed by three 3125 kVA generators. This appendix demonstrates the following aspects of starting large motors:-

- Errors between rigorous and simplified solutions.
- The use of simple formulae methods based on comparing the kVA rating of the motor with that of the generation capacity.

- The use of graphical methods that consist of a family of curves for different scenarios.
- The use of nomographs to easily find the volt-drops.

5.9 CRITICAL TIMES FOR MOTORS

There are two important time periods that are critical in the application of induction motors. One is the allowable run-up or starting time and the other is the maximum stalling time.

The run-up time is determined by the static torque versus speed characteristic, and the moment of inertia of the load. High inertia loads can cause very long run-up times. However, a long run-up time in itself is not usually a problem for the driven machine. Most induction motors in the oil industry are started direct-on-line and the starting and run-up currents drawn by the motor can be in the range between about 4 and 7 times the rated current. When these currents exist for, say, 20 seconds, the amount of heat created in the stator windings and the rotor bar conductors is considerable. The surface temperature of these conductors can reach values high enough to cause damage to the winding insulation and slot wedges. With hazardous area applications this temperature rise can be very significant for some types of enclosures, especially Ex(e) motors. Attention should be given to the temperature classification, e.g. T1 to T6 as defined for example in IEC60079 part 8.

When considering the run-up time it is also necessary to know how many times the motor needs to be started in, say, one hour because successive starting would not permit the conductors or the insulation time to cool down before the next start takes place. (In that event the insulation temperature would creep up and the material would eventually fail. This process could also cause the windings to become loose in their slots and such damage would be followed by vibrational wear of the insulation.)

The stalling time that can be tolerated needs to be known. This will enable the relay protection for stalling to be correctly set. A motor can withstand a stall condition for a limited period of time, during which the starting (or stalling) current will be much higher than the normal current. The same kind of damage that can occur during prolonged run-up times will be caused by a stalling condition, but the time taken will be less because the rotor remains stationary and so no air can be circulated to remove the heat. Therefore the rate of rise of surface temperature is bound to be faster in a stalling situation. Stalling can be caused by the drive shaft being seized, for example due to a loss of lubricating oil, corrosion of bearing surfaces, fluid in the driven machine becoming very thick or even solidifying. It can also be caused by an open circuit of one of the supply phases. Modern protective relays are available for detecting a stalling condition and a loss of one phase of the supply. See also Chapter 12.

5.10 METHODS OF STARTING INDUCTION MOTORS

When the maximum kW rating of an induction motor is reached for direct-on-line starting, it becomes necessary to introduce an alternative method of starting the motor. There are several methods used in the oil industry. The object is to reduce the starting current drawn from the supply during all or part of the run-up period. There are two basic approaches that can be used:-

- Select special-purpose designs for the motor in which the winding arrangements are modified by external switching devices that are matched to the motor, e.g. star-delta motor and starter.

- Select conventional motors but use special external starting devices, e.g. Korndorfer starter, auto-transformer starter, 'soft-starter' using a controlled rectifier-inverter system.

In all cases of reduced voltage starting, care must be taken to check that the motor will create sufficient torque at the reduced voltage to accelerate the load to the desired speed in as short a time as possible. Excessive run-up times must be avoided as explained in sub-section 5.9. When the run-up time is expected to be high the manufacturer of the motor should be consulted regarding the possibility of damage and infringement of its guarantees. The following methods are the most commonly used, typically in the order shown:-

- Star-delta method.
- Korndorfer auto-transformer method.
- Soft-start power electronics method.
- Series reactor method.
- Part winding method.

5.10.1 Star-Delta Method

A specially designed motor is used. The stator windings are arranged so that the start and finish of each phase winding in the stator is brought out to the main terminal box so that six terminals are available for connection to cables. Usually two three-core or four-core cables are used unless their conductor size becomes too large, in which case single-core cables would be used. The windings are connected externally in star for starting and delta for running. The external connections are made by using a special starter in the motor control centre which also provides control relays and current transformers that determine when the transfer from star to delta should take place. This method has several disadvantages:-

- The windings are open-circuited during the transfer and this is not considered good practice, a delay should be incorporated to allow the flux in the motor to decay during the transfer.
- The starting current and torque are reduced to 33% of their value during the run-up period. This reduction may be too much for some applications.
- The running condition requires a delta winding connection and this has the disadvantage that harmonic currents can circulate in the windings.

Figure 5.7 shows the basic circuit for a star-delta starter.

5.10.2 Korndorfer Auto-Transformer Method

A standard design of motor is used. An external auto-transformer is connected between the main circuit breaker, or contactor, and the motor during the starting and run-up period. Figure 5.8 shows the connections that are commonly used in a balanced three-phase arrangement. The voltage ratio of the auto-transformer needs to be carefully selected. If it is too high then the full benefit is not achieved. If too low then insufficient torque will be created. The most effective ratio is usually found

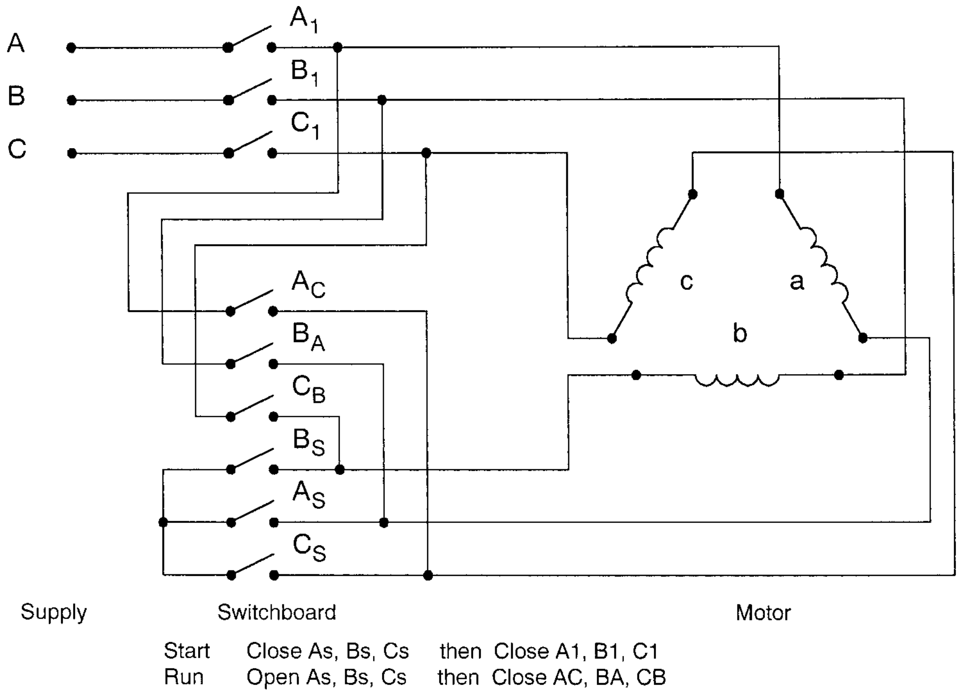


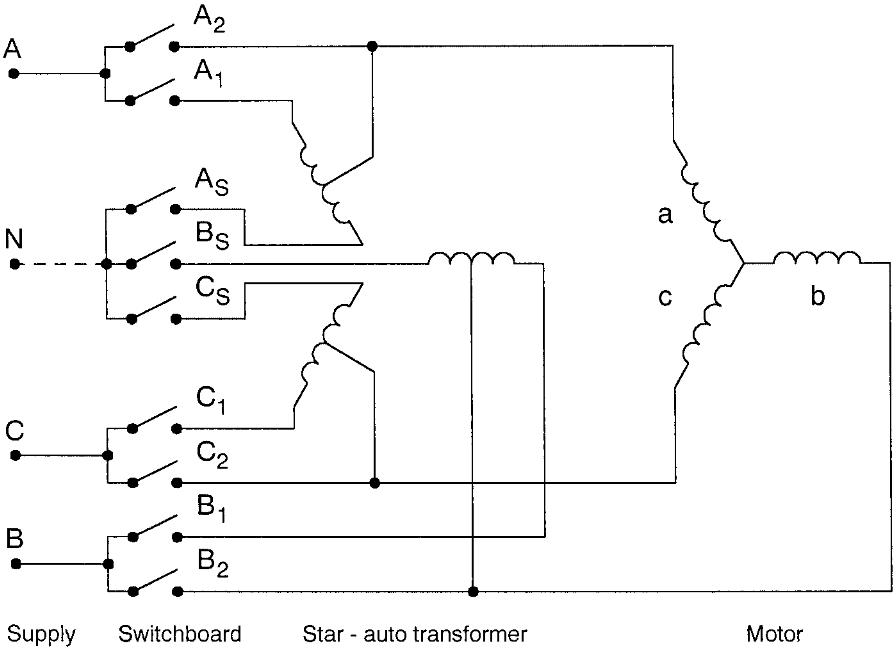
Figure 5.7 Circuit diagram for an induction motor using a star-delta starter.

between 65% and 80%. Table 5.14 illustrates the effect of reduced voltage on the starting current, line current and torque for various ratios. A disadvantage of the method is that two extra three-phase circuit breakers or contactors are necessary, thus making three in total for the motor circuit, which require space to be allocated. Retro-fitting a Korndorfer starter may therefore be difficult if space is scarce.

5.10.3 Soft-Start Power Electronics Method

A standard design of motor is used. An external rectifier-inverter is connected between the main circuit breaker, or contactor, and the motor during the starting and run-up period. The starter varies the frequency and voltage magnitude of the applied three-phase supply to the motor. Upon starting the frequency and voltage are set to their lowest values, and thereafter they are slowly raised as the shaft speed increases. The intent is to operate the motor in its near-synchronous speed state for each frequency that the motor receives. The process is explained in more detail in Chapter 14. The rectifier-inverter equipment is expensive when compared with other switching and transformer methods, but it has several advantages:-

- The starting current can be limited to a value that is equal to or a little higher than the full-load current of the motor.
- The torque created in the motor during the whole run-up period can be in the order of the full-load value, and so the shape of the inherent torque-speed curve of the motor is not a critical issue for most standard designs of motors.



Start Open A2, B2, C2 Close As, Bs, Cs then Close A1, B1, C1
Run Open A1, B1, C1 Close A2, B2, C2 then Open As, Bs, Cs

Figure 5.8 Circuit diagram for an induction motor using a Korndorfer auto-transformer starter.

Table 5.14. Auto-transformer starting of an induction motor

Voltage applied to motor in per cent of rated voltage	Line current in per cent of locked rotor current	Motor current in per cent of locked rotor current	Locked rotor torque in per cent of full voltage value
100	100	100	100
90	81	90	81
80	64	80	64
70	49	70	49
60	36	60	36
50	25	50	25

5.10.4 Series Reactor Method

A standard design of motor is used. This is a simple method that requires the insertion of a series reactor during starting. The reactor is bypassed once the motor reaches its normal working speed. Only one extra circuit breaker or contactor is required. The amount of reactance is calculated on the basis of the desired reduction of line current during starting, but the limiting factor is the reduced starting torque. The torque is reduced for two reasons, firstly because the total circuit impedance is increased and secondly the reactance-to-resistance ratio is increased.

5.10.5 Part Winding Method

A special design of motor is used. The stator has two three-phase windings that are arranged in parallel and wound in the same slots. If the two windings are the same then on starting and during run-up one winding would provide half of the total torque at any speed. Hence one winding is used for starting and both for running. The method is not suited to small or high speed motors. With two equal windings the starting current and torque are half of their totals. This method is seldom used in the oil industry because of the preference for standard motors, and the availability of satisfactory alternative methods.

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6

Transformers

6.1 OPERATING PRINCIPLES

A single-phase power system transformer consists basically of two windings wound onto an iron core. The iron core concentrates the flux and restricts it to a defined path. It also creates the maximum possible amount of flux for a given excitation. In order to maximise the mutual coupling the two windings are wound concentrically on to the same part of the iron core. Figure 6.1 shows the typical winding arrangement of a single-phase transformer. This is called shell-type construction.

Not all the flux created by one winding couples with the other winding. Furthermore the flux which does not couple both windings does not flow completely round the iron core, some of it flows in the air close to the windings. The common flux in the iron circuit is called the mutual or magnetising flux. The flux that escapes into the air and does not couple the windings is called the leakage flux. One winding is referred to as the primary winding and is connected to the source of supply voltage. The second winding is the secondary winding and is connected to the load. The primary may be either the low or the high voltage winding.

The magnetising flux is determined by the applied voltage to the primary winding. In power transformers the current drawn from the supply to magnetise the core is only a fraction of one percent of the rated primary winding current. The core design and type of iron is specially chosen to minimise the magnetising current.

When current is drawn from the secondary winding the effect on the magnetising flux is to reduce it. However, the magnetising flux density must be maintained and this is achieved by the primary winding drawing more current from the supply. More detailed explanations of the working principles of transformers can be found in References 1 to 4 in Chapter 5 herein.

Currents now exist in both windings. Therefore a volt-drop must exist in each winding due to its leakage reactance (due to leakage flux) and its conductor resistance. The equivalent circuit of a single-phase transformer can be represented as in Figure 6.2.

Where R_p Primary winding resistance.
X_p Primary winding leakage reactance.
R_s Secondary winding resistance.
X_s Secondary winding leakage reactance.
X_m Magnetising reactance.

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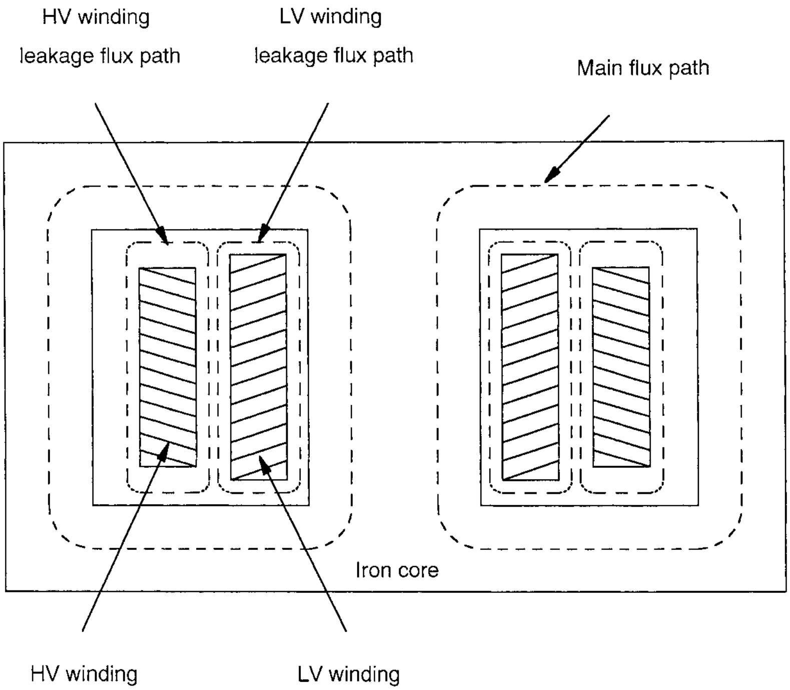

Figure 6.1 Flux paths in the core and windings of an iron cored transformer.

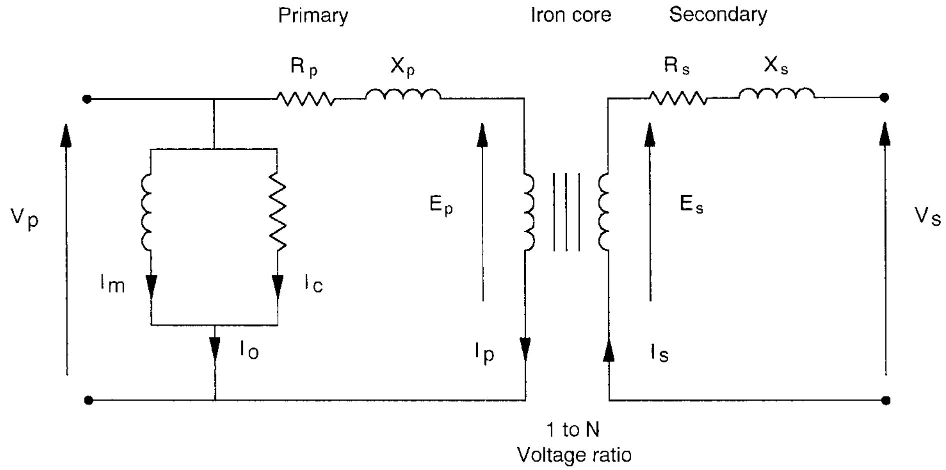

Figure 6.2 Equivalent circuit of an iron cored transformer.

R_c Resistance to account for eddy current losses in the iron core.
N Turns or transformation ratio.

It is possible to represent the equivalent circuit with all the winding components on either the primary side or the secondary side. The components that are moved across to the other side become what is called the 'referred' components. For example if the secondary winding impedance $R_s + jX_s$ is referred to as the primary side then the referred or equivalent impedance $R_s' + j\,X_s'$ in the primary circuit is,

$$R_s' + j\,X_s' = \frac{R_s + j\,X_s}{N^2}$$

Hence the total series impedance in the primary circuit becomes,

$$Z_p = (R_p + R_s') + j(X_p + X_s') \text{ ohms.}$$

At this stage all the components are ohmic values and are obtainable from tests.

The per-unit impedance Z_{pu} can be simply derived from the ohmic impedance values and knowing either the primary rated current or the kVA rating of the transformer. It will, however, be seen that the per-unit impedance Z_{pu} is the same whether it is calculated from the primary or the secondary data.

The standard kVA ratings of transformers follow the numbering sequence of ISO3 or BS2045 for units designed on the basis of European practice, e.g. 100, 125, 160, 200, 250, 315, 400, 500, 630, 800 kVA and decades above and below.

Figures 6.3 and 6.4 show typical values of the components of Z_{pu} for different ratings and voltage ratios of transformers (data given at a system frequency of 50 Hz and derived from different sources, for example References 1 and 2).

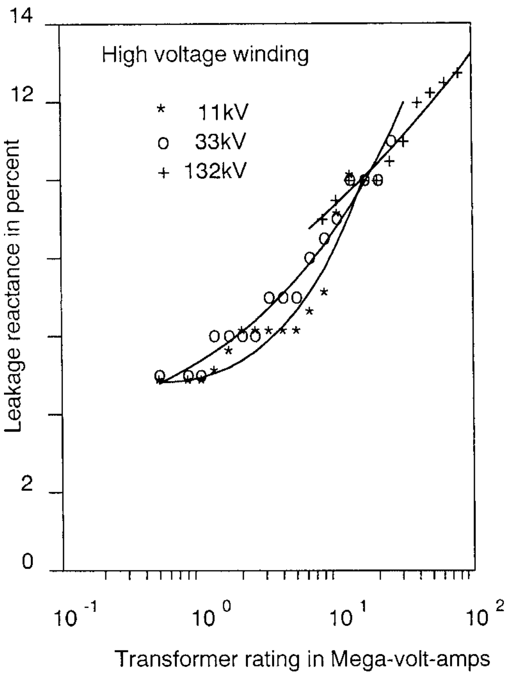

Figure 6.3 Leakage reactance in percent versus the MVA rating 50 Hz transformers.

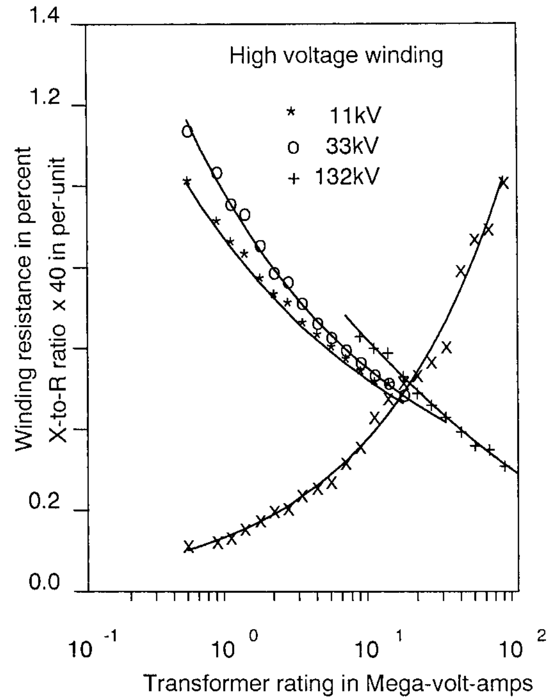

Figure 6.4 Winding resistance in percent and X-to-R ratio in per-unit versus the MVA rating of 50 Hz transformers.

6.2 EFFICIENCY OF A TRANSFORMER

Since the equivalent circuit contains two winding resistances and a core-loss resistance then power is lost as heating energy inside the transformer. Hence the conversion of power through the transformer cannot be 100%, a small loss of efficiency occurs. This is usually less then about 2% for power transformers. Assume all resistances and reactances are referred to the secondary winding. The efficiency can be expressed as,

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} = \frac{\text{Output power}}{\text{Output power} + \text{power losses}}$$

$$= \frac{V_s \cos \varnothing}{V_s \cos \varnothing + I_s(R_s + R'_p) + \dfrac{P_c}{I_s}}$$

Where $\cos \varnothing$ is the power factor of the load
P_c is the core-loss
I_s is the secondary current
V_s is the secondary voltage
E_s is the secondary emf.

This formula applies to single-phase transformers, or to one phase of a three-phase transformer.

6.3 REGULATION OF A TRANSFORMER

Regulation is a subject that regularly occurs in power systems. Regulation is a measure of the voltage drop in a device or circuit. It compares the volt-drop at full-load with the terminal voltage at no-load, both of which can be obtained for a transformer from simple factory tests.

The voltage regulation of a transformer is the change in the terminal voltage V_s between no-load and full-load at a given power factor. It is usually expressed as a percentage of the rated voltage. The phasor diagram for the single-phase transformer or one phase of three-phase transformer is Figure 6.5.

$$\text{Percentage regulation} = \frac{E_s - V_s}{V_s} \times 100\%$$

$$E_s = \sqrt{\mathrm{OC}^2 + \mathrm{AC}^2}$$

Let R_{se} = Equivalent resistance in the secondary circuit

X_{se} = Equivalent leakage resistance in the secondary circuit

For % regulations less than 20% it can be seen that the quadature components have little effect on the magnitude of E_s. Hence AC can be ignored and so.

$$E_s = \sqrt{(\mathrm{OC}^2)} = \mathrm{OC} = V_s + I_s\ R_{se} \cos \emptyset + I_s\ X_{se} \sin \emptyset$$

$$\%\ \text{Regulation} = \frac{(I_s R_{se} \cos \emptyset + I_s\ X_{se} \sin \emptyset)\ 100\%}{V_s}$$

(Note: See Chapter 9 for a similar expression used with cable volt-drop).

In most power transformers R_{se} is much smaller than X_{se} and so R_{se} can be ignored in regulation and fault level calculations.

Figure 6.4 shows the per-unit values of R_{se} for typical transformers.

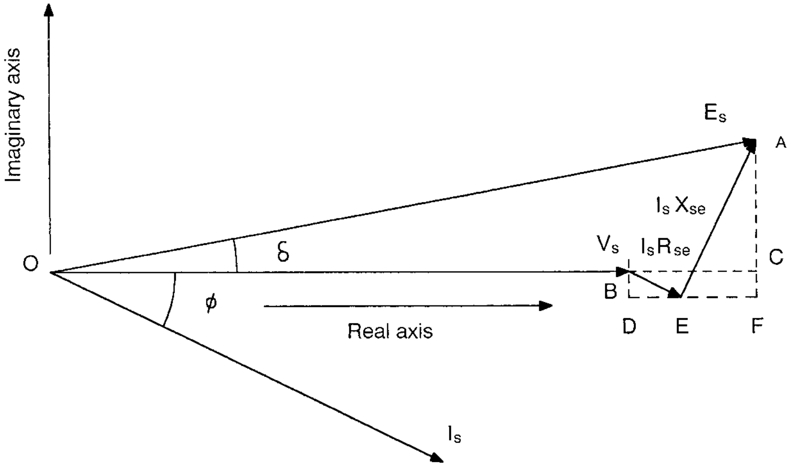

Figure 6.5 Phasor diagram of a loaded transformer at a lagging power factor.

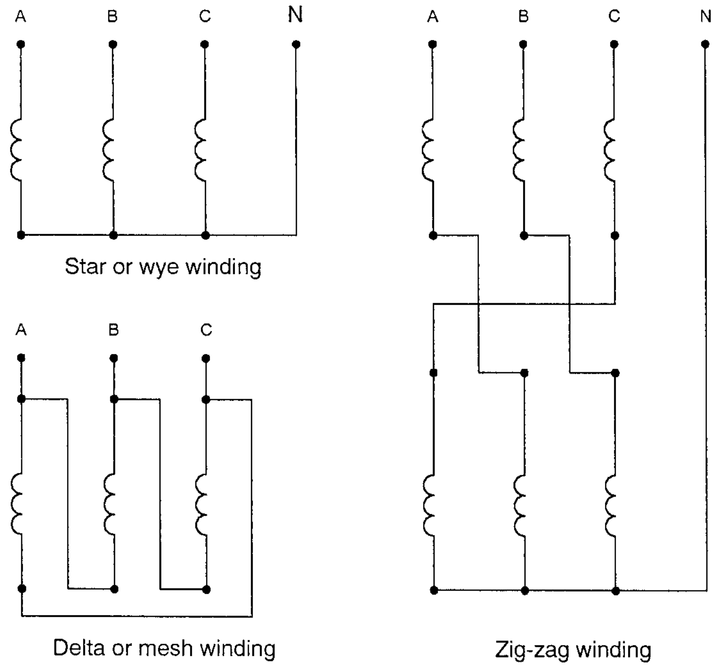

Figure 6.6 Commonly used primary and secondary winding connections for three-phase transformers.

6.4 THREE-PHASE TRANSFORMER WINDING ARRANGEMENTS

Three methods of arranging the windings of three-phase transformers are commonly encountered: star, delta and zig-zag. Each method can be applied to either or both of the primary and secondary windings, Figure 6.6 shows the three forms.

Star windings are used when a neutral connection is required for earthing or for un-balanced loads (these are usually groups of single-phase loads placed between separate phases of the supply and its neutral. Each group may not be identical and hence the system will be unbalanced).

Delta windings are most frequently used on the high voltage winding, which is usually the winding connected to the supply. The delta connection also allows third harmonic currents to circulate which improves the waveforms of the line currents and voltages on both side of the transformer. Delta windings may be slightly more expensive because the insulation has to withstand the full line-to-line voltage.

The zig-zag winding requires each three-phase winding to be split in half. Each half is interconnected with a half-winding on another core limb. Zig-zag windings are used to suppress third harmonics or to provide a neutral connection as an earthing transformer, and to obtain a phase angle shift. Zig-zag windings are sometimes used for power rectifier circuits when high order harmonic can be nuisance and have to be minimised.

A procedure has been adopted (IEC60076 part 4) for identifying the winding connections. Letters and numbers are used as follows. The high voltage (HV) terminals have upper-case letters e.g. A-B-C, R-Y-B, U-V-W, L1-L2-L3 and the low voltage (LV) terminals have lower-case letters

Table 6.1. Letters used to identify three-phase windings

Geographical area	Letters and numbers used		
USA	L1	L2	L3
	1	2	3
Europe	U	V	W
	R	S	T
United Kingdom	R	Y	B
	A	B	C

e.g. a-b-c, r-y-b, u-v-w, l_1-l_2-l_3. Each winding has a start numbered 1 and a finish numbered 2. Tappings are numbered 3, 4, 5 etc. from the start terminal.

The choice of letters and numbers tends to be a national preference, see Table 6.1 as a rule-of-thumb guide.

Corresponding windings on the same core limb are numbered such that if the emf in winding A_1 A_2 is in the direction of A_1 positive with respect to A_2 at a given instant, then the corresponding emf in the LV winding will have a_1 positive with respect to a_2. Figure 5a in IEC60076 Part 4, or Figure 46 in Reference 2, which gives more detail, shows the induced emf directions and phase angle displacements for the more common connection arrangements.

The type of winding e.g. star, delta is given a letter, again upper case for HV and lower case for LV windings. The letters are,

D for Delta HV,	d for delta LV
Y for Star HV,	y for star LV
Z for Zig-zag HV,	z for zig-zag LV

Since a phase angle displacement can occur across the transformer due to its method of connection it is necessary to identify this displacement. The numbering system for this is based on the hands of a clock. Each five-minute position on a clock gives 30° phase displacement hence,

12 o'clock gives zero displacement
1 o'clock gives $-30°$ displacement
6 o'clock gives 180° displacement
11 o'clock gives $+30°$ displacement

These are the commonly encountered displacements. (Note that the phasor rotation is anti-clockwise.)

For example a transformer has a delta HV winding a star LV winding and a $+30°$ displacement. It is described by letters and numbers as a Dyll transformer.

6.5 CONSTRUCTION OF TRANSFORMERS

Most power system transformers fall into two types of construction, dry-type or liquid immersed type. Dry-type include air insulated and solid insulated construction. Solid insulation is usually epoxy resin.

Liquid immersed types use various forms of oil and special synthetic liquids. The chlorinated liquids, e.g. polychlorinated-biphenyl, have been banned in most countries because they are very strong pollutants and are almost impossible to destroy, except by intensive burning in a special furnace. Modern liquids are synthetic compounds typically silicone based, and are usually specified to be flame retardant. IEC60296, 60836, and 60944 describe suitable liquids. These transformers are the type normally used in oil and gas plants. Resin insulated transformers are very suitable for indoor locations and off-shore plants because they contain no flammable liquid, produce no spillage and require minimal maintenance. They are usually more expensive than conventional liquid immersed transformers.

Liquid immersed transformers usually have some form of external radiator to dissipate the heat generated internally by the windings and the core. The radiator is often the surfaces of the tank specially folded into corrugated fins, or is in the form of fins, which are attached to the tank sides.

As the transformer ratings become larger it is more difficult to dissipate the heat. The next method used requires external tubes to be attached in groups at the top and bottom of the tank. The liquid circulates between the tubes and the tank by natural convection. Further increase in ratings require external banks of fin-type radiators with increased surface area. There are many variation in the design of tubes and radiators. Eventually the problem requires a separately mounted radiator and forced circulation liquid pump between the radiator and the tank. All of these methods of cooling liquid immersed transformers can be supplemented with external forced air fans. The addition of a simple system of fans can increase the base rating of the transformer by typically 25% to 35%. These fans can be arranged to start by detecting the temperature rise of the windings or liquid, or by measuring the current in either winding of the transformer. It is usual practice in oil and gas plant engineering to purchase transformers complete with the fans or at least with the fittings to enable fans to be added later. However, the power cables and switchgear associated with the transformer should be rated for the fan-assisted operation, otherwise the benefit of the fans will not be achieved conveniently or even economically.

A method of lettering is used to denote the form of cooling for a particular transformer.

Four upper case letters are used.

The first pair of letters are for the heat removal from the windings and core, i.e.

- AN AIR-NATURAL:- Natural cooling by the internal air circulating amongst the winding and core by natural convexion.
- ON OIL-NATURAL:- Natural cooling by oil that circulates amongst the windings and core by natural convexion.
- LN LIQUID-NATURAL:- As for ON but a synthetic liquid is used.
- OF OIL-FORCED:- The oil is circulated by the use of an oil pump, which is usually mounted externally in the lower interconnecting pipework between the external radiator bank and the side of the tank. This method is seldom used in the oil industry because it pertains to very large ratings of transformers.
- LF LIQUID-FORCED:- As for OF but a synthetic liquid is used.

The second pair of letters are for the external surface heat removal, i.e.

- AN AIR-NATURAL:- Natural cooling by atmospheric air circulation. The windings and core are directly exposed to the air, as in the case of a dry-type or resin insulated transformer.

- AF AIR-FORCED:- Air forced cooling is arranged by using fans and trunking on the outside of the transformer. These can be applied to dry-type or liquid insulated transformers.

Transformers rated up to approximately 2.5 MVA are usually fitted with cooling tubes or tank mounted radiators. These units would typically feed low voltage switchboards. Between 2.5 MVA and 15 MVA the use of tubes would be inadequate and tank mounted radiators would be necessary. Above about 10 MVA the radiators would be separately mounted from the tank and coupled by pipework.

The overall construction of oil and liquid filled transformers would be IP55 as defined in IEC60529.

Oil industry sites are often located in hostile environments which also have aggressive transport routes for the delivery of their equipment. It is therefore necessary to construct the windings and core components in such a manner that they can withstand impacts and rough handling during transportation to site. The windings should be robustly braced to ensure that they do not move during transportation.

Other variations including using water-cooling are possible but these are not commonly encountered.

The amount of heat typically dissipated from a liquid-immersed transformer is about 12.5 watts per square metre of surface area per degree C. If such a transformer is inside a room or module then this heat must be removed by changing the air regularly, or by the HVAC cooling system. The heat dissipation can also be calculated directly from the known efficiency of the transformer at full load.

Transformers are usually fitted with devices to indicate the temperature of liquid, windings and the core. These may be direct-reading thermometers, indirect resistance temperature detectors (RTDs) or thermocouples. Signals from these devices are used to trip the feeder switchgear in the event of excessive temperature.

Liquid-immersed transformers are fitted with special safety relays and devices to safeguard the unit from internal faults and explosions. Slowly generated faults tend to produce gas from the oil or liquid.

The gas accumulates in a special chamber which is fitted with two float switches, and these operate alarms and trips when the gas accumulates slowly or rushes in during internal explosions. This system is called a Buchholz relay, and is normally used only on transformers fitted with conservator tanks. Transformers below about 1600 kVA are often sealed type liquid-immersed units. Internal explosions are released by using a special blow-off valve. Often the space above the liquid level in this type of unit is filled with an inert gas such as nitrogen.

Reference 3 gives an excellent description of all the aspects of transformer design, testing and operation.

6.5.1 Conservator and Sealed Type Tanks

Conservator type transformers are fitted with an overhead tank which is approximately half full of the oil or liquid insulant. The overhead tank is allowed to breath to atmosphere as the liquid level varies with the average temperature inside the transformer. It breathes through a small vessel filled with silica gel which absorbs the water vapour that may pass into or out of the transformer.

An alternative design which has the advantage of reduced periodic maintenance of the oil or liquid is the sealed type. The main tank is designed not to breath and is provided with a gas or vapour space between the top surface of the liquid and the underside of the tank lid. The lid is bolted onto the tank using a gas tight gasket, to form a hermetic seal.

The expansion of the liquid requires extra space in the tank and so the liquid level rises and falls in the space provided under the lid. The space is usually filled with nitrogen gas at a pressure slightly above atmospheric pressure.

6.6 TRANSFORMER INRUSH CURRENT

Power transformers have a core that consists of a large volume of laminated iron. Under normal operating conditions the flux density in the core is just above or near to the point where saturation begins. The core has no air-gaps and is capable of retaining a significant amount of residual flux when the transformer is de-energised. The amount of flux retained depends upon the point on the sine wave of the applied voltage when the primary current is switched off. The iron core has a hysteresis characteristic associated with the magnetising current, which introduces a small lagging phase angle in the waveform of the magnetising current. For the purpose of illustrating the build up of current in-rush this phase angle can be ignored. It can therefore be assumed that the magnetising current lags the applied voltage by almost 90 degrees. A small angle will exist across the impedance of the primary winding both at no-load and at any load on the secondary winding. The residual flux is determined by the instant of opening the primary circuit, and by the phase and magnitude of the voltage in the winding at the instant.

Assume the transformer is energised by its primary winding but not connected to a load. Also assume that it is required to switch off the transformer. The opening process of the AC circuit relies on the fact that the switching device requires a current zero to de-ionise and extinguish the arc. Since the circuit is highly inductive the applied voltage will not be zero when the current is zero. It will be close to its maximum positive or maximum negative value. The flux will be almost zero when the opening process is complete, hence the residual flux will be very small or zero.

When the transformer is loaded the situation is different. The power factor of the load is usually between 0.8 and 0.95 lagging, which means that the primary current will be nearly in phase with the applied voltage, and the voltage across the magnetising branch in the equivalent circuit. At the instant of opening the primary circuit the current will be zero and these voltages will not be at or near to their maximum extremes. Hence the flux will not be zero and consequently a high value of residual flux will be retained in the core. It can be seen that switching a loaded transformer out of service will create a situation where a high residual flux will exist in the transformer. This flux will remain for a long time, long enough to be present when the transformer is required to be switched back into service. The existence of residual flux can be minimised by unloading the secondary circuit before switching off the primary circuit. However, in three-phase transformers this desirable situation cannot be completely achieved due to the 120 degree phase angles between three applied voltages. At least one limb of the core will have some residual flux established in it after the switching is complete, and this flux will then be distributed in the other limbs.

If the transformer is to be switched into service and its core has high level of residual flux stored in it, then upon closing the switch the magneto-motive force created by the applied voltage will cause the magnetising flux to be superimposed on the residual flux in the core. During the cyclic magnetisation the total flux density will exceed the designed or nominal level, which will be in the saturated region of the magnetisation curve. The magnetising current required to establish the total flux will be very large in comparison with its normal value. This high level of current is called the 'inrush current' and it contains significant harmonic components while it persists.

Suppose that the residual flux density at the instant of switching the transformer into service is B_o Wb/m^2, and that the range of flux density for rated primary voltage is ±1.0 Wb/m^2. If the primary impedance volt-drop is neglected during the initial switching process, then an excursion of 2.0 Wb/m^2 will be required above initial value of B_o Wb/m^2 in order that the required emf is induced to match the applied voltage. The following numerical example will illustrate what happens during the cyclic variations of the primary applied voltage. If B_o starts at say 0.7 Wb/m^2 as shown in Figure 6.7 then the theoretical maximum flux density will 2.7 Wb/m^2 corresponding to a magnetising current which is approximately 475 times the steady state maximum value of the magnetising current, or 10 time the rated primary current. Note that the design value of the magnetising inductive branch in the equivalent circuit can be further represented by a series circuit. This revised circuit consists of the primary winding resistance and constant inductance, together with a non-linear inductance that accounts for the saturation of the core iron. It can be seen that when the value of the magnetising current is high, during the saturated state of the core, the emf in the non-linear inductance is reduced because of the volt-drop in the primary winding components. This will have the effect of reducing the excursions of the flux density which may reach say 1.5 Wb/m^2, instead of 2.0 Wb/m^2 if the winding volt-drop were to be ignored. During the next two half cycles the emf must again be induced and so the range of flux density will need to be greater then 1.5 Wb/m^2, since at the lower instantaneous densities the current will be approaching its normal range of values. Let the range be 1.9 Wb/m^2 for the cycle, and so the minimum flux density will become say 0.3 Wb/m^2, which is significantly less than B_o. This process is repeated cyclically until B_o disappears and the variation in the flux density is symmetrical about the time axis and has extreme values of ±1.0 Wb/m^2 equal to the design values, and the magnetising current settles at its designed rms value.

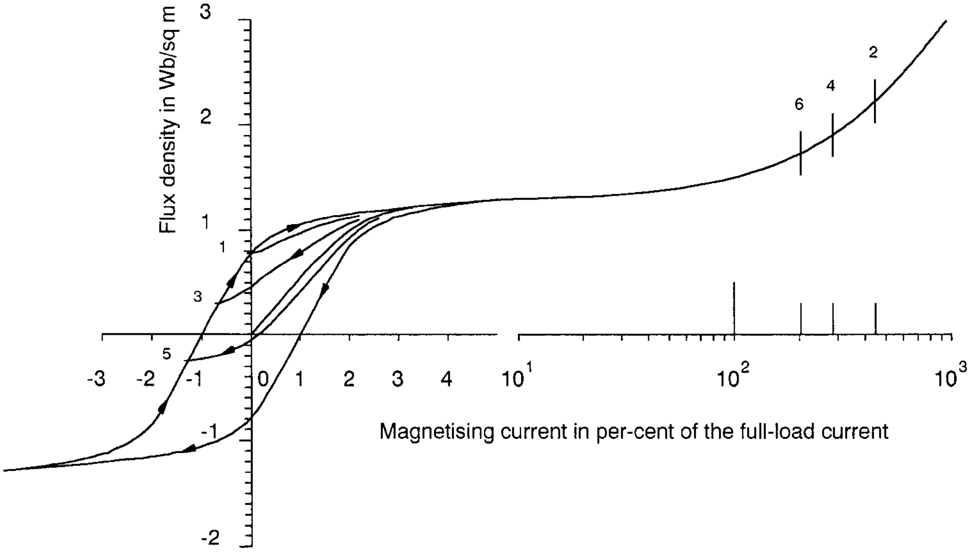

Figure 6.7 An illustration of the in-rush current in a transformer. The effect of residual flux and hysteresis is shown.

It can seen that the instantaneous, and short-term root-mean-square, values of the primary current can be much higher than their rated values, typically by as much as 10 times. Reference 4 Chapter 5 section XIV explains the phenomenon and offers a method of calculating the shape of the first half-cycle of in-rush current. The reference also points out that if a HV/LV transformer is energised from the LV secondary terminals, the in-rush current may in some designs be up to twice the value in per unit than if the energising is carried out at the primary terminals.

These high values of current cause two particular problems. Firstly the designer of the transformer must brace the winding to withstand the very high electromagnetic forces that will exist between the coils of the windings. These forces will be instantaneous and proportional to the square of the current magnitude. Secondly these asymmetrical large currents will be seen by the protective relays upstream of the transformer. They will appear as unbalanced currents in the three lines that are supplying the transformer. This imposes a stability problem for the designer of the overcurrent relays. A special circuit will be needed within the relay to stabilise its operation when these in-rush switching currents occur. Care also need to be taken in setting the relay current versus time curves. An amount of time delay is usually incorporated into the settings to override the transient time of the in-rush current, which usually lasts for about 5 cycles of fundamental current.

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7

Switchgear and Motor Control Centres

7.1 TERMINOLOGY IN COMMON USE

The terms ‘switchgear’ and ‘motor control centres’ are used in general to describe combinations of enclosures, busbars, circuit breakers, power contactors, power fuses, protective relays, controls and indicating devices. The standards used in Europe often refer to IEC60050 for definitions of general terms. Particular IEC standards tend to give additional definitions that relate to the equipment being described, e.g. IEC60439 and IEC60947 for low voltage equipment, IEC60056, IEC60298 and IEC60694 for high voltage equipment. An earlier standard IEC60277 has been withdrawn. These standards tend to prefer the general terms ‘switchgear’ and ‘controlgear’. Controlgear may be used in the same context as ‘motor control centres’ which is a more popular and specific term used in the oil industry.

In general switchgear may be more closely associated with switchboards that contain circuit breaker or contactor cubicles for power distribution to other switchboards and motor control centres, and which receive their power from generators or incoming lines or cables. Motor control centres tend to be assemblies that contain outgoing cubicles specifically for supplying and controlling power to motors. However, motor control centres may contain outgoing cubicles for interconnection to other switchboards or motor control centres, and circuit breakers for their incomers and busbar sectioning. Switchboards may be a combination of switchgear and motor control centres. For example a main high voltage switchboard for an offshore platform will have switchgear for the generators, busbar sectioning and outgoing transformer feeders. It will have motor control centre cubicles for the high voltage motors. IEC60439 applies to low voltage equipment that is described as ‘factory built assemblies’, or FBAs, of switchgear and controlgear.

Switchgear tends to be operated infrequently, whereas motor control centres operate frequently as required by the process that uses the motor. Apart from the incomers and busbar section circuit breakers, the motor control centres are designed with contactors and fuses (or some types of moulded case circuit breakers in low voltage equipment) that will interrupt fault currents within a fraction of a cycle of AC current. Circuit breakers need several cycles of fault current to flow before interruption is complete. Consequently the components within a circuit breaker must withstand the higher forces and heat produced when several complete cycles of fault current flow.

Switchgear is available up to at least 400 kV, whereas motor control centres are only designed for voltages up to approximately 15 kV because this is the normal limit for high voltage motors.

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7.2 CONSTRUCTION

The switchgear (SWGR) and motor control centres (MCC) considered in this section are those found in the onshore and offshore oil industry for supplying power to processes and utilities. Extra high voltage (EHV) transmission and distribution equipment used by electricity authorities is not considered herein. Hence most of the equipment used onshore and offshore is limited to an upper service voltage of between 11 kV and 15 kV. Occasionally voltages in the range of 30 kV to 40 kV are used when the incoming line or generating capacity exceeds approximately 120 MW. Voltages as high as 69 kV are used for long submarine cable systems.

The SWGR and MCC equipment are invariably housed in a building or enclosed module, or at least effectively protected against bad weather and aggressive environmental conditions. The construction is therefore of the metal clad type, in which all the live parts are housed in a mild-steel sheet metal enclosure. The enclosure is sub-divided so that personnel may work safely on some compartments without danger or the risk of electric shock.

Various degrees of personnel and ingress protection are commonly available. The degree of protection is defined in various international standards e.g. NEMA and NEC in USA, IEC in UK and Europe. For use inside buildings where manual operation and interference is infrequent and where the atmosphere is cool, dry and clean an enclosure of the IEC60529 type IP40, 41 or 42 or NEMA type 1 or 2 is usually adequate. If equipment is to be located in a poor atmosphere e.g. dust laden, damp, hot and where hose-pipes may be used to wash down adjacent plant, then a more demanding enclosure type is required e.g. IP54 or NEMA type 4, but this would normally only apply to low voltage equipment.

The main electrical components are:-

- Main busbars.
- Earthing busbar.
- Incoming and busbar section circuit breakers.
- Outgoing switching devices, contactors or circuit breakers.
- Fuses for MCC outgoing circuits.
- Safety interlocking devices.
- Electrical protective relays and devices for all power circuits.
- Control and indication devices.
- Communication or network interfacing system.
- Main connections and terminal compartments.

7.2.1 Main Busbars

The main busbars should be made of high-grade copper. Aluminium is not recommended because it suffers from mechanical problems associated with the soft nature of the metal, which makes the physical jointing and connection of auxiliary devices difficult. For voltages up to 600 V it is often required to use four busbars, one being for the neutral. This is because unbalanced loads need to be supplied as a 4-wire system. In this case a 4-wire feeder from the source is necessary, e.g. a HV/LV transformer, LV generator. Care needs to be taken when specifying the number of horizontal and

Table 7.1. Busbar normal current ratings in amps

HV MCCs and SWBDs	LV MCCs and SWBDs
400	
630	800
800	1600
1200	2400
1600	3000
2000	3150
2400	3500
3000	4000
3150	

vertical busbars in low voltage motor control centres. Often in oil industry motor control centres there is a mixture of motor controllers and static load feeder units. Motors seldom need a 4-wire supply but static loads are often unbalanced and require the fourth or neutral wire. The motor and static load units need not necessarily be segregated into different complete vertical assemblies, although this is good engineering practice, and so it is advisable to specify a fourth vertical busbar in each vertical assembly. When a 4-wire system is required the incoming and busbar section circuit breakers may be 3-pole with a linked neutral or be 4-pole. If the SWBD or MCC feeds equipment located in a hazardous area then the 4-pole circuit breakers should be used, as recommended in the international standards, see Chapter 10.

For balanced loads and for voltages above 1000 V a 3-wire source is used and hence only three busbars are needed. Unbalanced loads are seldom encountered at high voltages. Typical busbar normal current ratings used in the oil industry are shown in Table 7.1.

The maximum value of 4000 A for low voltage busbars roughly corresponds to the secondary current of a fully loaded 2500 kVA transformer. 2500 kVA is often chosen as the limit for transformers that feed motor control centres because the fault current that they allow through is typically near to the limit that the manufacturers can normally supply, e.g. 80 kA symmetrical rms current. A 2500 kVA transformer with a 6% leakage impedance and a 400 V secondary winding will pass approximately 60 kA of fault current. If the MCC feeds mostly motors then they will collectively contribute some fault current in addition to that from the transformer, see IEC60363 clause 4 and IEC60909 clause 13. In the above simple example some of the margin between 60 kA and 80 kA will be taken up by the sub-transient contributions from the motors. It can be noted at this point that if the transformer is subsequently increased in rating by the addition of forced air fans, then the fault current passed by the transformer will be unchanged. It is advisable to specify the rating of the transformer in its forced air-cooled mode of operation, if such cooling is considered likely to be needed in the future. This would ensure that the incoming circuit breakers and busbar normal rated currents would be correctly matched to the transformers.

High voltage switchboards are available with busbar ratings up to 5000 A. Consider for example an 11 kV switchboard that is fed by four 25 MVA generators, two connected to the left-hand side busbar section and two on the right-hand side section. The total rated current from a pair of generators is 2624 A, which is the maximum current that can flow across the busbar section circuit breaker. Hence the busbars can be adequately rated at 3000 A or 3150 A for this plant.

Busbars are mounted on insulated bushes that are strong enough to withstand the peak short-circuit currents and forces. The busbars may be air insulated or enclosed in an insulating sleeve.

The sleeve is used where the atmosphere may be damp or corrosive. Neutral busbars are usually rated at half the phase busbar current ratings. If the neutral is likely to carry harmonic currents then it is good practice to use a fully rated neutral busbar i.e. the same as the individual phase busbars.

7.2.2 Earthing Busbars

The earthing (grounding) busbar is separate from the neutral busbar, and is used to earth all conductors that need to be earthed as well as the metallic frame and casing of the switchboard or motor control centre. The earthing busbar is made of high-grade copper and is usually located at the front or rear of the enclosure at ground level.

7.2.3 Incoming and Busbar Section Switching Device

7.2.3.1 Low voltage systems up to 600 V

The incoming and busbar section switching devices are usually air-break circuit breakers, which can be fixed or withdrawable from the main frame or enclosure. They can be 3 or 4-pole depending upon whether a 3 or 4-wire supply is required. Some low power switchboards may use load-break switches for these functions.

7.2.3.2 High voltage systems up to 15 kV

Several types of circuit breakers are available for high voltage operation. The main types are:-

- Air-break.
- Sulphur hexafloride gas.
- Vacuum.

The use of oil in switchgear has become unnecessary and discontinued. The choice of circuit breaker type for a particular power system depends upon several main factors:-

- Ambient and environmental conditions, derating may be required for high ambient temperatures.
- Rated normal rms current.
- Fault peak making current with the appropriate DC offset.
- Fault rms breaking current with the appropriate DC offset if it is still present.
- Fault withstand duty.
- Cost and economics.
- Variety of choice in the market so that a technical and economic comparison can be made.
- Physical size and suitability for the intended location.
- Manufacturing time and delivery time.
- Obsolescence and the availability of spare parts.
- Post purchase follow up services.

- History of operation in similar plants and locations.
- Single or duplicate busbar system requirements.

Air-break circuit breakers are almost the same in design as the low voltage air-break devices described above except that they are more robust and insulated for the high voltage. They are only available in the 3-pole form, and up to about 24 kV is possible. They tend to be the most expensive and require more frequent maintenance due to their exposed construction and relatively more complicated mechanisms. Vacuum and sulphur hexafloride equipment is less expensive and tend to be preferred to air-break equipment.

Sulphur hexafloride (usually referred to as SF6) gas is also used as the arc extinguishing medium. SF6 circuit breakers are very robust, economical, small in size, and extremely reliable. They require almost no major maintenance for at least 10 years of operation. The gas is contained under a pressure slightly above atmospheric pressure and sealed in hermetically. There is no contact with the outside air. Metalclad equipment is available up to 36 kV and SF6 has to a large extent replaced all the air-blast equipment for distribution voltages up to 400 kV. At 11 kV the typical ratings are 400 A to 2500 A with fault making duties up to about 25 kA.

Vacuum and SF6 devices were developed at about the same time as competitors. There is little to choose between them since they are both simple mechanisms. Some engineers in the past considered the possibility that the vacuum could be lost while the circuit breaker was in its ‘on’ state was a serious disadvantage. However, the technology has greatly improved and thousands of vacuum circuit breakers are in service. Vacuum circuit breakers are limited to about 13.8 kV due to insulation difficulties across the open contacts. Current ratings at 13.8 kV are limited to about 3000 A, with corresponding fault making duties up to 100 kA peak. SF6 equipment tends to be preferred to vacuum equipment.

7.2.4 Forms of Separation

Cubicle type switchgear can be constructed in many different arrangements depending upon a variety of requirements. For example the following aspects may be important for a particular plant, environmental protection, ease of access to internal parts, ease of terminating cables, fixed or withdrawable switching devices, maintainability and level of personnel skill, cost and economics, expected life duration of the product, fitness for its purpose. The switchgear industry is very competitive and so it is essential to clearly specify what is required in the form of assembly and its construction. Otherwise a false or unsatisfactory decision may be made mainly based on a cost comparison.

The steel clading and compartments are necessary for support of the electrical and mechanical components, and for providing a safety barrier for the personnel who operate and maintain the switchgear. Safety risk has two main features. Firstly, electric shock and secondly, injury from explosive faults and fires. A well-designed enclosure should ensure that these features are minimised. The following discussion refers to IEC standards for low voltage switchgear in particular. However, the basic concepts also apply to high voltage switchgear.

The main IEC standard for low voltage switchgear assemblies is IEC60439 which has seven parts. Part 1 covers the basic requirements for internal separation, compartments, barriers and partitions. It uses the IPXY notation of IEC60529 as a basis for the ingress protection, mainly concentrating on ‘X’ for access by tools, fingers, hands, small particles and dust. The minimum value of ‘X’ used in the standard is 2 for protection against live parts, and for ingress between adjacent units of an assembly, in particular by the fingers of a person. The standard defines four basic 'forms' of separation:-

- Form 1. No separation is provided.
- Form 2. Separation is only provided between the busbars and other functional units.
- Form 3a. Separation of the busbars from the functional units. Separation of one functional unit from another. However, the terminals for the external cables need not be separated from the functional units, nor from each other.
- Form 3b. As for Form 3a except that the terminals as a group are separated from the functional units. The terminals need not be separated from each other in the group.
- Form 4. As for Form 3a except that the terminals are an integral part of a separated functional unit. The terminals need to be separated from each other in the group.

Also defined in the standard are many terms and expressions that are used to describe individual parts and components as well as combinations of them, e.g. assembly, functional unit, barrier. The standard states what is to be achieved but not how and with what materials. An annex has been issued in the UK that expands the general principles. In June 1996 The Electrical Installation Equipment Manufacturer's Association (EIEMA) published Reference 1. The four 'forms' were sub-divided as follows:-

- Form 1. No sub-divisions.
- Form 2. Sub-divisions as:-
  - Form 2a
  - Form 2b, Type 1
  - Form 2b, Type 2
- Form 3. Sub-divisions as:-
  - Form 3a
  - Form 3b, Type 1
  - Form 3b, Type 2
- Form 4. Sub-divisions as:-
  - Form 4a, Type 1
  - Form 4a, Type 2
  - Form 4a, Type 3

These various 'forms' and 'types' differ in detail regarding:-

- Separation of busbars and terminations.
- Separation provided between the busbars and cable terminals.
- Use of rigid barriers.
- Location of cable glands.
- Whether each functional unit has its own integral glanding arrangement.

Reference 1 has an excellent diagram in the form of a 'decision tree' to fully illustrate the above details. Another good summary which includes a table showing the relationship between busbars, functional units and terminations is Reference 2.

Oil industry users tend to prefer the various types of Form 4, with an ingress code of IP31, 32, 41 or 42 for use indoors.

7.2.5 Ambient Temperature Derating Factor

Switchboards and motor control centres are generally required to operate continuously at temperatures above 15°C, for example when the switchroom air conditioning fails or the ambient temperature is exceptionally high. However, switchboards are usually manufactured to meet the requirements of an ambient temperature of 40°C, see for example, IEC60439 clause 6.1.1 'ambient air temperature'.

7.2.6 Rated Normal Current

When choosing the root mean square ratings of switchboards due regard should be made for possible extra consumption of power in the future. The amount of extra power depends upon the particular situation, for example:-

- Updating an existing plant.
- New plant with detailed data.
- New plant with estimated data.
- Future plans for growth.

A good 'rule-of-thumb' guide is to assume that between 15% and 25% extra capacity will be required. Hence the chosen rating will be 115% to 125% of the best-known estimate at the early design stage. This requirement also applies to power transformers and their main cables or overhead power lines, and to outgoing feeder cables to auxiliary switchboards and motor control centres. It does not usually apply to individual motor consumers, see Chapter 1.

7.2.7 Fault Making Peak Current

The circuit breakers and busbars in the switchgear must be capable of withstanding the worst-case fault making situation, which should include the appropriate DC off-set. This is taken to be due to a zero impedance short circuit occurring within the switchboard, e.g. on the busbars, and is also assumed to exist or have been applied before the incoming feeder circuit breaker is closed. Hence the equipment must be capable of closing on to the worst possible fault, and clearing the fault within the breaking duty time period. Switchboards that are fed by generators usually have the most onerous fault conditions to clear, due to the high off-set of the current that can occur. High voltage induction motors can also contribute fault current that has a significant DC off-set, see Reference 3. The equation (7.1) below gives the transient phase current in Phase A for a three-phase worst-case fault on a generator.

$$
\begin{aligned}
I_a = V_{pk} & \left[\left[\frac{1}{X''_d} - \frac{1}{X'_d} \right] \exp^{\frac{-t}{T''d}} + \left[\frac{1}{X'_d} - \frac{1}{X_d} \right] \exp^{\frac{-t}{T'd}} + \frac{1}{X_d} \right] \cos[\omega t + \phi_o] \\
& + V_{pk} \exp^{\frac{-t}{Ta}} \left[\frac{1}{2} \left[\frac{1}{X''_d} + \frac{1}{X''_q} \right] \cos \phi_o + \frac{1}{2} \left[\frac{1}{X''_d} + \frac{1}{X''_q} \right] \cos[2\ \omega t + \phi_o] \right] \qquad (7.1)
\end{aligned}
$$

I_a = Fundamental AC part + DC part + Double frequency AC part

Where ϕ_o is the angle in the sine wave of the Phase A current when the short circuit is applied. It is also the angle between the axis of Phase A and the d-axis as the rotor rotates.

Suppose the generator is connected to a nearby switchboard. The generator and busbar section circuit breakers will need to at least withstand the fault current given in (7.1). The equation consists of three essential parts:-

- Fundamental AC part.
- DC part.
- Double frequency AC part.

7.2.8 Fundamental AC Part

This starts with high values of sinusoidal current that are determined by X''_d. After about 20 cycles the current will have decayed to a value determined by X_d. This part is symmetrically distributed above and below the zero axis. During the sub-transient and transient early period the automatic voltage regulator (AVR) action in the generator may be ignored since it will not have had time to respond. However, during the later period in the steady state the AVR will have caused the field current to reach and stay at its ceiling (maximum) value. This means that V_{pk} in (7.1) will have effectively risen by up to 170% of its prefault value. This aspect is more significant for the breaking duty of the circuit breakers. Reference 4 gives a method of calculating the decrement of short circuit for a generator, which includes a modification to the basic equations so that the effect of the AVR and exciter can be included. Figure 12.3 implements this method and shows the effect of AVR response in terms of the rms fault current. The method is well suited for programming in a small desktop computer.

7.2.9 DC Part

It is a particular characteristic in the solution of differential equations involving resistances and inductances that a DC component accompanies the symmetrical AC component. The magnitude of the DC component can equal that of the peak AC component since both are determined by X''_d. The decay of the DC component can be reasonably slow and is determined by T_a which is a function of X''_d and the armature winding resistance R_a. With machines that have significant values of X''_d and particularly low values of R_a, the value of T_a can become relatively high. When T_a is high in relation to T''_d and T'_d it is possible that the initial AC decay is faster than the DC decay. When this happens the AC instantaneous current does not reach zero until several cycles have passed. This puts an extra strain on the circuit breaker and can cause problems at the point when it starts to open to clear the fault current.

Hence the circuit breakers and the busbars in the switchboard may have to be derated for the breaking duty. The amount of DC component, or ‘off-set’ as it is often called, depends upon the point in time set by ϕ_o when the fault is applied. The occurrence of 100% off-set is seldom but cannot be ignored. The design and selection of the switchboard should be based on 100% off-set, especially if it is fed by generators and feeds a group of high voltage motors.

7.2.10 Double Frequency AC Part

A small double frequency part occurs due to sub-transient saliency of the rotor pole surfaces. Often the data from the manufacturer are not good enough to distinguish between X''_d and X''_q. The quadrature axis parameters are difficult to obtain from the normal factory tests. It is usually adequate to assume that X''_q equals X''_d and so the double frequency component becomes zero and can therefore be ignored.

The worst-case condition of (7.1) is when ϕ_o is zero, and if X''_q equals X''_d then the equation becomes:-

$$I_a = V_{pk}\left[\left[\frac{1}{X''_d}-\frac{1}{X'_d}\right]\exp^{\frac{-t}{T''_d}} + \left[\frac{1}{X'_d}-\frac{1}{X_d}\right]\exp^{\frac{-t}{T'_d}} + \frac{1}{X_d}\right]\cos(\omega t) + V_{pk}\exp^{\frac{-t}{Ta}}\left[\frac{1}{X''_d}\right] \tag{7.2}$$

In some cases it is also necessary to consider the fault current contributed by motor consumers, particularly if large synchronous motors are fed from the same busbars as the main generators or main transformer infeeds, see Chapter 11. Induction motors contribute fault current during the sub-transient period and so extra allowance must be made when calculating the making duty.

If generators are physically remote from the switchboard, e.g. interconnected by long cables or overhead lines, then the impedance between the generators and the switchboard may be large enough to swamp the sub-transient and transient current contributions, as well as reducing the DC component effects.

It has become the established practice to specify circuit breaker and switchboard making and breaking duty in kilo-amperes (kA) rather than mega-volt-amperes (MVA) which was earlier the case. This is partly due to the variety of nominal voltages used by equipment purchasers. For example a manufacturer may specify his equipment for a maximum continuous service voltage of 15 kV and yet the user will operate it at 11 kV for a particular plant. The limiting factor in all cases is the current and its associated mechanical forces. It is therefore more logical and practical to use current when specifying fault duties. Since making duty is determined by the value of the fault current at the peak of the first cycle it is customary to specify the 'fault making capacity' in terms of peak asymmetrical current (kA_{peak}). It is necessary for the engineer to assess the amount of DC off-set appropriate at the time the peak of the first cycle occurs. Table H.1b shows the properties of the fault current for different X-to-R ratios (see also Chapter 11) shows how the decay of the DC component determines the 'doubling factor' of the first cycle peak, and how the circuit X-to-R ratio determines the magnitude of the doubling effect. High voltage switchgear suffers far more from DC off-set currents than low voltage switchgear. This is due to the high X-to-R ratios that tend to occur at high voltages. At low voltages the X-to-R ratio typically ranges between 1 and 4, and so the DC off-set can often be ignored in low voltage networks.

Figure 7.1 shows the worst-case current decrement waveform for a generator that has the following data,

Rated MVA = 30.0
Rated power factor = 0.8 lagging
Rated line voltage = 11,000 volts
Synchronous reactance X_d = 2.5 pu
Transient reactance X'_d = 0.3 pu
Sub-transient reactance X''_d = 0.25 pu
Sub-transient reactance X''_q = 0.32 pu
Transient time constant T'_d = 1.08 sec
Sub-transient time constant T''_d = 0.042 sec
Armature time constant T_a = 0.375 sec

(Note, T_a was made 50% higher to show the effect more clearly in the graph).

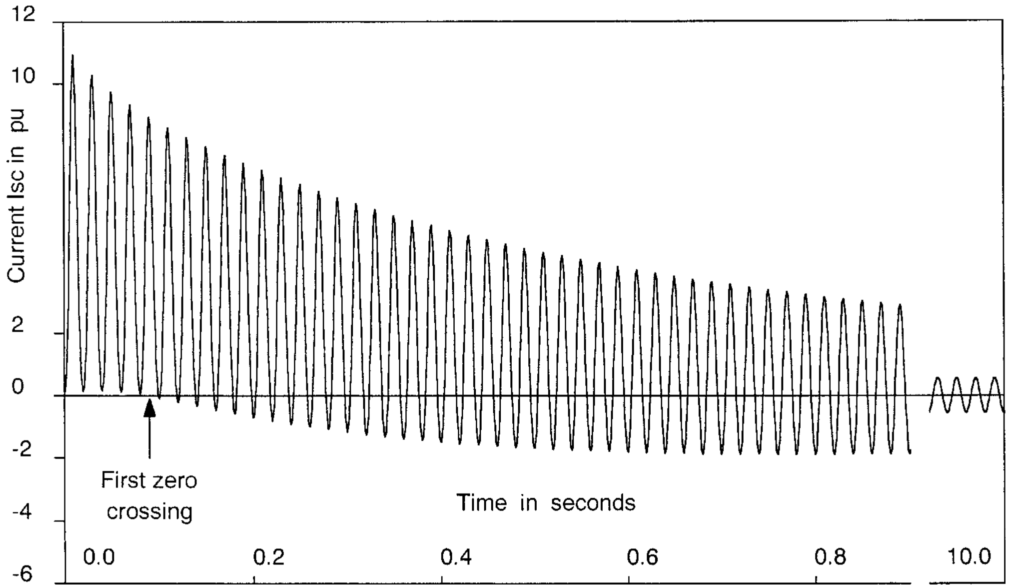

Figure 7.1 Short-circuit current decrement for a salient pole generator that has a high armature time constant T_a.

7.2.11 Fault Breaking Current

The fault current effects have been described above for the making duty. However, some further points are appropriate for the breaking duty. The breaking duty root-mean-square duty is usually specified to take place after a number of cycles of fault current have passed. (It may also be expressed as a peak value of current, although this is less common.) This is usually taken to be the time given by the manufacturer for the circuit breaker to open and clear the fault. This is typically 5 to 8 cycles of the fundamental current. The engineer should specify the requirements for the particular power system and the manufacturer should then confirm whether the equipment offered could meet the requirement. Each power system should be considered on its own merits in this regard.

Equation (7.2) can be used to calculate the situation at the time given for the breaking duty. Usually the sub-transient time decay term has fallen to zero, and the solution is in the transient period. When an 'external' impedance is present its resistance can be included in the T_a time constant and its reactance added to the appropriate machine reactances. References 5 and 6 explain how the 'derived' reactances and time constants are calculated and affected by the addition of the external impedance.

If the lower envelop of the transient AC part and the DC part of (7.2) are separated out then two functions can be presented as follows. At current zero the critical time t_c in seconds occurs when, $t = t_c$,

$$\frac{I_a}{V_{pk}} = -\left[\left[\frac{1}{X'_d} - \frac{1}{X_d}\right]\exp^{\frac{-t}{T'd}} + \left[\frac{1}{X_d}\right] + \left[\frac{1}{X''_d}\right]\right]\exp^{\frac{-t}{Ta}} \tag{7.3}$$

Let,

$$y_{lhs} = \left[\frac{1}{X'_d} - \frac{1}{X_d}\right] \exp^{\frac{-t}{T'd}} + \left[\frac{1}{X_d}\right] \tag{7.4}$$

and

$$y_{rhs} = \left[\frac{1}{X''_d}\right] \exp^{\frac{-t}{Ta}} \tag{7.5}$$

If these two functions are plotted on a graph which has a common base of time, then they will cross each other at the critical time. Figures 7.2 and 7.3 show critical times for several ranges of values for T'_d, T_a, X''_d and X'_d. The parameter that has the greatest sensitivity is the armature time constants T_a since it moves the crossing point from the left to the right very noticeably. Changes in the value of the sub-transient reactance X''_d move the curves 4 and 8 in (7.5) vertically. The higher the value of X''_d the lower is the critical time. It can be seen that in order to achieve low values of the critical time, or to keep the number of cycles to the first current zero to a low number, it is necessary to have a low value of T_a and a high value of X''_d.

7.2.12 Fault Withstand Duty

So far particular conditions have been considered, initial reaction to the severest fault and what happens at the time of clearing the fault. What happens during the fault is also of importance since

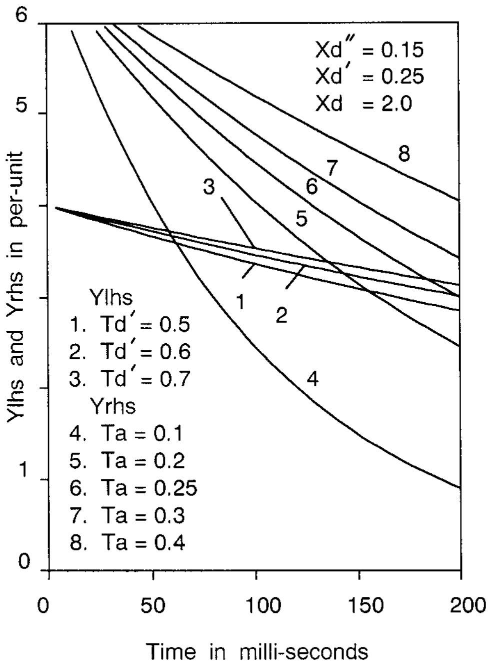

Figure 7.2 Functions pertaining to the calculation of the critical switching time of circuit breaker that disconnects a generator from a switchboard. The generator has low values of sub-transient and transient reactances. The sensitivity of the time constant T_a is shown.

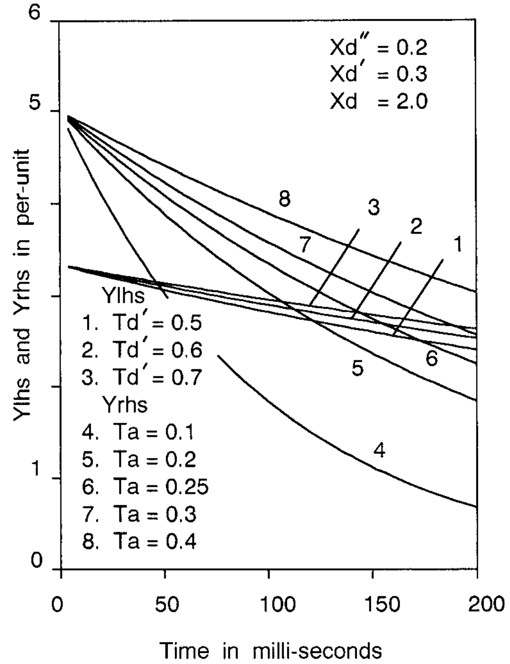

Figure 7.3 Functions pertaining to the calculation of the critical switching time of circuit breaker that disconnects a generator from a switchboard. The generator has high values of sub-transient and transient reactances. The sensitivity of the time constant T_a is shown.

extra heat is generated and the copper conductors are under considerable mechanical stress. In order to account for any cumulative effects it is necessary to rate the equipment for the long duration of a fault. The time duration usually adopted in European practice is one second, but occasional up to three seconds are applied for particularly severe service conditions. IEC60439 part 1, clause 4.3, and IEC60964 clause 4.7 give more details for the root-mean-square and peak values and duty. The withstand current duty is usually proportional to the making duty for a given voltage rating.

7.3 SWITCHING DEVICES

Switching devices for the power circuits that need to be operated frequently are usually circuit breakers and contactors. Manually operated load break switches, fuse-switch combinations and molded case circuit breakers are used for feeder circuits that are infrequently operated.

7.3.1 Outgoing Switching Device for Switchgear

The outgoing switching device in a high current, high fault level, switchboard will usually be a power circuit breaker if it feeds more that about 400 amps to the load. Below 400 amps the circuit could have a fuse-contactor combination, see sub-section 7.3.2 for comments on contactors and Chapter 8 on fuses. Therefore if the outgoing device must be a circuit breaker then the comments and discussion in sub-section 7.2.3 above apply. Low voltage switchboards often use moulded case circuit breakers for incoming and outgoing circuits, and these can be fitted with a variety of auxiliary devices such as motor operators for remote control, padlocks for safe isolation and shunt trip coils for rapid opening under some fault conditions.

7.3.2 Outgoing Switching Device for Motor Control Centres

Motor control centres and some switchboards use contactors as the frequently operated switching device for individual outgoing loads up to about 400 amps. The figure of 400 amps is about the limit of fuse and contactor design capability. See Chapter 8 for a discussion on fuses. Contactors and their accompanying fuses should be used where ever possible because:-

- Much less expensive than a circuit breaker.
- Much smaller and simpler in the construction.
- Heavy faults are cleared faster due to the fast action of the fuses.
- Enables the outgoing cable sizes to be significantly smaller due to the reduced fault clearing time provided by the fuses. Cables are sized for rated running current and fault current withstand when a major fault occurs at the load terminals. See Chapter 9.

Contactors differ from circuit breakers in that they are designed to handle rated running current and very short-term low fault level situations. Contactors cannot withstand the high fault currents. A fuse must be placed in series to interrupt fault currents and sustained overcurrents. This means that the device is physically much more compact than a circuit breaker and hence much less expensive. The fuses and the contactor must be carefully coordinated for fault current let-through capability. European practice often refers to IEC60158 part 1, 60292 part 1, 60947 part 2 and 60632 part 1. IEC60947 part 4, clause 7.2.5.1, applies to low voltage equipment and the coordination should be at least ‘Type 2’. IEC60632 applies similarly to high voltage equipment where the coordination is referred to as ‘Type C’, in clause B4.1 therein. The concept of this coordination is that the contactor may suffer permanent damage if it passes the fault current for too long a period. The less stringent Type 1 for low voltage switchgear requires the contactor or starter to be repaired or replaced after a short circuit has been cleared. Type 2 on the other hand, and Type C for high voltage switchgear, is more stringent and requires these devices to be suitable for further service after passing the short-circuit current. The more stringent situation has the risk of the contacts in the contactor becoming welded together by the heat produced by the short circuit, but this is recognised and deemed acceptable.

Low voltage contactors are simple air-break electromagnetic devices. High voltage contactors are air-break, vacuum or SF6 devices, although air-break is becoming obsolete. Most contactors are closed and held closed by the action of a powerful fast acting electromagnet. Occasionally a mechanically held arrangement is required to safeguard against a loss of supply and the need to maintain power to the load once the supply is restored. This practice often applies to feeders for distribution transformers, where restoration of the secondary supply must not be delayed by manual intervention. In all cases the opening of the contactor is carried out by a powerful spring. With a mechanically held arrangement an auxiliary solenoid is fitted to unlatch the holding mechanism.

Low voltage contactors are usually fitted with purpose-made protection devices for guarding against overloading and single-phase operation. These devices are used individually or in combination and operate on magnetic, thermal or electronic principles. Electronic static devices offer the widest range of time-current characteristics.

High voltage contactors use similar protection devices to those used with high voltage circuit breakers, except that high voltage fast-acting fuses are also connected in series with the contactor. The protection devices tend to be more sophisticated and are usually mounted away from the contactor and fuse assembly, in a relay compartment. Single-phase protection is usually required for high voltage motors. Earth fault protection also tends to be more sophisticated and special current transformers and relays are necessary. See Chapter 12 for details of protection relays and their coordination with each other and with their associated equipment.

7.4 FUSES FOR MOTOR CONTROL CENTRE OUTGOING CIRCUITS

Fuses are chosen to match the normal current of the load. The fuse current rating is always chosen to be higher than the load current by an amount called the 'fusing factor', which is given by:-

$$\text{Fusing factor} = \frac{\text{Fuse rating, in amps}}{\text{Normal load current, in amps}}$$

For low voltage motors the fusing factor is larger for the small motors (less than 15 kW) than it is for the large motors (up to 250 kW). Figure 7.4 shows how the typical fusing factor varies for low voltage motors. The slope and bias of the lines in the figure will be different for each type or 'model' of fuse. For high voltage motors the fusing factor tends to be between 1.5 and 2.5. The characteristics of the fuses vary according to the type of load, e.g. continuous motor load, very intermittent motor load, feeder transformers, static heaters, thyristor controlled loads, power rectifier loads.

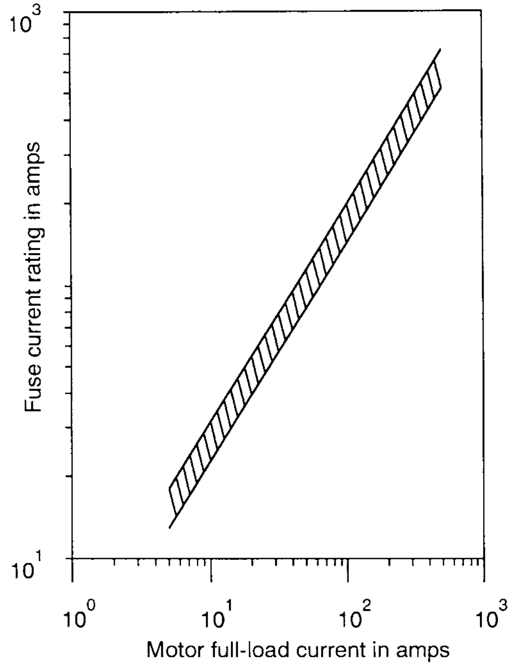

Figure 7.4 Low voltage fusing factor for induction motor circuits.

Fuse manufacturers will usually offer advice on the most appropriate fuses to be used in a particular installation.

7.5 SAFETY INTERLOCKING DEVICES

Most switchboards and motor control centres are fitted with a variety of electrical and mechanical safety interlocking devices. Their purposes are to protect against for example:-

- Withdrawing the switching device while it is carrying load or fault current.
- Prevent the switching mechanism from being inserted when it is in its 'on' state.
- Opening of access doors or panels before setting the switching device in its 'off' state.
- Gaining physical access by human operators while the main conductors and contacts are energised.
- Gaining access to the busbars when the switching devices have been withdrawn.
- To prevent earthing switches from being closed on to live circuits or busbars.
- Incorrect electrical operation of a complex process system in which various external devices, motors, pumps, etc. are intimately related. For example a lubrication oil pump must be running before the main drive motor is started on a pump or compressor.

Most of the above interlocks are mechanical latches, bolts and shutters. The last category is electrical functions using wired relays or electronic logic. Electrical interlocking is also used to ensure that certain closing and tripping functions take place in a particular sequence. The following examples are typical interlocking sequences:-

- Energising a downstream switchboard through a transformer or plain interconnector. The upstream switching device is closed first. The downstream device is then closed. If either trips on fault then the other may be caused to trip by auxiliary circuits and relays.
- 'Two-out-of-three paralleling' is a term used when a switchboard has two parallel feeders. It is the term given to a particular closing scheme applied to the two incoming and the busbar section circuit breaker. The feeders are usually transformers. The purpose of the scheme is to enable a no-break transfer of the feeders to take place, and to minimise the duration of a prospectively high fault level that may exist during the transfer. Auxiliary switches are fitted within the three circuit breakers to determine when all three are closed. As soon as the third circuit breaker is closed the fault level at the busbars will in most cases be too high, and a signal is then given to one of the circuit breakers to trip. A selector switch is sometimes used to choose which of the three will trip. Some installations use a timer relay to delay the automatic tripping action, and the time delay setting is typically 0.5 to 2.0 seconds. This scheme is not used for all dual feeder switchboards, but is common practice with low voltage switchboards.
- Where a situation can arise that two supplies could be switched in parallel, then it is necessary to check that they are in synchronism and come from the same source, e.g. either side of an upstream switchboard. Checking can be arranged in one of two methods, or a combination of both methods. The first method uses auxiliary switches on the upstream circuit breakers, usually the busbar section circuit breakers. These auxiliary switches give a signal that its circuit breaker is open, thereby signalling that an unsynchronised supply will exist at the downstream location. The signal is used to prevent the three downstream circuit breakers being closed all at the same time, i.e. the 'two-out-of-three paralleling' scheme is inhibited from closing its third circuit breaker. The

second method is popular and uses a 'synchronising check' relay (25) to sense the voltage on both sides of a circuit breaker. For the above mentioned dual incomer switchboard all three circuit breakers would be equipped with the synchronising check relays.

7.6 CONTROL AND INDICATION DEVICES

The requirements for control and indication vary considerably depending upon the type of circuit, e.g. incoming, busbar section or outgoing circuit, whether the equipment is a switchboard or a motor control centre, high or low voltage, process duty, the need for remote indication and control, and owner preferences. Table 7.2 gives typical minimum requirements for switchboard and motor control centre incoming, busbar section and outgoing circuits, but at the equipment and not including remote devices or recording instruments.

Some of these devices may be mounted on a local panel in the switchroom so as to avoid a human operator having to stand in front of a live cubicle to operate the open and close controls.

A modern plant requires more information, events and alarms to be made available at the main control room than was generally the case in the past. This has been made much easier to achieve by the use of computer networking and fibre optical technology. Most of the information that is available at the switchboard can be transferred to the main control room; so that, for example, a one-line diagram presentation can be made on a computer desk-top monitor (man-machine interface, MMI).

7.6.1 Restarting and Reaccelerating of Motors

During the normal operation of a power system there are occasions when the voltage profile of the whole system or just a part of it is lowered for a short period of time. This drop in voltage may be due to:-

Table 7.2. Control and indication devices

Device	Generator incoming	Transformer incoming	Busbar section	Motor outgoing	Transformer outgoing
Stop (open) button	Yes	Yes	Yes	Yes	Yes
Start (close) button	Yes	Yes	Yes	Yes	Yes
Note 2					
One ammeter	No	Yes	Yes	Yes	Yes
Three ammeter or a selector switch	Yes	Note 1	Note 1	No	Note 1
One voltmeter with or without a selector switch	Yes	Yes	Note 3	No	No
One wattmeter	Yes	Yes	No	Note 4	Note 1
One varmeter	Yes	Note 1	No	No	No
One power factor meter	Yes	Note 1	No	No	Note 1
One frequency meter	Note 1	Note 1	No	No	No
Synchronising devices	Yes	Note 1	Note 1	No	Note 1

Note 1: Optional, may be necessary.
Note 2: Some oil companies are not in favor of having a human operator standing in front of a high voltage switchboard to manually close the switching device.
Note 3: One voltmeter for each side of the switchboard busbars.
Note 4: Occasionally used for high voltage motors and variable speed drives.

- Starting a large motor.
- Occurrence and clearance of a fault.
- Malfunction of an automatic voltage regulator of a generator.
- Lightning surge from an overhead line.

In general motors are specified to be able to reaccelerate or restart their loads from a constant voltage that is 80% of its nominal value, assuming that it does not recover during these operations. This voltage should be that appearing at the terminals of the motor. For motors that are located at the end of short cables, the volt-drop in the cables may be neglected. Volt-drop in long cables may be high enough to aggravate the reacceleration or starting process, even to the extent that these operations cannot be completed.

If high voltage motors and transformers are switched by contactors that derive their coil voltage from the switchboard busbars, then the contactor coil may not hold in when the busbar voltage drops below a particular value. It is better practice to derive the coil voltage from a reliable source such as an uninterruptible power supply (UPS) or a battery. Switchboards are often provided with undervoltage (27) relays to trip predetermined loads when the busbar voltage falls below a certain limit for a preset length of time. The loads may be tripped individually or in groups. If group tripping is used then the motors in the group should be related to a particular process rather than being chosen by their kW rating or some other criterion.

The scheduling of the restarting of individual motors or groups of motors should be progressive so that a large surge of reactive power is avoided. Each oil company tends to have its own philosophy for restarting and reaccelerating motors, and schemes can become complicated to understand. The introduction of micro-computers has enabled almost any philosophy to be implemented.

If a severe disturbance occurs that causes the voltage to drop well below 80% then the duration should be relatively short, e.g. 0.15 second, otherwise recovery may be difficult. If a complete loss of voltage occurs then even progressive restarting in an automatic manner may prove difficult if the loss exceeds about 3 seconds.

7.6.2 Micro-computer Based Systems

Modern switchgear is available with micro-computer based intelligence and network communication facilities. These facilities enable much more information to be managed, manipulated and displayed than was possible in the past, when only analog devices were available. Modern practice for most major projects is to ensure that the network communication precisely matches that of other facilities within the plant. System control and data acquisition (SCADA) systems and distributed control systems (DCS) were developed in the industrial process control industries long before micro-computers became available for switchgear. In recent years there has been some convergence of approach between the more traditional SCADA and DCS network languages and protocols and those of the electrical power industries. Consequently it is now much easier to specify fully compatible process and electrical network systems.

Within switchgear the approach to control, indication and protection has changed. These functions are no longer separate entities. They are combined into micro-computer based electronic relay modules. A module is used for each incoming, busbar section and outgoing unit, that is capable of measuring currents, voltages, status of switching devices, interfacing with external interlocks. They are also capable of carrying out relatively simple calculations such as active power, reactive power and power factor of the circuit, number of attempted starts for a motor.

Transmission of information between switchboards and to other locations such as a control room can be achieved by either optical fibre or 'hard wire' cables. Suitable interfaces are placed at each end of the cables. As with many aspects of computing the speed of data transmission, method of porting, the protocols available, memory capacity and speed of calculation are upgraded, improved and superseded almost on a yearly basis. It is therefore necessary to be well aware of 'the state of the art' in these subjects so that a system that is about to be superseded is not purchased.

The following description of integrated motor control systems (IMCS) is based upon Reference 7, for which permission to use the material therein was kindly given by Switchgear and Instrumentation Ltd. The principles described can be used for low and high voltage switchgear that contain plain feeders, interconnectors, incomers and busbar section circuit breakers, in addition to motor feeders.

Four main units are used in the IMCS, which are the motor control unit (MCU), the feeder control unit (FCU), the circuit breaker control unit (CBCU) and the central control unit (CCU). A MCU is a microprocessor (micro-computer) based module which has integrated control, monitoring, protection functions, and a communication interface for the motor starter. An FCU is very similar to a MCU and interfaces communication for the plain feeder contactor or circuit breaker. A CBCU is also similar to a MCU but is used for incomers, interconnectors and busbar section circuit breakers. A CCU provides the facility to communicate simultaneously with MCUs, FCUs, CBCU, a distributed control system (DCS), system control and data acquisition (SCADA) and other digital information systems. Other discrete devices such as special protective relays can also be addressed by the CCU provided the software and porting systems are compatible.

Serial communication network equipment is used to couple all the microprocessor based units. Figure 7.5 shows the basic arrangement of a typical system. The number of switchboards and motor

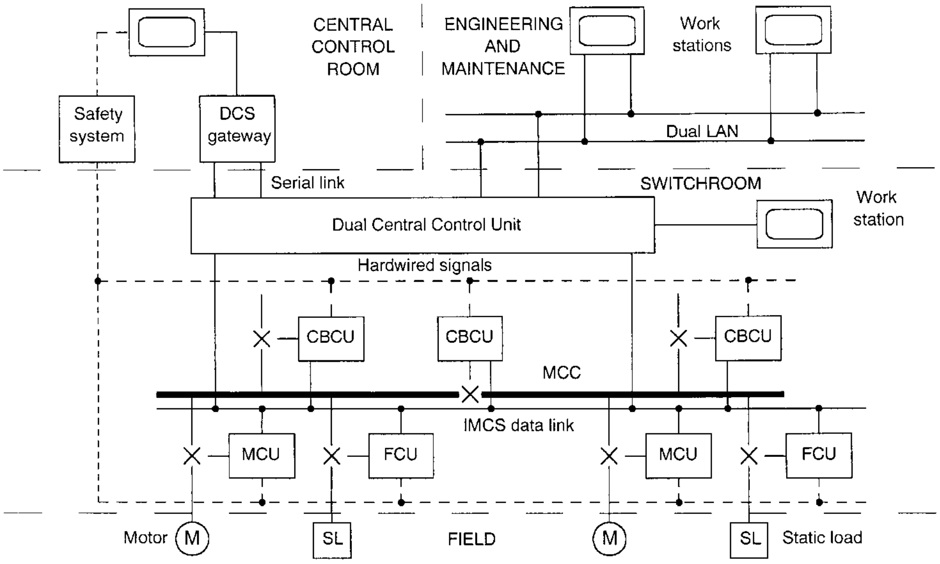

Figure 7.5 Intelligent motor control centre.

control centres can be increased to cater for a large plant. A typical IMCS should include at least the following components:-

- Each outgoing motor or plain feeder unit requires a MCU or a FCU.
- Each incoming interconnector and busbar circuit breaker also requires a FCU.
- A CCU should be provided for either, a complete switchboard, a group of switchboards, or all switchboards located in a switchroom. A dual redundant system may be chosen so as to raise the system reliability and availability.
- Interfacing equipment and software to communicate with a DCS and a SCADA system, if they exist.
- A local area network (LAN) to couple all the units within the IMCS, which should not be a shared system such as the DCS.
- Various sources of uninterruptible power will be required, if the plant is spread over a large site. These will provide the essential power to the IMCS processing units when other less reliable power supplies interrupt or fail.
- Protection circuits and devices to render the system immune from electromagnetic interference.

In switchboards that supply motors the protection, control and measurement functions will be the most varied for the motor circuits. Generator incomers would be the next lower in complexity. The following functions are typical of all but the lowest ratings of motors:-

- Motor current.
- Motor overload protection, settings, status, pre-alarms and time to trip.
- Unbalanced loading, settings, status and pre-alarms.
- Earth fault protection, settings, status, alarms.
- Thermal status information including inhibition of starting.
- Stalling protection, settings and status.
- Acceleration time.
- Automatic restarting information due to voltage drop at the busbars.
- Total operating time of the motor.
- Operating time since the last start command.
- Non-operating time since the last stop command.
- Number of operations of the contactor.
- Local stop command function, i.e. a push button or key.
- Manual resetting of all trips and alarms.
- Remote resetting of certain trip and alarm functions by using a password.
- Facilities to allow external hard-wired circuits, such as interlocks, to be monitored and used by the IMCS.
- Underpower protection of the motor and its driven equipment.
- Undervoltage tripping facilities for mechanically latched contactors.
- Historical event logging for all alarms, trips, commands and inhibiting of starting.
- Trend records should be stored for a predetermined period such as six weeks.

A similar set of functions are typical for plain feeder, incomer, interconnector and busbar circuit breakers:-

- Circuit current.
- Circuit voltage.
- Circuit power factor (optional).
- Circuit active power (optional).
- Circuit reactive power (optional).
- Open-close status of the switching device.
- Unbalanced loading, settings, status and pre-alarms (optional).
- Protective device performance information, settings and status.
- Manual resetting of all trips and alarms.
- Remote resetting of certain trip and alarm functions by using a password.
- Facilities to allow external hard-wired circuits, such as interlocks, to be monitored and used by the IMCS.
- Undervoltage tripping facilities for mechanically latched contactors.
- Historical event logging for all alarms, trips, commands and inhibiting of starting.
- Trend records should be stored for a predetermined period such as six weeks.

Indicative information such as running current should be displayed at the unit or starter itself, as well as being accessible at a console or visual display unit in a remote location.

Process control systems traditionally use an analog signal of 4 to 20 mA DC and so it is recommended that such signals should be interfaced with the MCUs by use of compatible high-speed analog-to-digital converters.

The IMCS will scan all the MCUs, FCUs and CBCUs on a continuous basis with a complete cycle time in the order of 0.5 second, regardless of the number of units in the system. Priority interrupting functions should be used for protective relaying functions, interlocking and safety related signals, where rapid action is necessary.

7.7 MOULDED CASE CIRCUIT BREAKERS

7.7.1 Comparison with Fuses

Low voltage switchgear incorporate circuit breakers and contactors as its main power switching and control devices, particularly for the outgoing plain and motor feeder circuits. The international standards that are often used for moulded case circuit breakers are, IEC60157 part 1 and IEC60292 part 1 which have been incorporated into IEC60947. IEC60947 parts 1, 2, 3 and 4 are for power circuit breakers, switches and contactors. In addition the international standards ANSI-C37.13, NEMA-SG3, NEMA-AB1 and VDE 0660 are regularly applied.

Circuit breakers are invariably used for the incomer, busbar section and switchboard interconnector switching devices, because the currents that they need to switch are too high for contactors to handle properly. Outgoing circuits can be static loads or motor loads, and these are usually limited to about 300 A to 400 A of line current. Such currents can be easily handled by a fuse-contactor combination or a moulded case circuit breaker. The lowest three-phase ratings are about 16 A. Historically systems that were designed on UK practice tended to favour fuse-contactor technology, whereas those based on European and American practices favoured a combination of a moulded case circuit breaker and a contactor. Both technologies have their own advantages and disadvantages. Reference 7 compares fuses and moulded case circuit breakers, as well as miniature circuit breakers for final sub-circuit applications. Fuses are simple, fast acting, economical and almost completely free of maintenance. They tend to enable smaller conductor sizes of cables to be used. On the other hand circuit breakers can be immediately reset after a fault has been investigated and removed, they require less spare units to be stored in a storeroom. Some types of moulded case circuit breakers have adjustable characteristics and one frame size can house many different ratings. Historically moulded case circuit breakers were placed downstream of current limiting fuses because they could not withstand high prospective fault currents that began to develop in power systems. Nowadays this problem seldom exists because of the advances made in the technology.

7.7.2 Operating Characteristics

Moulded case circuit breakers are available in two basic modes of operation, current limiting and non-current limiting. It is difficult to design a moulded case circuit breaker to have a cut-off characteristic that is less than 0.01 second when a fully asymmetrical short-circuit current flows. However, there are such circuit breakers available, and care is needed when selecting these devices for a circuit that has a high prospective fault current. Some manufacturers are able to provide a cut-off in the order of 0.006 second.

The protection characteristic of moulded case circuit breakers is divided into two main parts, a long time ($<$t) part and a short time ($\ll$t) part. The long time part provides overload protection and is created by a thermal bi-metal strip mechanism and a mechanical latch. This part functions when the current is in the range of 105% and 1000% of the rated current. In some designs, and those with ratings above about 250 A, the upper limit is adjustable between 500% and 1000%. These adjustments are made to the second part of the protection characteristic. This part ($\ll$t) is created by a magnetic repulsion mechanism or an electromagnet that is very fast acting once the fault current exceeds the set value. The fast action does, however, have a limit to the time that is taken, and is usually in the range of 0.003 second and 0.01 second. The lower value occurs at very high currents, e.g. 200 times the rated current.

Moulded case circuit breakers are also available for incoming and busbar section purposes, with ratings up to 6000 A and service voltages between 220 V and 660 V. (At 415 V a 4000 A circuit breaker would satisfy the duty of a 2500 kVA feeder transformer with about 15% spare capacity.) These are also available as 4-pole units. Circuit breakers having ratings of 800 A and above are often provided with several adjustments that widely modify the shape of the complete protection curve, as described in Chapter 12. This enables the curve to coordinate with almost any other protective device or equipment that is immediately upstream or downstream of the circuit breaker. Some circuit breakers with the higher rated currents are also provided with integral earth fault protection facilities.

Various external attachments can be fitted to moulded case circuit breakers, e.g. pad-locking tabs, shunt trip coils, hazardous area enclosure with an ‘on’ and ‘off’ operating handle, withdrawable rack mountings, undervoltage tripping units, auxiliary switches of the normally open and normally closed types, interlocking devices, ambient temperature compensation for the protection curves. Some models are provided with a comprehensive solid-state module for creating the protection functions such as, long time delay, short time delay, instantaneous tripping, earth fault detection and alarm messages. The solid-state module may be self-powered or will require an external voltage source from a UPS.

7.7.3 Cut-off Current versus Prospective Current

Fuses and moulded case circuit breakers that have cut-off characteristics have similar shaped curves for cut-off current plotted against the prospective current. For a fuse the cut-off current is the value of current at the end of the melting process of the fuse element, and at the beginning of the arc that is then created. For a moulded case circuit breaker it is the current that exists when enough energy has developed to force apart the power contacts, and again the value at the beginning of the arc. The cut-off current is the highest value of instantaneous current that passes through the fuse or circuit breaker. It is also called the 'peak let-through' current. This current is shown on the y-axis of the graph. The x-axis is the root-mean-square value of the fault current that is available in the actual circuit, and is usually taken to be the symmetrical value before any 'doubling' factor is included.

The graphs are plotted in two parts. The first part is a straight line that occupies all of the graphical area available, and is the line for the peak value of the asymmetrical current available against the symmetrical fault current available. The relationship between these variables is simply the appropriate 'doubling' factor, which can be found from the manufacturer's curves to be typically in the range of 2.1 and 2.4 per unit. The second part is a set of curves or lines of lower slope that apply to all the fuses or circuit breakers in the manufacturer's range of products. Each one of these lines intersects the single prospective line, at a point which represents the current that corresponds to melting a fuse or parting the contacts of a circuit breaker when the instantaneous current is at its peak value in the first half-cycle. This point is called the 'threshold current' in some of the literature, see Reference 8. At this point no cut-off occurs. Thereafter for higher symmetrical fault currents the particular rated device will experience an amount of cut-off, the higher the fault current the more the cut-off will occur. Theoretically the set of lines for the devices will be curved when plotted on a log-log scale, but in practice manufacturers may approximate these by straight lines. Figure 7.6 shows the characteristic for one fuse and one moulded case circuit breaker, each rated at 40 A for protecting an induction motor. The location of the device lines or curves in the vertical plane will vary considerably with different manufacturers and functions, such as motor feeders, heavy duty or light duty. In general they will be parallel lines or curves for a particular type of device, i.e. one type with many different ratings in the range of product.

7.7.4 *I*-squared-*t* Characteristic

When fuses or moulded case circuit breakers are applied to a circuit it is necessary to ensure that their *I*-squared-*t* characteristics coordinate properly with the thermal capabilities of the downstream equipment, especially the cables. In order to determine the *I*-squared-*t* characteristics of a protective device it is assumed that the current in the device suddenly changes from a normal load value to the fault value in a very short period of time, i.e. similar to a step change in a control system. Hence for each value of current along the x-axis of the device's time-current characteristic the value of the current squared multiplied by the corresponding time can be plotted. For cables and busbars the *I*-squared-*t* function equals a constant (k) for each cross-sectional area of conductor, as explained

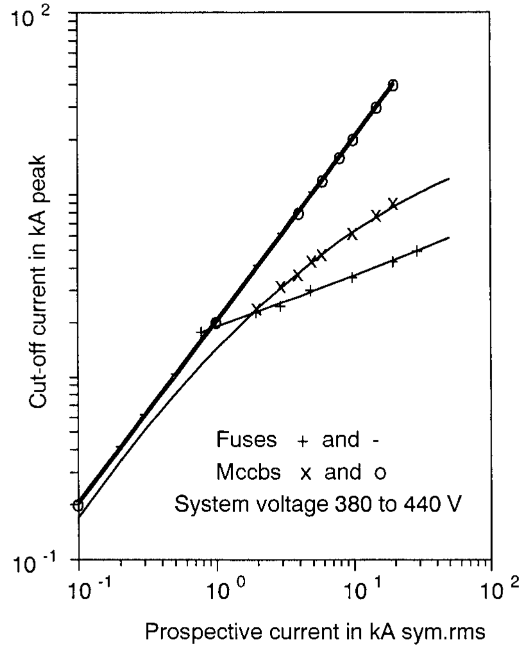

Figure 7.6 Cut-off and prospective current curves for a 40 A fuse and a 40 A moulded case circuit breaker.

in Chapter 9. For EPR and XLPE insulated cables with copper conductors the value of k is usually taken as 143 or 144.

Fuses or moulded case circuit breakers have known current-time functions and for practical purposes these functions can be simply converted into their I-squared-t characteristics by using the above method on as many sample points as can be conveniently transcribed. Figures 7.7 and 7.8 show the I-t and the corresponding derived I-squared-t characteristics for 32 A and 125 A fuses, 32 A and 125 A moulded case circuit breakers, and appropriate cables for the circuit.

7.7.5 Complete and Partial Coordination of Cascaded Circuit Breakers

Where moulded case circuit breakers are chosen for a plant in favour of fuses the coordination of cascaded units becomes a little more difficult than with fuses. This difficulty arises from the fact that these circuit breakers have a definite or ‘near definite’ minimum time limit to their time-current characteristic. This causes the lower part of the circuit breaker protection curve to be almost horizontal at a low value of time, typically in the range of 0.003 and 0.01 second.

If a particular type or model is chosen from a manufacturer it can be seen that this low horizontal part may be similar or the same for all ratings of circuit breakers within the range. Supposing a 2:1 or 3:1 ratio of upstream rating to downstream rating is chosen for a particular circuit. Selective tripping of the downstream unit can only be relied upon for fault currents beyond the magnetic vertical part of the curve for the downstream unit, but less than the vertical part of the upstream unit. For faults beyond the vertical part of the upstream unit there will be a race between both units and the upstream unit may trip before the downstream unit. This is not a satisfactory

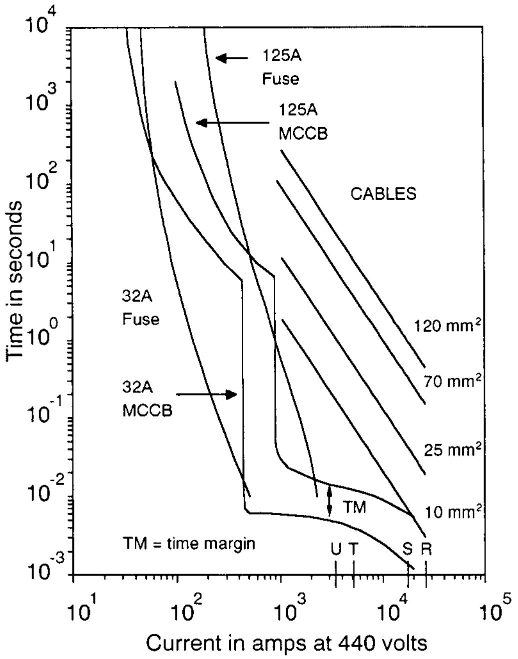

Figure 7.7 Clearing time versus fault current for fuses and moulded case circuit breaker curves.

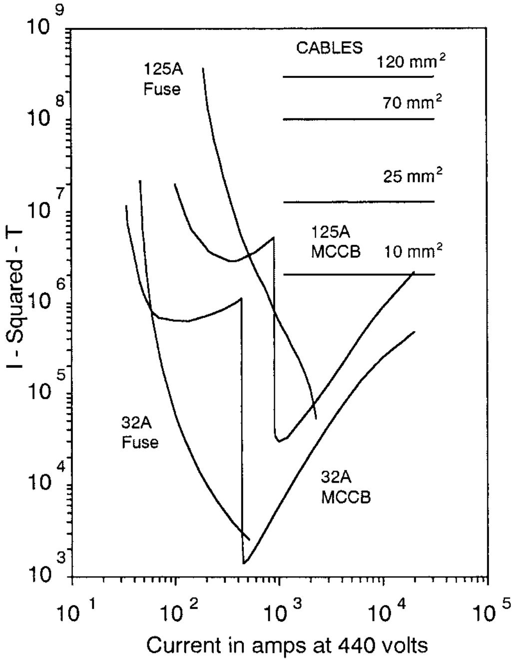

Figure 7.8 *I*-squared-*t* versus fault current for fuses and moulded case circuit breaker curves.

situation and is called ‘partial coordination’. What is called ‘complete coordination’ is obtained by ensuring that the horizontal part of the upstream curve is located above that of the downstream unit by a suitable time margin. This may not be easily obtained and it may be necessary to use different types or even models from different manufacturers to create a sufficient time margin. If the ratio of upstream to downstream rating is greater than about 3:1 and the upstream unit has an adjustable short-time delay then the difficulty can be overcome by suitable adjustments. This can be seen in Figure 7.7 by comparing the curves of the 32 A and 125 A circuit breakers.

7.7.6 Worked Example for Coordination of Cascaded Circuit Breakers

A 440 V 60 Hz switchboard feeds a 4-wire distribution board for small loads such as socket outlets. The switchboard has a fault making capacity of 100 kA rms. After applying diversity factors to the loads the total load current is 90 A. Moulded case circuit breakers (MCCBs) rated at 16 A and 32 A are to be used for the loads. The installation will use cables having copper conductors and XLPE insulation. The cable from the switchboard to the distribution board is 20 metres in length. A typical load cable is 15 metres in length and will carry a current of 29 A at a power factor of 0.85 lagging. Ignore the presence of induction motors at the switchboard. Find the following:-

- Rating of the incoming circuit breaker.
- Size of the incoming cable.
- Size of the load cable.
- Check that the MCCB coordination is complete.

The following sequence will be used to calculate the results:-

- Choose the upstream MCCB at the switchboard and its settings.
- Choose the incoming feeder cable.
- Choose the downstream load MCCB and its settings.
- Find the upstream fault source impedance.
- Find the cut-off, or let-through, current from the switchboard.
- Find the impedance of the incoming cable.
- Find the impedance of the load cable.
- Find the fault current at the distribution board, point B.
- Find the fault current at the beginning of the load cable, point C.
- Find the fault current at the end of the load cable, point D.
- Check the peak making capacity and peak let-through capacity of the MCCBs chosen above.
- Find the highest I-squared-t value for the upstream MCCB.
- Calculate a suitable size for the load cable to satisfy the I-squared-t duty.
- Calculate the volt-drop in the load cable.
- Select the largest conductor size from the above calculations.
- Plot the results.

Solution:

a) Choose the upstream MCCB at the switchboard and its settings.

From a manufacturer's data sheet a 125 A MCCB with an adjustable 100 A thermal release is chosen. The thermal release is set to 90 A to match the total load.

b) Choose the incoming feeder cable.

From a manufacturer's data sheet several cables can be compared for the same ambient conditions and laying arrangements. Their details are:-

$$50 \text{ mm}^2\text{cable, maximum current } 124\ A,\ R = 0.492,\ X = 0.110 \text{ ohms/km.}$$

$$70 \text{ mm}^2\text{cable, maximum current } 159\ A,\ R = 0.340,\ X = 0.106 \text{ ohms/km.}$$

$$95 \text{ mm}^2\text{cable, maximum current } 193\ A,\ R = 0.247,\ X = 0.093 \text{ ohms/km.}$$

The 70 mm^2 cable is chosen since the rating of the 50 mm^2 cable is just too low.

c) Choose the downstream load MCCB and its settings.

From a manufacturer's data sheet a 32 A MCCB with an adjustable 32 A thermal release is chosen. The thermal release is set to 29 A to match its load.

d) Find the upstream fault source impedance.

For a prospective symmetrical fault current of 100 kA rms the upstream fault source impedance Z_{up} is:-

$$Z_{up} = \frac{440.0}{1.732 \times 100000.0} = 0.0 + j\ 0.00254 \text{ ohms}$$

e) Find the cut-off, or let-through, current from the switchboard.

From a manufacturer's data sheet a 125 A MCCB has a let-through current I_p of 25 kA_{peak} for a prospective fault current I_s of 100 kA_{rms}.

f) Find the impedance of the incoming cable.

The impedance Z_{c1} of the incoming cable is:-

$$Z_{c1} = \frac{25.0(0.340 + j\ 0.106)}{1000.0} = 0.0085 + j\ 0.00265 \text{ ohms}$$

g) Find the impedance of the load cable.

The impedance Z_{c2} of the incoming cable is:-

From a manufacturer's data sheet several cables can be compared for the same ambient conditions and laying arrangements. Their details are:-

$$6 \text{ mm}^2 \text{ cable, maximum current } 33.8\ A,\ \ R = 3.91,\ \ X = 0.130 \text{ ohms/km.}$$

$$10 \text{ mm}^2 \text{ cable, maximum current } 46.7\ A,\ \ R = 2.31,\ \ X = 0.126 \text{ ohms/km.}$$

The 6 mm^2 cable is chosen provisionally, since its rating is above the 32 A rating of the MCCB that feeds it. The impedance Z_{c2} of the load cable is:-

$$Z_{c2} = \frac{15.0(3.91 + j\ 0.13)}{1000.0} = 0.0587 + j\ 0.00195 \text{ ohms}$$

h) Find the fault current at the distribution board, point B.

From a manufacturer's data sheet the contact impedance data for low voltage MCCBs are:-

MCCB Rating in amps	Resistance in ohms	Reactance in ohms at 60 Hz
16	0.01	neglect
20	0.008	neglect
25	0.0065	neglect
32	0.005	0.000009
50	0.0027	0.000016
63	0.002	0.000025
80	0.0014	0.000042
100	0.0011	0.00007
125	0.0008	0.0001
160	0.00055	0.00015
200	0.0004	0.0002
250	0.00029	0.00027
320	0.0002	0.0004

Hence the upstream MCCB impedance Z_{m1} is $0.0008 + \text{j}\ 0.0001$ ohms.

Therefore the fault impedance Z_{fb} is:-

$$Z_{fb} = Z_{c1} + Z_{m1} = 0.00093 + j\ 0.00275 \text{ ohms}$$

The fault making current I_{fb} is:-

$$I_{fb} = \frac{V_p}{Z_{fb}} = \frac{440.0}{1.732(0.0093 + j\ 0.00275)} = 26{,}195 A_{\text{rms}}$$

Where V_p is the line-to-neutral voltage. Locate the point R for 26,195 A on the prospective curve in Figure 7.9.

i) Find the fault current at the beginning of the load cable, point C.

Hence the downstream MCCB impedance Z_{m2} is $0.005 + j0.000009$ ohms. Add this to Z_{fb} to give the fault impedance Z_{fc} as:-

$$\begin{aligned} Z_{fc} = Z_{fb} + Z_{m2} &= 0.00093 + j\ 0.00275 + 0.005 + j\ 0.000009 \\ &= 0.0143 + j\ 0.002759 \text{ ohms} \end{aligned}$$

The fault making current I_{fc} is:-

$$I_{fc} = \frac{V_p}{Z_{fc}} = \frac{440.0}{1.732(0.0143 + j\ 0.02759)} = 17{,}443 A_{\text{rms}}$$

Locate the point S for 17,443 A on the prospective curve in Figure 7.9.

j) Find the fault current at the end of the load cable, point D.

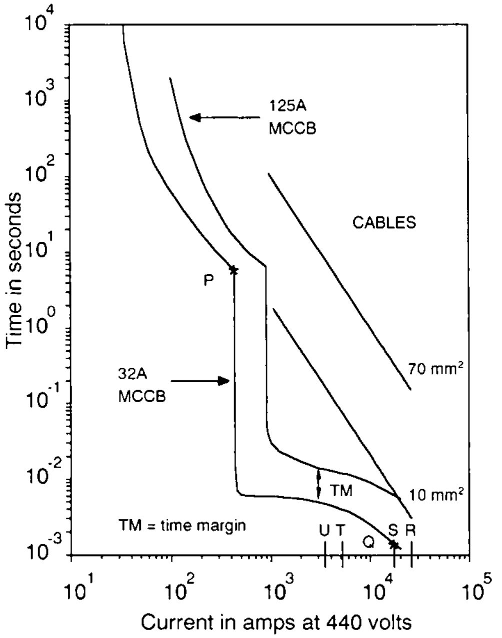

Figure 7.9 Coordination of MCCBs at a distribution board.

Add Z_{c2} to Z_{fc} to give the fault impedance Z_{fd} as:-

$$Z_{fd} = Z_{fc} + Z_{c2} = 0.0143 + j\ 0.002759 + 0.0587 + j\ 0.00195$$
$$= 0.073 + j\ 0.00471 \text{ ohms}$$

The fault making current I_{fd} is:-

$$I_{fd} = \frac{V_p}{Z_{fd}} = \frac{440.0}{1.732(0.073 + j\ 0.00471)} = 3473 A_{\text{rms}}$$

Locate the point U for 3473 A on the prospective curve in Figure 7.9.

k) Check the peak making capacity and peak let-through capacity of the MCCBs chosen above. The following manufacturer's data are typical for 125 A and 32 A MCCBs:-

MCCB rating	Making capacity		Let-through capacity kA_{peak} (cut-off)
	kA_{rms}	kA_{peak}	
		Note 1	
32 A	95	209	6.0
125 A	132	290	25.0

Note 1: Approximate values of the doubling factor taken to be 2.2.

Hence the peak making capacity of the 32 A MCCB is well in excess of the let-through peak current of the 125 A MCCB.

l) Find the highest I-squared-t value for the upstream MCCB.

Locate two points P and Q on the curve of the upstream MCCB as follows,

Point	Current in p.u.	Current in amps	Time in Seconds	I^2t
P	14	406	6	989016.0
Q	602	17,450	0.0016	487204.0

Hence I^2t at P exceeds that at Q.

m) Calculate a suitable size for the load cable to satisfy the I-squared-t duty.

For XLPE cables the 'k factor' for the I-squared-t is 143. The cross-sectional area A is:-

$$A = \frac{(I^2t)^{0.5}}{K} = \frac{(9{,}89{,}016)^{0.5}}{143} = 7.42 \text{ mm}^2$$

The next standard cross-sectional area is 10 mm^2.

n) Calculate the volt-drop in the load cable.

The usual limit to volt-drop in three-phase cables feeding static loads is 2.5% at full load.

$$\text{Volt-drop} = \frac{1.732 \times I_{\text{flc}} \times L(R\cos\phi + X\sin\phi)}{1000}$$

Where, $I_{flc} = 29$ A, L = 15 m and $\phi = 54.5495$ degrees.

For a 6 mm^2 cable the volt-drop is found to be:-

$$\text{Volt-drop} = \frac{1.732 \times 29.0 \times 15.0(3.91 \times \cos 54.5495 + 0.13 \times \sin 54.5495)}{1000}$$
$$= 2.504 + 0.0516 = 2.6 \text{ volts or } 0.58\% \text{ of } 440 \text{ V}$$

which is well within the limit of 2.5%.

o) Select the largest conductor size from the above calculations.

Comparing the conductor sizes found in m) and n) gives the larger as 10 mm^2, and this size should be used.

p) Revise the calculation of the fault current I_{fd}

The impedance Z_{c2} of the load cable is:-

$$Z_{c2} = \frac{15.0(2.31 + j\ 0.128)}{1000.0} = 0.0347 + j\ 0.00192 \text{ ohms}$$

Add Z_{c2} to Z_{fc} to give the fault impedance Z_{fd} as:-

$$Z_{fd} = Z_{fc} + Z_{c2} = 0.0143 + j\ 0.002759 + 0.0347 + j\ 0.00192$$
$$= 0.049 + j\ 0.00468 \text{ ohms}$$

The fault making current I_{fd} is:-

$$I_{fd} = \frac{V_p}{Z_{fd}} = \frac{440.0}{1.732(0.049 + j\ 0.00468)} = 5161 A_{\text{rms}}$$

Locate the point T for 5161 A on the prospective curve in Figure 7.9.

q) Plot the results.

The results are plotted in Figure 7.9.

7.7.7 Cost and Economics

A proper cost and economic analysis can only be made after all the invited manufacturers have fully complied with the details of the enquiry specification. The engineer must satisfy himself that this requirement has been properly met, otherwise a low bid price may indicate non-compliance or poor understanding of the enquiry specification. Apart from the important technical requirements there are often other engineering considerations that should be taken into account, e.g. vendor documentation, spare parts, delivery schedule, obsolescence, testing and inspection. Some of these aspects have a definite cost impact whereas some are somewhat intangible, e.g. history of performance, delivery schedule, obsolescence.

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8

Fuses

8.1 GENERAL COMMENTS

Fuses are used when it is possible to use a simple and economic method of protection against overcurrents and faults. They are fast to act when a major fault occurs and are very reliable.

The characteristics of fuses vary widely depending upon the application for example:-

- Distribution feeders to transformers.
- Induction motors.
- AC and DC services.
- Rectifier and thyristor circuits.
- Static load service, such as heaters.
- High voltage and low voltage services.

The terminology and standards vary considerably between countries. Typical international standard codes are:-

•	Europe.	IEC60282 and 60644 for high voltage fuses IEC60269 for low voltage fuses.
•	USA.	UL 248-1/CSA-C22.2 (15 parts)

Reference 1 gives a description of the standards used in the USA as well as a theoretical treatment of the subject.

Reference 2 gives a comprehensive description of most aspects of fuses including mathematical models together with comments on European and US practice. It also contains a full listing of the most useful IEC standards in its Chapter 8. See also Reference 3 article 110, sub-section 10, for applications where the rated voltages are up to 600 volts.

The melting process of a fuse is a complicated subject. However, for the practising electrical engineer in the design and application side of the industry it is usually only necessary to be familiar with some of the basic characteristics of fuses. Fuse manufacturers are able to vary the shape and steepness of the characteristics by carefully designing the shape of the fuse element, by surrounding the element with different heat removing media and by selecting different fusable metals and alloys. The main parameters concerning an application are,

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- Rated voltage.
- Rated current.
- Rated frequency.
- AC and DC service and type of load current.
- Time versus current characteristic.
- Time versus I^2t characteristic.
- Rated breaking capacity.
- Rated power dissipation of the fuse.
- Cut-off current in AC service.
- Pre-arcing and arcing times.
- Dimensions.

8.2 OPERATION OF A FUSE

The operating sequence of a fuse is:-

1. The fuse element heats up and finally melts.
2. As soon as melting occurs a gap is formed at one or more points along the element.
3. An arc is then established across each gap.
4. The heat of the arc further melts the ends of the elements at each gap and so the gap is increased.
5. Hence the arc length increases and the arc becomes weaker. A point is reached when the arc becomes unstable and cannot be maintained.
6. The arc is extinguished and the circuit is isolated by the fuse.

8.3 INFLUENCE OF THE CIRCUIT X-TO-R RATIO

The following discussion will only relate to AC circuits. Fuses are used mainly to interrupt large fault currents and so the discussions will concentrate on short circuits. Fuses can operate within a quarter of a cycle and so it is often the case that the short-circuit current is asymmetrical, see sub-section 7.2.7.

All circuits which contain inductive reactance and resistance have an X-to-R ratio, in practice between 2.0 and 100.00. In short-circuit analysis it is usually necessary to relate the asymmetrical current to the symmetrical current. This can only be done if the short-circuit power factor of the circuit and hence the X-to-R ratio is known. Table 8.1 shows the relationship between these parameters and currents. Normally the short-circuit power factor is low, between 0.01 and 0.45. It is customary in short-circuit analysis to assume that one of the phases has the worst-case situation of fully asymmetrical current. Figure 8.1 shows an example, together with the various definitions of times and currents.

The fuse will operate during the first half-cycle if it is properly selected. As the current increases the fuse element melts and eventually the melting causes the circuit to become interrupted. During melting the period is called the ‘melting time’ (US terminology) or ‘pre-arcing time’ (UK terminology). After the melting time an arc is maintained for a short period called the ‘arcing time’. If the fuse failed to operate, or was not included in the circuit, the current would continue to rise to

Table 8.1. Characteristic currents that are related to the X-to-R ratio of a circuit

		Ratio to rms symmetrical current		
Short circuit X-to-R ratio	Short circuit power factor	Max 1-phase peak current	Max 1-phase rms current at 1/2 cycle	Avg 3-phase rms current at 1/2 cycle
Infinity	0.0	2.828	1.732	1.394
100	0.01	2.785	1.696	1.374
49.993	0.02	2.743	1.665	1.355
33.322	0.03	2.702	1.630	1.336
24.979	0.04	2.663	1.598	1.318
19.974	0.05	2.625	1.568	1.301
9.9501	0.1	2.455	1.436	1.229
6.5912	0.15	2.309	1.330	1.171
4.8990	0.2	2.183	1.247	1.127
3.1798	0.3	1.978	1.130	1.066
2.2913	0.4	1.819	1.062	1.031
1.7321	0.5	1.694	1.026	1.013
1.3333	0.6	1.594	1.009	1.004
1.0202	0.7	1.517	1.002	1.001
0.75	0.8	1.460	1.0002	1.00005
0.6198	0.85	1.439	1.00004	1.00002
Zero	1.0	1.414	1.0	1.0

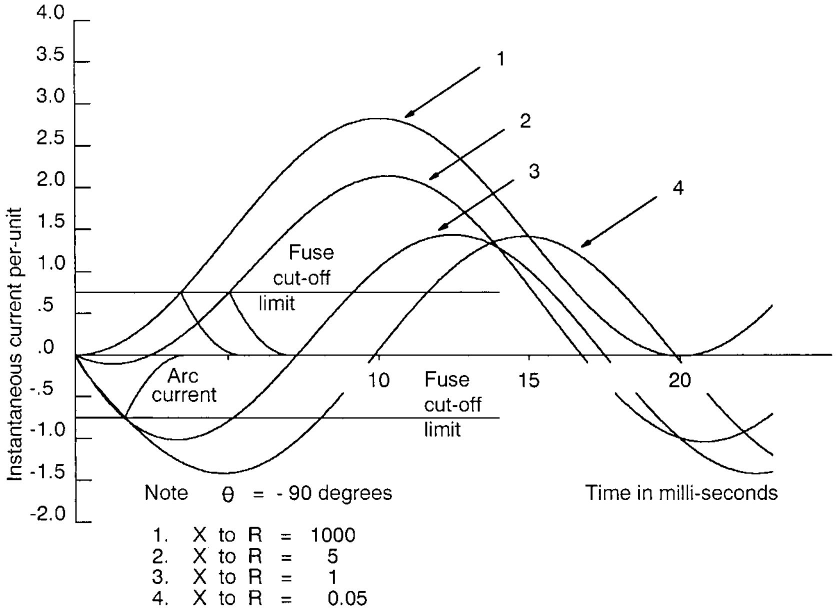

Figure 8.1 Fuse cut-off curves for different X-to-R ratios of the fault circuit. The curves show how the clearance time varies with the ratio..

its maximum possible value, called the ‘maximum asymmetrical’ (US) or ‘asymmetrical prospective’ (UK) current. The peak value of the actual fault current that the fuse allows to pass is called the ‘peak let-through’ current.

Clearly the higher the fault current the faster the fuse will operate, which is the required characteristic of a fuse. However, the application engineer must balance speed of operation with other factors such as the type of load. For example when an induction motor is started direct-on-line, the starting current will be as much as 7 times the running current. This starting current will actually fall within the range of currents that can cause the fuse to operate. Therefore a compromise is required between fast action during a fault and allowing the motor sufficient time to run up. Static loads do not require such a compromise and so fast action can be optimised by choosing a lower fusing factor (see sub-section 7.4). Rectifiers and thyristors require extra-fast fuses since permanent damage can be done very quickly when fault currents occur.

8.4 THE I^2t CHARACTERISTIC

During operation the fuse may be regarded as a constant resistance (R) until interruption occurs. The power dissipated by the fuse is therefore I^2R. The energy release by the fuse is therefore approximately:-

$$\text{Energy } U = I^2Rt$$

Where t is the melting time plus the arcing time and I is the current flowing in the fuse.

Therefore a fuse can be described by its I^2t characteristic as being a measure of the energy released during its operation. Obviously the mechanical design of the fuse must be capable of containing this energy, which is released in an explosive manner.

Historically early designs began to fail until it was realised that the prospective fault currents in typical power systems had gradually increased. This was due to the natural development and expansion of those systems. Reference 1 gives a good description of the I^2t characteristic.

Different types of fuse for the same rated voltage and current will release different amounts of energy since their characteristics are deliberated designed to be different. The energy released is due to two separate functions, melting the fuse element and extinguishing the arc.

The actual value of let-through current for a given fuse will depend upon the nature and magnitude of the prospective fault current e.g. asymmetrical or symmetrical. This is because a greater current has to be reached in the symmetrical case than in the asymmetrical case to create the same amount of melting energy. This is due to the shape of the current waveform in the first cycle, which can be seen in Figure 8.1.

The maximum value of the let-through current is called the ‘peak let-through current I_p’.

The importance of the peak let-through current is in relation to the thermal and mechanical stresses that occur in the downstream equipment e.g. contactors, cables.

Furthermore the I^2t characteristics of any of the downstream equipment must be greater than the fuse, otherwise the equipment will suffer thermal damage. (For a given fault current the fuse clearance time must always be at least several times lower than the corresponding I^2t time of the downstream device.)

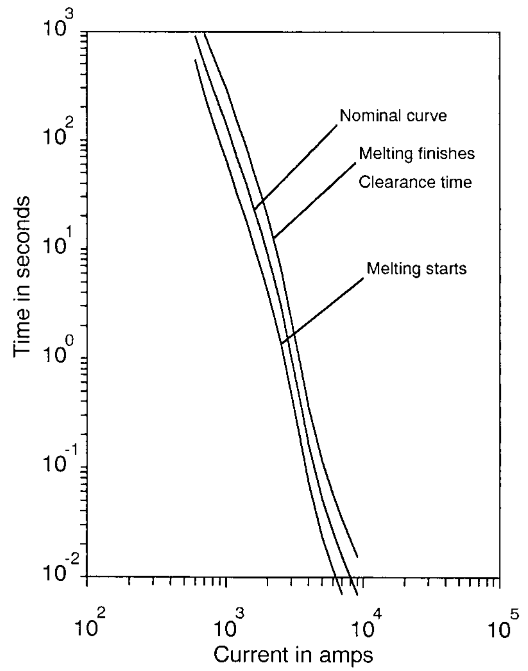

Figure 8.2 Melting, nominal and clearance time curves versus current for a typical 250 A fuse.

The melting time and clearing time are of related significance when two fuses, which are in series, need to be coordinated, e.g. a feeder fuse and a large outgoing fuse. The feeder fuse must not melt during the clearing time of the outgoing fuse when a common fault current passes. Figure 8.2 shows the important times and currents of a typical 250 amp fuse. The shape of the curve is typical.

A fuse may be called upon to operate in one of two ways:-

— Current limiting-short time duty.

— Non-current limiting-long time duty.

In a 60 Hz system the peak of the fault current will occur in 0.0042 sec (symmetrical) or 0.0084 sec (fully asymmetrical). For a 50 Hz system the times are 0.005 sec and 0.01 sec respectively. If the fuse clears the fault in less than about 0.003 sec then the fuse is said to be current limiting.

However if the prospective current is not at its maximum then several cycles of current may occur before sufficient heat is created to melt the fuse. In this situation the fuse is said to be non-current limiting. This applies to times beyond about 0.01 sec on the fuse curve of Figure 8.2. As the prospective current is reduced the non-current limiting time, or operating time, increases considerably. A particular design of fuse may take several hours to operate if the prospective current is only a small amount above the asymptotic value of the fuse. Four hours is used by manufacturers as a reference value. It can be seen therefore that times less than 0.003 sec are important when high currents occurs.

It should be noted that when the melting time exceeds about 0.1 sec the corresponding arcing time is less than 0.01 sec. Therefore for times above 0.1 sec it may be assumed that the melting or pre-arcing time is in fact the clearance time. The fuse manufacturers normally give curves for the time range of 0.01 to 1000 seconds. For times less than 0.01 sec it is better to seek the advice of a particular manufacturer.

During the current limiting phase the operating time is influenced by whether the prospective current is asymmetrical or fully symmetrical. The time is determined by the integrated amount of heat generated and this is a function of the current waveform shape. To help overcome difficulties in relating the terminology used in the non-current limiting phase to that applicable in the current limiting phase, the term 'virtual time' was introduced some years ago.

Note that during current limiting operation the melting time and the arcing time are of the same order, see Figure 8.2. The term virtual time (t_v) can be used in conjunction with the melting, arcing and clearing times by using the following mathematical expressions:-

$$\text{Melting } t_v = \frac{\text{Melting energy (amp}^2\text{ secs)}}{\text{Prospective current (rms sym amps)}^2}$$

$$= \frac{1}{I^2}\int_o^{t_m} i^2 \mathrm{d}t \text{ seconds}$$

Similarly,

$$\text{Arching } t_v = \frac{\text{Arcing energy}}{\text{Prospective current}^2}$$

$$= \frac{1}{I^2}\int_{t_m}^{t_c} i^2 \mathrm{d}t \text{ seconds}$$

And,

$$\text{Clearing } t_v = \frac{1}{I^2}\int_o^{t_c} i^2 \mathrm{d}t \text{ seconds}$$

Where, t_m is the melting time period.

t_c is the clearing time period.

$t_c - t_m$ is the arcing time period.

The manufacturers use this procedure to extrapolate their curves below 0.01 sec and t_v is therefore a theoretical time. Virtual time is related to the prospective current by definition and so the manufacturer will quote the maximum prospective current that can be used in conjunction with his curves. At this point the engineer is encouraged to consult the manufacturers for advice on the selection of fuses for current-limiting duty.

The above discussion on current limiting and virtual time have been included for completeness so that the reader is made aware of their significance.

8.4.1 Worked Example

An example of fuse selection:-

A 6600 volt induction motor is fed from a fuse-contactor starter. Find the most appropriate fuse rating and the appropriate size of a PVC cable for the motor. The following data are known:-

Motors:

- Rated kW = 760 kW.
- Rated cos Ø = 0.9.
- Rated efficiency = 0.96.
- Starting current = 4 times rated current.
- Starting cos Ø = 0.3.
- Starting time = 5 seconds.

Cable:

- Route length is short and volt-drops are negligible for starting and running.
- Derating factor to account for grouping, burying, racking, ambient temperature is 0.65.
- 3-core cable sizes available are 25, 35, 50, 70, 95 mm sq, their nominal current ratings are, 100, 125, 155, 190, 235 amps respectively.
- I^2t characteristics can be found by using a 'k' value of 110 for PVC cables with copper conductors.

Power system:

- Fault level 150 MVA.
- Assume a three-phase fault at the motor.
- Assume an X-to-R ratio of 25.
- Fuse characteristics as shown in Figure 8.4.

The calculations can be carried out in various sequences; the following is just one sequence.

Step 1. Calculate the motor running and starting current.

$$\text{Running current} = \frac{P}{\sqrt{3}V\cos Ø}$$

$$= \frac{7{,}60{,}000}{\sqrt{3} \times 6600 \times 0.96 \times 0.9} = 76.95 \text{ amps}$$

$$\text{Starting current} = 4 \times 76.95 = 307.8 \text{ amps}$$

Step 2. Scale-down the cable ratings to suit the derating factors, prepare a revised table:-

Core size mm sq	25	35	50	70	95
Scaled-down ratings A	65	81	101	124	153

Hence the 'minimum' cable core size to suit the motor running current is 35 mm sq.

Step 3. Calculate the prospective symmetrical and asymmetrical fault currents.

$$I_{\text{sym}} = \frac{\text{Fault MVA of system } (S_f)}{\sqrt{3} \text{ rated voltage } (V)} = \frac{S_f}{\sqrt{3}V}$$

$$= \frac{1{,}50{,}000{,}000}{\sqrt{3} \times 6600} = 13{,}122 \text{ amps rms}$$

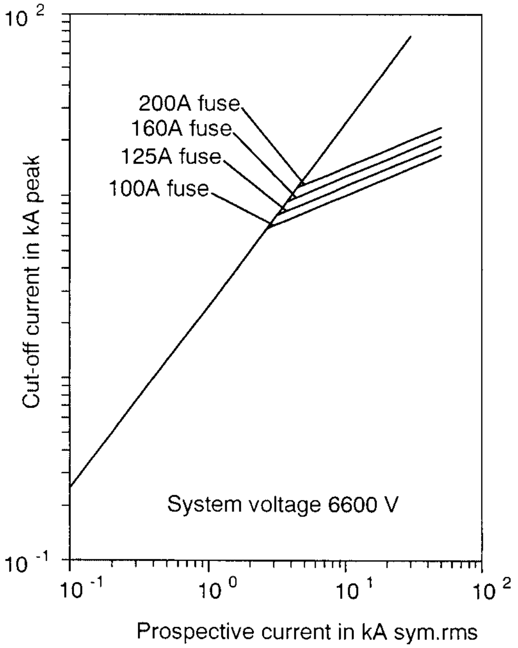

Figure 8.3 Peak cut-off current versus prospective symmetrical rms current for typical fuses in the range of 100 A to 200 A.

See Table H.1b for X-to-R ratio of 25, the doubling factor is 2.661.

Therefore the peak asymmetrical current is I_{pkasym},

$$I_{\text{pkasym}} = 13{,}122 \times 2.661 = 34{,}944 \text{ amps pk}$$

Step 4. Decide upon suitable cut-off current.

Choose the maximum cut-off current to be 45% of the peak asymmetrical fault current

$$I_{\text{pkcutoff}} = 0.45 \times 34{,}944 = 15{,}724 \text{ amps pk}$$

Round this up to 16,000 amps pk

Step 5. Select the largest fuse to suit the cut-off limit.

Use Figure 8.3 even through the prospective current is shown as rms symmetrical. This example is a special case since the X-to-R ratio is known.

$$\text{Prospective current} = \frac{34{,}944}{\sqrt{2}} = 24{,}713 \text{ amps rms}$$

Hence the 'largest' fuse for cut-off limit is 160 amp rating.

Step 6. Compare the I-squared-t characteristic of the fuses with the I-squared-t characteristic of the cables, in Figure 8.4. A 160 amp fuse will protect the 35 mm sq cable for fault currents beyond

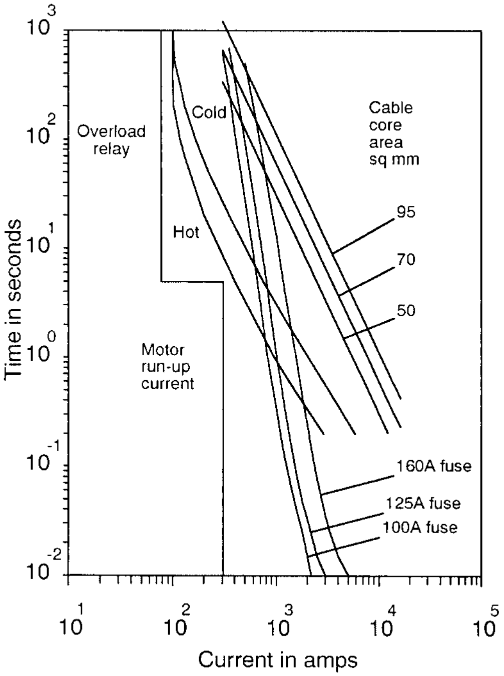

Figure 8.4. Protection of an induction motor and its feeder cable.

about 1200 amps. A 125 amp fuse would reduce this to 1000 amps. Below these fault currents it is necessary to use other additional protection devices e.g. inverse-time thermal image relay, which is the standard practice. The relay curve will need to intersect the fuse curve before the cable is damaged for fault currents within a certain range. To allow the relay to have good coverage it is advisable to choose a smaller fuse and a larger cable. The recommended choice is a 125 amp fuse and a 70 mm sq cable. The fuse gives good protection in this choice for all fault currents above about 650 amps, which is twice the motor starting current. The 125 amp fuse also gives improved cut-off or current limiting performance than the 160 amp fuse.

Step 7. Check the motor starting current versus time characteristic. Assume the starting current to be constant throughout the starting period. Insert the starting current versus time curve on the Figure 8.4. The curve is well clear of the fuse and the cable and gives plenty of scope for the overload relay. In fact the starting time could be as high as 8 or 9 seconds before coordination problems occur.

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2. Hermann W. Reichenstein, *The application of low-voltage fuses.* Classes and characteristics. McGraw-Hill Book Company, Inc. ISBN 0 076-06577-4
3. M. W. Earley, J. V. Sheehan and J. M. Caloggero, *National electric code 1999 handbook.* National Fire Protection Association,USA. Eighth edition. Library of Congress Card No. 89–63606 ISBN 0 877-65437-9

9

Cables, Wires and Cable Installation Practices

Cables provide a highly reliable and compact method of transmitting power from its source to its consumer. Cables are installed in open air on racks or ladders, in the ground, or underwater as in the case of submarine cables. Power at all the voltages normally encountered in the oil industry i.e., less than 100 V and up to 33 kV, can be transmitted efficiently by single and multi-core cables.

Over the last 30 years there has been a progressive improvement in the materials used in the construction of cables, especially in the non-metallic materials. This has been due to several necessary requirements e.g.,

a) To maximise the conductor temperature and hence the power transmitted.
b) To provide high resistance to mechanical wear and tear, both during the laying of the cables, and in their on-going use when they may be disturbed in the future.
c) To withstand the effects of chemical attack from their environment e.g., when laid in polluted ground.
d) To withstand the damaging effects of steady state and transient overvoltages.
e) To withstand the impact of heat from the environment when exposed to fire and high radiant temperatures.
f) To withstand freezing temperatures and embrittlement.
g) To be resistant to ultraviolet light when exposed to bright sunlight.

Not all of the above requirements are needed for a particular plant. The specification of the cable and its materials should take account of the changes in its environment throughout a one-year cycle. The conductor current rating should be based on the worst-case conditions if the cable is to be fully utilised and expected to give a long life time of service.

9.1 ELECTRICALLY CONDUCTING MATERIALS USED IN THE CONSTRUCTION OF CABLES

References 1 and 2 give detailed information about the metallic materials used in cables. Some of the more commonly used data are presented herein.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

ISBN: 0-471-49631-6

9.1.1 Copper and Aluminium

Copper and aluminium are used in their highly refined form for the power conductors of cables. The total impurities contained in high conductivity copper should be less than 0.1% and for aluminium less than 0.5%. The measured conductivity of these metals will have its highest value when they are annealed. Hard drawn conductors will have conductivity that is several percentage points lower than the annealed value. Note that castings made of these materials will generally have conductivity slightly lower than their rolled and drawn forms.

The presence of oxygen in the form of oxides is the most common impurity. It slightly reduces the conductivity, malleability and ductility of the metal.

Table 9.1 shows some of the electrical and physical properties of these two metals. For use in most power cable applications these metals are formed into annealed conductors.

Copper is generally the preferred material for cable conductors used in the oil industry. Aluminium is seldom chosen for conductors. It is sometimes used for the armouring of single-core cables that carry AC, or DC, if a substantial AC ripple is present e.g., DC, motors fed from a thyristor controlled power source.

9.1.2 Tin

Tin metal is occasionally specified to provide a thin layer on the outer surface of copper conductors. Historically this tin layer gave protection against corrosion of the copper surface from rubber insulation, which contained substances such as sulphur. Large proportions of sulphur were added during the vulcanising process to increase the hardness and tensile strength of the rubber. The modern use of ‘plastic’ insulation instead of rubber compounds means that the layer of tin is no longer required in most applications. Tin is beneficial in situations where soldered lugs are used to terminate the copper conductors, although modern methods of crimping lugs onto their conductors has tended to make the use of tin unnecessary.

Table 9.1. Electrical and physical properties of cable conductors

Property	Copper		Aluminum	
	Annealed	Hard drawn	Annealed	Hard drawn
Resistivity at 20°C (ohm-m × 10^{-8})	1.72	1.78 to 1.80	2.80	2.83
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.00393	0.00393	0.00403	0.00403
Coefficient of linear expansion per unit per °C	17.0×10^{-6}	17.0×10^{-6}	23.0×10^{-6}	23.0×10^{-6}
Approx. 0.1% proof stress, tons/sq inch	4.0	20.0	2.0	10.0
Thermal conductivity W/mK	384.0	384.0	209.4	209.4
Density kg/m^3	8.89×10^{-3}	8.89×10^{-3}	2.71×10^{-3}	2.71×10^{-3}
Specific heat kJ/kg K	0.394	0.394	0.904	0.904
Modulus of elasticity lbs/sq inch	–	18.0	9.6	10.0

Tin is also used as a coating for copper armour wires or armour braiding where rubber compounds are used in the inner or outer sheathing.

9.1.3 Phosphor Bronze

Phosphor bronze is an alloy of mainly copper, 5 to 10% tin and approximately 0.1% phosphorous. The alloy has superior mechanical strength when compared with copper. It is also very resistant to corrosion, particularly in the presence of water.

Phosphor bronze is used as wire in the armouring of cables to provide moderate protection against mechanical damage. It is formed into a tightly woven braid to form a non-magnetic, highly conductive, armoring and electromagnetic screen.

It is a practical alternative to tinned copper braid in many applications where steel wire should not be used.

The alloy is also used in the form of a thin tape for the purpose of repelling insects e.g., ants, termites and marine teredo worms. The tapes are placed underneath the main armouring and on top of the inner sheathing. Table 9.2 shows some of the electrical and physical properties of phosphor bronze.

9.1.4 Galvanised Steel

Galvanised steel is used for the cable armour where a high degree of mechanical protection is required, and where high pulling forces are experienced during the installation of the cable, especially in the laying of submarine cables. The armour wires are formed into a helical cage to give the highest protection or as a braid when flexibility is required during the installation and a lesser level of protection can be accepted.

Mild steel is used for the armouring of cables laid on land. For submarine cables the material can be specified as carbon steel, which has a higher tensile strength.

The depth of the galvanising is specified in the international standards. The cross-sectional area of each armour wire (in a helix and not in a braid) varies from typically 0.9 mm for small power and control cables e.g. 1.5 and 2.5 mm^2 conductors, to 2.5 mm for 400 mm^2 low voltage high

Table 9.2. Electrical and physical properties of phosphor bronze

Property	Phosphor bronze
Resistivity at 20°C ohm-m	9.50×10^{-8}
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	Similar to copper
Coefficient of linear expansion per unit per °C	18.0×10^{-6}
Thermal conductivity W/mK	75.0
Density kg/m^3	8.92×10^{-3}

Table 9.3. Electrical and physical properties of galvanised steel wire

Property	Mild steel	Carbon steel
Resistivity at 20°C (ohm-m × 10^{-8})	13.2	15.9
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.0045	0.0045
Coefficient of linear expansion per unit per °C × 10^{-6}	12.2	12.2
Thermal conductivity W/mK	59.4	51.9
Density kg/m^3	7.86×10^{-3}	7.86×10^{-3}

power cables. For submarine cables the wire diameter can be up to 6.0 mm and for some deep ocean applications two layers of armour wires are used. Table 9.3 shows some of the electrical and physical properties of mild steel and carbon steel, see also volume 1 of Reference 1.

Steel wire armour as opposed to steel wire braid has lower electrical impedance for a given length of cable. This is an important benefit in networks that are solidly earthed at their power source. Some special applications that require as low an impedance as is practical to achieve in the cable have some of the armour wires replaced by copper wires. Hence the parallel circuit consisting of the steel and copper wires has a lower total impedance than the steel wires on their own. The impedance of the armouring, with or without the copper wires, is predominantly resistive and so the inductive reactance at the power frequency can therefore be ignored.

9.1.5 Lead

Metallic lead is occasionally used as an extruded sheath to provide protection against chemical corrosion where it is necessary to bury cables in polluted or aggressive soils. Examples of these are found in chemical plants, refineries, storage tank farms and areas that have high water tables.

The lead is often alloyed with small amounts of tin and antimony to improve its ability to withstand mechanical fatigue, such as fatigue experienced in long distance transportation to site. Lead sheathed cables should not be installed where regular cyclic physical movement will be experienced. Table 9.4 shows some of the electrical properties of metallic lead used for sheathing cables.

Table 9.4. Electrical and physical properties of metallic lead sheathing

Property	Lead sheathing
Resistivity at 20°C (ohm-m × 10^{-8})	20.6
Temperature coefficient of electrical resistance at 20°C, in per unit of constant mass	0.00336
Coefficient of linear expansion per unit per °C × 10^{-6}	29.0
Thermal conductivity W/mK	34.3
Density kg/m^3	11.3×10^{-3}

9.2 ELECTRICALLY NON-CONDUCTING MATERIALS USED IN THE CONSTRUCTION OF CABLES

9.2.1 Definition of Basic Terminology

Some terms are used loosely in various engineering disciplines e.g. plastic, rubber. However, they have particular connotations in electrical engineering, especially in the field of cable manufacturing.

9.2.1.1 Rubber

Rubber is obtained in two basic forms, natural rubber and synthetic rubber. Natural rubber is the sap of the particular species of trees called *Hevea brasiliensis*, see References 3 and 4, which is sticky when at tropical temperature, reasonably hard at low temperatures and oxidises when exposed to the atmosphere. Natural rubber is a naturally occurring compound of carbon and hydrogen, and is of little use as a basic material. It is therefore mixed with other chemical compounds, filler materials such as carbon black and then vulcanised to produce 'vulcanised rubber' or more generally called simply 'rubber'. The vulcanising process requires sulphur to be added and the application of heat and pressure. The molecules of rubber are formed in long chains. Individual chains are not bonded to adjacent chains; hence the chains can slide alongside each other with little resistance to movement. This gives processed rubber the ability to recover without permanent deformation. Natural rubber does not necessarily recover to its original shape, since its stability depends on its ambient temperature. Vulcanising or 'curing' causes the sulphur to cross-bond adjacent chains, which stiffens the material thereby making it more useful. By increasing the sulphur content or extending the vulcanising time, or a combination of both functions, the rubber becomes progressively harder with higher tensile strength. Increasing additives such as carbon black can reduce the dielectric strength, thereby making the rubber a poorer insulator. Carbon by itself is of course a conductor.

Synthetic rubbers are also composed of carbon and hydrogen molecules, but they are combined by manufacturing processes. A synthetic rubber, which closely resembles natural rubber, is polyisoprene, which has the same chemical composition.

Reference 5 also describes many types of insulating materials.

9.2.1.2 Elastomer

The term 'elastomer' is the most appropriate technical term for rubber, and is generally applied to synthetic rubbers, e.g. ethylene propylene rubber. It derives its name from the well-known elastic property of rubber.

However some non-rubber compounds are also called elastomers if they exhibit a non-deforming elastic property similar to rubber at room temperature, even if the compound is relatively hard. The two main groups of non-rubber elastomers are thermoplastics, e.g., polyvinyl chloride, polypropylene and thermosets, e.g., ethylene propylene rubber, cross-linked polyethylene. These two groups are also covered by the term 'plastic'.

9.2.1.3 Polymer

A polymeric compound contains several different molecules e.g., carbon, hydrogen, oxygen, silicon, chlorine, sulphur. These molecules combine in small groups usually with a carbon molecule in the middle. The group is repeated linearly many times in the form of a chain.

Polymers can be natural or synthetic materials, which include but are not limited to rubbers, elastomers and plastics.

When two polymers are combined the resulting compound is called a copolymer.

9.2.1.4 Plastic

This is a very widely used term to describe typical household, automobile and industrial components that are moulded from man-made chemical compounds. In the electrical engineering field the term has a more specific definition, especially where insulation materials are being described.

Plastic materials are those that are formed from synthetic compounds e.g., polymers or natural compounds that have previously been modified, for example hydrocarbons refined from crude oil, natural gas or derivatives of ethane, methane and naphtha. By definition the manufacturing of a plastic component should include a viscous flowing process that usually requires heat and pressure, for example extrusion or injection moulding.

Two important groups of insulating and sheathing materials that also come within the definition of plastic are the thermoplastic and thermoset polymeric compounds.

9.2.1.5 Resin

The preferred term for synthetic polymers is resin polymers or simply resins. Hence the two main groups are thermoplastic resins and thermoset resins.

9.2.1.6 Thermoplastic resins

Thermoplastic resins (elastomers and polymers) are plastics that retain their flexibility and chemical composition when heat is applied and removed. The applied heat is only sufficient to steadily melt the resin.

The most widely used thermoplastic resins used in cables are polyvinyl chloride (in various forms), polyethylene (in several forms), polypropylene and polytetrafluoroethylene.

In general these resins in their basic forms do not have sufficiently good properties to make them attractive as materials for cables. The necessary properties for insulation are usually different from those required for sheathing and bedding, even though the same basic resin may be used for these purposes. Other substances are polymerised or mixed with the basic resin during its manufacture. These substances are used to improve or provide:-

- High dielectric strength.
- Low dielectric loss angle.
- High insulation resistivity.

- High melting temperature.
- High tensile strength and resistance to mechanical impact.
- Good flexibility.
- Good handling properties for installation and termination.
- Good resistance to ultraviolet light.
- Good dimensional stability.
- Long service life.
- Low water absorption.
- Low emission of smoke and acid gases during fire situations.
- Low flammability.
- Low solubility in mineral oils (drilling mud), acids, alkalis, organic compounds and solvents.
- Good extrusion performance.
- High resistance to ozone.

Not all of the above can be optimised for a particular type of cable. Some sacrifices need to be made when a particular property or overall performance is to be obtained. For example good performance during a fire inside a building where people are present and smoke and gas must be minimised.

9.2.1.7 Thermoset resins

Thermoset resins do not melt when heated, and are irreversibly changed after the heat is removed. They are produced from a two-stage chemical process. The second stage is called ‘cross-linking’, and is similar to vulcanising. The process requires heat, pressure, catalysts, or irradiation, or a combination of these additives to produce the desired material.

Thermoplastic resins can be further processed by ‘cross-linking’ techniques to produce thermosets.

The thermoset elastomers most frequently used for cables are ethylene propylene rubber and cross-linked polyethylene.

Additives are used in a similar manner to produce the same improvements as listed in subsection 9.2.1.6.

Thermosets are widely used as sheet type insulating materials, adhesives, jointing compounds for cables and solid mouldings such as post insulators.

See Table 9.5 for electrical and physical properties of thermoset resins.

9.2.1.8 Electrical and physical properties of thermoplastic and thermoset resins

There are many thermoplastic and thermoset resins but only a few developed for use in manufacturing cables. Table 9.5 summarises the main properties of the more frequently used resins.

Table 9.5. Electrical and physical properties of thermoplastic and thermoset resins as insulators

Property	PVC	EPR	XLPE	PP	PE	PCP	CSP	PTFE
Dielectric relative permittivity at 50 Hz	4 to 7	3.5	2.2 to 5.0	2.25	2.35	—	10	2.0
Dielectric strength used for continuous service MVrms/m 15 kV × 25 mm^2 single core	3.5	3.8	3.8	—	4.5	—	—	—
Volume resistivity at 20°C ohm-m × 10^9	10^2 to 10^4	2×10^4	10^4 to 6×10^4	10^7	10^7	—	30	10^7
Loss angle tan δ at 50 Hz	0.1	0.005	0.0005 max	0.0005	0.0006	—	0.06	0.003
Temperature in °C at which distortion or softening occurs	120	180	130	120	90 to 100	—	160	300
Density kg/m^3		1.2 to 1.5	0.92		0.95 to 0.97	—	—	—
Tensile strength kg/cm^2 or N/mm^2	12.0 to 14.0	4 to 8	12 to 18	37	37	10	10 to 20	22
Water absorption Note a)	3	9	9	9	9	3	4	—
Conductor maximum continuous temperature °C	70	85 to 90	90	80	70 to 75	75	85	260
Minimum environmental temperature °C	Zero Note b)	−40	−50	−10	−50	−10	−30	—
Thermal resistivity Km/W	5.5	4.5	3.5		3.5	5.5	—	—
Max conductor temp °C for 5 sec short circuit IEC 502	160	250	250	150	130	—	200	300
Resistance to heat Note a)	5	9	5	5	1	9	5	9
Flame retardance Note a)	9	9	1	1	1	8	9	9
Resistance to acids and alkalis Note a)	5	(3)	9	9	9	8	5	9
Resistance to mineral oils Note a)	5	1	1	9	1	7	7	9
Resistance to weather Note a)	5	9	5	7	1	—	7	9
Resistance to abrasion Note a)	7	5	3	9	7	7	7	3
Resistance to ozone Note a)	9	7	5	9	9	—	9	5
Emission of acid gas Note a)	9	1	—	—	—	—	4	—
Low oxygen index %	25 to 35	20 to 40	18	18	18	40	30 to 40	95

Note a) 1 denotes poor performance.
4 denotes an average performance.
9 denotes excellent performance.
Note b) For special compounds the minimum temperature can be as low as 30°C.

9.3 COMPOSITION OF POWER AND CONTROL CABLES

The composition of a power cable is dependent upon the rated voltage at which it will be expected to operate continuously without breakdown.

IEC60038 gives the standard voltages for electrical equipment. However, for cables the AC rms voltages are defined for example in IEC60502, in terms of their line-to-earth and line-to-line values.

See Tables 9.6 and 9.7. Table 9.7 is derived from BS6622.

Note that occasionally u_o is quoted as the value obtained by dividing u by 1.732 and rounding to one decimal place. u_o is derived from IEC60038.

IEC60502 covers the construction and factory testing of polymeric solid insulated cables in the voltage range 1000 to 30,000 volts. IEC60183 gives guidance on the selection of cables for high voltage systems. BS6622 is similar to IEC60502 but is restricted to cables operating at voltages between 6600 and 33,000 volts, with screened XLPE or EPR insulation. BS5467 covers unscreened thermosetting insulated cables that operate between 1000 and 3300 volts; hence the standard is reasonably applicable to low voltage systems e.g. 380, 400, 415, 440, 600 and 750 volts (line to

Table 9.6. IEC standard rated voltages of power cables

Line-to-earth voltage u_o	Line-to-line voltage u	Maximum value of the highest system line-to-line voltage u_m
600	1,000	—
1,800	3,000	3,600
3,600	6,000	7,200
6,000	10,000	12,000
8,700	15,000	17,500
12,000	20,000	24,000
18,000	30,000	36,000

Table 9.7. UK standard rated voltages of power cables

Line-to-earth voltage u_o	Line-to-line voltage u	Maximum value of the highest system line-to-line voltage u_m^* Note a)
600	1,000	—
3,800	6,600	(8,000)
6,350	11,000	(13,200)
8,700	15,000	(17,500)
12,700	22,000	(26,400)
19,000	33,000	(39,600)

Note a) This column is not shown in BS6622 but is included to be consistent with Table 9.6 where a 20% upward margin is added to u to obtain u_m before rounding is applied.

Note b) A method of rounding numbers upwards or downwards is given in Appendix B of IEC60502.

line). BS5468 is similar to BS5467 but only applies to XLPE insulated cables in the same voltage range. BS6746 specifies the requirements of PVC for insulation and sheathing of cables. BS6469 specifies factory-testing methods for insulation and sheathing compounds. IEC60227 and 60245 give the manufacturing and factory testing requirements for PVC and EPR in insulated cables respectively, for voltages up to 1000 volts.

9.3.1 Compositional Notation

A commonly used notation for indicating the main components within a power or control cable uses abbreviations, listed from left to right, that represent the core and its surrounding components, e.g. STR CU/EPR/CSP/GSWB/CSP. This list denotes the following:-

- Conductor is stranded copper, STR CU.
- Insulation is ethylene propylene rubber, EPR.
- Inner sheath is chlorosulphonated polyethylene, CSP
- Armouring is galvanised steel wire braid, GSWB
- Outer sheath is chlorosulphonated polyethylene, CSP

See Appendix A for abbreviations used in specifying cables.

There may be additional materials within the cable such as semiconductor screens for the core-insulation interface; jute, hessian or bitumen for giving extra water resistance to the wire armouring; bronze tape for repelling insects.

Some of the international standards that are frequently used in the specification of cables in the oil industry are, BS801, BS2627, BS4066, BS5308, BS5467, BS5468, BS6234, BS6360, BS6387, BS6469, BS6622, BS6724, BS6883, BS7622, BS7629, BS7655, BS7835, BSEN10257, IEC60227, IEC60245, IEC60331, IEC60332, IEC60502, IEC61034, see Table 9.8 which summarises where the standards are particularly suited to components within a cable. Appendix B gives the titles of these standards.

It can be seen from the above examples that many standards can be used. In fact a particular cable may have its various components specified from different standards. Some standards attempt to cover all aspects of cables that are suitable for certain situations or industries e.g. BS6883 for marine and offshore structures; BS5467, BS6622, IEC60502 for land based plants. Care should be taken when preparing a purchasing specification for a particular project. It is necessary to avoid requirements that may be conflicting between the international specifications that are quoted in the project specification. Such conflicting requirements could lead to a cable that is unnecessarily difficult to manufacture and expensive to purchase or replace. See also Chapter 19.

9.3.2 Conductor

The conductors are usually copper or aluminium. Aluminium is seldom used in the oil industry because it work hardens during installation, has higher losses, has high volt-drop at rated current and requires special attention during termination.

Table 9.8. International standards that are commonly applied to cables

Conductors	Insulation	Screening of conductors and insulation	Inner and outer sheathing	Armouring wires and braids	Fire resistance flame, retardance and smoke emission
BS6360	BS6234	BS6622	BS801 Note b)	BS2627	BS4066 Pts 1, 2, 3
IEC60228	BS6899	IEC60502	BS6724	BS2873	BS6387
VDE0295	BS7655		BS7655	BS4109	BS7622
	IEC60502		BSEN61067	BSEN12166	BSEN61067
			IEC60502	BSEN102571	IEC60331
				IEC60502	IEC60332
					IEC61034

Note a) The table is a summary of standards that relate to particular components of power, control and instrumentation cables.
Note b) Lead alloy.

Copper and aluminium conductors are described in IEC60228 (BS6360), which divides them into a number of classes. Class 1 applies to single stranded conductors, but these are only used in sizes normally less than 1.5 mm^2, and even then finely stranded conductors are preferred. For sizes equal to or greater than 1.5 mm^2 Class 2 is used, and the lowest number of strands used is 7 for sizes up to 16 mm^2 for marine and offshore installations and up to 35 mm^2 for onshore installations. Marine and offshore installations usually require the cable to be more flexible for handling during laying and smaller bending radii during termination. Higher flexibility can be obtained by finer stranding as given by Class 5 of the standard is preferred with a maximum of 400 mm^2 for single core cables due to difficulties in laying larger sizes.

For LV cables having a cross-sectional area above approximately 25 mm^2 the conductors would usually be formed into sector shaped conductors.

In general cable sizes above 400 mm^2 are rarely used in the oil industry.

Note that BS6622 permits the use of sector shaped conductors above certain core sizes for high voltage cables e.g. up to 6600 volts the smallest section is 70 mm^2 and for use up to 11,000 volts the smallest is 95 mm^2.

The stranding of wires in the core can be achieved efficiently in three configurations of the wires at the centre of the core. The first configuration is the simplest, in which one wire is surrounded by the first layer of six wires. Hence the lowest number of strands is seven. The second configuration begins with three wires in a triangle. The third begins with four wires in a square. The first configuration is preferred for Class 2 cores.

The total number of wires (N_c) in a Class 2 stranded core is given by:-

$$N_c = 1 + 3n(1 + n)$$

Where n is the number of layers over the central wire. N_c has the sequence 7, 19, 37, 61, 127, 169, 217 etc.

The outside diameter (d_c) of the core is given by:-

$$d_c = (1 + 2n)d$$

Where d is the diameter of each circular wire.

Table 9.9 shows the calculated cross-sectional area, equivalent core diameter and overall core diameter of a selection of stranded circular conductors. The table applies to cores that are not compacted or tin coated, i.e. before compaction is applied. The preferred sizes are shown in bold type.

Table 9.9. Stranding of circular section cable cores

Dia. of each wire (mm)	No. of wires in core	Nominal CSA (mm^2)	Actual CSA (mm^2)	pu error in CSA	Equivalent dia. of core (mm)	Overall dia. of core mm
0.522	7	**1.50**	1.498		1.381	2.044
0.522	19	4.00	4.066	0.01654	2.275	3.088
0.672	7	**2.50**	2.483		1.778	2.344
0.853	7	**4.00**	4.000		2.257	2.706
0.853	61	35.00	34.859	0.00402	6.662	7.824
0.853	169	95.00	96.577	0.01660	11.089	12.942
1.042	7	**6.00**	5.969		2.757	3.084
1.042	19	16.00	16.202	0.01265	4.542	5.168
1.042	217	185.00	185.048	0.00026	15.350	17.672
1.349	7	**10.00**	10.005		3.569	3.698
1.349	19	**25.0**	27.156	0.08624	5.880	6.396
1.349	127	185.00	181.517	0.01883	15.202	17.188
1.349	169	240.00	241.546	0.00644	17.537	19.886
1.530	19	**35.0**	34.932	0.00194	6.669	7.120
1.695	7	**16.00**	15.795		4.485	4.390
1.695	217	500.00	489.654	0.02069	24.696	28.120
1.830	19	**50.00**	49.974		7.977	8.320
1.830	37	**95.00**	97.318	0.02440	11.131	11.980
1.830	91	240.00	239.350	0.00271	17.457	19.300
2.310	37	**120.00**	119.870		12.354	13.186
2.031	91	300.00	294.816	0.01728	19.375	21.310
2.149	7	25.00	25.390	0.01560	5.686	5.298
2.149	19	**70.00**	68.915		9.367	9.596
2.149	217	800.00	787.086	0.01614	31.657	35.384
2.255	37	**150.00**	147.769		13.717	14.530
2.255	61	**240.00**	243.620		17.612	19.040
2.255	127	500.00	507.209	0.01442	25.413	28.0602
2.527	7	35.00	35.107		6.686	6.054
2.527	19	95.00	95.291		11.015	11.108
2.527	37	**185.00**	185.568		15.371	16.162
2.527	61	**300.00**	305.936		19.736	21.216
2.537	127	**630.00**	636.948		28.478	31.324
2.861	19	120.00	122.146	0.01788	12.471	12.444
2.861	37	240.00	237.863	0.00890	17.403	18.166
2.861	61	**400.00**	392.153		22.345	23.888

Table 9.10. Equivalence between metric and American cable sizes

Actual CSA (mm^2)	Nominal CSA (mm^2)	Circular mils	American wire gauge
0.82	(0.75)	1,624	18
0.97	—	1,910	—
—	1.0	—	—
1.29	—	2,546	—
1.31	(1.5)	2,583	16
—	1.5	—	—
1.94	—	3,820	—
2.08	(2.5)	4,110	14
—	2.5	—	—
2.90	—	5,730	—
3.31	(4.0)	6,530	12
—	4.0	—	—
4.51	—	8,910	—
5.26	(6.0)	10,380	10
—	6.0	—	—
6.45	—	12,730	—
8.37	(10)	16,510	8
9.35	—	18,460	—
—	10	—	—
13.30	(16)	26,250	6
14.51	—	28,650	—
—	16	—	—
19.35	—	38,200	—
21.15	(25)	41,740	4
—	25	—	—
25.80	—	50,930	—
26.67	—	52,630	3
33.63	(35)	66,370	2
—	35	—	—
38.70	—	76,390	—
42.41	—	83,690	1
48.37	—	95,490	—
—	50	—	—
53.48	(50)	105,500	0
64.50	—	127,300	—
67.43	(70)	133,100	00
—	70	—	—
77.40	—	152,800	—
85.03	(95)	167,800	000
—	95	—	—
96.75	—	191,000	—
107.2	—	211,600	0000
—	120	—	—
127.0	(120)	250,000	250 MCM
129.0	—	255,000	—

(*continued overleaf*)

Table 9.10. (*continued*)

Actual CSA (mm^2)	Nominal CSA (mm^2)	Circular mils	American wire gauge
—	150	—	—
152.0	(150)	300,000	300 MCM
161.0	—	318,000	—
177.0	(185)	350,000	350 MCM
—	185	—	—
194.0	—	382,000	—
203.0	—	400,000	400 MCM
—	240	—	—
253.0	(240)	500,000	500 MCM
258.0	—	509,000	—
—	300	—	—
304.0	(300)	600,000	600 MCM

It can be seen that the preferred choices give an accuracy of better than 2.1% in the calculated cross-sectional area if the wire diameter is as shown. Different combinations of the wire diameter and the number of layers can in several cases give almost the same cross-sectional areas. The preferred choices are the most economical in terms of stocking wire sizes in a factory. The largest wire diameter is usually 3.199 mm.

Where the insulation is a rubber-based elastomer it is common practice to tin coat the copper wires, to protect against chemical attack from the elastomer.

9.3.3 Conductor Semiconducting Screen

A semiconducting screen of tape or extruded compound is normally specified for cables that have a rated line voltage of 3000 V and above. IEC60502 applies to solid extrusions of insulation, and requires PE and XLPE compounds to have the screen for 3000 V and above. Likewise the standard requires the screen for 6000 V and above for PVC and EPR compounds. BS6622 calls for screens for all cables for voltages between 6600 and 33,000 volts.

The purpose of the screen is to reduce the voltage gradient (electric stress) at the surface of the conductor where it interfaces with the insulation. Otherwise irregularities in the interface could initiate failure of the insulation in the longer term.

9.3.4 Insulation

The most frequently used insulating compounds are PVC, XLPE and EPR. For most onshore applications PVC and XLPE are preferred because of economic reasons, and XLPE is becoming more popular than PVC. Marine and offshore applications tend to prefer XLPE and EPR. EPR is usually more expensive than XLPE. Both compounds have the advantage that they permit the conductors to operate at higher temperatures (85 to 90°C) than those of PVC (70°C). PVC compounds can be specially manufactured to tolerate conductor temperatures up to 85°C. Silicon rubber can be specified if high conductor temperatures (up to 180°C), and for even higher temperatures (up to 260°C) the compound PTFE can be used. These compounds would tend to be used for special situations such as control circuits and emergency power circuits where overloading could be allowed for a limited period of time, or if exceptionally high surrounding temperatures need to be tolerated e.g. near engines, hot vessels, hot pipes, boilers.

Note that when high voltages are used in marine and offshore installations it is usually necessary to adopt the international standards that apply to onshore oil industry installations.

See sub-section 9.5 for the choice of insulations materials needed for fire survival services.

9.3.5 Insulation Semiconductor Screen

The need for a semiconductor screen is very similar to that for a conductor screen, as described in sub-section 9.3.3. IEC60502 and BS6622 specify the same applicable voltage limits for screens with different compounds.

The insulation screen is important in three-core cables because it prevents the inter-core electric stressing that would occur if the screen were not present. It maintains a radial stress pattern in each core, which is independent of the other cores.

However, the application of the screen itself is slightly different. It is carried out in two parts. The first part is a non-metallic semiconducting tape or polymeric cross-linked compound that is applied over the whole surface of the insulation. This material should be capable of being removed from the insulation without damaging its surface. This requirement is necessary for terminating and jointing the cable during its installation. The second part requires a metallic tape or braid, usually copper or aluminium, to be applied over the non-metallic part to make full contact with it. The metallic part is connected to an external circuit during termination and installation of the cable. The connection is usually only made at one end of the cable so that induced circulating currents do not occur and damage the screen itself.

9.3.6 Inner Sheath

An inner sheath, usually made of extruded polymer, is used to cover the insulation screen, and to fill in the interstices between the cores of a multi-core cable. It is important to fill the interstitial spaces for two reasons. Firstly to ensure good circularity and dimensional accuracy of the finished cable, and secondly to prevent an internal passage within the cable along which flammable gases could travel. The transmission of such gases along a cable must be eliminated by design and construction for cables that are used in hazardous areas.

The sheathing material need not necessarily be the same as the insulation material. It is usually more economical to use a different material such as PE, PVC, CSP, EVA, for general applications and HOFR or ZH for situations where fire resistance and smoke emission must be considered.

The specifications of sheathing materials can be found, for example, in BS7655, BS6724 and IEC60502.

9.3.7 Lead Sheathing

Lead is used as a sheathing material for protecting the cable from chemical attack whilst it is buried directly in hostile ground conditions, e.g. in chemical and refinery plants.

9.3.8 Armouring

Most cables used in oil industry plants are installed for at least part of their length in exposed machinery areas or on trays or ladders. This exposure can permit mechanical damage to occur to the cables e.g. objects falling on to them or impacting into them. Even buried cables are at risk from excavation mistakes, e.g. digging machines.

In order to minimise the possible damage to a cable, and to provide a safe path for electrical earth return currents, it is necessary to specify a metallic armouring. There are several types of metallic armouring used in the oil industry, i.e. galvanised steel wires (GSWA), aluminium wires (AWA), tinned copper wire braid (TCUWB), phosphor bronze wire braid (PBWB).

Various standards specify the diameter, number and design of the wires and braids, e.g. BSEN10257 part 1 and IEC60502 for steel armouring, BS2873 for phosphor bronze and BS4109 for copper braid armouring. GSWA and PBWB are the most commonly used armouring. Armouring in the form of metallic tape is not normally used for oil industry installations.

9.3.9 Outer Sheath

Oil industry cables are usually finished with an extruded heavy-duty polymeric sheath such as PVC, PE or CSP. For situations where resistance to heat, oil and flames is necessary it is the practice to use special elastomerics that are identified as HOFR types. These compounds include EVA, EMA, CPE, and EPR together with suitable fillers that are used during their curing processes. BS7655 details the requirements for HOFR cables, and IEC60332 for their fire retardance.

9.4 CURRENT RATINGS OF POWER CABLES

The choice of cross-sectional area of cable conductors depends upon several factors, the main factors being:-

- Continuous load current.
- Continuous rated current of cable.
- Volt-drop developed across the cable under steady state and transient conditions.
- Dissipation of heat from the conductors during short-circuit conditions.
- Earth loop impedance.

9.4.1 Continuous Load Current

Cables are used to supply power to individual loads such as motors, and to groups of loads as in the case of a feeder to a switchboard. Selecting the load current for the first case is reasonably simple. Most individual loads have a manufacturer's nameplate that gives details such as rated power, voltage, current and power factor. If the current is not given on the plate then it should be calculated from the output power, power factor and efficiency of the load.

Determining the continuous current for a feeder to a switchboard or to its incoming transformer is a little more complicated. All the loads in a group need to be identified into continuous loads, intermittent loads and de-energised standby loads.

The individual loads may be known to have diversity from their nameplate values. If this is the case then the diversity should be included in the estimation of the consumed power. The total load is estimated by adding together the continuous loads, a nominal proportion of the intermittent loads e.g. 30 to 50%, and a small proportion of the standby loads e.g. zero to 10%. The summation should be carried out in two parts, the first part for the active power and the second part for the reactive power. This is necessary because not all the loads in a group have the same power factor. Once these two totals are estimated the total volt-amperes can be found and then the current.

A feeder to a switchboard should be sized on the basis of the known loads at the plant design stage plus a contingency for future expansions. Oil industry plants tend to be upgraded and expanded once or even several times during their lifetime. Hence a contingency of typically 15% to 25% should be added to the feeder current estimated above.

See Chapter 1 for examples of loading and load flow estimation.

9.4.2 Continuous Rated Current of a Cable

A given size of a bare circular section conductor will carry a certain current when it is placed in still air at 25°C and allowed to have a surface temperature of say 85°C. If the same conductor is surrounded by insulating material and also placed in still air at 25°C, it will need to carry less current in order to maintain a surface temperature of 85°C. The electrical insulation will act as thermal insulation. The more layers of thermal insulation that are added e.g. screens, sheathing, armouring, the lower the current will need to be for the same conductor temperature.

The maximum surface temperature of the conductor is determined by the thermal and physical properties of the insulating materials. Some materials melt or deteriorate at lower temperatures than others.

When a cable is placed in a group of cables on a rack, directly buried in the ground, or laid in underground ducts the surroundings provide additional thermal insulation. Each situation adds a different amount. The overall effect is to reduce the rated current of the cable when compared to its performance in still air by itself.

A similar reduction in rated current occurs when several conductors are combined in one cable. Single-core cables can carry more current than three or four core cables. Vertically run cables carry less current than those run horizontally by a factor of approximately 5%, due to the convection of heat given out by the lower part of the cable.

The above thermal insulating effects are taken into account by the manufacturers of cables, before they publish their tables of rating data. International standards such as BS5467, BS6724, BS7671 and IEC60364 also provide tables of rating data. Care should be taken when using or comparing these tables of data because they are not necessarily compiled on the same basic parameters e.g., ambient air temperature, standard ground temperature.

The following tables of current ratings are typical for the cable constructions and service voltages given. There are many tables available in the international standards e.g. BS7671, which is also the IEE Wiring Regulations in its sixteenth form. Such tables cover a wide range of installation configurations and environmental conditions, not all of which are applicable in the oil industry. The following tables were compiled to be on similar bases and for installations commonly used in the oil industry. For example all the reactance data are given for a frequency of 50 Hz. The conductor temperatures are those suitable for the insulation where rated current follows in the cable. The resistance data of the armouring has been given at a temperature of 80°C for wire armouring and 60°C for braided armouring so that the earth loop impedance can be calculated under fault conditions. The depth of burial of cables is taken to the 0.5 m and the ground temperature 15°C. They should be used as guidance in estimating cable sizes. When calculations are being finalised for a project then the data from a particular manufacturer should be used. Most of the data presented were kindly made available by the Anixter Wire and Cable group of companies, see Reference 6. Reference 4 also provides comprehensive data on many types of cables, and was used as a source for PVC insulated cables. Reference 7 although somewhat dated is also a valuable source of data.

Table 9.11. Summary of cable rating and data tables

Table	Cable voltage grade	Brief description
		Land based installations:
9.12	600/1000 V	PVC insulation Current ratings of 1-core cables
9.13	600/1000 V	PVC insulation Impedance data in ohms/km
9.14	600/1000 V	PVC insulation Current ratings of 3 & 4-core cables
9.15	600/1000 V	XLPE insulation Current ratings of 1-core cables
9.16	600/1000 V	XLPE insulation Impedance data in ohms/km
9.17	600/1000 V	XLPE insulation Current ratings of 3 & 4-core cables
9.18	3800/6600 V 6350/11,000 V 8700/15,000 V	XLPE insulation Current ratings of 1-core cables
9.19	3800/6600 V	Impedance data in ohms/km
9.20	6350/11,000 V	Impedance data in ohms/km
9.21	8700/15,000 V	Impedance data in ohms/km
9.22	3800/6600 V 6350/11,000 V 8700/15,000 V	Current ratings of 3-core cables
		Marine installations:
9.23	600/1000 V	EPR insulation Current ratings of 1, 3 & 4-core cables
9.24	600/1000 V	Impedance data in ohms/km

Table 9.12. Land based installations. 600/1000 V. Cu/PVC/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	193	247	193	203	193	202	Thermal resistivity of soil is 1.2°C m/W
70	243	307	229	248	233	243	
95	298	372	269	297	277	288	Ambient air temperature is 30°C
120	347	429	302	337	315	326	
150	395	472	324	376	347	355	Depth of laying cables is 0.5 m
185	452	528	356	423	386	393	
240	532	606	398	485	441	443	Standard ground temperature is 15°C
300	607	672	435	542	490	486	
400	690	719	460	600	533	516	Conductor surface temperature is 70°C

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.02	1.0	0.94	0.87	0.79	0.71	0.61	0.50

Table 9.13. Land based installations. 600/1000 V. Cu/PVC/PVC/AWA/PVC single core Cu/PVC/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Single cores in trefoil		3 and 4 cores		Approximate armouring resistance	
	Resistance at 70°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 70°C (ohm/km)	Reactance at 50 Hz (ohm/km)	AWA at 80°C (ohms/km)	SWA at 80°C (ohms/km)
1.5			14.451	0.104	2.39	11.40
2.5			8.868	0.101	1.99	9.48
4			5.518	0.099	1.16	5.52
6			3.688	0.094	1.03	4.92
10			2.186	0.090	0.857	4.08
16			1.380	0.087	0.554	2.64
25			0.870	0.084	0.529	2.52
35			0.627	0.081	0.479	2.28
50	0.464	0.112	0.464	0.081	0.328	1.56
70	0.321	0.107	0.321	0.079	0.302	1.44
95	0.232	0.103	0.232	0.077	0.247	1.176
120	0.184	0.103	0.184	0.076	0.179	0.852
150	0.150	0.101	0.150	0.076	0.164	0.780
185	0.121	0.099	0.121	0.076	0.149	0.708
240	0.0927	0.096	0.0929	0.075	0.131	0.624
300	0.0751	0.094	0.0752	0.074	0.118	0.564
400	0.0600	0.091	0.0604	0.074	0.0857	0.408

Table 9.14. Land based installations. 600/1000V. Cu/PVC/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
10				
16	87	78	97	
25	116	103	126	
35	142	123	150	
50	175	146	178	Thermal resistivity of soil is 1.2°C m/W
70	218	181	220	
95	268	218	264	Ambient air temperature is 30°C
120	310	247	299	Depth of laying cables is 0.5 m
150	355	279	335	
185	407	314	377	Standard ground temperature is 15°C
240	480	363	435	Conductor surface temperature is 70°C
300	547	407	486	
400	627	466	546	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor for cables laid in air	1.02	1.0	0.94	0.87	0.79	0.71	0.61	0.50

Table 9.15. Land based installations. 600/1000 V. Cu/XLPE/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	231	296	231	231	231	242	Thermal resistivity of soil is 1.2°C m/W
70	295	373	278	284	283	295	
95	362	452	327	340	337	350	Ambient air temperature is 25°C
120	420	519	366	386	381	395	
150	483	577	396	431	424	434	Depth of laying cables is 0.5 m
185	555	649	437	485	474	482	
240	654	745	489	558	542	545	Standard ground temperature is 15°C
300	745	825	534	623	601	597	
400	851	887	567	691	657	637	Conductor surface temperature is 90°C

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for Cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

9.4.2.1 Derating factor due to ambient air temperature

Manufacturers quote current ratings of their cables laid in air at a particular ambient temperature e.g., 25°C, 30°C and 45°C. They also provide tables of derating factors (K_{air}) based on the chosen ambient temperature, see the above tables, and Chapter 8 of Reference 4.

Table 9.16. Land based Installations. 600/1000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC 3 and 4 core

Nominal conductor area (mm^2)	Single core in trefoil		3 and 4 cores		Approximate armouring resistance	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	AWA at 80°C (ohm/km) 1-core	SWA at 80°C (ohm/km) 3/4 core
1.5			15.4	0.103		11.40
2.5			9.45	0.101		9.48
4			5.88	0.0929		5.52
6			3.93	0.0885		4.92
10			2.33	0.0835		4.08
16			1.47	0.0815		2.64
25			0.927	0.0818		2.52
35			0.668	0.0771		2.28
50	0.494	0.104	0.494	0.0765	1.018	1.56
70	0.342	0.101	0.342	0.0754	0.919	1.44
95	0.246	0.0969	0.247	0.0727	0.795	1.176
120	0.196	0.0920	0.197	0.0723	0.559	0.852
150	0.160	0.0945	0.160	0.0728	0.509	0.780
185	0.128	0.0932	0.128	0.0730	0.460	0.708
240	0.0985	0.0902	0.0989	0.0722	0.410	0.624
300	0.0799	0.0883	0.0802	0.0717	0.385	0.564
400	0.0639	0.0886	0.0656	0.0715	0.286	0.408

Table 9.17. Land based installations. 600/1000 V. Cu/XLPE/PVC/SWA/PVC 3 and 4 cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
1.5	26	26	32	
2.5	35	34	42	
4	47	45	55	
6	59	56	69	
10	82	75	92	
16	107	96	119	Thermal resistivity of soil 1.2°C m/W
25	140	124	152	
35	172	149	182	Ambient air temp. is 25°C
50	209	177	217	Depth of laying cables is 0.5 m
70	263	218	266	
95	324	263	319	Standard ground temp. is 15°C
120	376	300	363	Conductor surface temp. is 90°C
150	430	338	406	
185	495	382	458	
240	584	442	529	
300	666	496	592	
400	766	570	667	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.18. Land based Installations. 3800/6600 V. 6350/11,000 V. 8700/15,000 V. Cu/XLPE/PVC/AWA/PVC single core

Nominal conductor area (mm^2)	Air trefoil	Air 3 horizontally spaced	Ducts trefoil	Direct buried			Notes
				trefoil	3 horizontally touching	3 horizontally spaced	
50	250	300	220	220	220	230	Thermal resistivity of soil is 1.2°C m/W
70	310	370	260	270	270	280	
95	375	460	305	320	317	335	Ambient air temp. is 25°C
120	430	530	340	360	355	380	
150	490	600	375	410	403	430	Depth of laying cables is 0.5 m
185	550	690	410	455	445	485	
240	650	820	470	520	505	560	Standard ground temp. is 15°C
300	740	940	500	580	560	640	
400	840	1100	530	650	620	730	Conductor surface temp. is 90°C.

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.19. Land based Installations. 3800/6600 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.137
25			0.927	0.129
35			0.668	0.121
50	0.494	0.134	0.494	0.115
70	0.343	0.125	0.343	0.108
95	0.248	0.119	0.248	0.102
120	0.196	0.114	0.196	0.0988
150	0.159	0.111	0.159	0.0962
185	0.128	0.109	0.128	0.0931
240	0.098	0.105	0.098	0.0900
300	0.080	0.103	0.080	0.0874
400	0.064	0.100	0.064	0.0849

9.4.2.2 Derating factor due to ground temperature

Manufacturers quote current ratings of their cables laid in the ground at a particular ambient temperature e.g., 15°C and 20°C. They also provide tables of derating factors (K_{grd}) based on the chosen ground temperature, see the above tables, and Chapter 8 of Reference 4.

Table 9.20. Land based Installations. 6350/11,000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.137
25			0.927	0.129
35			0.668	0.121
50	0.494	0.138	0.494	0.115
70	0.343	0.130	0.343	0.108
95	0.248	0.123	0.248	0.102
120	0.196	0.118	0.196	0.0988
150	0.159	0.117	0.159	0.0962
185	0.128	0.112	0.128	0.0931
240	0.098	0.109	0.098	0.0900
300	0.080	0.105	0.080	0.0874
400	0.064	0.101	0.064	0.0849

Table 9.21. Land based Installations. 8700/15,000 V. Cu/XLPE/PVC/AWA/PVC single core Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Single core in trefoil		3 cores	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)
16			1.47	0.147
25			0.927	0.138
35			0.668	0.129
50	0.494	0.144	0.494	0.123
70	0.343	0.135	0.343	0.115
95	0.248	0.129	0.248	0.109
120	0.196	0.124	0.196	0.105
150	0.159	0.121	0.159	0.102
185	0.128	0.117	0.128	0.0986
240	0.098	0.113	0.098	0.0952
300	0.080	0.108	0.080	0.0922
400	0.064	0.107	0.064	0.0893

9.4.2.3 Derating factor due to thermal resistivity of the ground

Cables that are laid in the ground need to dissipate heat into their surroundings. The thermal conductivity of soil varies considerably from 0.7 km/W for wet soil e.g. near lakes, coastal areas, high water tables, to 3.0 km/W for very dry soil such as desert sand, see Reference 7.

The higher the value of thermal resistivity the more difficult it becomes to remove the heat from the cable. A value of 1.2 km/W is frequently used as the base value in data given by a manufacturer.

A typical value of 2.5 km/W is used for dry desert locations, which would cause the cable to be derated to approximately 75% of its nominal rating.

Cables are either laid directly in the ground, in some form of buried ducting system, or in air-filled trenches with lids. The most economical method is direct buried as far as the laying cost is concerned. However, factors such as ground bearing pollution and corrosive substances may require ducts or lined trenches to be used for the full route length. Direct burial will generally provide better heat removal than a ducting system, unless the soil is very dry. Dampness in the soil assists in the process of heat removal. Some installations such as refineries prefer concrete lined trenches with 'shelves' and lids. These will tend to have 'still air' conditions and the concrete enclosure will provide a thermal insulation effect. Hence a concrete trench may have a poorer heat removal property than direct burial in the same soil. See Reference 4 Chapter 8 for tables of derating factors for soil resistivity and grouping of cables that are buried.

9.4.2.4 Derating factor due to grouping cables together

Manufacturers quote current ratings of their cables laid in air or in the ground for a few simple cases of grouping cables together e.g., in trefoil, 3 cables touching horizontally, 3 cables touching vertically, cables spaced apart by a multiple of their outside diameter. The number of combinations of groups of cables, with different spacings and surroundings, becomes far too many to tabulate. This subject has received much attention by cable manufacturers, research establishments and the international standards organisations, see References 8 and 9, BS7672, IEC60287, IEC60364.

For a particular project it is common practice to determine a small number of grouping cases that will apply to most of the cable routes. Special cases such as the trenches entering a large substation or a switch house would require a separate set of factors and derating calculations, because these trenches could be tightly filled with cables. It is common for cables to be laid in horizontal groups e.g., on trays or racks, and vertically e.g., one tray above another. The spacing between the vertical groups will influence the derating factors to apply at each level.

9.4.2.5 The worst-case scenario

A cable may experience various different environments along its route. For example it may start at a switchboard, run through the switch room in a trench with a lid or steel flooring, pass through a duct in a wall and under a roadway, run a long way directly buried and finish on a ladder rack at the consumer. At each of these environments the thermal resistivity and ambient temperature will be different. The environment that causes the most derating of the rated current should be taken and used for the whole cable.

9.4.2.6 Worked example

A 5 MVA 11,000/6900 V ONAF transformer is installed in a desert in the Middle East. Its 11,000 V primary 3-core cable is laid in the ground in a duct at a depth of 1000 mm. Its 6900 V secondary 3-core cable is run above ground in air. The air temperature is 45°C. The primary 3-core cable runs in the same ducted trench as several other cables, less than 6, in horizontal spacing. The trench is back filled with dry sand that has a thermal resistivity of 2.5 km/W. The ground temperature is 35°C.

The secondary cable runs on its own cable rack to a switchboard. Both cable routes are short enough to neglect volt-drop considerations. Find suitable Cu/XLPE/PVC/SWA/PVC cable conductor sizes.

Suitable derating factors:-

a) For air ambient temperature $K_{\text{air}} = 0.84$
b) For ground temperature $K_{\text{grd}} = 0.86$
c) For grouping cables in air $K_{\text{ga}} = 1.00$
d) For grouping cables in the ground $K_{\text{gg}} = 0.65$
e) For ground thermal resistivity $K_{\text{gth}} = 0.75$
f) For depth of burial $K_{\text{bury}} = 0.98$
g) For using ducts in ground $K_{\text{duct}} = 0.875$
h) Overall derating factor for air $K_a = K_{\text{air}} \times K_{\text{ga}} = 0.84$
i) Overall derating factor for ground $K_g = K_{\text{grd}} \times K_{\text{gg}} \times K_{\text{gth}} \times K_{\text{bury}} \times K_{\text{duct}}$
$= 0.86 \times 0.65 \times 0.75 \times 0.98 \times 0.875 = 0.36$

Solution for primary cable:

Calculate the primary current for the ONAF loading of 5 MVA.

$$\text{Primary current } I_p = \frac{5000000}{\sqrt{3} \times 11000} = 262.4 \text{ amps}$$

Overall derating factor $= K_g = 0.36$

$$\text{Cable equivalent current at } 25^\circ\text{C} = I_{c25} = \frac{I_p}{K_g} = \frac{262.4}{0.36} = 728.9 \text{ amps}$$

From Table 9.22 the nearest cable rated current equal to or greater than 728.9 amps for cables run in air is 740 amps for a 400 mm^2 3-core cable. This choice would have a spare capacity in the cable of only 1.5%, which is rather low for a practical design. A 400 mm^2 high voltage cable is also difficult to manipulate during laying. A better choice would be two cables in parallel. The same overall derating factor can be used if the two cables are spaced sufficiently far apart.

$$\text{Cable equivalent current at } 25^\circ\text{C} = \frac{I_{c25}}{2} \text{ per cable} = 364.4 \text{ amps.}$$

From Table 9.22 a suitable cable size to provide at least a 10% margin is 150 mm^2, giving a rated current in air of 430 amps. Hence the appropriate choice for the primary is 2 × 3c × 150 mm^2 cables. The margin will allow for short duration overloading of the transformer.

Solution for the secondary cable:

The corresponding secondary current

$$I_s = 262.4 \times \frac{11000}{6900} = 418.3 \text{ amps}$$

Overall derating factor $= K_a = 0.84$

$$\text{Cable equivalent current at } 25^\circ\text{C} = I_{\text{c25}} = \frac{I_s}{K_a} = \frac{418.3}{0.84} = 498.0 \text{ amps}$$

Table 9.22. Land based Installations. 3800/6600 V. 6350/11,000 V. 8700/15,000 V. Cu/XLPE/PVC/SWA/PVC three cores

Nominal conductor area (mm^2)	Air	Ducts	Direct buried	Notes
25	145	125	140	Thermal resistivity of soil is 1.2°C m/W
35	175	150	170	
50	220	180	210	Ambient air temp. is 25°C.
70	270	215	255	Depth of laying cables is 0.5 m
95	330	255	300	
120	375	290	340	Standard ground temp. is 15°C
150	430	330	380	
185	490	370	430	Conductor surface temp. is 90°C.
240	570	425	490	
300	650	470	540	
400	740	530	600	

Ambient air temperature °C	25	30	35	40	45	50	55	60
Rating factor K_{air} for cables laid in air	1.0	0.96	0.92	0.88	0.84	0.79	0.73	0.68
Ground temperature °C	10	15	20	25	30	35	40	
Rating factor K_{grd} for cables laid in the ground	1.03	1.0	0.97	0.93	0.89	0.86	0.82	

Table 9.23. Marine and offshore 600/1000 V Cu/EPR/CSP/GSWB or PBWB/CSP or PVC installations. Cables run on open trays or enclosed in air. 1 to 6 × single, 3 or 4 cores

Nominal conductor area (mm^2)	Single cores	3 and 4 cores	Notes
1.0	17	12	Ambient air temperature is 45°C
1.5	21	15	
2.5	30	21	
4	40	29	Conductor surface temperature is 90°C.
6	51	36	
10	71	50	
16	95	67	
25	125	89	
35	155	105	
50	190	135	
70	240	170	
95	290	205	
120	340	240	
150	385	270	
185	440	305	
240	520	365	
300	590	415	
400	670	470	

Ambient air temperature °C	35	40	45	50	55	60	65	70	75	80
Rating factor for cables laid in air	1.11	1.05	1.0	0.94	0.88	0.82	0.75	0.69	0.58	0.47

Table 9.24. Marine and offshore 600/1000 V. Cu/EPR/CSP/GSWB or PBWB/CSP or PVC installations. Cables run on open trays or enclosed in air. 1 to 6 × single, 3 or 4 cores

Nominal conductor area (mm^2)	Single cores in trefoil		3 cores		Approximate armouring resistance	
	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	Resistance at 90°C (ohm/km)	Reactance at 50 Hz (ohm/km)	PBWB at 60°C 1-core (ohm/km)	GSWB at 60°C 3–4 cores (ohm/km)
1.5	15.6	0.185	15.6	0.118		46.2
2.5	9.64	0.173	9.64	0.111		51.3
4	5.99	0.163	5.99	0.108		60.3
6	3.97	0.153	3.97	0.105		30.5
10	2.35	0.148	2.35	0.0983		36.7
16	1.48	0.134	1.48	0.0933		23.1
25	0.936	0.125	0.936	0.0892		28.1
35	0.674	0.121	0.674	0.0867		10.43
50	0.499	0.118	0.499	0.0858		11.81
70	0.344	0.112	0.344	0.0850		13.61
95	0.271	0.108	0.271	0.0825		10.87
120	0.214	0.106	0.214	0.0808		11.92
150	0.175	0.105	0.175	0.0808		7.38
185	0.140	0.105	0.140	0.0808		8.15
240	0.108	0.103	0.108	0.0800		8.94
300	0.087	0.101	0.087	0.0800		10.10
400	0.069	0.0992	0.069	0.0795		10.00

From Table 9.22 the nearest cable size to provide at least 10% margin is 240 mm^2. Hence the appropriate choice for the secondary is 1 × 3c × 240 mm^2 cable.

9.4.3 Volt-drop within a Cable

The actual voltage received by the load at its terminals must be taken into account when selecting a suitable size of cable. An individual consumer is the last item in a series of power system components. Upstream of the load is its own cable, a switchboard, a feeder transformer to switchboard and a cable or overhead line feeding the transformer. All these components will have a volt-drop associated with the current passing through their conductors. When the switchboard is fully loaded, and the tap setting of its feeder transformer is optimally selected, its busbar voltage may not necessarily be the nominal voltage of the system. It could be slightly above or below the nominal value. It is customary to assume a slightly lower busbar voltage when the switchboard is fully loaded under steady state conditions, typically a reduction of 1% can be assumed.

If a switchboard acts as a motor control centre, and it has a predominance of induction motors that are started direct-on-line, then consideration should be given to the voltage deviation at the busbars when groups of motors need to be automatically reaccelerated. Plant processes often require automatic reacceleration of motors shortly after there is a large voltage drop at the busbars, see sub-section 7.7.

Large or complete voltage depressions occur as a result of short circuits at or near the switchboard. The duration of the voltage depression is mainly determined by the response time of the relay or fuse protective devices closest to the point of fault. Individual oil companies tend to have their own philosophy for detecting and responding to the voltage depressions, and to the reacceleration of motors. In order to account for voltage depression and the reacceleration of large groups of motors it may be necessary to allow up to 10% for the drop in busbar voltage during the whole reacceleration period, which may be several seconds. At the same time the voltage received at the terminals of each load should not fall below 80% of its nameplate value. This represents a serious constraint on the sizing of motor feeder cables in particular, due to the high starting currents and their very low power factors. The situation is made worse for long route lengths with low voltage high power motors e.g., 400 volts, 90 to 200 kW motors. Unusually large conductor sizes will result in these situations, which can also make their termination at the load end awkward.

The voltage drop in a cable is due to its series resistance and series inductive reactance. The shunt capacitive reactance is usually too large to be considered for cables installed in a typical plant. However, for long distance high voltage cables, such as submarine cables, the shunt capacitance may need to be included in the calculations of voltage drop.

9.4.3.1 Volt drop in short cables

Let the series resistance be R ohms and the series inductive reactance be X ohms for a cable of length 1 kilometre. Manufacturers usually quote the impedance data in ohms/km or mohms/m. Assume a load current I amperes with a lagging power factor of $\cos\emptyset$. The sending end phase voltage is V_s and the receiving end phase voltage is V_r. Figure 9.1 shows the phasor diagram of the volt-drop conditions in the cable.

The components of the phasor voltages are:-

$$AB = IR\cos\emptyset$$

$$BE = IR\sin\emptyset$$

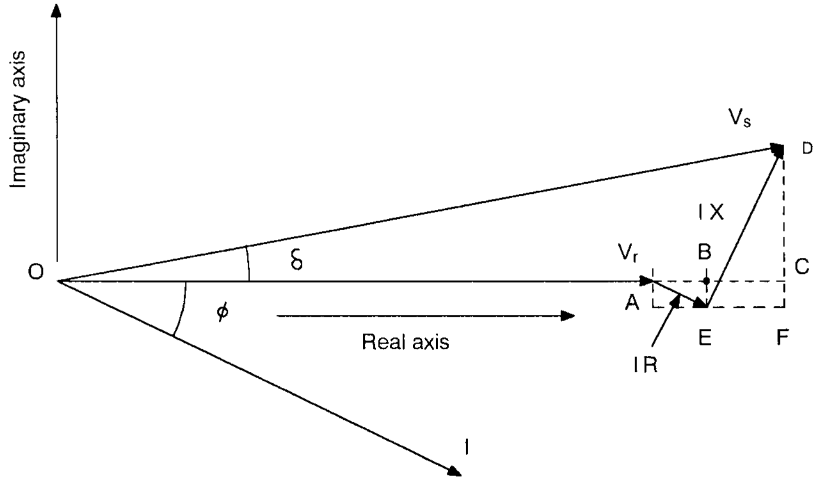

Figure 9.1 Phasor diagram of a loaded cable at a lagging power factor.

$$\mathrm{EF} = \mathrm{IX}\sin\emptyset$$

$$\mathrm{DF} = \mathrm{IX}\cos\emptyset$$

$$\mathrm{AC} = \mathrm{AB} + \mathrm{BC} = \mathrm{AB} + \mathrm{EF} = \mathrm{IR}\cos\emptyset + \mathrm{IX}\sin\emptyset \tag{9.1}$$

$$\mathrm{DC} = \mathrm{DF} - \mathrm{CF} = \mathrm{DF} - \mathrm{BE} = \mathrm{IX}\cos\emptyset - \mathrm{IR}\sin\emptyset$$

$$V_s = \mathrm{OD} = \sqrt{(\mathrm{OA} + \mathrm{AB} + \mathrm{BC})^2 + (\mathrm{DF} - \mathrm{BE})^2}$$

Unless the cable is exceptionally long the bracketed terms can be compared as:-

$$(\mathrm{OA} + \mathrm{AB} + \mathrm{BC})^2 \gg (\mathrm{DF} - \mathrm{BE})^2 \tag{9.2}$$

Therefore the right-hand bracket can be ignored, and:-

$$\begin{aligned} V_s &\simeq \mathrm{OA} + \mathrm{AB} + \mathrm{BC} \\ &= V_r + \mathrm{IR}\cos\emptyset + \mathrm{IX}\sin\emptyset \quad \text{volts/phase} \end{aligned}$$

The ‘volt-drop’ ΔV is normally considered as a per-unit or percentage quantity with respect to the sending end line-to-line voltage V, therefore:-

$$\Delta \mathrm{V} \simeq \frac{\sqrt{3}I(\mathrm{R}\cos\emptyset + \mathrm{X}\sin\emptyset)100}{V} \quad \% \tag{9.3}$$

which is the equation often quoted in cable data publications.

Note $R = rl$ and $X = xl$

Where, r is the specific resistance and x is specific reactance in ohm/km or m ohm/m and l is the route length in km.

9.4.3.1.1 Worked example

A 120 mm^2 3-core XLPE insulated cable 150 m in length feeds a 110 kW induction motor that has a starting current of 6.5 times the full-load current of 180 amps. The starting power factor is 0.35 lagging. The sending end line-to-line voltage is 400 volts. The specific resistance r and reactance x for the cable are 0.197 and 0.072 ohm/km respectively at 90°C and 50 Hz. Find the percentage volt-drop on starting the motor.

The cable.

The series impedance is:-

$$R = rl = \frac{0.197 \times 150}{1000} = 0.0296 \text{ ohms/phase}$$

$$X = xl = \frac{0.072 \times 150}{1000} = 0.0108 \text{ ohms/phase}$$

Note that for low voltage cables R is greater than X until the size is in the order of 300 mm^2.

The motor.

The starting current is:-

$$I = 6.5 \times 180.0 = 1170.0 \text{ amps}$$

The power factor is:-

$$\cos \text{Ø} = 0.35, \text{ therefore } \sin \text{Ø} = 0.9368$$

Solution:

From (9.1), assume the sending voltage is constant at 400 volts.

$$\begin{aligned} AB &= 1170.0 \times 0.0296 \times 0.3500 = 12.121 \text{ volts/phase} \\ BE &= 1170.0 \times 0.0296 \times 0.9368 = 32.443 \text{ volts/phase} \\ EF &= 1170.0 \times 0.0108 \times 0.9368 = 11.837 \text{ volts/phase} \\ DF &= 1170.0 \times 0.0108 \times 0.3500 = 4.423 \text{ volts/phase} \end{aligned}$$

From (9.3),

$$\begin{aligned} \Delta V &\simeq \frac{\sqrt{3} \times 1170.0(0.0296 \times 0.35 + 0.0108 \times 0.9368) \times 100}{400} \\ &= 506.625(0.01036 + 0.01012) \\ &= 10.374\% \end{aligned}$$

Therefore,

$$\begin{aligned} V_r &\simeq \frac{400}{\sqrt{3}}(1.0 - 0.10374) \\ &= 206.98 \text{ volts/phase} \end{aligned}$$

From (9.2),

$$\begin{aligned} (OA + AB + BC)^2 &= (206.98 + 12.121 + 11.837)^2 \\ &= 230.939^2 = 53333.05 \end{aligned}$$

And

$$\begin{aligned} (DF - BE)^2 &= (4.423 - 32.443)^2 \\ &= 28.02^2 = 785.12 \end{aligned}$$

Hence the inequality in (9.2) is valid and the solution is accurate.

Since the volt-drop is less than 20% the motor will accelerate to full speed without difficulty.

9.4.3.2 Volt-drop in long cables

Let the series resistance be R ohms, the series inductive reactance be X_l ohms and the total shunt capacitive reactance X_c ohms for a cable of 1 kilometre. Manufacturers usually quote the shunt capacitance data in microfarads/km.

The method described in sub-section 9.4.3.1 may not always be sufficiently accurate for long cables where the shunt capacitive reactance cannot be neglected. Two more accurate methods can be used in which the cable is treated as an equivalent ‘Tee’ or an equivalent ‘Pye’ circuit, see Figures 9.2 and 9.3.

In these methods the complete solution must be found without the simplification made in (9.2). These methods will be shown by an example.

9.4.3.2.1 Worked example

A 240 mm^2 3-core polymeric insulated cable 25 km in length feeds a static load of 20 MVA at a power factor of 0.95 lagging. The nominal system voltage is 33,000 V and the sending end voltage

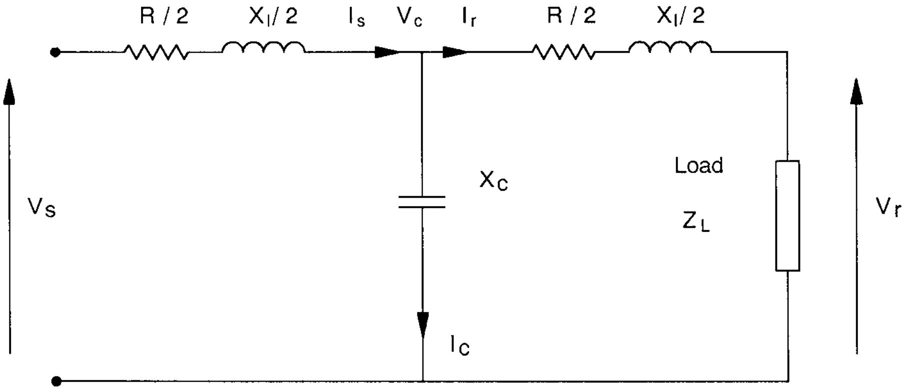

Figure 9.2 Equivalent Tee circuit of a long cable.

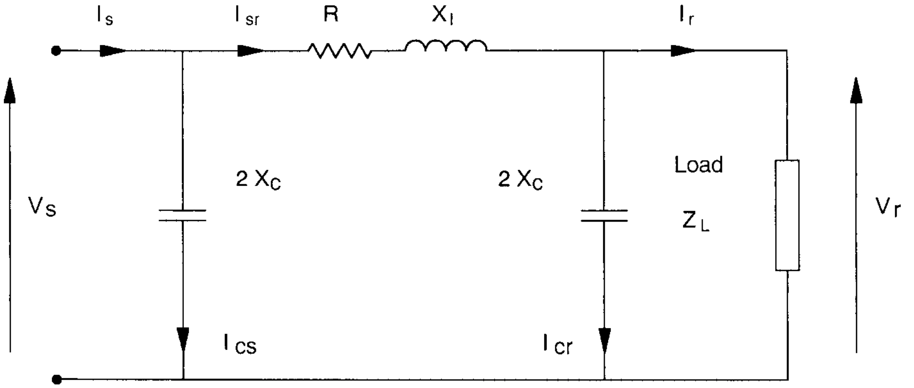

Figure 9.3 Equivalent Pye circuit of a long cable.

is 33,700 V. The specific resistance r, inductive reactance x_l and capacitance c are 0.100 ohm/km, 0.110 ohm/km and 0.24 microfarad/km respectively at 90°C and 50 Hz. Find the percentage volt-drop at the receiving end.

The cable.

The series impedance is:-

$$R = r.l = 0.100 \times 25 = 2.50 \text{ ohms/phase}$$

$$X_l = x_l.l = 0.110 \times 25 = 2.75 \text{ ohms/phase}$$

$$C = c.l = 0.24 \times 25 = 6.00\ \mu\text{F/phase}$$

$$X_c = \frac{10^6}{2\pi fC} = \frac{10^6}{2\pi \times 50 \times 6.0} = 530.52 \text{ ohms/phase}$$

The load.

The system nominal voltage V_n is 33,000 volts.

The line current I_r received at the load is,

$$I_r = \frac{\text{Load MVA} \times 10^6}{\sqrt{3} \text{ line voltage}} = \frac{S_L \times 10^6}{\sqrt{3}\ V_n}$$

$$= \frac{20.0 \times 10^6}{\sqrt{3} \times 33000.0} = 349.91 \text{ amps/phase}$$

The load star connected impedance Z_L is,

$$Z_L = \frac{V_n}{\sqrt{3} I_r} = \frac{33000}{\sqrt{3} \times 349.91} = 54.45 \text{ ohms/phase}$$

The resistive component R_L is,

$$R_L = Z_L \cos \text{Ø} = 54.45 \times 0.95 = 51.728 \text{ ohms/phase}$$

The inductive component X_L is,

$$X_L = Z_L \sin \text{Ø} = 54.45 \times 0.3123 = 17.002 \text{ ohms/phase.}$$

a) The ‘Tee’ equivalent circuit.

The two series elements are,

$$\frac{R}{2} + j\frac{X_1}{2} = 1.25 + j1.375 \text{ ohms/phase}$$

The single shunt element is

$$X_c = -j530.52 \text{ ohms/phase}$$

The solution sequence.

i) Calculate the total impedance seen by the sending end voltage.
ii) Calculate the total sending current.
iii) Calculate the voltage at the centre of the cable, which supplies the shunt capacitance.
iv) Calculate the voltage at the load.

i) The impedance Z_1 to the right-hand side of the shunt reactance is,

$$\begin{aligned}Z_1 &= \frac{R}{2} + j\frac{X_1}{2} + R_L + jX_L\\ &= 1.25 + j1.375 + 51.728 + j17.002 \text{ ohms/phase}\\ &= 52.978 + j18.377 \text{ ohms/phase}\end{aligned}$$

Z_1 is connected in parallel with X_c and so their total impedance is Z_2, which is,

$$\begin{aligned}Z_2 &= \frac{Z_1.X_c}{Z_1 + X_c} = \frac{(52.978 + j18.377)(j530.52)}{52.978 + j18.377 - j530.52}\\ &= 56.246 + j13.218 \text{ ohms/phase}\end{aligned}$$

Z_2 is connected in series with the left-hand side series impedance; hence their total is,

$$\begin{aligned}Z_3 &= Z_2 + \frac{R}{2} + j\frac{X_1}{2}\\ &= 56.246 + j13.218 + 1.25 + j1.375\\ &= 57.496 + j14.593 \text{ ohms/phase}\end{aligned}$$

ii) This impedance is seen by the sending end phase voltage V_s, hence the sending end current I_s is,

$$\begin{aligned}I_s &= \frac{V_s}{Z_3} = \frac{33700.0}{\sqrt{3}(57.496 + j14.593)}\\ &= \frac{19456.7(57.496 - j14.593)}{3518.75}\\ &= 317.92 - j80.691 \text{ amps}\\ |I_s| &= 328.00 \text{ amps}\end{aligned}$$

The volt-drop in the left-hand side of the cable is V_{sc},

$$\begin{aligned}V_{sc} &= I_s\left(\frac{R}{2} + j\frac{X_1}{2}\right) = (317.92 - j80.691)(1.25 + j1.375)\\ &= 508.35 + j336.28 \text{ volts/phase}\end{aligned}$$

iii) Hence the voltage across the capacitance is,

$$\begin{aligned}V_c &= V_s - V_{\mathrm{sc}}\\&= 19456.7 + j0.0 - 508.35 - j336.28\\&= 18948.35 - j336.28 \text{ volts/phase}\end{aligned}$$

The charging current I_c for the capacitance is,

$$\begin{aligned}I_c &= \frac{V_c}{X_c} = \frac{18949.35 - j336.28}{-j530.52}\\&= 0.634 + j35.716 \text{ amps}\end{aligned}$$

Deduct I_c from I_s to find I_r,

$$\begin{aligned}I_r &= I_s - I_c = 317.92 - j80.691 - 0.634 - j35.716\\&= 317.286 - j116.41 \text{ amps}\end{aligned}$$

The volt-drop in the right-hand side of the cable is V_{cr},

$$\begin{aligned}V_{cr} &= I_r\left(\frac{R}{2} + j\frac{X_1}{2}\right) = (317.286 - j116.41)(1.25 + j1.375)\\&= 556.671 + j290.756 \text{ volts/phase}\end{aligned}$$

iv) Hence the voltage received at the load is,

$$\begin{aligned}V_r &= V_c - V_{cr}\\&= 18948.35 - j336.28 - 556.671 - j290.756\\&= 18391.68 - j627.04 \text{ volts/phase}\\|V_r| &= 18402.36 \text{ volts/phase}\end{aligned}$$

The total actual volt-drop

$$\begin{aligned}\Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100\\&= \frac{(19456.7 - 18402.36)100}{19456.7} = 5.419\%\end{aligned}$$

The receiving end volt-drop with respect to the nominal system voltage is ΔV_n,

$$\begin{aligned}\Delta V_n &= \frac{|V_n| - |V_r|}{|V_n|} \times 100\\&= \frac{(19052.6 - 18402.36)}{19052.6}100 = 3.413\%\end{aligned}$$

b) The 'Pye' equivalent circuit.

The single series element is,

$$R + jX_1 = 2.50 + j2.75 \text{ ohms/phase}$$

The two-shunt elements are,

$$2\mathrm{X}_c = -\mathrm{j}1061.04 \text{ ohms/phase}$$

The solution sequence.

i) Calculate the total impedance seen by the sending end voltage.
ii) Calculate the total sending end current.
iii) Calculate the sending end shunt current.
iv) Calculate the receiving end voltage.

i) The parallel combination of the load impedance and the right-hand side shunt capacitive reactance is,

$$\begin{aligned} Z_4 &= \frac{(R_L + jX_L)2X_c}{R_L + jX_L + 2X_c} \\ &= \frac{(51.728 + j17.002)(-1061.04)}{51.728 + j17.002 - j1061.04} \\ &= 53.296 + j14.638 \text{ ohms/phase} \end{aligned}$$

Z_4 is connected in series with the series impedance of the cable, hence their total is,

$$\begin{aligned} Z_5 &= Z_4 + R + jX_1 \\ &= 53.296 + j14.638 + 2.50 + j2.75 \\ &= 55.795 + j17.388 \text{ ohms/phase} \end{aligned}$$

Z_5 is connected in parallel with the left-hand side shunt capacitive reactance, hence this total Z_6 is,

$$\begin{aligned} Z_6 &= \frac{Z_5 2X_c}{Z_5 + 2X_c} = \frac{(55.795 + j17.388)(-j1061.04)}{55.795 + j17.388 - j1061.04} \\ &= 57.506 + j14.603 \text{ ohms/phase} \end{aligned}$$

This impedance is seen by the sending end phase voltage V_s, hence the sending end current I_s is,

$$\begin{aligned} I_s &= \frac{V_s}{Z_6} = \frac{33700.0}{\sqrt{3}(57.506 + j14.603)} \\ &= \frac{19456.7(57.506 - j14.603)}{3520.19} \\ &= 317.85 - j80.713 \text{ amps} \\ |I_s| &= 327.93 \text{ amps} \end{aligned}$$

The charging current at the sending end I_{cs} is,

$$I_{cs} = \frac{V_s}{2X_c} = \frac{19456.7}{-j1061.04} = +j18.337 \text{ amps}$$

Deduct I_{cs} from I_s to obtain I_{sr},

$$\begin{aligned} I_{sr} &= I_s - I_{cs} = 317.85 - j80.713 - j18.337 \\ &= 317.85 - j99.05 \end{aligned}$$

The volt-drop V_{sr} in the series impedance is,

$$\begin{aligned} V_{sr} = I_{sr}(R + jX_1) &= (317.85 - j99.05)(2.5 + j2.75) \\ &= 794.63 + j874.09 - j247.625 + 272.39 \\ &= 1067.02 + j626.46 \text{ volts/phase} \end{aligned}$$

Hence the voltage received at the load is,

$$\begin{aligned} V_r &= V_s - V_{sr} \\ &= 19456.7 - 1067.02 - j626.46 \\ &= 18389.68 - j626.46 \\ |V_r| &= 18400.35 \text{ volts/phase} \end{aligned}$$

The total actual volt-drop

$$\begin{aligned} \Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100 \\ &= \frac{(19456.7 - 18400.35)100}{19456.7} = 5.429\% \end{aligned}$$

The receiving end volt-drop with respect to the nominal system voltage is ΔV_n,

$$\begin{aligned} \Delta V_n &= \frac{|V_n| - |V_r|}{|V_n|} \times 100 \\ &= \frac{(19052.6 - 18400.35)100}{19052.6} = 3.423\% \end{aligned}$$

c) Neglecting the shunt capacitive reactance.

The method of 9.4.3.1 can be used for a long cable to compare the results and accuracy obtained. The current in the load based on the nominal system voltage is I,

$$I = \frac{S_L \times 10^6}{\sqrt{3}V_n} = 349.91 \text{ amps/phase}$$

And from Figure 9.1,

$$AB = 349.91 \times 2.50 \times 0.9500 = 831.04$$

$$BE = 349.91 \times 2.50 \times 0.3123 = 273.19$$

$$EF = 349.91 \times 2.75 \times 0.3123 = 300.51$$

$$DF = 349.91 \times 2.75 \times 0.9500 = 914.14$$

$$\Delta V \simeq \frac{\sqrt{3}(831.04 + 300.51)\ 100}{33700} = 5.816\%$$

Alternatively the volt-drop can be calculated by solving the circuit conditions shown in Figure 9.4, as follows:-

By simple proportions V_r can be found from V_s as follows,

$$\begin{aligned}\frac{V_r}{V_s} &= \frac{Z_L}{R + X_l + Z_L}\\ &= \frac{51.728 + j17.002}{2.5 + j2.75 + 51.728 + j17.002}\\ &= 0.94299 + j0.02995\end{aligned}$$

Therefore,

$$\begin{aligned}V_r &= (0.94299 + j0.02995)(19456.7)\\ &= 18347.47 + j582.73\end{aligned}$$

And

$$|V_r| = 18356.73 \text{ volts/phase}$$

The total actual volt-drop

$$\begin{aligned}\Delta V &= \frac{|V_s| - |V_r|}{|V_s|} \times 100\\ &= \frac{(19456.7 - 18356.73) \times 100}{19456.7} = 5.653\%\end{aligned}$$

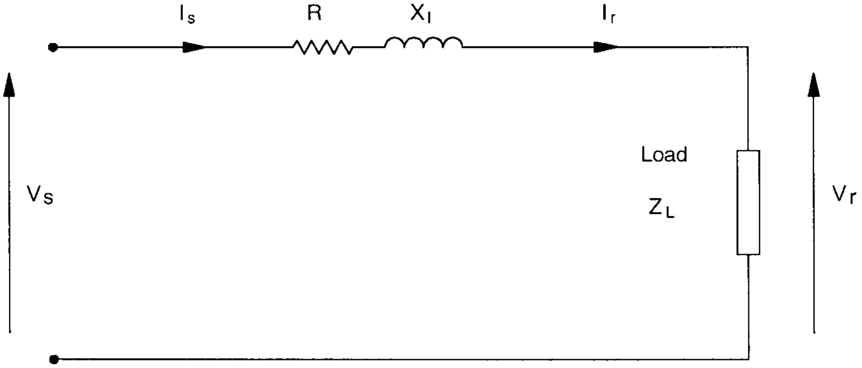

Figure 9.4 Equivalent simple circuit of a long cable. A long cable as a simple series circuit.

By comparing the four methods it can be seen that the results in order of pessimism are:-

Method	Result	Note
Tee equivalent circuit	5.419%	Optimistic
Pye equivalent circuit	5.429%	
Simple series circuit	5.653%	
ΔV formula	5.816%	Pessimistic

In the early stages of a project the pessimistic estimate by the ΔV formula, (9.3), would give a conservative result. Towards the end of a project the 'Tee' or 'Pye' equivalent circuit would give a more appropriate result.

9.4.3.3 Volt-drop in motor feeder cables

When calculating the volt-drop in low voltage motor feeder cables it is necessary to consider three factors in particular:-

a) The full-load running current.

b) The starting current.

c) The maximum route length.

Typical limiting values for the steady state volt-drop at the receiving end of LV and HV cables are:-

Receiving end consumer	Allowable volt-drop% of nominal
HV switchboard (no motors)	1.0
HV motor control centre	1.0
LV main switchboard (no motors)	1.0
LV main motor control centre	1.0
LV auxiliary motor control centre	2.0 to 3.0
HV motor terminals at full-load	1.5 to 3.0
LV motor terminals at full-load	2.5 to 5.0
HV motor terminals at starting	15 to 20
LV motor terminals at starting	20

Equation (9.3) can be used to determine the maximum route length that can be accepted for a) and b) above. Usually two different values of route length will be obtained and the shortest should be taken for selecting the cable size. Equation (9.3) can be transposed to find the route length as follows,

$$\Delta V = \frac{\sqrt{3}I(rl\cos\text{Ø} + xl\sin\text{Ø})}{V}100\%$$

$$l = \frac{V.\Delta V}{100\sqrt{3}I(r\cos\text{Ø} + x\sin\text{Ø})}\ \text{km} \qquad (9.5)$$

9.4.3.3.1 Worked example

A 132 kW induction motor is connected to a 415 V 3-phase 50 Hz supply. The motor has the following performance data,

- Running power factor $\cos Ø_r = 0.88$
- Running efficiency $\eta = 95.2\%$
- Starting current $= 7.0 \times$ running current
- Starting power factor $\cos Ø_s = 0.35$ lagging

Find the smallest cable size and its maximum route length to satisfy a running volt-drop of 5% and a starting volt-drop of 15%. Choose an XLPE insulated 600/1000 V 3-core cable to be routed in air. The ambient air temperature is 25°C.

Solution:

Running conditions:-

The full-load current I_{fl} of the motor is:-

$$\begin{aligned} I_{\text{fl}} &= \frac{\text{Rated power}}{\sqrt{3}\ \text{Line voltage} \times \text{Power factor} \times \text{Efficiency}} \\ &= \frac{132000}{\sqrt{3} \times 415 \times 0.88 \times 0.952} = 219 \text{ amps} \end{aligned}$$

From Table 9.17 the smallest cable size for a running current of 219 amps is 70 mm^2 which from Table 9.16 has a specific resistance r of 0.342 ohm/km and a specific reactance x at 50 Hz of 0.0754 ohm/km.

From (9.5) the route length l_{fl} full-load consideration is,

$$\begin{aligned} l_{\text{fl}} &= \frac{415 \times 5.0}{100\sqrt{3} \times 219 \times (0.342 \times 0.88 + 0.0754 \times 0.4750)} \\ &= 0.1624 \text{ km} = 162 \text{ metres.} \end{aligned}$$

Starting conditions:

The starting current I_{st} of the motor is:-

$$I_{\text{st}} = 7.0 \times I_{\text{fl}} = 7.0 \times 219 = 1533 \text{ amps}$$

From (9.5) the route length l_{st} is,

$$\begin{aligned} l_{\text{st}} &= \frac{415 \times 15.0}{100\sqrt{3} \times 1533 \times (0.342 \times 0.35 + 0.0754 \times 0.9368)} \\ &= 0.1229 \text{ km} = 123 \text{ metres.} \end{aligned}$$

It can be seen that starting current determines the route length to be no greater than 123 metres. If the actual route length is longer than 123 metres then a larger size of cable must be used. If the starting volt-drop is allowed to be 20% then the route length l_{st} would be 164 metres, and the running current would determine the maximum route length to be 162 metres.

9.4.3.4 Cable-sizing tables

It is common practice to prepare cable-sizing tables for low voltage cables that are to be used for a particular project. These tables are usually prepared for,

- Three-phase motors.
- Three-phase static loads.
- Single-phase static loads.
- DC static loads.

Each table should state the operating conditions that apply e.g.,

- Ambient temperature.
- Cable type and construction.
- Cable conductor maximum operating temperature.
- Derating factor for ambient air temperature.
- Derated cable current for each size of cable.
- Motor or static load kW rating.
- Motor or static load running power factor.
- Motor or static load running current.
- Type of protection e.g., fuses, moulded case circuit breakers.

Table 9.25 is a typical example for induction motors and EPR insulated cables.

9.4.3.5 Heat dissipation during short circuits

When a short circuit occurs in a cable the surface temperature of the conductor will rise rapidly. If the short circuit is allowed to persist the temperature will increase to values that will permanently damage the cable insulation. Protective devices such as fuses or circuit breakers will normally operate well before damage can occur. However, the cable manufacturers design cables to withstand a certain level of current for a specified length of time. The level of current will depend mainly on the insulating material used. Table 9.5 shows the maximum temperature that can be allowed to exist for a period of 5 seconds for different insulating materials, see IEC60502, IEC60364, Chapter 9 of Reference 4.

The heat Q developed in the conductor due to its resistance R when current I passes for a time of t seconds is,

$$Q = I^2 Rt \text{ joules}$$

This amount of heat is absorbed into the insulation material. If the initial temperature θ_1 of the conductor is its maximum continuous value e.g., 70°C for PVC, 90°C for XLPE and EPR when rated current I_{fl} flows, and the temperature limit θ_2 is the maximum allowed for the insulation e.g., 160°C for PVC, 250°C for XLPE and EPR when a short-circuit current I_{sc} flows, then an equation relating current and time can be given as (see Reference 4 Chapter 9, or Appendix A of IEC60364),

$$(I_{\text{sc}} - I_{\text{fl}})^2 = \frac{A^2k^2}{t} \log_e \left[\frac{\theta_2 + 234.5}{\theta_1 + 234.5} \right] \tag{9.6}$$

Table 9.25. Cable-sizing chart for DOL induction motors

Motor information				Cable information EPR cable size in mm^2													
Motor rating (kW)	Motor FLC current (A)	Motor FLC power factor	Motor I_s/I_n ratio	2.5	4	5	10	16	25	35	50	70	95	120	150	185	240
				Derated cable current in amps													
11	19	0.86	6.5	19	26	33	46	62	83	99	124	159	193	223	253	288	343
15	25	0.87	7.2	Maximum route length in metres (in this case limited by starting current)													
18.5	30	0.89	7.0		105	156	254	389									
22	36	0.88	7.0			99	162	249	375								
30	51	0.86	7.0				123	190	287	377							
37	63	0.85	7.0				106	164	249	328							
45	76	0.85	7.0					110	166	219	278						
55	94	0.84	7.0						187	241	299	379					
75	124	0.86	7.0						155	200	248	314					
90	146	0.87	7.0							164	204	257	307				
110	178	0.88	7.0								154	195	233	276			
132	214	0.88	7.0									165	198	234	256		
150	243	0.88	7.0										162	192	210	230	
185	297	0.88	7.0											163	178	194	210
200	317	0.89	7.0												156	171	185
																152	158
																	148

Note:
a) Volt-drop on starting 15%.
b) Volt-drop at full-load 5%.
c) Ambient temperature 30°C.
d) System voltage 440 V at 60 Hz.
e) Cable derating factor for ambient temperature and grouping in air is 0.93.

Let

$$K^2 = k^2 \log_e \left[\frac{\theta_2 + 234.5}{\theta_1 + 234.5} \right]$$

For copper conductors

$$k = 226$$

$$K^2 \text{ for PVC} = 226^2 \log_e \left[\frac{160 + 234.5}{70 + 234.5} \right]$$

$$= 226^2 \times 0.25589$$

Therefore

$$K = 226 \times 0.5088 = 115$$

Similarly for XLPE and EPR, $K = 143$.

For bare copper in air with a final temperature of 150°C and an initial temperature of 70°C the value of K is 109. If the initial current is zero and the initial temperature is 30°C then K is 138. See Table 54 B of IEC60364 Part 5, Chapter 54. If the final temperature is allowed to be 250°C then the value of K will be in the order of 170 to 180.

In the calculation of short-circuit current it is usually assumed that this current is much larger than the normal load current even if it is its full-load value. Hence I_{fl} in (9.6) can be ignored, thereby giving the form of equation found in the reference literature,

$$I_{sc} = \frac{AK}{\sqrt{t}} \text{ amps} \tag{9.7}$$

Or

$$A = \frac{I_{sc}\sqrt{t}}{K} \text{ mm}^2$$

If the time duration t is taken to be 5 seconds then the lowest acceptable cross-sectional area A for the cable for the various insulating materials is:-

$$\text{PVC, } A = 0.01944 I_{sc} \text{ mm}^2$$

$$\text{XLPE and EPR, } A = 0.01564 I_{sc} \text{ mm}^2$$

$$\text{Bare copper, } A = 0.02051 I_{sc} \text{ mm}^2$$

Equation (9.7) can be used for plotting the time-current characteristic of the cable when this needs to be coordinated with those of the protective relays and fuses in the circuit.

In which case the equation is transposed as,

$$t = \frac{A^2K^2}{I_{sc}^2}$$

When plotted on log-log paper the equation has the form,

$$\log_{10} t = \log_{10}(A^2K^2) - 2\log_{10} I_{sc}$$

Or of the form $y = a - bx$

Where $y = \log_{10} t$, $a = \log_{10}(A^2K^2)$

$b = -2$ and $x = \log_{10} I_{sc}$

which is a straight line having a slope of −2.

The straight line is usually plotted over the time range of 0.1 to 5.0 seconds, to correspond with the operating times of the protective devices.

When cables are to be sized for a particular project with regard to their short-circuit performance it is necessary to consider the let-through current of the protective device in the circuit e.g., fuse, circuit breaker. It is also necessary to determine whether the consumer has ‘fixed’ equipment such as a motor, or ‘temporary’ equipment such as a portable tool plugged into a socket, because this establishes the minimum time duration. This aspect is described in more detail when the earth-loop impedance is being considered, see sub-section 9.4.3.6.

Low voltage three-phase power systems often have their star-points earthed (grounded) by a very low impedance conductor, usually the TT method of IEC60364, sub-section 13.3.3. Therefore all the cables and consumer equipments are subject to a very high prospective short-circuit current when a line-to-ground fault occurs. Low voltage induction motors used in the oil industry are usually started direct-on-line. They have starting currents that can be as high as 7.5 times their full-load currents. The starting, or run-up, time durations for low voltage motors are usually in the order of a few seconds whereas for high voltage motors the duration can be up to 15 seconds when pumps and compressors are being started.

Table 9.26 of maximum starting times can be used as a guide for typical low voltage three-phase induction motors.

It is therefore common practice to use 5 seconds in (9.7) as the disconnection time for motor cables. This choice also corresponds with standardised data given by the manufacturers of fuses and moulded case circuit breakers for their let-through current as calculated from their graphical data.

When a fuse is used in a motor circuit its main purpose is to protect against short circuits in the cable and not against overloading of the motor. A second protective device such as a thermal overload relay should be used. The fuse rating should have a minimum margin above the motor full-load current of 1.3, see sub-section 7.4. The fuse must not ‘blow’ during the starting period, nor during several successive startings of the motor.

For high voltage cables, and low voltage feeder cables between switchboards, the disconnection time can be reduced from 5 seconds to not less than 0.2 seconds. The time of 0.2 seconds is determined from the total clearance time of a circuit breaker protected by a fast acting over-current relay. For high voltage motor circuits in which the short-circuit protection is provided by high-speed fuses, the disconnection time may be determined from the cut-off characteristic of the fuses.

9.4.3.5.1 Worked example

A 440 V 60 Hz emergency switchboard is normally fed by one of two 2.5 MVA transformers. Each 11,000/460 V transformer has a leakage reactance X pu of 6.4% and a resistance R pu of 1.08%. The fault level S_f at the primary winding terminal is 150 MVA, from a circuit that has an X-to-R ratio of 10.0.

A second auxiliary switchboard is fed from the emergency switchboard by a short length of cable which is protected by a set of 200 A fuses. Choose a suitable 3-core XLPE insulated cable and check that the fuses will function in their cut-off mode. Assume a short circuit occurs at the auxiliary switchboard when both transformers are operating in parallel. The 440 V cable is run in air at an ambient temperature of 35°C.

Solution:

The first step is to find the peak asymmetrical prospective fault current seen by the 200A fuses.

Table 9.26. Typical starting ratios and times for LV induction motors

Induction motor rating (kW)	Ratio of starting to running current	Maximum starting time duration (seconds)
Up to 1.0	5	5
1.1 to 75	7	10
Above 75	6.5	15

The base current I_{base} at 11,000 V is,

$$I_{\text{base}} = \frac{S_f \times 10^6}{\sqrt{3} \times V_{\text{base}}} = \frac{150 \times 10^6}{\sqrt{3} \times 11000} = 7872.9 \text{ amps}$$

The base impedance Z_{base} is,

$$Z_{\text{base}} = \frac{V_{\text{base}}}{\sqrt{3} \times I_{\text{base}}} = \frac{11000}{\sqrt{3} \times 7872.9} = 0.8067 \text{ ohms/phase}$$

This impedance has an X/R ratio of 10, its resistance R_{base} and reactance X_{base} are,

$$\begin{aligned} Z_{\text{base}} &= \sqrt{R_{\text{base}}^2 + X_{\text{base}}^2} = \sqrt{\left(\frac{X_{\text{base}}}{10}\right)^2 + X_{\text{base}}^2} \\ &= X_{\text{base}}\sqrt{0.1^2 + 1.0^2} = 1.00499 X_{\text{base}} \\ X_{\text{base}} &= \frac{0.8067}{1.00499} = 0.8027 \text{ ohms/phase} \end{aligned}$$

And

$$R_{\text{base}} = \frac{X_{\text{base}}}{10} = 0.08027 \text{ ohms/phase}$$

Transfer these components to the secondary circuit at 460 volts, and call them Z_{bs}, R_{bs} and X_{bs}.

The transformation ratio u_{ps} of the impedance is,

$$\begin{aligned} u_{\text{ps}} &= \frac{460^2}{11000^2} = 0.001749 \\ Z_{\text{bs}} &= Z_{\text{base}} \times u_{\text{ps}} = 0.8067 \times 0.001749 = 0.001411 \text{ ohms/phase} \end{aligned}$$

Similarly $R_{\text{bs}} = 0.000140$ ohms/phase

And $X_{\text{bs}} = 0.001404$ ohms/phase

The ohmic impedance of the load on the transformer Z_{flt} seen at its secondary winding is found as follows:-

Full-load current I_{flt} of the transformer secondary winding is,

$$I_{\text{flt}} = \frac{S_t \times 10^6}{\sqrt{3} \times V_{\text{os}}}$$

Where, S_t is the MVA rating of the transformer, and V_{os} is the open-circuit line voltage of the secondary winding.

$$I_{\text{flt}} = \frac{2.5 \times 10^6}{\sqrt{3} \times 460} = 3137.8 \text{ amps/phase}$$

The equivalent full-load impedance Z_{flt} is,

$$Z_{\text{flt}} = \frac{V_{\text{os}}}{\sqrt{3}I_{\text{flt}}} = \frac{460}{\sqrt{3} \times 3137.8} = 0.08464 \text{ ohms/phase}$$

This impedance also represents the 100% impedance of the transformer, hence by simple proportion the ohmic resistance R_t and reactance X_t are,

$$R_t = R_{\text{pu}} \times Z_{\text{flt}} = \frac{1.08 \times 0.08464}{10} = 0.000914 \text{ ohms/phase}$$

And

$$X_t = X_{\text{pu}} \times Z_{\text{flt}} = \frac{6.40 \times 0.08464}{100} = 0.005417 \text{ ohms/phase}$$

The total impedance Z_f upstream of the fuses when both transformers are operating is,

$$\begin{aligned} Z_f = Z_{\text{bs}} + \frac{Z_t}{2} &= R_{\text{bs}} + \frac{R_t}{2} + j\left[X_{\text{bs}} + \frac{X_t}{2}\right] \\ &= 0.000597 + j0.004113 \text{ ohms/phase at 460 V.} \end{aligned} \tag{9.8}$$

The magnitude of which is 0.004156 ohms/phase.

This impedance has an X/R ratio of 6.8894 which will give rise to a current ‘doubling factor’ D of,

$$\begin{aligned} D &= \sqrt{2}\left[1.0 + e^{\frac{-\pi R}{x}}\right] = \sqrt{2}\left[1.0 + e^{\frac{-\pi}{6.8894}}\right] \\ &= 2.3106, \text{ see sub-section 11.6.1 for an explanation of } D. \end{aligned}$$

The prospective rms fault current at or near to the fuses is I_f,

$$I_f = \frac{V_{\text{os}}}{\sqrt{3}Z_f} = \frac{460}{\sqrt{3} \times 0.004156} = 63903.1 \text{ amps}$$

Hence the peak value of the asymmetrical fault current $I_{\text{fpka}} = 2.3106 \times 63903.1 = 147{,}654$ amps.

To ensure that a good cut-off occurs in the fuses, choose the cut-off current I_{co} to be say 20% of the peak fault current I_{fpka},

$$\begin{aligned} I_{\text{co}} \simeq 0.2 \times I_{\text{fpka}} &= 0.2 \times 147{,}654 \\ &= 29{,}531 \text{ amps} \end{aligned}$$

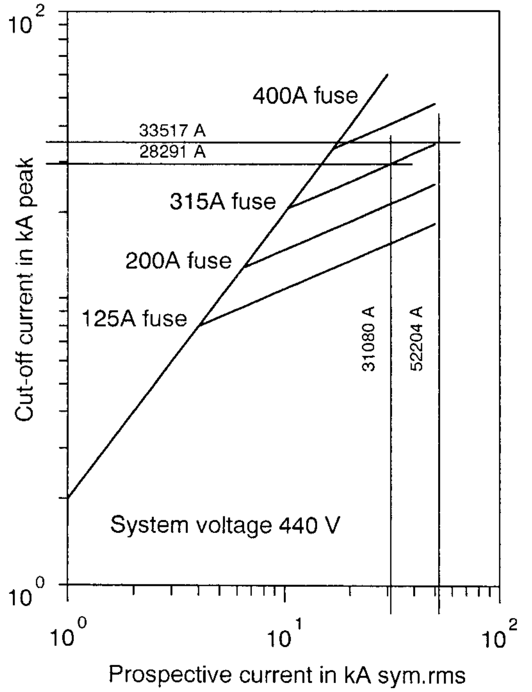

Figure 9.5 Cut-off and prospective current of fuses.

For the selection of fuses the prospective symmetrical rms value of the off-set fault current I_{frms} is calculated as,

$$I_{\text{frms}} = \frac{I_{\text{fpka}}}{2\sqrt{2}} = \frac{147{,}654}{2\sqrt{2}}$$
$$= 52{,}204 \text{ amps}$$

From the graphical characteristics given by the manufacturer the maximum fuse rating can be selected, see Figure 9.5.

The maximum fuse rating is 315 A and so the choice of 200 A is satisfactory.

Select a cable and check that its I-squared-t characteristics are adequate.

From Table 9.17 the derating for ambient temperature K_{air} is 0.92 and assume no derating for the grouping of cables. Hence the nearest cable rating to carry 200 amps at 35°C has a 70 mm^2 cross-sectional area. This cable has a thermal energy constant K of 143. Hence its time-current characteristic is given by two or more points on a straight line on a log-log graph. From the following,

$$\sqrt{t} = \frac{KA}{I} = \frac{143 \times 70}{I} = \frac{10010.0}{I}$$

Several suitable points on the graph are given in Table 9.27.

Table 9.27. Cable and fuse currents and time data

Cable current (kA)	Time (seconds)	Fuse operating current (kA)	
100.1	0.01	4.0	6.5
44.77	0.05	3.0	5.0
31.65	0.10	2.5	4.3
14.16	0.50	1.8	3.1
10.01	1.00	1.5	2.6
4.48	5.00	1.05	1.9

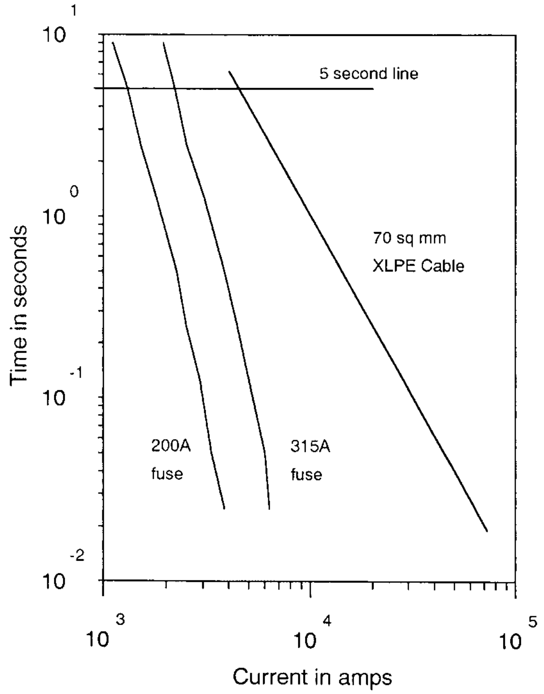

Figure 9.6 Fuse and cable time versus current curves.

A suitable fuse characteristic and the cable I-squared-t characteristic are plotted in Figure 9.6.

It can be seen that the fuse will operate rapidly for a wide range of fault currents and that there is a wide I-squared-t margin between the fuses and the cable.

9.4.3.5.2 Worked example

The emergency switchboard in Example 9.4.3.5.1 also supplies a 440 V 160 kW induction that is started direct-on-line. The motor has an efficiency of 93%, a running power factor of 0.92, a starting to running current ratio of 6.75 and a starting power factor of 0.33. Fuses and a thermal image overload relay protect the motor circuit. The starting time duration is 15 seconds. Each main incoming transformer is protected by an extremely inverse time delay relay in its primary circuit. The current transformer for this relay has a primary current rating of 150 amps. Assume only one of the main transformers is operating. Let the route length of the motor cable be 250 metres and assume that the volt-drop in the cable is 15% during the starting period.

Find a suitable XLPE insulated cable for the motor and ratings for its fuses. Plot the results on a log-log graph.

Solution:

The first step is to find the lowest fuse rating that can be used for the motor.

As a preliminary guide the fuse rating should be not less than approximately 1.3 times the motor full-load current, sub-section 7.4.

The full-load current I_{flm} of the motor is,

$$\begin{aligned} I_{\text{flm}} &= \frac{\text{Rated power}}{\sqrt{3}\ \text{Line voltage} \times \text{Power factor} \times \text{Efficiency}} \\ &= \frac{160000}{\sqrt{3}440 \times 0.93 \times 0.92} = 245.4 \text{ amps} \end{aligned}$$

Hence the lowest fuse rating would be just above 1.3 × 245.4 amps i.e., 355 amps is a standard rating. However, this may not be adequate to withstand the long starting time.

Since the cable volt-drop is significant it is necessary to revise the starting time duration and current from the data given by the manufacturer of the motor.

The motor receives a reduced terminal voltage of 85% during starting. Consequently the starting current I_{stm} is also reduced to 85% of its design value,

$$I_{\text{stm}} \text{ at reduced voltage} = 0.85 \times 245.4 \times 6.75 = 1408 \text{ amps instead of } 1656.5 \text{ amps.}$$

The torque developed by the motor is proportional to the square of its terminal voltage; hence throughout the starting period the torque applied to the driven machine will be reduced to 0.85 × 0.85 times its design amount. This reduction will apply to nearly the whole of the starting period. As a reasonably accurate approximation the revised starting time t_{str} can be given as,

$$\begin{aligned} t_{\text{str}} &= t_{\text{st}} \times (1.0 - \Delta V)^{-2} \\ &= 15.0 \times (1.0 - 0.15)^{-2} \\ &= 20.76 \text{ seconds, round up to 21 seconds.} \end{aligned}$$

Where t_{st} is the designed starting time at 100% terminal voltage and ΔV is the known volt-drop at the motor.

Hence the shape of the time-current curve for the motor will be elongated towards the fuse curve. At the end of the starting time the current falls rapidly to its full-load value, hence the curve has a corner point P_m, see Figure 9.7. There needs to be a margin between the corner point P_m of the motor and the fuse operating time point P_f at the value of the reduced starting current, so that the manufacturing tolerances do not interact and cause the fuse to operate. Assume a suitable margin

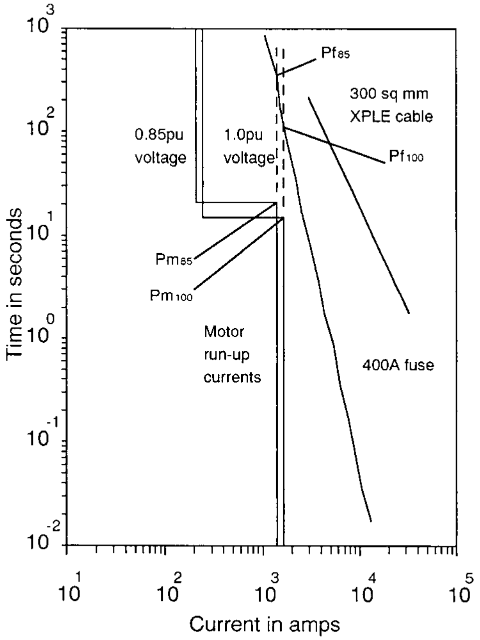

Figure 9.7 Fuse and cable time versus current curves.

to be no less than 3 at the corner point. Hence a fuse must be chosen that has an operating time no less than 63 seconds at a current of 1408 amps. A suitable fuse for motor applications would be rated at 400 amps, see Figure 9.7, the next lower rating of 355 amps may not prove reliable.

Find the cable size to suit the starting current and the route length.

From (9.3) the R and X components can be found in terms of the volt-drop ΔV_{stm} and the current I_{stm} during the starting period,

$$r \cos \emptyset_{\text{stm}} + x \sin \emptyset_{\text{stm}} \leq \frac{V.\Delta V_{\text{stm}}}{l\sqrt{3}I_{\text{stm}} \times 100}$$

Where l is the route length of 250 metres
V is the rated line voltage of 440 volts
$\cos \emptyset_{\text{stm}}$ is the starting power factor of 0.33
and $\sin \emptyset_{\text{stm}} = 0.9440.$

Therefore,

$$0.33r + 0.944x \leq \frac{440 \times 15.0}{0.250 \times \sqrt{3} \times 1408 \times 100}$$

$$\leq 0.10825 \text{ ohm/km for the cable.}$$

Assuming the cable is routed in air which has an ambient temperature of 35°C and that the cable is not grouped with others then its rating at 25°C must be at least 245.4/0.92 i.e., 266.74 amps.

Table 9.28. Cable data for the worked example

Cable conductor area (mm^2)	Resistance at 90°C (ohm/km)	Reactance at 60 Hz (ohm/km)	$0.033r + 0.944x$ (ohm/km)
95	0.247	0.0872	0.16383
120	0.197	0.0868	0.14694
150	0.160	0.0874	0.13531
185	0.128	0.0876	0.12493
240	0.0989	0.0866	0.11439
300	0.0802	0.0860	0.10765

Hence from Tables 9.16 and 9.17 the small size of cable could be 95 mm^2. Table 9.28 can be prepared for cables of 95 mm^2 and above, routed in air.

Hence a 300 mm^2 would be necessary for the starting duty. Check the actual volt-drop for both starting and running currents.

$$\begin{aligned}\Delta V_{\text{start}} &= \frac{\surd 31408(0.0802 \times 0.33 + 0.086 \times 0.944)0.25 \times 100}{440} \\ &= 14.92 = 14.9\% \\ \Delta V_{\text{run}} &= \frac{\surd 3245.4(0.0802 \times 0.92 + 0.086 \times 0.3919)0.25 \times 100}{440} \\ &= 2.596 = 2.6\%\end{aligned}$$

The choice of a 300 mm^2 may just be acceptable for a running volt-drop of 2.6%, but satisfies the required starting volt-drop.

Calculate the cut-off capability of the 400 A fuses. The same approach is used as in the previous Example 9.4.3.5.1. The fault impedance Z_f in (9.8) is higher due to operation of only one transformer,

$$Z_f = Z_{\text{bs}} + Z_t = 0.001054 + j0.006821 \text{ ohms/phase}$$

The magnitude of this is 0.006902 ohms/phase, which has an X/R ratio of 6.4715. The doubling factor is,

$$D = \surd 2\left[1.0 + e^{\frac{-\pi}{6.4715}}\right] = 2.2846$$

The prospective RMS fault current at or near to the fuses is I_f,

$$I_f = \frac{V_{\text{os}}}{\surd 3 Z_f} = \frac{460}{\surd 3 \times 0.006902} = 38478.9 \text{ amps}$$

Hence the peak value of the symmetrical fault current

$$I_{\text{fpka}} = 2.2846 \times 38478.9 = 87908.8 \text{ amps}$$

Again let the cut-off current be 20% of I_{fpka},

$$I_{\text{co}} \simeq 0.2 \times 87909 = 17582 \text{ amps}$$

And

$$I_{\text{frms}} = \frac{I_{\text{fpka}}}{2\sqrt{2}} = \frac{87909}{2\sqrt{2}} = 31080 \text{ amps}$$

From Figure 9.5 it can be seen that a 400 amp fuse will cut-off, with a higher cut-off current than 17,582 amps but still within a good margin at 30,000 amps, i.e. a factor of 34% instead of 20%.

The I-squared-t characteristic of a 300 mm^2 XLPE cable can be found from,

$$\sqrt{t} = \frac{143 \times 300}{I} = \frac{42900}{I}$$

Several points on the graph are given in Table 9.29.

A suitable fuse characteristic and the cable I-squared-t characteristic are plotted in Figure 9.7. It can be seen that the fuse will operate rapidly for a wide range of fault currents, that there is a wide I-squared-t margin between the fuse and the cable, and that the corner point of the motor starting current is well avoided.

9.4.3.6 Earth fault loop impedance

When an earth fault occurs at the far end of a cable it is possible that the armouring, cable gland and the frame of the consumer equipment can be raised to a dangerous potential with respect to electric shock exposure to human operators. This subject has been given considerable attention over the last 20 years, and is well documented in for example IEC60364. The international documentation concentrates on low voltage fixed and portable equipment protected by fuses and miniature circuit breakers. See also Chapter 13.

BS7430 (1998), sub-section 3.13, defines the earth fault loop impedance Z_{loop} in relation to the various types of earthing systems, as follows.

For TN systems:

$$Z_{\text{loop}} = Z_{\text{nez}} + Z_{\text{sec}} + Z_c + Z_a + Z_{\text{bond}} + Z_{\text{mr}} \tag{9.9}$$

Table 9.29. Cable and fuse currents and time data

Cable current (kA)	Time (seconds)	400 A fuse operating current (kA)
429.0	0.01	11.0
191.8	0.05	9.0
135.7	0.10	7.5
60.7	0.50	5.3
42.9	1.00	4.3
19.2	5.00	3.0

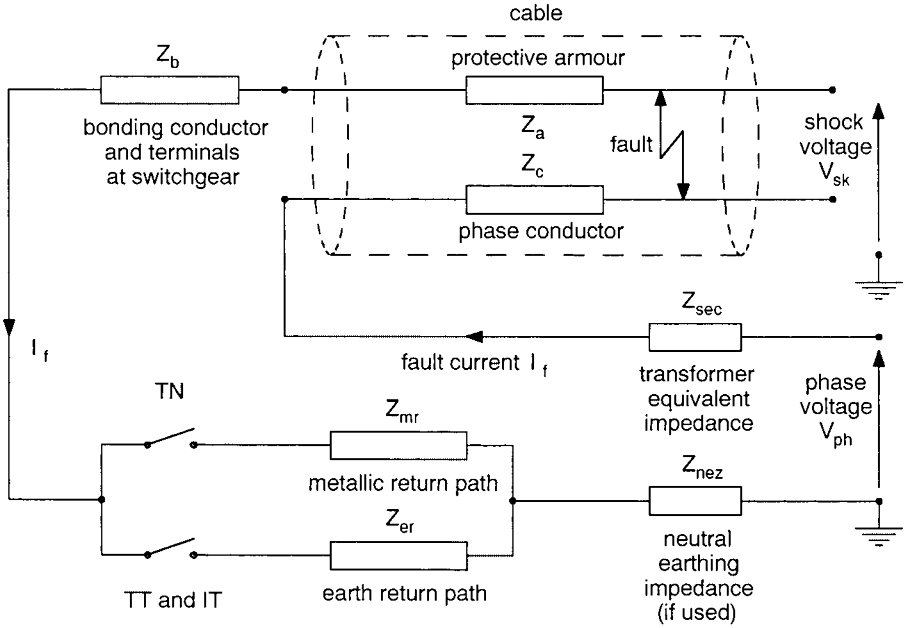

Figure 9.8 Earth loop impedance diagram.

For TT and IT systems:

$$Z_{\text{loop}} = Z_{\text{nez}} + Z_{\text{sec}} + Z_c + Z_a + Z_{\text{bond}} + Z_{\text{er}} \tag{9.10}$$

These components are shown in Figure 9.8.

Where Z_{nez} is the impedance of the neutral earthing device at the source winding.

Z_{sec} is the positive sequence impedance of the source. For a transformer this includes both windings and the upstream impedance. For a generator this will be the sub-transient impedance.

Z_c is the impedance of one phase conductor of the particular cable.

Z_a is the impedance of its armouring of the particular cable. This impedance can be taken as purely resistance (R_a).

Z_{bond} is the impedance of the earthing terminals and bonding conductors at the sending end of the cable.

Z_{mr} is the metallic return path impedance of a TN system. This impedance can be taken as purely resistance, but will usually be low enough to ignore. For offshore installations the multiple series and parallel branches of steel work in three dimensions will render such an impedance as almost zero.

Z_{er} is the impedance of the earth return path of the ground for a TT or IT system. It will be approximately the total impedance of the ground rod or grid at the source and the ground rod or grid at the consumer. The impedance will be almost purely resistance, being typically a fraction of an ohm for damp soil conditions to several ohms for dry sandy and rocky soils. See also the international standard IEEE 80, 1986, section 12.

V_{ph} is the nominal phase-to-neutral voltage of the source.
I_{f} is the fault current at the far end of the feeder cable where the point of fault occurs.

In this sub-section the main concern is for human safety in low voltage networks, hence some simplifications can be made to (9.9 and 9.10). The majority of low voltage networks are solidly earthed and short large cross-section bonding conductors are used. Hence Z_{nez} and Z_{bond} can be assumed to be zero. The current ratings of most consumer cables are much lower than the current rating of the source transformer or generator. Hence in most situations Z_{sec} can be taken as zero. As a first approximation the return path is Z_{mr} and Z_{er} could be taken as 1.0 ohm (see also IEC60079 Part 14 (1996) subsection 12.2.4 for hazardous areas). The approximate expressions for Z_{loop} is therefore:

For TN systems and for TT and IT systems in high conductivity soils

$$Z_{\mathrm{loop}} = Z_c + R_a + 1.0 \tag{9.11}$$

As the cross-sectional area of the cable phase conductors reduces, its impedance increases. Similarly the resistance of the cable armouring also increases. In practice it is usually found that minimising Z_{loop} becomes difficult for small sizes of cables when their route lengths exceed more than about 100 m. The critical length depends upon the type of armouring i.e. wires or braid, and the material used i.e. steel, aluminium, copper, and phosphor bronze. When the critical length is exceeded the circuit should be fitted with an earth leakage current relay, because the overcurrent fuses or circuit breakers will not respond quickly enough to satisfy the recommended international practices.

IEC60364 Part 4 Chapter 41 makes reference to several important definitions regarding the design of the insulation within low voltage equipment, whether the equipment is portable or fixed, and the necessary disconnection time of the source protective device. These are summarised as follows:-

a) Class 1 equipment:

   When the insulation fails in Class 1 equipment the fault current passes from the phase conductors to its conductive frame. The fault current must be interrupted very quickly at the point of supply. This applies to fixed rotating and stationary equipment. It also applies to some forms of hand-held portable equipment. See also BS7430.

b) Class 2 equipment:

   This type of equipment has two levels of insulation. The first level may be considered as being equivalent to that of Class 1 equipment. The first level is then completely surrounded by a second level of insulation so that no contact can be made between the phase conductors and the outer frame. Hence the protective device at the source of supply need not be involved in circuit disconnection when the first level insulation fails. This type of equipment is sometimes referred to as ‘double insulation’ or ‘doubly insulated’ equipment e.g. hand-held domestic electric drilling machines. This type of equipment is not considered in the following discussions and calculations. See also BS7430.

c) Portable equipment:

   Portable equipment is not necessarily hand-held equipment, it may be too heavy to carry or lift by one person.

d) Hand-held equipment:

   Hand-held equipments are usually light-weight tools such as drilling machines, sanding machines etc., that are held in one or both hands.

e) Disconnection time:

The standard recommends two nominal disconnection times 0.4 and 5.0 seconds. The time of 0.4 seconds is based on a nominal phase-to-neutral voltage of approximately 240 Vac, where as the time of 5.0 seconds is invariant of voltage.

Where the distribution circuit feeds a stationary item of equipment, not socket outlets and not portable equipment, the disconnection time may be taken as 5.0 seconds. This applies to motors.

The nominal time of 0.4 seconds is intended for circuits supplying socket outlets, regularly moved portable equipment and Class 1 hand-held equipment. For voltages (V_{ph}) different from 240 Vac, the disconnection time (t_{dis}) of 0.4 seconds becomes approximately related as,

$$t_{\text{dis}} \simeq 1.149 \log_{10}\left[\frac{600}{V_{\text{ph}}}\right] \text{ seconds}$$

with a lower limit of 0.1 second.

The maximum value of Z_{loop} can be determined from the following information,

- The network phase-to-neutral voltage V_{ph}.
- The operating current that causes the supply protective device to disconnect the consumer in the specified time t_{dis}. This can be found from the manufacturer's data.

9.4.3.6.1 Worked example

A 37 kW 415 V induction motor is protected by fuses at the motor control centre. The route length of the motor feeder cable is 200 metres. The supply frequency is 50 Hz. The MCC is fed by one 250 kVA, 4.5% impedance, transformer. Assume an X/R ratio of the transformer of 10.0. The motor running efficiency at full-load is 92% and its power factor is 0.85. The starting to running current ratio is 7.0, and the starting power factor is 0.45. The cable is routed in air that has an ambient temperature of 40°C. The conductor maximum temperature is 90°C. The insulation material is EPR and the armouring is galvanised steel wire braid. Assume the cable data in Tables 9.23 and 9.11 for 3-core cables is applicable. The motor fuse data are shown in Figure 8.4 for 100 A, 125 A and 160 A fuses. The permissible volt-drops in the cable for running and starting are 3.0% and 15.0% respectively.

Find the most appropriate cable and fuses for the motor. Determine whether or not an earth leakage current relay should be used at the motor control centre. Assume a TN earthing arrangement.

Replace the steel wire braid armour with round steel wires (GSWA) and reduce the metallic return path impedance Z_{mr} to 0.1 ohm, and compare the effect on the hazardous shock voltage.

Then replace the fuses with moulded case circuit breakers.

Solution:

a) Find the source impedance for a line-to-ground fault of negligible impedance. Refer all calculations to the nominal supply voltage of 415 V. The source impedance is that of the single transformer feeding the MCC.

Full-load current I_{txfl} of the transformer

$$= \frac{S_{\text{tx}}}{\sqrt{3}\ V} = \frac{250000.0}{\sqrt{3} \times 415} = 347.8 \text{ amps}$$

The 100% impedance Z_{Ipu} of the transformer

$$= \frac{V}{\sqrt{3}\ I_{\text{txfl}}} = \frac{45}{\sqrt{3} \times 347.8} = 0.6889 \text{ ohms/phase}$$

Therefore the 4.5% leakage impedance

$$Z_{\text{sec}} = |R_{\text{sec}} + jX_{\text{sec}}| = 0.045 \times 0.6889 = 0.031 \text{ ohms/phase}$$
$$\text{or } 0.00308 + \text{j}0.0308 \text{ ohms/phase}$$

b) Find the motor impedances for the starting and running conditions:

Full-load current I_{flmr} of the motor

$$= \frac{S_m}{\sqrt{3} \times V \text{ Efficiency} \times \text{Power factor}}$$
$$= \frac{37000}{\sqrt{3} \times 415 \times 0.92 \times 0.85} = 65.82 \text{ amps}$$

The 100% impedance Z_{mrn} of the motor

$$= \frac{V}{\sqrt{3}\ I_{\text{flmr}}} = \frac{415}{\sqrt{3} \times 65.82} = 3.64 \text{ ohms/phase at a power factor of } 0.85$$

The starting impedance Z_{ms} of the motor

$$= \frac{Z_{\text{mm}}}{\text{Starting to running current ratio}}$$
$$= \frac{3.64}{7.00} = 0.52 \text{ ohms/phase at a power factor of } 0.45$$

c) Find the conductor and armouring impedances for various cables that may be suitable.

From Tables 9.23 and 9.24 the impedance data for the circuit temperature and power frequency conditions are shown below.

d) Since the motor is fixed equipment of the Class 1 type, the disconnection time t_{dis} is 5.0 seconds.

The fuse operating currents at 5.0 seconds are shown in Table 9.31.

e) Find the I-squared-t parameters for the cable conductors with respect to the fuse operating current (I_s) at 5.0 seconds.

From (9.7)

$$A_{\min} = \frac{I_s\sqrt{5}}{K}$$
$$= I_s \times 0.01564$$

Table 9.30. Cable data for the worked example

Nominal conductor area (mm^2)	Current rating at 40°C (amps)	3-core conductor		GSWB armouring
		Resistance at 90°C ohms R_c	Reactance at 50 Hz (ohms) X_c	resistance (ohms) R_a
16	0.2960	0.0268	4.62	70.35
25	0.1872	0.0250	5.62	93.45
35	0.1348	0.0242	2.086	110.3
50	0.0998	0.0236	2.362	141.8
70	0.0688	0.0224	2.722	178.5

Table 9.31. Fuse data for the worked example

Fuse rating (amps)	Operating current at 5.0 sec (amps)	Maximum earth loop impedance at 240 V/phase Z_{loopf} (ohms)
100	500	0.4792
125	650	0.3686
160	850	0.2819
200	1100	0.2179

Table 9.32. Cable data for the worked example

Fuse rating (amps)	Operating current at 5.0 sec (amps)	Minimum conductor CSA $A_{\min}$ (mm^2)	Nearest practical CSA above $A_{\min}$ (mm^2)
100	500	7.82	10
125	650	10.17	16
160	850	13.29	16
200	1100	17.20	25

Where $K = 143$ for EPR insulation and $A_{\min}$ is the smallest conductor cross-sectional area.

The resulting $A_{\min}$ for the four sizes of fuses are given in Table 9.32:

Hence all the cables 16 mm^2 to 70 mm^2 in c) that suit the motor full-load current will be adequately protected by the fuses in the range given.

f) Calculate the volt-drops for running and starting the motor.

From (9.3) for 'running' conditions,

$$\cos \text{Ø} = 0.85 \text{ and } \sin \text{Ø} = 0.5268$$

Assume the cable conductor area is 16 mm^2,

Therefore,

$$R = 0.2960 \text{ ohms and } X = 0.0268 \text{ ohms}$$

$$\Delta V_{\text{run}} = \frac{\sqrt{3}65.82(0.2960 \times 0.85 + 0.0268 \times 0.5268)100}{415}$$
$$= 7.299\%.$$

From (9.3) for ‘starting’ conditions,

$$\cos \emptyset = 0.45 \text{ and } \sin \emptyset = 0.8930$$
$$\Delta V_{\text{start}} = \frac{\sqrt{3}460.74(0.2960 \times 0.45 + 0.0268 \times 0.8930)100}{415}$$
$$= 30.216\%.$$

Table 9.33 shows the volt-drop results for all the available cables.

g) Check if the earth loop impedance of the motor circuit is greater than that allowed by the fuses. The motor circuit is shown in Figure 9.9.

Where

$$V_{\text{ph}} = \frac{415}{Z_{\text{loopc}}}$$
$$Z_{\text{sec}} = 0.00308 + j0.0308 \text{ ohms/phase}$$

Table 9.33. Volt-drop in the motor feeder cable for the worked example

Nominal conductor area (mm^2)	Running volt-drop (%)	Starting volt-drop (%)	Accept or reject
16	7.299	30.216	Reject
25	4.733	20.492	Reject
35	3.498	15.820	Reject
50	2.672	12.792	Accept
70	1.9306	9.800	Accept

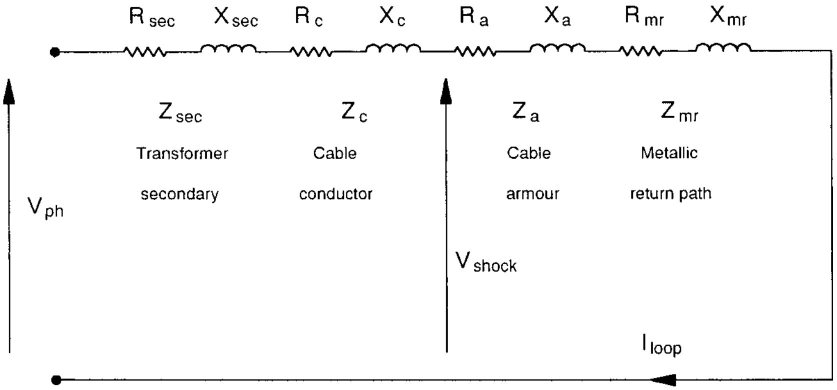

Figure 9.9 Circuit diagram for the earth loop impedance.

Table 9.34. Earth loop impedance results for the worked example with braided armouring

Nominal conductor area (mm^2)	$Z_a + Z_c$	Z_{loopc} magnitude (ohms)	V_{shock}
16	$4.916 + j0.0268$	5.9193	227.49
25	$5.807 + j0.0250$	6.8102	232.91
35	$2.221 + j0.0242$	3.2244	229.31
50	$2.462 + j0.0236$	3.4654	232.45
70	$2.791 + j0.0224$	3.7944	235.03

$$Z_{mr} = 1.0 + j0.0 \text{ ohms}$$

Z_c and Z_a are given in c)

The resulting Z_{loopc} calculated from the circuit for each cable is given in Table 9.34.

Comparing the tabulated results above with those for the fuses in d) shows that all the cables have an earth loop impedance much greater than that permitted by the fuse, by a ratio of approximately 10:1.

Hence an earth leakage circuit breaker should be used in the MCC to protect the circuit against electric shock hazard.

The most appropriate choice of cable cross-sectional area and fuse rating are,

- Cable cross-sectional area should be at least 50 mm^2, to comply with volt-drop.
- Fuse rating should be below the rating of the cable since its primary purpose is to protect the cable. Hence the largest fuse should be 125 A for a 50 mm^2 cable. (If a larger fuse is needed the cable size would need to be increased.)

h) Calculate the electric shock voltage

From Figure 9.9 the shock voltage V_{shock} is,

$$V_{\text{shock}} = \frac{(Z_a + Z_{\text{mr}})V_{\text{ph}}}{Z_{\text{sec}} + Z_c + Z_a + Z_{\text{mr}}}$$

For the 16 mm^2 cable

$$V_{\text{shock}} = \frac{4.62 + 1.0}{5.9193}\left(\frac{415}{\sqrt{3}}\right) = 227.49 \text{ volts}$$

i) Replace the braided armour with round steel wires.

Assume the resistances of the armour wires to be 0.72, 0.50, 0.46, 0.40 and 0.36 ohms for the 200 m route length. Repeat the calculations of g).

For a 16 mm^2 cable,

$$\begin{aligned} Z_a + Z_c &= 0.2960 + j0.0268 + 0.72 = 1.016 + j0.0268 \\ Z_{\text{loopc}} &= Z_a + Z_c + Z_{\text{sec}} + 0.1 \\ &= 1.016 + j0.0268 + 0.00308 + j0.0308 + 0.1 \\ &= 1.119 + j0.0576 \\ \text{Magnitude of } Z_{\text{loopc}} &= 1.1206 \text{ ohms} \end{aligned}$$

The resulting Z_{loopc} calculated from the circuit for each cable is given below,

For the 16 mm^2 the shock voltage is,

$$V_{\text{shock}} = \frac{0.72 + 0.1}{1.1206}\left(\frac{415}{\sqrt{3}}\right) = 175.3 \text{ volts}$$

If a 50 mm^2 cable and a fuse rating of 125 amps are chosen as recommended in g) then the circuit earth loop impedance is still too high by a ratio of about 1.65:1. Hence an earth leakage circuit breaker should still be used for this motor circuit. The hazardous shock voltage is still too high.

j) Now replace the fuses with moulded case circuit breakers and show whether or not the situation is improved. From Figure 7.9 it can be seen that a typical MCCB for motor application operates in its inverse region for times equal to 5.0 seconds.

Repeating d) but for MCCBs gives the following limits for Z_{loopf},

Table 9.35. Earth loop impedance results for the worked example with steel wire armouring

Nominal conductor area (mm^2)	$Z_a + Z_c$	Z_{loopc} magnitude (ohms)	V_{shock}
16	$1.016 + j0.0268$	1.1206	175.3
25	$0.6872 + j0.0250$	0.7922	181.5
35	$0.5948 + j0.0242$	0.6999	191.7
50	$0.4998 + j0.0236$	0.6053	197.9
70	$0.4288 + j0.0224$	0.5344	206.2

Table 9.36. Limiting values of earth loop impedance when MCCB is used

MCCB rating (amps)	Lowest operating current at 5.0 sec (amps)	Maximum earth loop impedance at 240 V/phase Z_{loopf} (ohms)
100	370	0.6476
125	470	0.5098
160	720	0.3328
200	900	0.2662

If the 50 mm^2 cable and a MCCB rating of 125 amps are chosen then the circuit earth loop impedance is still too high by a reduced ratio of about 1.19:1. Hence an earth leakage circuit breaker is still required.

Note: In most practical power systems of the TN or TT types it is found that an earth leakage core-balance relay is recommended for all LV motors above approximately 18.5 to 30 kW.

Note: Some oil companies specify a lower disconnection time t_{dis} than 5.0 seconds, e.g., 1.0 second. This significantly increases the disconnection current by a factor of about 3.0 times. This ensures a much lower permissible limit to Z_{loopf}, and thereby making it more necessary to use an earth leakage circuit breaker. Indirectly this reduction in time should be accompanied by ensuring that the earth return impedance Z_{mr} (and Z_{er}) is kept very low i.e. as far below 0.1 ohms as possible. For an offshore platform this should be reasonably easy to achieve, e.g. 0.01 ohms, for a TT system because the general mass of steel is connected in parallel with the neutral conductor if a 4-wire supply is provided. Even for a 3-wire supply the steelwork impedance should be very low.

9.4.4 Protection against Overloading Current

IEC60364 Part 4, section 433, applies to cables and consumer equipment that are protected against overloading current by a fuse or relay device at the source of supply. This requirement should not be confused with protection against short-circuit currents that are disconnected in a short period of time. Overloading currents tend to cause the protective device to disconnect the circuit only after a long period of time has passed e.g. tens of minutes, one hour. The standard defines three particular currents, I_n, I_B and I_2 as follows,

I_n is the nominal current if this is non-adjustable, or the setting current I_{ns} if this is adjustable, of the protective device.

I_2 is the operating current of the protective device.

I_B is the design current of the circuit. This will often be the rated current of the cable under the ambient and grouping conditions of the installation.

I_Z is the rated current of the lowest capacity component in the series circuit, but excluding the load of the consumer.
However, if a cable feeds a motor then the rated current I_Z of the motor should be I_B.

The standard requires the following constraints to be fulfilled,

$$\text{a)}\quad I_B \le I_n \le I_z \tag{9.12}$$

and

$$\text{b)}\quad I_z \le 1.45 I_z \tag{9.13}$$

The circuit diagram showing these currents for a motor consumer is Figure 9.10.

In this situation the main concern is the near-to-asymptotic behaviour of the protective device.

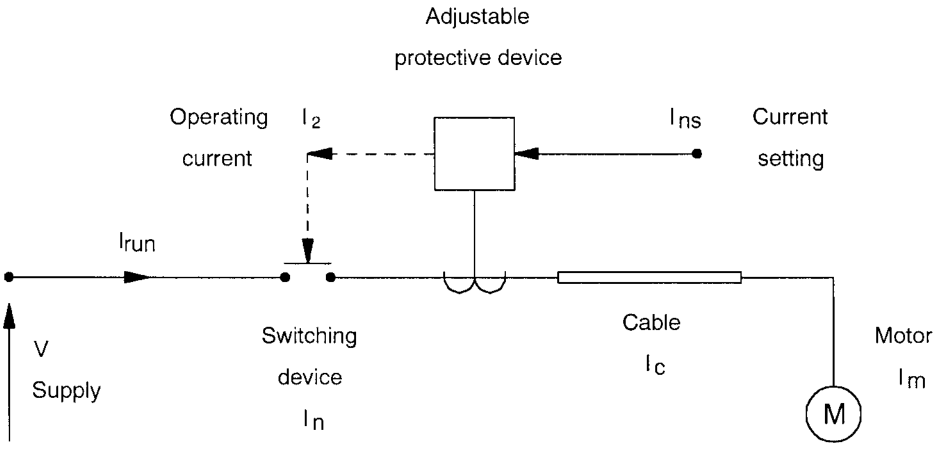

Figure 9.10 Overcurrent protection of a cable and motor.

For the circuit shown the following design conditions should apply,

- Cable 'derated' current I_c should be greater than the rated motor current I_m.
- In practice the motor running current I_{run} would normally be slightly less than I_m, since the motor should have a rating greater than that of its driven machine. The margin in current would depend upon the rating of the motor, see sub-section 1.6.

The following worked example illustrates how (9.12) and (9.13) are applied.

9.4.4.1 Worked example

Consider the worked example in sub-section 9.4.3.5.2 for a 160 kW motor, a 3-core 300 mm^2 XLPE cable, and a 400 amp fuse. Assume the cable is routed in air at an ambient temperature of 35°C.

The motor has a full-load current I_m of 245.4 amps.

The fuse rating is 400 amps and a near-asymptotic current I_2 of between 600 and 800 amps.

The 'derated' current of the cable is 0.92 × 666 = 613 amps (see Tables 9.15, 9.16 and 9.17). This is the current I_c.

Now I_B should be the least of I_m and I_c, i.e. $I_B = 245.4$ amps.

I_n should be the rated current of the fuse, i.e. $I_n = 400$ amps

I_z should be the cable 'derated' current I_c i.e., $I_z = 613$ amps.

From (9.12),

$$I_B[245.4] \leq I_n[400] \leq I_z[613]$$

which is satisfactory.

From (9.13):

$$I_2[600 \text{ to } 800] \leq 1.45 I_z[889]$$

which is also satisfactory.

Hence the requirements of IEC60364 are satisfied.

9.5 CABLES WITH ENHANCED PERFORMANCE

Sub-sections 9.1 and 9.2 described the materials and designs for cables that are intended for general use. The oil industry has additional requirements for cables that may be routed in normal hot surroundings, in areas where a fire situation must be tolerated and for the emergency control of critical safety circuits and systems. Examples of these situations are,

a) Normally hot surroundings.

   Cables for ignition and control circuits at the burner face of boilers and furnaces.

   Cables routed close up against hot vessels and pipes.

b) Fire situations

   Cables routed near to wellhead equipment.

   Cables routed in hazardous areas.

   Cables installed in offshore living quarters.

c) Emergency control and power.

   Cables associated with emergency power supplies and control systems.

   Cables that must function as long as possible in safety control systems e.g., fire and gas detection systems, ventilation damper control and power systems, UPS, public address and communication systems, intrinsically safe systems.

There are three important factors regarding the above requirements,

- Fire retardance.
- Fire resistance.
- Emission of toxic gases and smoke.

Fire retardance or reduced flame propagation is described in IEC60331 and fire resistance in IEC60332 (3 parts).

9.5.1 Fire Retardance

The early editions of IEC60332 mainly concerned definitions and testing single lengths of cables. This is useful for making a comparison between one cable and another.

Practical installations more often than not have several or many cables bunched together by cleats on a rack, or in close proximity to each other due to the close spacing of tiered racks. In this respect the IEC60332 Part 3 is more useful and relevant.

The standard describes various testing regimes in which the cable is set in a vertical test rig. A naked flame is applied at the base of the cable. The flame is applied for a given period of time. The extent of burning of the cable is measured from the base. The lower the measured amount of burnt cable, the better is the flame retardant property. IEC60332 Part 3 defines three categories of the volume of combustible non-metallic material present in the test before the flame is applied,

Class A specifies 7 litres of material per metre length.
Class B specifies 3.5 litres of material per metre length.
Class C specifies 1.5 litres of material per metre length.

Good flame retardance can be achieved by PVC, PCP, PTFE and compounds rich in EPR and containing CSP. However, some of these materials may cause the cable to have a poor performance when the emission of toxic gases and smoke are considered.

Reference 10 provides full descriptions of the IEC60331 and IEC60332 tests, together with practical aspects of cable choice and installation.

Reference 11 also describes the testing of cables and the materials that are available.

9.5.2 Fire Resistance

Fire resistance is a much more demanding requirement than fire retardance, and is more difficult to achieve in the manufacturing processes. The fire resistance tests of IEC60331 impose a severe duty on the cable sample. A 1.2 metre sample is mounted horizontally and subjected to a ribbon flame from below for a given period of time at a pre-described temperature. The cable is energised at its rated voltage so that a fault current can be detected. The general requirement is that the cable remains in tact, albeit in a fragile state, throughout the test and that no fault current passes across the insulation material.

In a practical situation a fire could otherwise destroy the cable, but it should still perform as a cable for a period of time sufficient to provide a necessary emergency or shut down service.

Fire resistance is primarily a function of the insulation material. In addition fire resistant mica tapes are often wound round the conductors in the form of a continuous helix. The mica is a good electrical insulator as well as being very resistant to directly applied flames and heat. Fire resistance requires the material to be self-extinguishing after the flame is removed.

It should be noted that fire resistance performance is not normally designed into high voltage cables. This is because the time required to burn down a live high voltage cable, to the point where it fails electrically, is usually much greater than the time required to shut-down and control the emergency. It is also unusual to have high voltage power supplies involved directly in shutdown and emergency services.

9.5.3 Emission of Toxic Gases and Smoke

When some elastomers are burned they evolve what is known as ‘acid gas’ or ‘halogen gas’. These gases are typically composed of hydrochloric or hydrofluoric acid. They are toxic even in relatively small volumes and can cause serious damage to the human respiratory system. Fatal results can occur from bad fire situations.

In addition to injury to health these acid gases can also cause very corrosive damage to equipment, especially if water is employed during the fighting of the fire. Electronic equipment and fine stands of wire are particularly susceptible to damage.

Smoke is usually evolved in the combustion of elastomers, e.g., PVC, PCP and CSP especially if carbon black is present in the compound.

A type of cable known as the 'low smoke zero halogen' (LSOH) type has been developed over the past 20 years for use in enclosed environments where good visibility and damage minimisation are of high importance e.g., electronic equipment rooms, corridors, emergency exit routes, medical treatment rooms, living quarters, caissons and basements. The IEC60754 specifies a maximum limit of 0.5% halogen acid shall be emitted in a fire for a cable to be classed as being of the LSOH type.

Non-metallic materials that provide fairly good 'low-smoke' characteristics are EVA, silicon rubber, XLPE and EPR.

9.5.4 Application of Fire Retardant and Fire Resistant Cables

The application of fire retardant and fire resistant cables to particular services can be shown in tabular form, see Table 9.37 below.

Table 9.37. Application of fire retardant and fire resistance cables in a typical oil industry plant

Services and systems	Fire retardance	Fire resistance
Deluge systems		√
Drilling system cables	√	
Emergency and escape lighting		√
Emergency power and associated control systems		√
Emergency shutdown systems		√
Emergency telephone systems		√
Emergency UPS cabling systems		√
Escape lighting and signs		√
Fire and gas systems		√
Fire extinguishing systems		√
Fire pump cables		√
Helideck lighting		√
HVAC fire dampers and control systems		√
Instrumentation cables	√	
Internal wiring in switchboard, Panels etc.	√	
Intrinsically safe systems		√
Navigational aides		√
Normal service systems		√
Normal UPS systems	√	
Public address systems		√
Telecommunications		√

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10

Hazardous Area Classification and the Selection of Equipment

10.1 HISTORICAL DEVELOPMENTS

Some of the earliest work on the subject of hazardous area classification was documented by the API, IP and BS institutions, and the chemical manufacturing company ICI. Their particular documents are given in Table 10.1.

Some of these documents have become obsolete or little used, e.g. BS229, BS1259, Electrical Installations in Flammable Atmospheres (from ICI) whilst others have been up-dated several times. New standards have also been introduced. A similar situation exists with the international standards pertaining to the selection of equipment for hazardous areas, many more references could be quoted.

In the period up to about 1980 it was common practice for senior electrical engineers to determine the various hazardous areas on a site. This was historically due to the fact that electrical power equipment was the easiest to identify as a possible cause of ignition. It would often be the first equipment to be investigated when an incident occurred.

The modern approach has changed for the better. It is now the more common practice that senior mechanical and senior process engineers manage this task in co-operation with electrical, instrumentation and safety personnel. The emphasis in this approach is the clear identification of possible sources of leaking gas or vapour. This is by nature more within the experience of mechanical and process engineers because they tend to be mainly responsible for the layout of the plant at the start of a project. Thereafter the electrical engineers select the type and design of manufactured equipment to suit the hazardous areas that have been identified on scaled drawings.

10.2 PRESENT SITUATION

For the classification of hazardous areas the notable standards that are most frequently used are IEC60079 Part 10 for UK and Europe, BS5345 Part 2 for UK only, API 500 A for USA. Although the territories of origin are given it is found in practice that an oil company operating in a particular country may adopt any one or a combination of standards to comply with the governing rules of the country e.g. European standards are adopted in Abu Dhabi and Qatar, whereas the standards of the USA are preferred in Saudi Arabia. A similar situation exists in the Far East for example.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

ISBN: 0-471-49631-6

Table 10.1. Early publications pertaining to hazardous area classification

Institution	Document reference (See also Appendix B)
American Petroleum Institute	RP 500A. Recommended practice for classification of location for electrical installations of petroleum facilities classified as class 1 division 1 or division 2
Institution of Petroleum	Model Code of Practice in the Petroleum Industry
British Standards Institution	BS229, 1259, 5345
Imperial Chemicals Industry	Electrical Installations in Flammable Atmospheres
Electrical Engineers (UK) (IEE)	Third International Conference of Electrical Safety in Hazardous Areas (1982)

Table 10.2. Summary of the most frequently used parts of IEC60079

Part of IEC60079	Title of Part
0	General requirements, plus Amendments.
1	Construction and verification test of flameproof enclosures of electrical apparatus, plus Amendments. Note that the type of protection ‘d’ is incorporated into this part.
2	Electrical apparatus, type of protection ‘p’.
7	Electrical apparatus, type of protection ‘e’ plus Amendments.
10	Classification of hazardous areas (similar to BS5345 Part 2).
11	Electrical apparatus type of protection ‘i’.
13	Construction and use of rooms or buildings protected by pressurisation.
14	Electrical installations in hazardous areas (other than mines).
15	Electrical apparatus, type of protection ‘n’.
18	Electrical apparatus, type of protection ‘m’.

For the purposes of this book the European standards will be used as appropriate references for illustrating the principles involved and for designing installations. In practice the principles upon which all the standards are based are very similar. Some standards are more stringent and comprehensive than others. For the area classification IEC60079 Parts 0 and 10 are most relevant. For the selection and design requirements of equipment all the remaining parts, 1 to 20 should be applied, where necessary. The parts given in Table 10.2 would normally be referred to most frequently.

Reference 1 gives a very comprehensive discussion on most of the standards that exist in Europe and USA, and is recommended for further reading. The reference gives excellent comparisons of the standard identity numbers e.g. IEC, BS, CENELEC, BASEEFA, VDE and NEC.

Reference 2, Chapter 5, gives a full description of the American practices including a comprehensive part for conduit equipment and systems.

The concepts of hazardous area classification and the legislation that supports the subject are in a continuous state of revision and so the engineer should keep abreast of such developments.

10.3 ELEMENTS OF HAZARDOUS AREA CLASSIFICATION

The objective is to determine the zonal number for an area surrounding a definable source of hazard. These areas are identified as non-hazardous with no zonal number and hazardous of the types Zone 2, Zone 1 and Zone 0. This will be described in more detail later on in this chapter.

A hazardous area is one in which a flammable mixture of gases or vapours may exist. Upon ignition the flammable mixture will burn or explode, usually the latter. A similar situation can arise with combustible dust. The ignition can be caused by one of two methods. The usually attributed method is by a spark. The second is by a high surface temperature being attained, usually by operating equipment.

Sparks can occur by electrical or mechanical activity. Electrically the sparks are usually made by switching contacts, loose contacts in a circuit carrying current, poorly mating metallic faces that are carrying current and static discharges. In addition there is the source of sparks produced by maintenance operations such as welding and grinding. Mechanical sparks can be caused by the impacting of steel or iron components, especially if there is some surface rust. Oxidised aluminium alloys can also cause sparks on impact with themselves or other metals.

This sub-section will mainly be concerned with sparks caused by electrical methods and hot surfaces.

10.3.1 Mixtures of Gases, Vapours and Air

Ignition can only lead to fire or explosion if three necessary components occur simultaneously, these are:

a) A flammable gas or vapour is present in sufficient quantity.

   This occurs due to leakage or accidental discharge from an enclosed vessel, pump, compressor, value, flange or the like.

b) Sufficient air is present.

   It can be assumed that there will always be sufficient air in the area. The oxygen in the air is required for the combustion.

c) A source of ignition occurs.

   This will be a spark having sufficient energy, or a hot surface that will cause spontaneous or autoignition e.g. a hot exhaust manifold and piping of a diesel engine.

10.3.1.1 Gases and vapours

When gases and vapours are present in air the resulting mixture may be flammable. Not all gases and vapours produce flammable mixtures. Imagine a flammable gas or vapour slowly leaking into a confined volume of air that is not replenished. Initially the concentration of the gas or vapour in the mixture will be too low to support combustion. As the concentration increases a critical point will be reached when combustion will be possible. This is called the Lower Explosive Limit (LEL). If the concentration is increased beyond this point by a significant amount then a second critical point will be reached. At this point the mixture will not contain sufficient oxygen to enable combustion to occur. This is called the Upper Explosive Limit (UEL), above which no combustion or explosion is possible. In terms of hazardous area analysis the UEL is not normally of practical significance. Various institutions have determined the LEL for most of the regularly encountered gases and vapours. Both the LEL and UEL are expressed in percentage of volume. Reference 1 Appendix 8 and Reference 2 Article 500 Table 2.1 give comprehensive listings of LEL, UEL and other important data.

When it is necessary to identify the hazardous gas or vapour the designer will also need to know whether or not the gas or vapour is heavier or lighter than air. It is normally assumed that the hazard appears and persists in 'still air' conditions. The effect of wind or forced air ventilation is not considered for this purpose, because 'still air' conditions can always arise in practice and so this becomes the 'worst case' condition. Heavier than air gases and vapours have a relative vapour density greater than air, air has a value of unity. Likewise lighter than air gases and vapours have a density less than unity. This aspect is important when the boundaries of the hazardous area are being determined, especially in elevated parts of a plant, where open flooring is used and where open drains exist.

10.3.1.2 Temperature class

In order to classify a gas or vapour by its ability to be ignited by a hot surface, the definition Temperature Class is used. Ignition by this classification is spontaneous or automatic. The classification is simple to apply and consists of a two-digit code, the first digit is the letter 'T' and second a number between 1 and 6. The lower the number the higher the maximum allowable surface temperature. Hence a T6 gas or vapour is relatively more hazardous than one with a T1 code, see Table 10.3.

The above table complies with the same classification used in the USA, except that the NEC sub-divides the classes in some cases to further A, B and C classes.

10.3.1.3 Grouping of gases and vapours

In order to classify a gas or vapour by its ability to be ignited by a spark, the definition Gas Group is used. Again the classification is simple to apply. It consists of a three-digit code. The first and second digits are I or II [The IEC may add Group III in future for dust hazards.] The third digit is letter A, B or C.

For the oil industry the Group I is of little concern because it pertains only to underground mining. Hence Group IIA, IIB and IIC are of concern in this sub-section. A Group IIA gas or vapour is the hardest of the three sub-groups to ignite by a spark. Conversely a Group IIC gas or vapour is the easiest to ignite.

Table 10.3. Temperature class for gases and vapours

'T' classification by IEC60079 Part 0	Maximum surface temperature, °C
T1	450
T2	300
T3	200
T4	135
T5	100
T6	85

The definitions in the USA differ slightly by the use of ‘Class’ rather than ‘Group’.

The grouping code influences the design of jointed and mating surfaces and shaft seals, because the gases in different groups have different explosive and burning characteristics e.g. speed of flame propagation, rate of rise of explosive pressure. Hence the grouping codes influence the physical design of enclosures. The gases hydrogen and acetylene for example are notably difficult gases to cater for in designs. Hydrogen is often encountered in the oil industry, and acetylene in the chemical industry.

10.4 HAZARDOUS AREA ZONES

In the European and UK standards the term Zone is used for hazardous areas, whereas the term Division is used in the USA. In practice the end result of selecting appropriate equipment for a Zone or Division is usually very similar. There are a few subtle differences, especially when selecting electric motors. The zonal definitions vary in wording from one document to another but the essential elements are as follows.

10.4.1 Non-hazardous Area

In the earlier period the term Safe Area tended to be used to mean an area that was deemed to be completely free of potential hazards. As with many technologies their terms and definitions take on slight changes as time passes, usually because of the feedback effect of experience. In this way the term Non-hazardous Area seems to have superseded Safe Area. (Curiously the zonal numbering is in opposite sense to the severity of hazard, zero is the worst and 2 is the least, as discussed below.)

10.4.2 Zone 2 Hazardous Area

The lowest non-zero risk of hazard is to be found in a Zone 2 area. In a properly designed and maintained plant the occurrence of leakage of flammable gas, vapour or volatile liquid from within the vessels, tanks, piping, valves, seals, pumps, compressors and the like is accepted as being unlikely but possible. The possibility is deemed to exist when a fault develops in the equipment e.g. a flange gasket fails, a pipe fractures. These occurrences come under the category of ‘wear and tear’. It is possible that a leakage may result from some mal-operation e.g. a heavy object is accidentally dropped onto equipment that contains a hazardous fluid e.g. a pipe, which either pierces the metal or loosens a joint. These occurrences may be categorised as ‘accidental’ causes, and can be considered as being statistically low, hence the risk of explosion is also low. They may be considered unlikely to occur over a long period of time (months, years) or if they do then the time period will be short (up to 10 hours per year, see Reference 1).

10.4.3 Zone 1 Hazardous Area

A higher risk of hazard than that applicable to a Zone 2 area, is found in a Zone 1 area. Again it can be considered that the plant is properly designed and maintained. However, some parts of the plant are more prone to leakage than others, some types of seals used in rotating shafts of pumps and compressors, discharges from safety valves, some methods of venting gases and vapours, some types of open drains for volatile liquids. Hence leakage may be considered likely to occur some time during a long period (tens of hours or longer in a year, see Reference 1). The risk of an explosion in a given period of time is therefore higher than with a Zone 2 area.

10.4.4 Zone 0 Hazardous Area

The highest risk of hazard is to be found in a Zone 0 area. These areas are usually the gaseous volume immediately above a volatile liquid contained in a vessel or tank. In some situations the contents of a vessel or tank will normally be at atmospheric pressure e.g. crude oil storage tanks in an exporting tank form, refinery feed stock tanks, temporary storage of liquid products in a chemical plant. Some designs of vessels and tanks need a means of venting to prevent an increase in surface pressure as the liquid rises, or a reduction in pressure as the same liquid falls. In a large tank these small changes in surface pressure, and hence the enclosed vapour pressure, can cause serious damage to the tank walls and roof if some form of two-way venting is not allowed. The surroundings close to the atmospheric vent aperture would therefore be a Zone 0 area.

10.4.5 Adjacent Hazardous Zones

In many locations where a hazardous area is identified and numbered as 0, 1 or 2 the immediate surroundings are given the next higher number, except for an original Zone 2 area, which automatically is surrounded by a non-hazardous area. A Zone 0 area is surrounded by a Zone 1 area, which in turn is, surrounded by a Zone 2 area. A Zone 2 area stands alone.

During the preparation of drawings that show the extent and shapes of the areas surrounding a source, it is usually found that overlapping areas create complicated geometrical shapes, e.g. two adjacent circular boundaries almost touching each other. In these situations the shapes should be simplified by using tangent lines. Local pockets within the geometry should be absorbed into a more uniform shape, especially non-hazardous pockets in Zone 2 geometry. Experience shows that equipment located in a non-hazardous area that is ‘near’ to a Zone 2 area will usually be of the same specification as that which is to be installed in the Zone 2 area. The same approach is sometimes used for Zone 2 areas near to a Zone 1 area if the equipment are small items e.g. junction boxes, lighting fittings, instrument casings, and local control stations.

10.5 TYPES OF PROTECTION FOR HAZARDOUS AREAS

Most electrical equipment consists of live or active static parts, and in some cases such as motors, solenoid valves and relays moving mechanical parts, encased in an enclosure. The electrically live conductors are kept out of touch to prevent electric shock hazards. The detrimental effects of the atmosphere e.g. rain, sprayed water, fine dust and particles are kept out of contact with the conductors, insulation, bearings and the like. For equipment that is to be used in hazardous areas there is the additional requirement that gases and vapours should be restricted from entering into the enclosure. There are various basic methods that attempt to ensure that this requirement is achieved at a more or less degree, which generally is dependent upon the Zone of the intended area of installation.

The design of the enclosure with regard to hazardous area applications is defined by several lower case letter codes, mostly single digits for electrical power equipment but occasionally two

Table 10.4. Enclosure codes for hazardous area equipment

Ex or EEx code	Brief description
d	Flameproof enclosure
e	Increased safety
i	Intrinsic safety. There are two types ia and ib
m	Encapsulated enclosure
n	Basically a UK concept that is similar to type 'e', but only for use in Zone 2 areas
o	Oil-immersed enclosure
p	Pressurisation and continuous dilution by non-hazardous air or inert gas such as nitrogen
q	Sand-filled enclosure
s	Special designs of enclosure or system of components

digits for very low energy electronic equipment. The most frequently encountered codes are d, e, n, p and i. The lesser used codes are o, m, s and q. Table 10.4 gives a brief description of each code. The codes are usually embraced with double or single quotation marks, or less often single round brackets ( ). The code is prefixed with the letters Ex or EEx. Occasionally two letters are combined for special designs of equipment e.g. Ex 'de' for some types of motors.

Reference 3 gives a useful Table 1 therein, that relates various international standards to the different types of protection 'd' to 's'.

10.5.1 Type of Protection 'd'

This type of protection is also referred to as 'flameproof' in some literature. An enclosure that is designed as type 'd' will be able to withstand an internal explosion of the gas-air mixture without being damaged beyond repair. Furthermore the mating surfaces of joints e.g. terminal boxes, bearing seals on shafts, will be so designed that the flame inside the enclosure will not pass to the outside with sufficient energy to ignite the environmental gas-air mixture. In effect the design of the surfaces is such as to act as a very slow pressure relief system for the internal explosion. (Care should be exercised when dismantling such an enclosure after an internal explosion has occurred, because there may be some residual pressure internally.)

By the form of the design these enclosures are usually robust, 'heavy duty' and often made of thick cast iron, steel or bronze with many bolts to fasten the fabricated sections and lids. They are therefore the most expensive enclosures when compared with the 'e' or 'p' types. It becomes impractical to manufacture 'd' type enclosures for very large ratings of motors. The amount of metal and machining required would not be economical and so the 'p' type would be an alternative.

This type of protection is mainly intended for Zone 1 areas.

In addition the electrical components inside the enclosure may be of the sparking type e.g. commutators for DC motors, local control stations with push buttons, relay boxes.

When an internal explosion occurs or under normal running conditions, the outside surface of the enclosure must not exceed the gas-air autoignition temperature i.e. Temperature Class.

The maintenance procedures for working with Ex ‘d’ equipment need to be exercised with care so that the machined surfaces are not degraded or damaged. BS5345 was introduced in 1976 to address this and similar subjects. See Reference 4 for practical view of the problems involved with maintenance of hazardous area equipment.

10.5.2 Type of Protection ‘e’

Type ‘e’ is also called ‘increased safety’ and intended for apparatus that is to be installed in a Zone 1 area. Two of the allowable features of the type ‘d’ enclosures, namely permitting sparking components and no Temperature Class limit to the internal components, cannot be incorporated into the type ‘e’ designs. The practical aspect of this is the removal of a source of ignition i.e. a spark or a hot surface. In many types of equipment e.g. luminaries, terminal boxes, junction boxes, some designs of motor control stations, telephones and public address speakers, the elimination of these two sources of ignition is not a difficult problem.

For motors the removal of sparking components, such as a commutator is not too difficult, but the prevention of a hot internal surface is a problem for the designer. Clearly a DC motor cannot be designed as an ‘e’ type machine. The identification of hot-spots in the windings or core of a motor at the design stage is extremely difficult. This applies especially to the rotor cage of an induction motor. Consequently the design of an ‘e’ motor needs to be somewhat conservative. For example the temperature rise of the windings needs to be reduced. The power output of an ‘e’ type motor for a given frame size is generally found to be less than for type ‘d’ or ‘p’ motors. There are also restrictions on the allowable starting current and run-up time. Hence the motor characteristics will need to be more carefully matched to the driven machine. High inertia rotors in the driven machines should therefore be avoided. This conservativeness is also supported by the requirement that the protective relay equipment at the motor control centre shall have special characteristics. Hence the use of an ‘e’ type motor means that a ‘system’ of components or equipment must be used, not just the motor by itself. This adds an element of ‘unusualness’ to the circuits in a motor control centre, and for this reason the use of ‘e’ type motors in the oil industry is not common practice.

10.5.3 Type of Protection ‘i’

Intrinsically safe type ‘i’ protection is not applicable to electrical power equipment. It is mainly intended for electronic measuring and control circuits i.e. instrumentation and telemetry. The principle behind ‘i’ protections is that a circuit and its devices do not have sufficient operating energy or stored energy to cause a spark that will ignite the gas-air mixture. A spark can occur but it must be inherently too weak to ignite the mixture. There are two sub-divisions of type ‘i’, namely ‘i_a’ and ‘i_b’. The type ‘i_a’ has a more stringent specification than ‘i_b’ and is therefore allowed to be used in a Zone 0 area. Type ‘i_b’ equipment cannot be used in a Zone 0 area.

Like the type ‘e’ protection of motors a ‘system’ approach is required for type ‘i’ equipment. The system includes the source of power and its Zener Barrier, the interconnecting cables which by their nature have inductance and capacitance, and the connected apparatus or load. If the connected apparatus has inherent capacitance or inductance then extra attention must be paid to the design and certification of the system. Reference 1 Chapter 13 gives more information about certifying a system of components.

10.5.4 Type of Protection ‘m’

Type ‘m’ enclosures are encapsulations, for example an electronic circuit encapsulated in solid epoxy resin or fire-resistance solid material. There are very few examples in electrical power equipment used in the oil industry.

10.5.5 Type of Protection ‘N’ and ‘n’

This type of protection does not have any particular title description. It also has some mixed connotations with type of protection ‘N’ which is very similar but not identically the same.

The subject of type of protection ‘N’ attracted much debate in the 1980s and 1990s, as explained in Chapter 6 of Reference 1 and Reference 5, much of which centred around whether or not sparking equipment could be included in an enclosure.

The ‘N’ was originally developed in the UK and became covered by BS4683 Part 3. BS4683 has been superseded by BS6941, which has been updated in 1997. BS5000 part 16 covers non-sparking motors with the type of protection ‘N’. The use of type of protection ‘N’ in zone 2 areas may not be universally assumed to be completely satisfactory, as described in Reference 5 which recommends that some action should be taken to reduce the hazardous situation when a release of gas occurs. Taking appropriate action manually may not be achievable on a highly reliable basis in practice. A form of automatic action will be needed such as a ‘fire and gas detection’ scheme, with alarms and tripping functions.

References 1 and 5 give good descriptions of the background to the development of the type ‘N’ concept.

Type ‘n’ was not covered by the early editions of IEC60079, it became included as Part 15 in 1987.

The basic concept of type ‘n’ protection was to have an enclosure design that would be suitable for Zone 2 areas. The application to Zone 1 areas was deliberately excluded. Consequently it should be possible to design an enclosure which is ‘better’ than standard industrial designs of good quality and which has some similarity with type ‘e’ designs. The intent was to have non-sparking components inside a suitable enclosure, and to have a certifiable item of equipment for Zone 2 use. Inherent in the concept of a good quality industrial design for use in a Zone 2 area is the need for a robust water and dust resistant enclosure. Hence the IEC and BSI standards require a certain high level of ‘ingress protection’, see sub-section 10.6. In most cases the minimum ingress protection is IP54, but fully insulated conductors IP44 may be used e.g. motors.

As far as motors are concerned, the emphasis on hot surfaces, high starting currents and extended run-up times is not as great as with type ‘e’ for Zone 1 areas, due to the inherently lower risk of hazard in a Zone 2 area. Special protective relays are not required and a ‘system’ approach is not used. Similar design features in the mechanical part will be found e.g. clearances of fan blades, length of the air-gap between the rotor surface and the stator inner surface. Oil company specifications often call for non-sparking materials for the construction of the fans.

Other types of equipment than motors are often chosen with type ‘n’ enclosures, e.g. luminaries, junction boxes, terminal boxes, if the designer can be sure that they will be located in a Zone 2 or non-hazardous area.

Note: Until 1999 the practice in the USA did not recognise type 'n' or the certification of equipment for Zone 2 (Division 2) areas. In these areas good quality, standard industrial equipment may be installed. It is worth noting, however, that the NEC, Reference 2, was revised in 1999 and Article 500 now includes the IEC system of zones and the types of protection 'd', 'e', 'm', 'n', 'o', 'p' and 'q' in Article 505. Type of protection 'N' is not included.

10.5.6 Type of Protection 'o'

With this type of protection the active and sparking parts of the equipment are immersed in mineral oil. The concept is similar to that used in the manufacture of bulk oil immersed and small volume oil immersed switchgear (both of which are seldom encountered nowadays). Oil immersion finds application with electronic and telemetering equipment.

Type 'o' protection is only permitted in Zone 2 and non-hazardous areas. Oil immersed switchgear is not normally specified in the oil industry because there are far better insulating media available in modern designs e.g. SF6 and vacuum.

10.5.7 Type of Protection 'p'

This is also known as pressurisation or continuous dilution. It is mainly applied to large motors, control panels, display panels, and occasionally special purpose generators. Type 'p' protection is suitable for Zone 1 and Zone 2 areas.

Type 'p' protection allows well-designed standard industrial equipment to be used in hazardous areas, provided that the enclosure is suitable for pressurisation by air or an inert gas. The enclosure should be reasonably airtight so that the pressurisation can be maintained by a modest throughput of air or gas.

The pressurisation process is carried out in two parts, the first part when the equipment is ready to be energised and the second part to cater for the running and shutdown of the equipment.

The first part is called 'purging'. Air or inert gas is passed into and vented from the enclosure, to purge out any gas-air mixture that may be present. The equipment is prevented from being energised until the purging cycle is complete. The purging cycle will need to pass a prescribed volume of air or inert gas through the equipment. Measuring devices will be incorporated into the purging equipment to ensure that the necessary volume of air or gas has been passed. If the purging equipment fails then the enclosure cannot be energised. The purging equipment maintains a throughput of air or gas to balance the leakage to atmosphere from joints, bearing seals, gaskets and the like, and to maintain a prescribed pressure inside the enclosure.

The purging air must be drawn from a non-hazardous area source e.g. through suitable ducting or from a plant air compressor. If the enclosure is large, as in the case of high voltage motors, then the use of plant air may present problems of air consumption. The purging gas for a small enclosure may be taken from high-pressure storage cylinders, using a suitable pressure reduction regulator.

Wherever the purging medium is derived from, it should be filtered and dried so that the enclosure is not contaminated or dampened, and the insulation of the internal components degraded.

10.5.8 Type of Protection ‘q’

This type of protection uses sand or similar dry powder to exclude the flammable gas-air mixture. It is mainly intended for electronic equipment as it has very little application in the oil industry.

10.5.9 Type of Protection ‘s’

Type ‘s’ protection is also called ‘special’ protection and enables unusual designs to be designed, tested and certified. It is a little used method and the applications are mainly suited to electronic and low power equipment.

10.5.10 Type of Protection ‘de’

The type of protection ‘de’ is a hybrid of the ‘d’ and ‘e’ types. It is mainly used for motors. The concept is that the motor is type ‘d’ whilst its terminal boxes are type ‘e’. This hybrid concept evolved from the difficulties experienced with the use of ‘direct’ and ‘indirect’ entry of the cables at their terminal boxes. A direct entry requires a barrier gland, which is filled with a compound to displace all the air pockets inside the gland where the cable conductors are exposed. An indirect entry does not require a barrier gland. However, with both methods the cable gland must be of the type of protection ‘d’, with the correct threading to suit the terminal box.

The type ‘e’ terminal box contains the winding terminations, which are usually in the form of threaded studs mounted on a robust flameproof partition or interface. The studs are sealed into ‘through-type’ insulators, which are often made of epoxy resin compound. The arrangement ensures a strong hermetical seal between the internal volume of the motor and that of the terminal box. Since the components inside the terminal box are of the non-sparking type and their surface temperature is kept low by design, then the box can be certified as type ‘e’. There must be a fully sealed barrier or interface between the type ‘d’ part and the type ‘e’ part.

Barrier glands are generally unpopular in the oil industry because of the practical difficulties associated with making and remaking the glands in difficult environments, for example during periods of routine maintenance.

The introduction of BS5345 in the mid-1970s focused attention on maintenance and installation of hazardous area equipment for the first time. It placed responsibility on the user of equipment in addition to that which already existed for the manufacturers.

Keeping the materials clean and dry whilst the glanding is being prepared is sometimes difficult e.g. outdoors offshore in bad weather, in dusty desert conditions.

Overall the type ‘e’ terminal box with a non-barrier type ‘d’ gland provides an economical as well as a very practical method of terminating cables.

The method has potential with equipment other than motors e.g. local control stations, switched socket outlets.

10.6 TYPES OF PROTECTION FOR INGRESS OF WATER AND SOLID PARTICLES

10.6.1 European Practice

Whether equipment is certified for hazardous area use or not, it needs to be suitable for the daily environment in which it will be installed. The description of the environment as 'daily' takes account of human interaction with the equipment. For example motors may be installed in a normally dry location either indoors or outdoors, but the plant personnel may regularly hose down the location with water. Equipment may be installed in a plant room that is protected against fire by water spray heads.

IEC60529 is the most commonly used standard for defining the 'degree of ingress protection' for both liquids and particles. (IEC60694, 1996 version, also describes the coding with particular emphasis on switchgear and controlgear, and IEC60034 part 5 to rotating electrical machines.) The most familiar form of the 'IP' code is described herein. The 1989 and later versions of the standard do have some additional refinements for special situations.

The basic code has six digits of the form, I P n m a s. The first two signify 'Ingress Protection' and do not change. The third digit n, refers to ingress by particles. The fourth digit, m, refers to ingress by liquids. The digits n and m range from 1 to 9, the higher the number the more protection is provided. Some combinations of n and m have a generally accepted connotation. The fifth digit a, is called an 'additional letter' and relates to the diameter and length of across probes that can gain access to parts that are a hazard in terms of electric shock. The sixth digit s, is called a 'supplementary letter', and relates to high voltage, rotating and stationary dangerous internal parts. It also relates to extra protection requirements for specified weather conditions. The fifth and sixth letters are often omitted.

Note: Large particles should be read as to include human hands, fingers, insects, tools and foreign bodies.

The familiar form is that which is well understood by manufacturers, suppliers and their customers.

The protection against particles is summarised in the Table 10.5:

Table 10.5. Ingress protection against particles

Third digit	Brief description of the protection provided against particles
0	No mechanical protection
1	Particles greater than 50 mm diameter e.g. human hands and several fingers, rods, screwdrivers
2	Particles greater than 12 mm diameter e.g. one finger, rods, screwdrivers
3	Particles greater than 2.5 mm diameter e.g. thin rods, thin screwdrivers
4	Particles greater than 1.0 mm diameter e.g. wire, course dust, sand
5	Small particles less than 1.0 mm diameter e.g. find dust, cement powder.
6	Complete protection

Table 10.6. Ingress protection against liquids

Forth digit	Brief description of the protection provided against liquids (typically water)
0	No mechanical protection
1	Water droplets falling vertically, i.e. condensation droplets, not heavy rainfall
2	As for 1, except that the enclosure can be inclined in angle up to 15° from its normal position
3	Rain water or sprayed water. Falling vertically or at angle up to 60° from the vertical (horizontal spray is excluded e.g. man with a hose pipe)
4	Water being splashed from any direction e.g. rain water hitting the ground, but not under pressure
5	Water applied by jets from any direction e.g. hose pipe with a nozzle
6	Conditions on the deck of a ship (or offshore platform), during stormy seas and high waves; this implies good water tightness at atmospheric pressure
7	Submersed in water at a given depth for a given time e.g. 1 m depth for 30 minutes; this prescribes a hydrostatic pressure greater than atmospheric pressure
8	Submersed in water at a given depth for an indefinite time; this implies that almost complete protection is provided

The protection against liquids is summarised in Table 10.6:

It can be seen in practice that the design of a jointed surface or an enclosure grill to protect against particles will, by its physical construction, satisfy to some extent the requirements for ingress of liquid. Table 10.7 shows an approximate relationship between the two requirements, and shows those codes which are generally available from manufacturers.

When hazardous area equipment is being specified, it will need to be given a minimum degree of ingress protection. The degree will depend upon whether the equipment is to be installed outdoors and exposed to the extremes of the weather, or indoors and exposed (or not) to dust or liquid ingress. The degree may also depend upon whether the equipment is located at ground level or, for example, attached to a ceiling in a plant room. If the location is outdoors, then the IP code will typically vary between IP54 and IP66. For indoor equipment in a hazardous area not exposed to particles or water, the minimum IP code would be typically IP44. The installation designer should consult the manufacturers of particular types of equipment e.g. motors, luminaries, in order to determine what minimum IP is normally available. It is often easy to overspecify equipment by being too cautious or conservative, and this results in severely restricting the manufacturers that are available in the market place or they will decline to offer equipment. This causes delay in a project and necessitates revising a specification and repeating the enquiry process.

10.6.2 American Practice

A similar approach to the IP code is used in the USA and is described in the ANSI/UL and ANSI/ISA standards but a ‘Type Number’ is used instead of the two or four digit code (n, m, a, s). The basic principles are very similar. Reference 2 Article 500-4 summarises the subject and quotes the appropriate codes and standards.

Table 10.7. Commonly used IP codes for protection of enclosures against particles and liquids

First number for particles					Second number for liquids				
	0	1	2	3	4	5	6	7	8
0		–	–	–	–	–	–	–	–
1		IP 11	IP# 12	–	–	–	–	–	–
2		IP# 21	IP# 22	IP# 23	–	–	–	–	–
3		IP 31*	IP 32	IP 33	IP 34	– –	– –	– –	– –
4		IP 41*	IP 42*	IP 43	IP# 44	–	–	–	–
5	–	–	–	–	IP# 54*	IP# 55*	–	–	–
6	–	–	–	–	–	IP 65*	IP 66*	IP 67	IP 68

Complete code = IP + first number + second number
These are the usually preferred combinations of the first and second numbers.
*Note: These are the codes most frequently used in general.
#Note: These are the codes most frequently used for motors.

In the USA the National Electrical Manufacturing Association (NEMA) places certain standards on electrical products. This organisation has established a 'NEMA' type coding system for enclosures. Each type, numbered from 1 to 13, describes a specific type of protection, see ANSI/NEMA standard 250.

The NEMA coding system specifically includes three categories for equipment that is to be installed in oil industry hazardous areas, namely Types 7, 8 and 9, but only for indoor locations.

In the interest of completeness all the NEMA 'types' are summarised below:

10.6.2.1 Type No. 1: General purpose

An enclosure intended for indoor use where there are normal atmospheres. The enclosure protects against accidental contact of personnel with the enclosed control.

10.6.2.2 Type No. 2: Drip-proof

An enclosure intended for indoor use to protect the enclosed control against falling non-corrosive liquids and falling particles. These enclosures must have provisions for drainage.

10.6.2.3 Type No. 3: Dust-tight, rain-tight and sleet (ice) resistant

An enclosure intended for outdoor use to protect the enclosed control against windblown dust and water. These enclosures must have provisions for watertight connectors, provisions for mounting external to the enclosure cavity and provisions for locking.

10.6.2.4 Type No. 3R: Rainproof and sleet (ice) resistant

An enclosure intended for outdoor use to protect the enclosed control against rain. These enclosures must have provisions for watertight connectors, for locking and for drainage.

10.6.2.5 Type No. 3S: Dust-tight, rain-tight and sleet- (ice) proof

An enclosure intended for outdoor use to protect the enclosed control against windblown dust and water and to provide for its operation when the enclosure is covered by external ice or sleet. These enclosures do not protect the enclosed equipment from malfunction due to internal icing. These enclosures must have provisions for watertight connectors, for mounting external to the enclosure cavity and for locking. In addition, these enclosures must have the ability to support the additional weight of ice and to withstand the removal of ice by a hand tool to permit access to the enclosure interior.

10.6.2.6 Type No. 4: Water-tight and dust-tight

An enclosure intended for indoor use to protect the enclosed control against splashing water, seepage of water, falling or hose-directed water and severe external condensation. These enclosures must have provision for watertight connectors and for mounting external to the enclosure cavity.

10.6.2.7 Type No. 4X: Water-tight, dust-tight and corrosion-resistant

Same as Type No. 4 with corrosion-resistant construction.

10.6.2.8 Type No. 5:

Superseded by Type No. 12

10.6.2.9 Type No. 6: Submersible, water-tight, dust-tight and sleet-(ice) resistant

An enclosure intended for use indoors or outdoors where occasional submersion is encountered. The enclosure protects the enclosed control against a static head of water of 6 feet for 30 minutes, dust, splashing or external condensation of non-corrosive liquids, falling or hose-directed water, lint and seepage. These enclosures must have provisions for watertight connectors and mounting external to the enclosure cavity.

10.6.2.10 Type No. 7: Class I, Group A, B, C or D indoor hazardous locations air-break equipment

An enclosure intended for indoor use in the atmospheres and locations defined as Class I, Group A, B, C or D in the National Electrical Code. The letters A, B, C or D, which indicate the gas or vapour atmospheres in the hazardous location must appear as a suffix to the designation Type 7, to give the complete NEMA designation.

Note: Type 7 enclosures are termed explosion proof as defined in NEMA and the National Electrical Code.

10.6.2.11 Type No. 8: Class I, Group A, B, C or D indoor hazardous locations oil immersed equipment

Same requirements as for Type 7 regarding locations, atmospheres, marking and use of suffix letters to designate NEMA type.

Note: Type 8 enclosures are used for oil immersed equipment and are 'not' considered explosion proof as defined in NEMA or National Electrical Code.

10.6.2.12 Type No. 9: Class II, Group E, F or G indoor hazardous locations air-break equipment

Type 9 enclosures are intended for use indoors in atmospheres defined as Class II and Group E, F or G in the National Electrical Code. The letters E, F or G, which indicate the dust atmospheres in the hazardous location, must appear as a suffix to the designation Type 9, to give the complete NEMA designation. These enclosures prevent the ingress of explosive amounts of hazardous dust. If gaskets are used, they must be mechanically attached and of a non-combustible, non-deteriorating, vermin-proof material.

Note: Type 9 enclosures are 'not' considered explosion proof as defined in NEMA or the National Electrical Code.

10.6.2.13 Type No. 10: Bureau of mines

Type 10 enclosures must meet the requirements of the US Bureau of Mines, which relate to atmospheres containing mixtures of methane and air, with or without coal dust present.

Note: Type 10 enclosures are termed explosion proof as defined in NEMA and National Electrical Code.

10.6.2.14 Type No. 11: Corrosion resistant and drip proof-oil immersed

An enclosure intended for indoor use to protect the enclosed control against dripping, seepage and external condensation of corrosive liquids. In addition, the enclosures protect against the corrosive effects of fumes and gases by providing for the immersion of the control in oil. These enclosures must have provisions for watertight connectors and for mounting external to the enclosure cavity.

10.6.2.15 Type No. 12: Industrial use dust-tight and drip-tight

An enclosure intended for indoor use to protect the enclosed controls against fibres, flyings, lint, dust, dirt and light splashing, seepage, dripping and external condensation of non-corrosive liquids. All accesses to the enclosure cavity must have oil-resistant gaskets and where necessary dust-tight or oil-tight mechanisms. These enclosures must have mounting means external to the enclosure cavity, captive closing hardware and provisions for locking.

10.6.2.16 Type No. 13: Oil-tight and dust-tight

An enclosure intended for indoor use primarily to house pilot devices such as limit switches, foot switches, push-buttons, selector switches, pilot switches etc., and to protect these devices against lint and dust, seepage, external condensation and spraying of water, oil or coolant. These enclosures must have oil-resistant gaskets and when intended for wall or machine mounting, must have mounting means external to the enclosure cavity. There are no conduit knockouts or unsealed openings providing access into the enclosure cavity. All conduit openings must have provisions for oil-tight conduit entry.

10.7 CERTIFICATION OF HAZARDOUS AREA EQUIPMENT

In general the installation designer and the user require confidence that manufactured equipment for use in a hazardous area carries an internationally recognised certificate. In addition the certificate should be the result of laboratory testing of a sample of the same equipment. The laboratory should be specialised in the type of testing required.

In the UK and Europe a certificate is required from the manufacturer for equipment that is to be used in Zone 1 and Zone 2 areas. In some situations a certificate will be obtained for a system of components, for example with intrinsically safe equipment.

In the USA the practice is slightly different. Only equipment that will be installed in a Division 1 area should require a certificate.

For manufacturers offering a range of products, the process of testing and obtaining a certificate is expensive and time consuming. Subsequent modification to a design can also be a long and expensive process for retesting and re-approval.

Over the last 15 years there has been a process called ‘harmonisation’ of the various national standards within the UK and Europe with the internationally accepted IEC standards. This has made the subject of certification rather complicated, but as time passes the results should be simpler to obtain both for the manufacturer and to the satisfaction of the user.

The harmonisation process has been managed by the Committee of Electrotechnical Standardisation (CENELEC) in Europe. The committee standardises many subjects of electrical and electronic engineering, not only those pertaining to hazardous area equipment and its installation. When equipment is certified in accordance with a CENELEC standard the symbol ‘Ex’ is modified to become ‘EEx’. This serves to give the designer and the user extra confidence in the certification.

The certification process, like so many other manufacturing functions, is now being influenced by the generally accepted requirement for quality assurance, through the ISO9000, 9001 and 9002 standards.

There are several permutations for certification involving European harmonisation and countries inside or outside the EC (European Community). Equipment can be manufactured in any country. The manufacturer may choose to design his equipment to the national standards of his country, or he may wish to cover a wider market by using an international or even a CENELEC standard. Once the equipment is manufactured, samples of it will need to be tested. There may be a testing authority in the particular country, or for some reason the manufacturer may choose to have the testing carried out in another country e.g. the testing laboratory may have a wider scope of facilities. Eventually the manufacturer will obtain a certificate. The installation designer and the user may need to carefully scrutinise the whole sequence of events leading up to the issuance of a valid certificate. Reference 1 explains the European situation in detail, together with the various types of certificates that are obtainable from within Europe and from other continents. The subject is complex and requires careful study to ensure that the correct documentation is obtained.

10.8 MARKING OF EQUIPMENT NAMEPLATES

Hazardous area equipment that has been tested and approved by a recognised laboratory should have a marking plate attached to its surface, in a place easily seen by the user. This plate is usually the nameplate that shows the normal information such as the name of the manufacturer, voltage, rated power, full load current, frequency, model number, serial number, ambient temperature and date of manufacture. The additional information to be shown for the hazardous area application, should be at least the following:

- Applicable national or international standard e.g. BS5501 Part 5, IEC60079 Part 2.
- Name or abbreviation of the testing laboratory that issued the certificate, e.g. BASEEFA.
- Approved symbol for the certifying authority, and if appropriate the EEC hexagonal symbol.
- Type of protection e.g. EEx 'd', Ex 'e', Ex 'n'.
- Gas Group e.g. IIA, IIB, IIC.
- Temperature Class e.g. T6.
- Certificate unique identification number.

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FURTHER READING

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11

Fault Calculations and Stability Studies

11.1 INTRODUCTION

When a short circuit occurs in a power supply, larger than normal currents are caused to flow into the short circuit. The magnitude of the short-circuit current is determined by the impedance of AC systems, or the resistance of DC systems, that exists between the short circuit and the sources of voltage. That impedance or the resistance will be called the 'source impedance' in the discussions that follow. In DC systems the source impedance is often the series addition of the supply cable resistance, the rectifier or thyristor internal resistance and any other resistance that may be connected in the circuit. The calculation of the short-circuit current in a DC circuit is therefore a reasonably simple process once the resistance data are known.

For AC systems the calculation of the short-circuit current is more complicated, particularly when generators and motors are both present in the system. The simplest calculations occur when the source of voltage can be assumed to be of constant magnitude during the fault duration. In AC systems the source impedance will be the addition of the cable impedance, busbar impedance, transformer internal impedance, the appropriate internal impedance of the generator, the appropriate internal impedance of the motors in system and the impedance of the overhead transmission lines.

The sub-sections that now follow will begin with the simplest situations and end with the more complicated.

11.2 CONSTANT VOLTAGE SOURCE – HIGH VOLTAGE

A constant voltage source is one in which the voltage that drives the short-circuit current maintains a constant magnitude before, during and after the fault occurs. This is usually considered to be the case when the source power capacity is very much greater than the normal power rating of the circuit in which the fault has occurred. An example of such a situation is shown in Figure 11.1 for an onshore, high voltage transmission network.

The cables and busbars connecting the transformers to the switchboards are very short in comparison with the length of the transmission lines and the transformer reactances and so their impedances may be ignored. Consider the fault being applied to the busbars of the T4 switchboard. The fault circuit for the switching configuration shown is through T2 and T4.

The simple series circuit for this configuration is shown in Figure 11.2.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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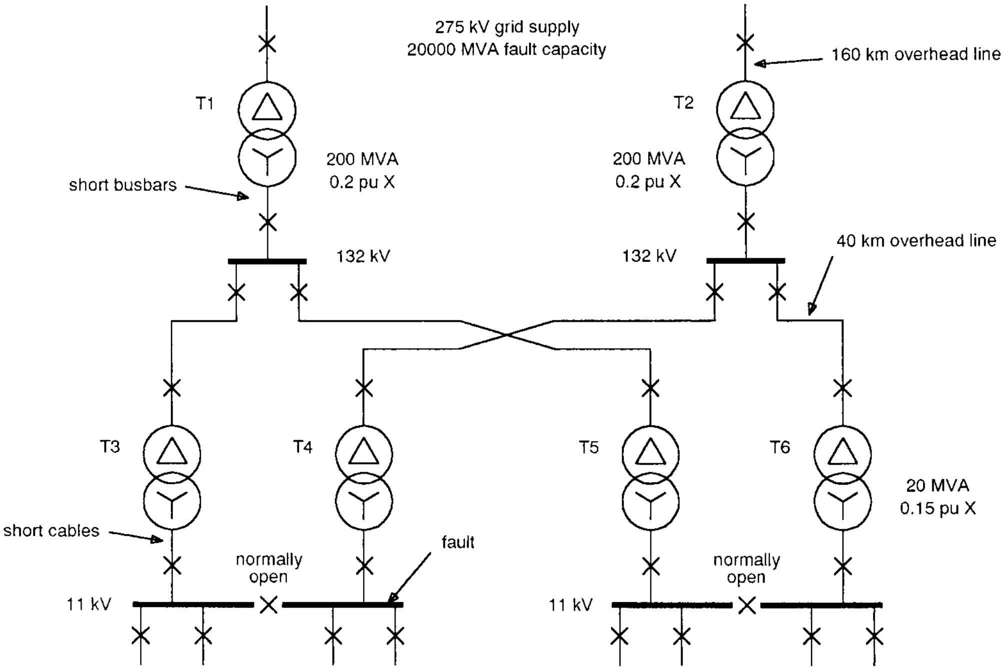


Figure 11.1 One-line diagram of faulted high voltage system.

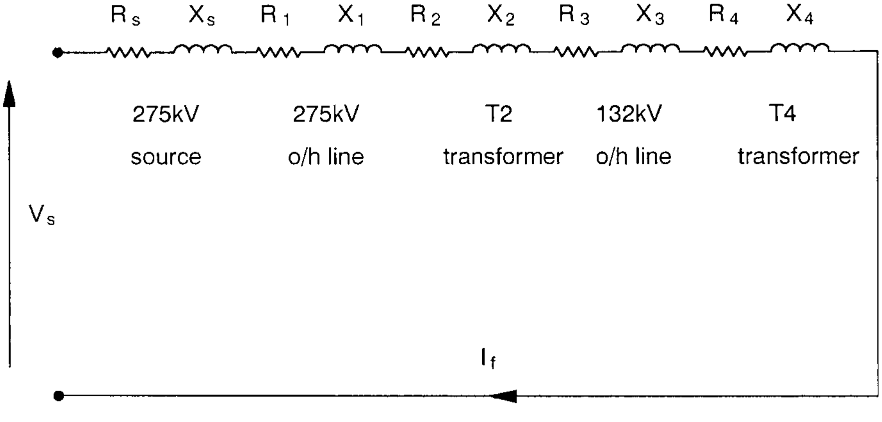


Figure 11.2 Equivalent circuit of faulted high voltage system.

The base MVA rating chosen for this system is 100 MVA. The impedance data is given in Table 11.1.

Hence the total series per unit impedance is $R = 0.069$ pu, $X = 1.021$ pu. The short-circuit current is therefore:

$$I_f = \frac{V}{R + jX} = \frac{1.0}{0.069 + j1.02.1} = 0.9775 \text{ pu}$$

Therefore the fault MVA is $0.9775 \times 100 = 97.75$ MVA.

Table 11.1. Impedance data values

Item	R (ohms)	X (ohms)	R (pu)	X (pu)
			at 100 MVA	
Source fault impedance				0.005
275 KV				
O/H line	5.47	53.91	0.0072	0.0713
T2	–	–	0.0010	0.10
132 KV				
O/H Line	6.235	16.495	0.0358	0.0947
T4	–	–	0.025	0.75
TOTAL			0.069	1.021

Observations:

- It can be seen that for most of the circuit items their X-to-R ratio is more than 10. Hence their resistance may be neglected for fault calculations but this only applies to high voltage systems, e.g. above 3300 volts. The X-to-R ratio of LV components is usually low, e.g. between 1 and 3.
- For different switching configurations the equivalent circuit will be different, and so appropriate additional calculations must be made to find the worst-case situation.

11.3 CONSTANT VOLTAGE SOURCE – LOW VOLTAGE

Consider a LV motor control centre fed from a HV/LV transformer as shown in Figure 11.3.

In this case the cables and busbars are not ignored, as will be demonstrated in the calculations. The base MVA is assumed to be 100 MVA in this case, and the equivalent circuit is given in Figure 11.4.

The impedance data is given in Table 11.2 from which it may be seen that the total series per unit impedance is $R = 0.6092$ pu and $X = 3.9614$ pu.

The short-circuit current is therefore:

$$I_f = \frac{V}{R + jX} = \frac{1.0}{0.6092 + j3.9614} = 0.038 + j0.247 \text{ pu.}$$

Observations:

a) It can be seen that the X-to-R ratio for the LV items is less than 10 and that the total impedance has an X-to-R ratio of 6.5. Since R is relatively large it cannot be ignored in the LV circuits.

b) When designing a new installation in the early stages, it is acceptable to ignore the impedance of the LV busbars and cables. However, as the design becomes more defined it may occur that,

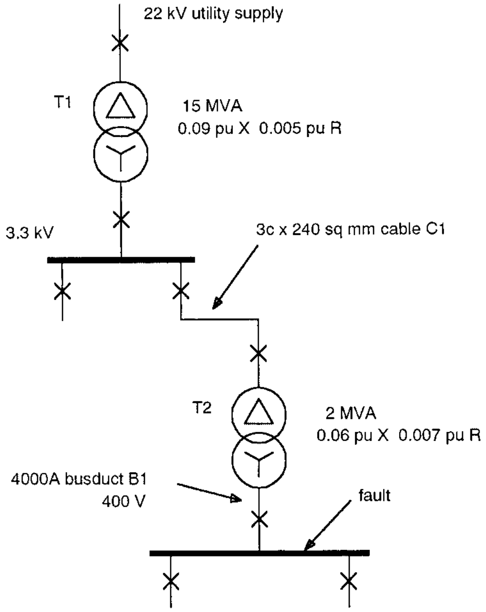


Figure 11.3 One-line diagram of faulted low voltage system.

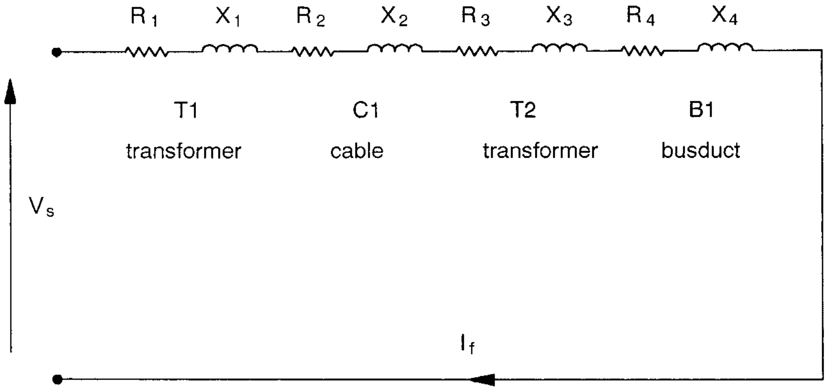


Figure 11.4 Equivalent circuit of faulted low voltage system.

Table 11.2. Impedance data values

Item	R1	X1	R2	X2	R3	X3	R4	X4
T1		0.0333*pu	0.6*pu					
3c-240 mm^2			0.01976	0.0146				
Cable C1			0.1815*pu	0.1343*pu				
T2					0.35*pu	3*pu		
Busbars							0.000086	0.00044
B1							0.0444*pu	0.2273*pu

*per unit at 100 MVA base.

for economic or technical reasons, a choice of MCC ratings may become critically dependent on fault ratings. In such a situation, the resistances and reactances of the LV components should be used in the fault calculations.

c) When designing modifications or uprated systems it is essential that both the resistances and reactances of the LV components are used in the fault calculations, otherwise the existing equipment might be exposed to fault currents higher than expected and a dangerous situation could ensue. This is particularly the case when the HV system is being uprated, e.g. by adding more generators or transformers, and it is too easy to ignore the effects on the LV part of the system. Uprated system design can be more difficult in practice than new system design.
d) Fault currents can be contributed by LV generators and LV motors and so care must be taken to allow for this possibility. This subject will be discussed in detail in later pages.

11.4 NON-CONSTANT VOLTAGE SOURCES – ALL VOLTAGE LEVELS

So far it has been assumed that the source impedance and the source voltage remain constant during a fault situation. This is the case for power systems that do not contain rotating machines, i.e. generators and motors. Motors, and especially generators, exhibit peculiar reactance and voltage characteristics during fault situations and these are generally grouped into three types:-

- Sub-transient effects.
- Transient effects.
- Steady state (or synchronous) effects.

For installations that have self-contained power generation plants, e.g. offshore platforms and onshore gathering stations, proper allowance must be made for the presence of generators and motors, especially at the generator switchboard. This subject is a complicated one and so it is now necessary to give due attention to the design and dynamic characteristics of firstly the generators and secondly the motors.

A synchronous generator (and a synchronous motor) can be represented by many inductances and reactances to account for transformer-type induction, rotational induction, mutual coupling between windings, leakage and self-induction, magnetising and excitation induction and the effects of the pole-face damper windings. Extremely complex equivalent circuits have been developed for synchronous machines, see References 1 and 2 as examples.

For most hand calculations in power systems, only three of the generator reactances are of particular interest:

- The sub-transient reactance X''_d.
- The transient reactance X'_d.
- The synchronous reactance X_{sd}.

The suffix '*d*' relates to the 'direct axis' values, i.e. those that can be represented along the pole axis of the excitation winding. Occasionally, the 'quadrature axis' reactances are encountered and these are denoted by the suffix '*q*'. See Chapter 3 for a further discussion of the '*d*' and '*q*' axis parameters.

The quadrature axis reactances are those that can be represented on an axis at right angles to the pole or direct axis. These reactances do not normally appear in the hand calculation of fault currents.

When generators are being considered it is usually necessary to know the form and magnitude of fault currents when a fault occurs close to the main terminals of the generators. Several aspects of the fault current are of interest:

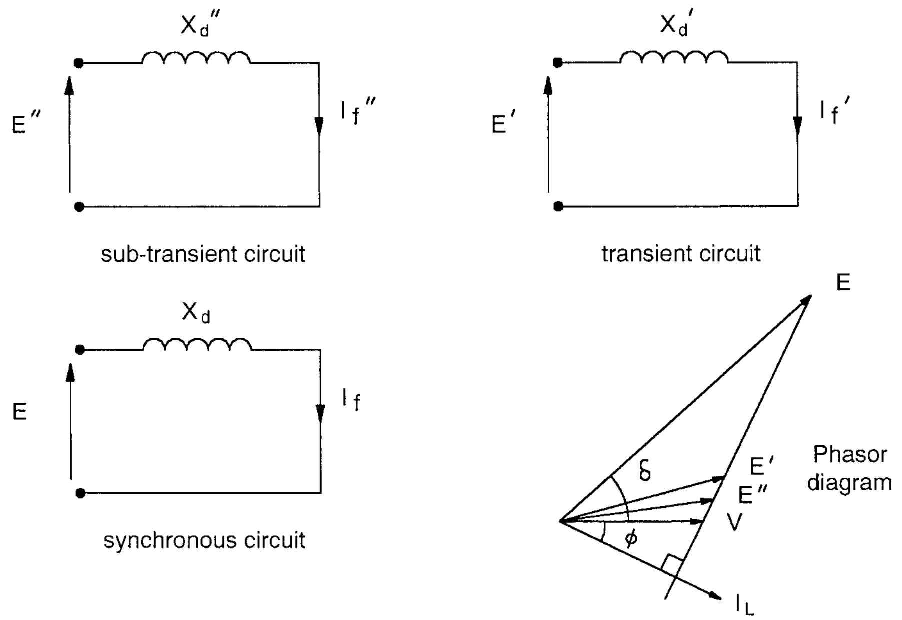
- The peak value of the fault current during the first cycle of instantaneous current. This value determines the ‘peak asymmetrical’ duty of the switchgear connected to the generator. This value is determined by the sub-transient reactance.
- The rms value of the symmetrical component of the fault current during the first cycle. This is the first result obtained from the calculation process and from this is then calculated, or estimated, the peak value mentioned above (due to the phenomenon called ‘current doubling’). This value is determined by the sub-transient reactance.
- The rms value of the symmetrical component of the fault current several cycles after the fault occurs. This value determines the ‘symmetrical breaking’ duty of the switchgear connected to the generator. This value is determined by the transient reactance
- Occasionally a critical situation occurs in which the alternating fault current does not reach a zero value, or becomes negative, until several cycles have passed, see sub-section 7.2.10 and Figure 7.1. This is very important because the basis of interrupting fault current in a circuit breaker is highly dependent on current zeros and crossing points occurring naturally in the circuit. When a current zero occurs, the arc-gap has a short time to become de-ionised and the dielectric strength of the insulating medium in the gap to be restored. While arcing occurs, these two processes cannot take place and energy is released in the arc. If this process is overly delayed then too much energy will be released in the arc and damage due to overheating can occur.
- The switchboard must be specified to withstand this peculiar situation and it is the task of the engineer to investigate the possibility of it taking place, see sub-section 7.2.11. The controlling factor that determines whether or not it takes place is the X-to-R ratio of the source impedance of the generator and its connecting components (cables, busbars and transformers) up to the switchboard. If X is very much larger than R then the phenomenon described may occur. The time constant T_a of the generator influences the time taken for a zero-crossing to occur.

11.5 CALCULATION OF FAULT CURRENT DUE TO FAULTS AT THE TERMINALS OF A GENERATOR

11.5.1 Pre-Fault or Initial Conditions

Since the peak value of the fault current reduces in time due to the effects of the sub-transient and transient reactances, it is necessary to establish a driving voltage suitable for each part of the process and calculation. The concept used is one which assigns an emf ‘behind’ an appropriate impedance of, in the case of generators, an appropriate reactance.

This is shown diagrammatically in Figure 11.5.



sub-transient circuit

transient circuit

synchronous circuit

Phasor diagram

Figure 11.5 Equivalent circuits and the phasor diagram of a faulted synchronous generator.

E'' denotes the sub-transient emf behind the sub-transient reactance X''_d. Used to calculate the initial peak asymmetrical and symmetrical fault currents.

E' denotes the transient emf behind the transient reactance X'_d. Used to calculate the fault-breaking currents several cycles after the fault occurs.

E shows the synchronous emf behind the synchronous reactance X_{sd}. Used for calculating the steady state fault current, which will then be fully symmetrical, since all the sub-transient and transient effects will have decayed to zero. The emf E will be the ceiling voltage of the exciter since the AVR will have seen a severe depression in terminal voltage and will have forced the exciter to give its maximum possible output. See also sub-sections 7.2.8 and 12.2.2.1.

The next step is to determine each of the emfs E'', E' and E that apply to the circuit before the fault occurs. In order to do this it is necessary to know the pre-fault load conditions of the generator. It is usually the case to assume that the generator is running at its rated output just before the fault occurs.

The phasor diagram for full load conditions is shown in Figure 11.5.

Where Ø is the power factor angle, V is the terminal voltage $= 1.0$ pu and I_L is the terminal rated current.

The same method that is described for transformers in sub-section 6.3 is used to find E'', E' and E. Simply replace X_{se} in the equations by X''_d, X'_d or X_{sd} as appropriate and assume R and R_{se} to be equal to zero. Now that the driving voltage has been calculated, it is a simple matter to calculate the symmetrical fault currents.

11.5.2 Calculation of Fault Current – rms Symmetrical Values

From sub-section 11.5.1 the emf E (E'', E' or E) and appropriate reactance X (X''_d, X'_d or X_{sd}) are known. Hence the symmetrical fault current I_f may be easily calculated:

$$I_f = \frac{E}{X} \text{ per unit}$$

For example:

A 6600 V, 4.13 MVA generator has $X''_d = 15.5\%$, $X'_d = 23.5\%$ and $X_{sd} = 205\%$

At full load with a power factor of 0.8 lagging the corresponding emfs are therefore:

$$E'' = 1.1 \text{ pu}, E' = 1.156 \text{ pu and E } = 2.77 \text{ pu}$$

The rms fault currents are therefore:

$$I''_f = \frac{1.1}{0.155} = 7.097 \text{ pu (2564 amps)}$$

$$I'_f = \frac{1.156}{0235} = 4.919 \text{ pu (1776 amps)}$$

$$I_f = \frac{2.77}{2.05} = 1.351 \text{ pu (488 amps)}$$

A typical oil industry power system can be approximated as shown in Figure 11.6. The majority of oil industry systems are of the radial distribution type, with feeders radiating away from a

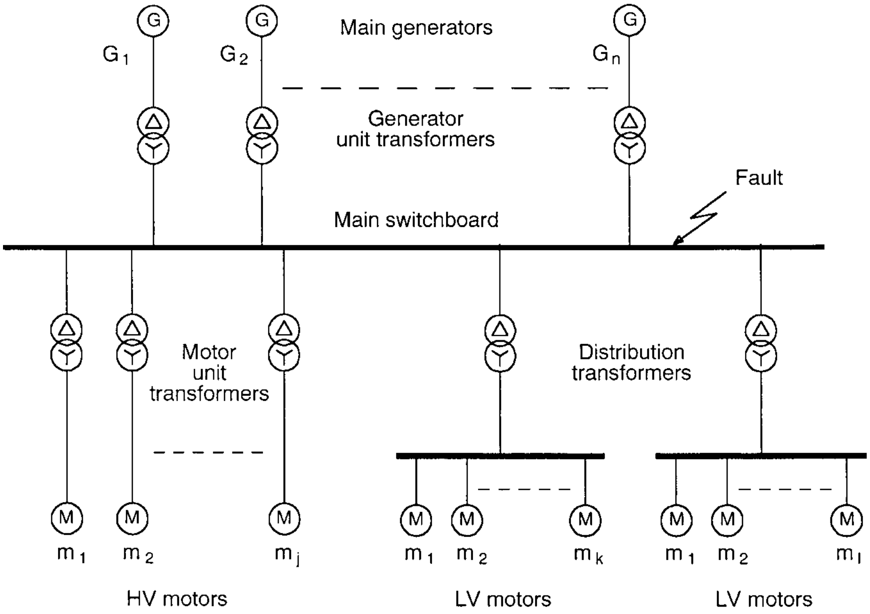


Figure 11.6 One-line diagram of an equivalent power system that has its own dedicated generators.

centralised main switchboard. Mesh or looped systems such as those found in utility or countrywide networks are rarely used. Occasionally a simple form of a 'ring-main' may be used between adjacent plants to improve power equipment utilisation and availability. Radial systems have the benefit that the calculation of load flows and fault currents are relatively easy to carry out by hand or with the use of a simple digital computer program.

Estimating load flows and fault currents are two of the earliest tasks that are necessary to undertake when designing a new plant. Such estimates are carried out so that budget costs and physical dimensions can be established at an early stage of a project.

The sub-transient rms and peak fault currents are needed so that the worst-case maximum fault making duty of the main switchgear can be assessed. The decaying components of the fault current are also of interest in assessing the fault breaking duty of the switchgear at the times that correspond to the circuit breaker clearing times e.g. 0.08 to 0.2 seconds. The long-term steady state fault current is of little concern, unless the system is fed from a utility grid instead of close-up generators. The long-term decrement of the generator current that feeds into a major fault is mainly of interest in setting the protective relays in the generator circuit breaker.

The following discussion and worked example for an LNG plant show how to carry out simple but reasonably accurate estimates of the sub-transient fault current and its decay in the first few cycles. Following is a discussion on how to assess the fault breaking current.

If the total generating capacity exceeds about 120 MVA then the generators should be connected to the main switchboard through unit transformers. The main switchboard voltage should be about 33 kV. Each of the various groups of generators, transformers and motors can be represented by a single equivalent unit, using the methods given below.

11.5.2.1 The load

A preliminary estimate of the load is S_l, which may be assumed to consist of a certain amount of motor load and some static load. The motor load can be assumed to be connected to the main high voltage switchboard and at lower voltage switchboards. Let the high voltage motor load be S_{hm} and the lower voltage motor load be S_{lm}. Assume the static load S_{ls} to be connected to the lower voltage switchboards. Typical power factors for these loads are 0.87, 0.85 and 0.97 respectively. The total active and reactive power estimates are,

$$P_{\text{load}} = 0.87S_{hm} + 0.85S_{lm} + 0.97S_{ls}$$

$$Q_{\text{load}} = (0.493S_{hm} + 0.527S_{lm} + 0.243S_{ls})\, 1.015$$

$$S_{\text{load}} = P_{\text{load}} + j\,Q_{\text{load}}$$

Where the factor 1.015 is an allowance for the I^2X reactive power losses in the transformers.

11.5.2.2 Generators and their transformers

For a new plant it may be assumed that all the generators that are connected to the main switchboard have the same rating and parameters, i.e. identical machines. Similarly their transformers may be assumed to be identical. The total capacity of the generators S_{gen} must be greater than the load S_{load}.

Therefore,

$$S_{\text{gen}} = \sum_{i=1}^{n} S_{gi} = K_g S_{\text{load}}$$

Where S_{gi} is the rating of the i_{th} generator and K_g is a marginal factor > 1.0.

The generator unit transformers have a total capacity S_{tg} slightly higher than S_{gen},

$$S_{tg} = K_{tg} S_{\text{gen}}$$

Where K_{tg} is a marginal factor > 1.0.

Assume the leakage reactance X_{tg} of each generator unit transformer to be 0.08 per unit, and ignore the resistance.

11.5.2.3 High voltage motors and their transformers

The high voltage motor unit transformers have a total capacity S_{tm} slightly higher than that of the motors S_{hm},

$$S_{tm} = K_{tm} S_{hm}$$

Where K_{tm} is a marginal factor > 1.0.

Assume the leakage reactance of each motor unit transformer to be 0.06 per unit, and ignore the resistance.

11.5.2.4 Lower voltage distribution transformers

Assume that the lower voltage switchboards are each fed by two transformers and that the bus-section circuit breaker is normally open. In this configuration each transformer carries half the load on its switchboard. Therefore the total capacity of the distribution transformers S_{td} is at least twice that of the load,

$$S_{td} = 2K_{td}(S_{lm} + S_{ls})$$

Where K_{td} is a marginal factor to account for future increase in load, assume K_{td} to be 1.3.

Assume the leakage reactance X_{td} of each transformer to be 0.055 per unit, and ignore the resistance.

11.5.2.5 Equivalent transformer

Suppose a main switchboard feeds load through transformers of different ratings and impedances. For the purpose of estimating fault current at an early stage in a project it is reasonable to combine all the distribution transformers into one equivalent transformer. The equivalent rating S_{te} of all the transformers is simply the arithmetic sum of their individual ratings S_{ti}.

$$S_{te} = \sum_{i=1}^{n} S_{ti}$$

The equivalent impedance Z_{te} of the transformers may be found from,

$$Z_{te} = \frac{S_{te}}{\displaystyle\sum_{i=1}^{n} \frac{S_{ti}}{Z_{ti}}}$$

11.5.2.6 *Worked example*

Three transformers feed a load from a main switchboard. Their ratings and impedances are,

$$\begin{aligned}
\text{Transformer No. 1} \quad & S_{ti} = 10\ \text{MVA} \\
& Z_{ti} = 0.008 + j0.09\ \text{pu} \\
\text{Transformer No. 2} \quad & S_{t2} = 15\ \text{MVA} \\
& Z_{t2} = 0.009 + j0.1\ \text{pu} \\
\text{Transformer No. 3} \quad & S_{t3} = 25\ \text{MVA} \\
& Z_{t3} = 0.01 + j0.12\ \text{pu} \\
\text{The total capacity} \quad & S_{te} = 10.0 + 15.0 + 25.0 \\
& \phantom{S_{te}} = 50.0\ \text{MVA}
\end{aligned}$$

$$\begin{aligned}
\sum_{i=1}^{n} \frac{S_{ti}}{Z_{ti}} &= \frac{10.0}{0.008 + j0.09} + \frac{15.0}{0.009 + j0 + 1} + \frac{25.0}{0.01 + j0.12} \\
&= 40.432 - j465.93 \\
Z_{te} &= \frac{50.0}{40.432 - j465.93} = 0.0092 + j0.1065\ \text{pu}
\end{aligned}$$

11.6 CALCULATE THE SUB-TRANSIENT SYMMETRICAL RMS FAULT CURRENT CONTRIBUTIONS

The method adopted below is based upon the principles set out in IEC60363 and IEC60909, both of which describe how to calculate sub-transient and transient fault currents, and are well suited to oil industry power systems. The method will use the per-unit system of parameters and variables. Choose the base MVA to be S_{base}.

It is customary to assume that all the generators are operating and that they are heavily loaded. In which case the emf E''_g behind the sub-transient reactance X''_d is about 5 to 10% above the rated terminal voltage, hence assume E''_g is 1.1 pu. This emf drives the fault current around the circuit. In IEC60909 the elevation in driving emf, or voltage, is given in Table I as 'factor c' and discussed in Clause 6 therein.

The contribution of fault current I''_g from the generators is,

$$I''_g = \frac{E''_g}{\left(\dfrac{X''_d}{S_{\text{gen}}} + \dfrac{X_{tg}}{S_{tg}}\right) S_{\text{base}}} \text{ pu}$$

$$= \frac{1.1}{\left(\dfrac{X''_d}{S_{\text{gen}}} + \dfrac{0.08}{K_{tg} S_{\text{gen}}}\right) S_{\text{base}}}$$

$$I''_g = \frac{1.1 S_{\text{gen}}}{\left(X''_d + \dfrac{0.08}{K_{tg}}\right) S_{\text{base}}} \tag{11.1}$$

The contribution from the high voltage motors is found as follows.

It may be assumed that the average ratio of starting current to rated current (I_s/I_n) of the motor is,

$$\frac{I_s}{I_n} = 6.0 \text{ pu for high voltage motors}$$

Consequently the sub-transient impedance Z''_{hm} of the motors is,

$$Z''_{hm} = \frac{1.0}{6.0} = 0.167 \text{ pu (at } S_{hm})$$

For typical high voltage motors the starting power factor is between 0.15 and 0.2 lagging, hence assume 0.2. The sub-transient impedance becomes,

$$Z''_{hm} = 0.033 + j0.164 \text{ pu}$$

The equivalent impedance Z_{tm} of the motor unit transformers is 0.06 pu at a total capacity of S_{tm}.

$$Z_{tm} = 0.0 + j0.06 \text{ pu}$$

The emf E''_{hm} behind the motor sub-transient impedance is the air-gap emf and will in practice be slightly less than 1.0 pu, hence it is reasonable and conservative to assume it to be 1.0 pu.

The contribution of fault current I''_{hm} from the main switchboard motors is

$$I''_{hm} = \frac{E''_{hm}}{\left(\dfrac{Z''_{hm}}{S_{hm}} + \dfrac{Z_{tm}}{K_{tm} S_{hm}}\right) S_{\text{base}}} \text{ pu}$$

$$= \frac{1.0 S_{hm}}{\left(0.033 + j0.164 + \dfrac{j0.06}{K_{tm}}\right) S_{\text{base}}} \tag{11.2}$$

The contribution from the lower voltage motors is found as follows.

The average ratio of starting current to rated current (I_s/I_n) for the lower voltage motors may be assumed to be,

$$\frac{I_s}{I_n} = 6.5 \text{ pu for lower voltage motors}$$

Their sub-transient impedance Z''_{lm} is

$$Z''_{lm} = \frac{1.0}{6.5} = 0.153 \text{ pu(at } S_{lm})$$

Typical lower voltage motors have a starting power factor of between 0.25 and 0.35 lagging, hence assume 0.35.

The sub-transient impedance Z''_{lm} of the motors becomes,

$$Z''_{lm} = 0.054 + j0.143 \text{ pu}$$

The equivalent impedance Z_{td} of the distribution transformers can be found by the method in sub-section 11.5.2.5 or taken as,

$$Z_{td} = 0.0 + j0.055 \text{ pu(at } S_{td})$$

Again assume that the air-gap emf E''_{lm} is 1.0 pu.

The contribution I''_{lm} from the lower voltage motors is,

$$\begin{aligned} I''_{lm} &= \frac{E''_{lm}}{\left(\dfrac{Z''_{lm}}{S_{lm}} + \dfrac{Z_{td}}{2K_{td}(S_{lm} + S_{ls})}\right) S_{\text{base}}} \\ &= \frac{1.0 S_{lm}}{\left(0.054 + j0.143 + \dfrac{j0.06}{K_{td2}}\right) S_{\text{base}}} \end{aligned} \tag{11.3}$$

Where

$$K_{td2} = 2K_{td}\left(1.0 + \frac{S_{ls}}{S_{lm}}\right)$$

The total sub-transient symmetrical rms fault current I''_{frms} is,

$$I''_{frms} = I''_g + I''_{hm} + I''_{lm} \tag{11.4}$$

11.6.1 Calculate the Sub-Transient Peak Fault Current Contributions

Many power system networks can be reduced to a simple series-connected circuit containing a resistance R and an inductance L, for the purpose of calculating the transient fault current. Furthermore a

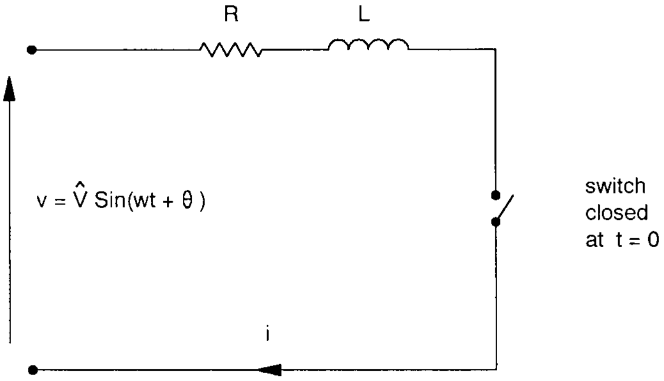


Figure 11.7 Instantaneous current response in a series-connected R-L circuit that is fed by a sinusoidal voltage.

single-phase AC circuit can be used to represent a three-phase circuit in which a line-to-line-to-line short circuit occurs.

Figure 11.7 shows the single-phase circuit, which is supplied by a sinusoidal voltage v.

The differential equation for the current i that responds to the applied voltage v is,

$$\mathrm{Ri} + L\frac{di}{dt} = v = \hat{V}\sin(\omega t + \theta)$$

Where ω = the angular frequency in rad/sec
θ = the angular displacement of v at $t = 0$
t = the time in seconds
$\hat{V}$ = peak value of V the rms applied voltage, i.e. $\surd 2V$.

The complete solution of this equation can be found by several methods e.g. Laplace transforms, method of undetermined coefficients, see Reference 3. The solution for i is,

$$i = \frac{\hat{V}}{Z}\left(-e^{\frac{-Rt}{L}}\sin(\theta - \phi) + \sin(\omega t + (\theta - \phi))\right) \tag{11.5}$$

where

$$Z = \surd(R^2 + \omega^2 L^2)$$

$$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right) = \tan^{-1}\left(\frac{X}{R}\right)$$

and

$$X = \omega L \text{ the inductive reactance.}$$

The exponential term has its maximum positive value when $\theta - \phi$ equals $-\pi/2$ radians. Therefore the maximum value occurs when $\theta = \phi - \pi/2$.

The oscillating term reaches its first maximum value when $\mathrm{w}t + \theta - \phi$ equals $+\pi/2$, or,

$$t_{m1} = \frac{1}{\omega}\left(\frac{\pi}{2} - \theta + \phi\right) \text{ seconds}$$

There are two important cases to consider. Firstly when the resistance is much smaller than the inductive reactance and secondly when it is much greater, Tables 11.3 and 11.4 show the peak maximum and minimum values of the instantaneous current when the maximum value of V is 1.414 per unit,

Z = 1.0 per unit, and the ratio of X to R has different values over a wide range.

11.6.1.1 Resistance smaller than inductive reactance

This case often represents a circuit in which a circuit breaker or a contactor is subject to its most onerous duty, because ‘current doubling’ occurs.

The angle ϕ approaches $\pi/2$, and θ approach zero. The first maximum value then occurs at,

$$t_{\mathrm{m1x}} = \frac{1}{\omega}\left(\frac{\pi}{2} - 0 + \frac{\pi}{2}\right) = \frac{\pi}{\omega} \text{ seconds}$$

Which is half the periodic time of the sinusoidal forcing function v.

Table 11.3. Values of maximum and minimum currents for a 50 Hz power system

X-to-R ratio	I_1 (pu)	I_2 (pu)	I_3 (pu)	I_4 (pu)	I_5 (pu)	I_6 (pu)
500.0000	2.8196	−.0177	2.8020	−.0351	2.7847	−.0523
100.0000	2.7845	−.0864	2.7011	−.1672	2.6227	−.2432
50.0000	2.7418	−.1680	2.5850	−.3151	2.4467	−.4449
30.0000	2.6863	−.2697	2.4459	−.4859	2.2509	−.6612
25.0000	2.6593	−.3176	2.3825	−.5612	2.1672	−.7507
20.0000	2.6196	−.3861	2.2944	−.6631	2.0570	−.8655
16.0000	2.5714	−.4661	2.1952	−.7737	1.9413	−.9816
14.0000	2.5378	−.5197	2.1310	−.8428	1.8716	−1.0493
12.0000	2.4943	−.5868	2.0533	−.9237	1.7926	−1.1235
10.0000	2.4355	−.6729	1.9581	−1.0182	1.7041	−1.2028
8.0000	2.3520	−.7864	1.8406	−1.1275	1.6084	−1.2834
6.0000	2.2246	−.9402	1.6971	−1.2474	1.5133	−1.3556
5.0000	2.1327	−1.0368	1.6172	−1.3064	1.4719	−1.3835
4.0000	2.0105	−1.1475	1.5369	−1.3585	1.4397	−1.4026
3.0000	1.8444	−1.2667	1.4664	−1.3959	1.4206	−1.4120
2.0000	1.6267	−1.3710	1.4232	−1.4123	1.4146	−1.4141
1.0000	1.4341	−1.4134	1.4143	−1.4142	1.4142	−1.4142
.5000	1.4143	−1.4142	1.4142	−1.4142	1.4142	−1.4142
.2000	1.4142	−1.4142	1.4142	−1.4142	1.4142	−1.4142
.1000	1.4142	−1.4142	1.4142	−1.4142	1.4142	−1.4142

Table 11.4. Values of time corresponding to the currents in Table 11.3

X-to-R ratio	T_1 (sec)	T_2 (sec)	T_3 (sec)	T_4 (sec)	T_5 (sec)	T_6 (sec)
500.0000	.010000	.02002	.03000	.04002	.0500	.0600
100.0000	.010000	.02006	.03000	.04006	.0500	.0601
50.0000	.010000	.02012	.03002	.04012	.0500	.0601
30.0000	.010020	.02020	.03002	.04018	.0500	.0602
25.0000	.010020	.02022	.03004	.04020	.0501	.0602
20.0000	.010040	.02028	.03006	.04024	.0501	.0602
16.0000	.010040	.02034	.03008	.04028	.0501	.0603
14.0000	.010060	.02038	.03012	.04032	.0502	.0603
12.0000	.010080	.02042	.03014	.04036	.0502	.0603
10.0000	.010140	.02048	.03020	.04040	.0503	.0604
8.0000	.010220	.02058	.03028	.04048	.0503	.0604
6.0000	.010300	.02070	.03042	.04058	.0505	.0605
5.0000	.010440	.02080	.03054	.04068	.0506	.0606
4.0000	.010000	.02092	.03072	.04082	.0508	.0608
3.0000	.010700	.02114	.03098	.04104	.0510	.0610
2.0000	.011240	.02152	.03146	.04148	.0515	.0615
1.0000	.012460	.02250	.03250	.04250	.0525	.0625
0.5000	.013520	.02352	.03352	.04352	.0535	.0635
0.2000	.014380	.02438	.03438	.04438	.0544	.0644
0.1000	.014680	.02468	.03468	.04468	.0547	.0647

Notes:

a) I_1, I_3 and I_5 are the maximum or upper peak values at times T_1, T_3 and T_5.

b) I_2, I_4 and I_6 are the minimum or lower peak values at times T_2, T_4 and T_6.

c) If the supply frequency is 60 Hz then multiply the times by the ratio of 50:60.

The worst case is where the resistance is zero. The current i response is,

$$
\begin{aligned}
i &= \frac{\hat{V}}{\omega L}\left(-\sin\left(\theta - \frac{\pi}{2}\right) + \sin\omega t\left(+\theta - \frac{\pi}{2}\right)\right) \\
&= \frac{\hat{V}}{\omega L}(\cos\theta - \cos(\omega t + \theta))
\end{aligned}
$$

With $\theta = 0$ this current becomes

$$i = \frac{\hat{V}}{\omega L}(1 - \cos\omega t)$$

The sinusoidal term in the brackets oscillates between zero and +2.0. This term is called the ‘doubling factor’ when the time is $t = \pi/\omega$ has the value of 2.0.

The bad cases occur when the resistance is small, see Figure 11.8.

The response is then,

$$i = \frac{\hat{V}}{Z}\left(e^{\frac{-Rt}{L}} - \cos\omega t\right) \tag{11.6}$$

The term in brackets is again called the 'doubling factor' but it is now less than 2.0 when $t = \pi/\omega$. Table H.1b shows the doubling factor for different ratios of X to R.

Note: The doubling factor is sometimes combined with $\sqrt{2}$ when V is given as the root-mean-square value. In which case the doubling factor has a maximum value of 2.8284 and a minimum value of 1.4142.

11.6.1.2 Resistance larger than inductive reactance

This case represents the least onerous duty for the switchgear. The angle ϕ becomes small as the resistance increases. The worst-case switching angle θ approaches zero. The conditions that produce a minimum or a maximum can be found by differentiating i in equation (11.5) with respect to the time t and equating the result to zero. This yields the following conditions,

$$\frac{+Re^{\frac{-Rt}{L}}}{L} = \frac{-\omega\cos(\omega t + \theta - \phi)}{\sin(\theta - \phi)} \tag{11.7}$$

When $R >> L$, $e^{\frac{-Rt}{L}}$ approaches zero for t in the range of one or two periods.

The angle ϕ approaches zero.

Transposing equation (11.7) for the cosine term gives,

$$\cos(\omega t + \theta) = -\frac{R}{\omega L}\Delta\sin\theta$$

Where Δ is the small value of $e^{\frac{-Rt}{L}}$, which approaches zero.

The right-hand side approaches zero as Δ becomes very small. Therefore the left-hand side becomes,

$$\cos(\omega t + \theta) = 0$$

Now since θ also approaches zero $\cos\omega t$ equals zero for the first time when $\omega t = \pi/2$.

If the above conditions are substituted into (11.5) the current becomes,

$$i = \frac{\hat{V}}{Z}\sin(\omega t + (0 - 0)) = \frac{\hat{V}}{R}\sin\omega t$$

Which is in phase with V as can be expected. Note, the switching angle θ need not be zero when the inductance is negligible, see Figure 11.9.

11.6.1.3 The doubling factor

The conditions given by equation (11.7) apply to all combinations of resistance and inductance, and the switching angle θ. Equation (11.7) can be used with little error for cases where the resistance

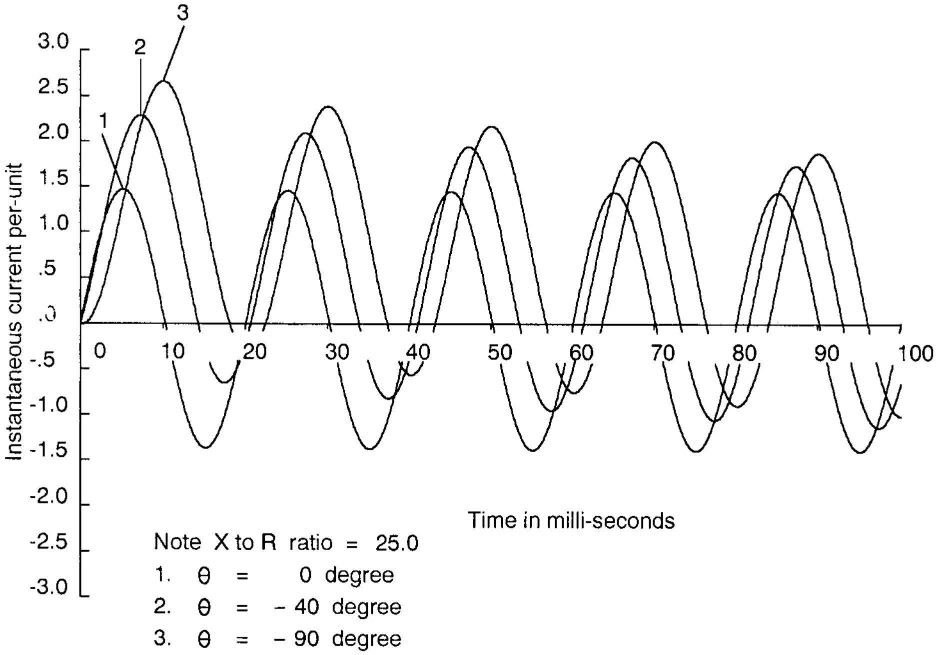


Figure 11.8 Short-circuit current waveform of a series connected R-L circuit that is fed by a sinusoidal voltage. The X-to-R ratio of the circuit is 25 pu. The responses are for three values of the switching angle θ.

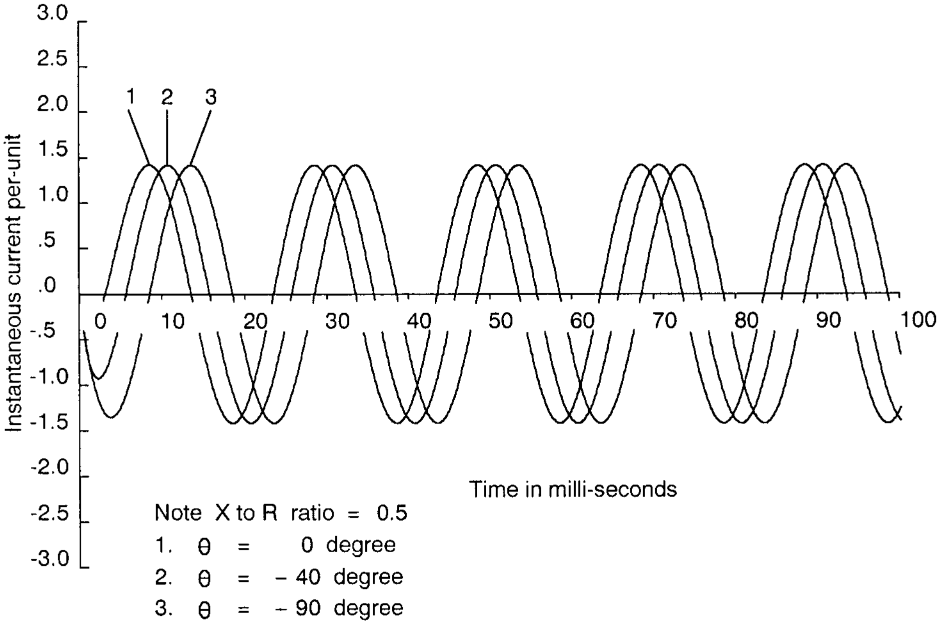


Figure 11.9 Short-circuit current waveform of a series connected R-L circuit that is fed by a sinusoidal voltage. The X-to-R ratio of the circuit is 0.5 pu. The responses are for three values of the switching angle θ.

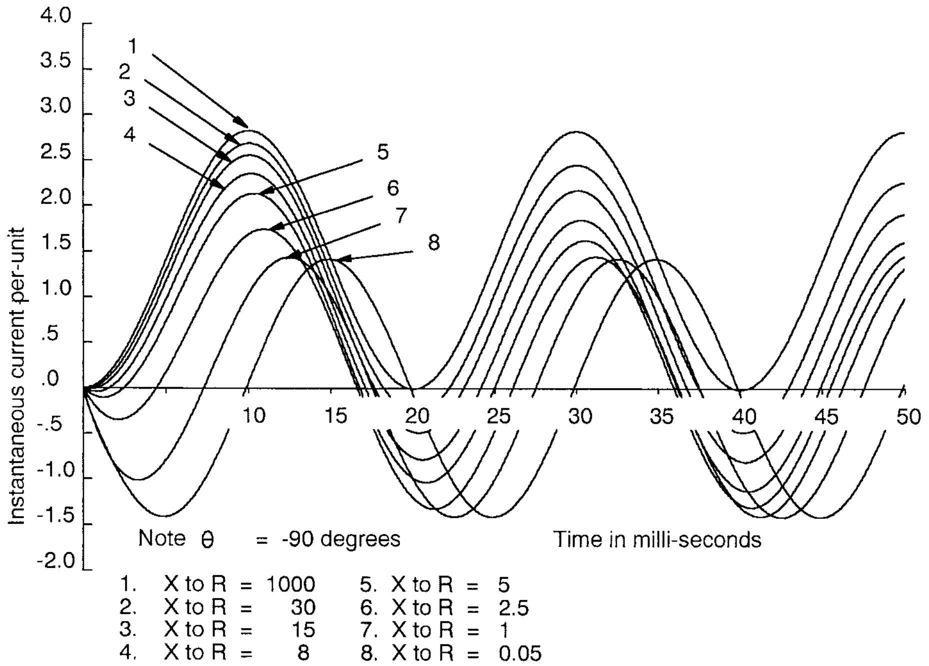


Figure 11.10 Short-circuit current waveform of a series-connected R-L circuit that is fed by a sinusoidal voltage. The switching angle θ is -90 degrees, which represents the worst case. The responses are for eight values of the circuit X-to-R ratio.

is small i.e. X-to-R ratios greater than about 5.0. Hence substituting for $\omega t = \pi$ gives the doubling factor (DF) as,

$$\mathrm{DF} \cong e^{\frac{-R\pi}{x}} + 1.0$$

For intermediate X-to-R ratios i.e. 0.1 to 5.0, the equality in (11.7) must be satisfied, which is best achieved by iteration for a solution in the vacinity of $\omega t = 3\pi/4$, e.g. by Newton's method, see Reference 4.

Figure 11.10 shows 'worst-case' responses of i for different values of the ratio X to R.

11.7 APPLICATION OF THE DOUBLING FACTOR TO FAULT CURRENT I''_{frms} FOUND IN 11.6

Now returning to the rms equations for I''_g, I''_{hm} and I''_{lm} in sub-section 11.6 it can be seen that each of these currents can have different X-to-R ratios and will therefore decay at different rates. The peak fault current is,

$$I''_{fpk} = \sqrt{2}(DF_g I''_g + DF_{hm} I''_{hm} + DF_{lm} I''_{lm})$$

Where the doubling factors DF_g, DF_{hm} and DF_{lm} are evaluated from the X-to-R ratios of each component using equation (11.5) or their nearest ratio given in Table 11.3 as I_1 (pu) or in Table H.1b.

11.7.1 Worked Example

An LNG plant has an estimated load of 90 MW and is supplied by five 34.0 MVA generators. The main switchboard operates at 33 kV, and supplies DOL induction motors with unit transformers totalling 35 MW. There is a group of 10 DOL motors operating at 6.6 kV the total kW of which is 25 MW. There is a total of 5 MW of low voltage motors operating at 400 V. A large group of high voltage motors operate from variable speed power electronic rectifier-inverters. These consume a total of 23 MW , and can be regarded as static loads in that they do not contribute fault currents to the main switchboard. There is a miscellaneous static load at 400 V totalling 2 MW.

Each generator has a sub-transient reactance of 0.13 pu.

Each generator unit transformer is rated at 42.5 MVA and has a reactance of 0.08 pu.

The marginal factors for MVA ratings are,

- $K_{tg} = 1.25$
- $K_{tm} = 1.10$
- $K_{td} = 1.3$

The operating power factors of the loads are,

- 0.87 for high voltage motors
- 0.85 for low voltage motors
- 0.86 for high voltage static loads (motors)
- 0.97 for low voltage static loads.

The MVA values for these loads are,

$$\begin{aligned}
S_{hm1} &= 35.0/0.87 = 40.23\ \text{MVA}\\
S_{hm2} &= 25.0/0.87 = 28.74\ \text{MVA}\\
S_{lm} &= 5.0/0.85 = 5.88\ \text{MVA}\\
S_{hs} &= 23.0/0.86 = 26.74\ \text{MVA}\\
S_{ls} &= 2.0/0.97 = 2.06\ \text{MVA}
\end{aligned}$$

The summations of active and reactive powers are,

$$\begin{aligned}
P_{hm1} &= 35.0\ \text{MW},\ P_{hm2} = 25.0\ \text{MVA}\\
P_{lm} &= 5.0\ \text{MW},\ P_{hs} = 23.0\ \text{MVA}\\
P_{ls} &= 2.0
\end{aligned}$$

Hence

$$\begin{aligned}
P_{\text{load}} &= P_{hm1} + P_{hm2} + P_{lm} + P_{hs} + P_{ls}\\
&= 90.0 \text{ MW}\\
Q_{hm1} &= 19.84 \text{ MVA}_r,\ Q_{hm2} = 14.17 \text{ MVA}_r\\
Q_{lm} &= 3.10 \text{ MVA}_r,\ Q_{hs} = 13.65 \text{ MVA}_r\\
Q_{ls} &= 0.5 \text{ MVA}_r\\
Q_{\text{load}} &= (Q_{hm1} + Q_{hm2} + Q_{lm} + Q_{hs} + Q_{ls})\,1.015\\
&= 52.03\\
S_{\text{load}} &= \sqrt{}(P_{\text{load}}{}^2 + Q_{\text{load}}{}^2) = 103.96 \text{ MVA}
\end{aligned}$$

The operating power factor PF_{load} is,

$$\text{PF}_{\text{load}} = \frac{P_{\text{load}}}{S_{\text{load}}} = \frac{90.0}{103.96} = 0.8657 \text{ lagging}$$

The generator MVA is S_{gen} which equals 37.5.

Choose the base MVA to be $S_{\text{base}} = 100$.

Assume all five generators are operating when the three-phase zero impedance fault occurs.

Calculate the rms symmetrical fault currents for the generators and each type of load.

a) The generators and unit transformers

$$I''_g = \frac{5 \times 1.1 \times 34.0}{j\left(0.13 + \dfrac{0.08}{1.25}\right)100.0} = 0.0 - j9.639 \text{ pu}$$

- The high voltage motors and unit transformers.
  These consist of two groups S_{hm1} and S_{hm2}, let their total be S_{hm}.

$$\begin{aligned}
I''_{hm} &= \frac{1.0 \times (40.23 + 28.74)}{\left(0.033 + j0.164 + \dfrac{j0.06}{1.10}\right)100.0}\\
&= \frac{0.6897}{0.033 + j0.164 + j0.0545}\\
&= 14.1184(0.033 - j0.2185)\\
&= 0.4659 - j3.0849 \text{ pu}
\end{aligned}$$

- The high voltage variable speed drive motors.
  These can be ignored as sources of sub-transient current.

- The low voltage motors and distribution transformers.

  There is one group of low voltage motors connected to various switchboards. Their total MVA is S_{lm}. The transformer ratings also require the value of the total static MVA which is S_{ls}.

$$\begin{aligned}
K_{td2} &= 2K_{td}\left(1.0 + \frac{S_{ls}}{S_{lm}}\right) \\
&= 2 \times 1.3\left(1.0 + \frac{2.06}{5.88}\right) \\
&= 3.511 \\
I''_{lm} &= \frac{1.0 \times 5.88}{\left(0.054 + j0.143 + \dfrac{j0.055}{3.511}\right)100.0} \\
&= \frac{0.0588}{0.054 + j0.143 + j0.0157} \\
&= 2.0924(0.054 - j0.1587) \\
&= 0.1130 - j0.3321 \text{ pu}
\end{aligned}$$

- The total rms symmetrical sub-transient fault current.

The total rms fault current I''_{frms} is,

$$\begin{aligned}
I''_{frms} &= I''_g + I''_{hm} + I''_{lm} \\
&= 0.0 - j9.639 \\
&\quad + 0.4659 - j3.0849 \\
&\quad + 0.1130 - j0.3321 \\
&= 0.5789 - j13.056 \text{ pu}
\end{aligned}$$

The base current I_{base} is,

$$\begin{aligned}
I_{\text{base}} &= \frac{S_{\text{base}}}{\sqrt{3}V_{\text{base}}} = \frac{100 \times 10^6}{\sqrt{3} \times 33{,}000} \\
&= 1749.6 \text{ amps}
\end{aligned}$$

Hence the total fault current in rms amps is,

$$\begin{aligned}
I''_{frms} &= 1749.6(0.5789 - j13.056) \\
&= 1012.8 - j22842.7 \text{ amps}
\end{aligned}$$

The magnitude is,

$$|I''_{frms}| = 22{,}865 \text{ amps}$$

Find the peak sub-transient fault current.

The X-to-R ratios of the three symmetrical currents can be found from their real and imaginary parts, as shown in the table below:-

Current	Imaginary part	Real part	X-to-R ratio
I''_g	9.639	0	infinity
I''_{hm}	3.0849	0.4659	6.6214
I''_{lm}	0.3321	0.1130	2.9389

The three 'doubling factors' are 2.0, 1.622 and 1.343 per unit. The magnitudes of the three rms currents in amps are 16,864, 5458 and 614 respectively. Multiply each of these currents by 1.414 × doubling factor,

$$I''_{gpk} = 2.828 \times 16{,}864 = 47{,}691 \text{ amps}$$

$$I''_{hmpk} = 2.294 \times 5458 = 12,518 \text{ amps}$$

$$I''_{lmpk} = 1.899 \times 614 = 1166 \text{ amps}$$

The total of these currents is the peak asymmetrical sub-transient fault current I''_{pk} which is 61,375 amps. This is a conservative summation because it assumes that the three peaks occur at the same time. The fault making duty of the main switchboard must be greater than this value of current, i.e., choose a duty of at least 70,000 amps.

11.7.2 Breaking Duty Current

Modern switchboard circuit breakers are often able to clear a major fault current within 120 milliseconds, which is typically five or six cycles of the fundamental current. When these circuit breakers are used with generators, and switchboards that are fed by generators located only a short distance away, the decay of the sub-transient current merges with the decay of the transient current. Even at 120 milliseconds the current may have a substantial value. There are several ways of assessing the breaking duty current,

- Use the rigorous equations for a salient pole generator,

$$i_{fa} = \hat{V}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{\frac{-t}{T'd}} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{\frac{-t}{T''d}}\right]\cos(\omega t + \theta) - \hat{V}\left[\frac{(X''_d + X''_q)}{2X''_d X''_q}e^{\frac{-t}{Ta}}\right]$$
$$\cos\theta - \hat{V}\left[\frac{X''_q - X''_d}{2X''_d X''_q}\right]e^{\frac{-t}{Ta}}\cos(2\omega t + \theta) \qquad (11.8)$$

  See sub-sections 3.4 and 7.2.7 for an explanation of the variables and parameters.

- Use the above equation but ignore the sub-transient terms, thereby leaving,

$$i_{fa} = \hat{V}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{\frac{-t}{T'd}}\right]\cos(\omega t + \theta) \qquad (11.9)$$

- Use equation (11.5) and substitute suitable values for R and L the transient parameters of the generator.

- Use a set of multiplying factors to modify the precalculated value of the rms symmetrical sub-transient current I''_f. Apply the factor at the given fault clearance time. (This factor functions in a manner similar to the 'doubling factor' described in sub-sections 11.6 and 11.6.1.3.) Suitable values of the factor are given in clause 12.2.1.3 of IEC60909, equation (47) and Figure 16 therein.

Whichever method is used it is not usually necessary to include the contribution of fault current from induction motors, because such current will have decayed to almost zero at the fault clearance time. If there are large motors connected to the main switchboard then their contribution will be similar to a generator and should be included, see sub-section 7.2.7 and Reference 3 therein, and sub-section 11.8.5.

11.8 COMPUTER PROGRAMS FOR CALCULATING FAULT CURRENTS

Now that computers have become so widely available in both the office and in the home, it is relatively easy to program the calculations described in the previous sub-sections. Radial system equations are particularly easy to compute.

As a project moves into the detail design phase it acquires more precise data for all aspects of the work. It is then possible to calculate the fault currents more accurately. However, it should be noted that the tolerances on most of the data are seldom better than plus or minus 15%, and so increasing the quantity of data will not necessarily improve the results significantly. During the detail design phase the power system tends to be modified and additional switchboards added. It is then necessary to calculate the fault currents at least at the busbars of each switchboard, and this can become a laborious task if hand calculations are attempted.

There are many commercially available computer programs for calculating fault currents. Some programs include other features such as load flow, harmonic penetration, transient stability, motor starting and volt-drop calculations, since these features tend to use the same database. Usually a program that calculates fault currents will have several special features for different types of faults e.g.,

- Radial and meshed networks.
- Three-phase zero impedance fault.
- Three-phase non-zero impedance fault.
- Single-phase faults.
- Line-to-line faults.
- Line-to-line-to-ground faults.

These features are calculated with the aid of symmetrical component theory, see Reference 5 to 8. Apart from the simplest situations the solutions are too complicated and time consuming to attempt by hand.

11.8.1 Calculation of Fault Current – RMS and Peak Asymmetrical Values

For most LV and all HV generators it is often acceptable to ignore the armature resistance as far as calculating the magnitude of 'first-cycle' fault currents is concerned. It is usual to assume that the

X-to-R ratio of generators is high, e.g. between 20 (for LV generators) and 100 (for HV generators). However, the value of armature resistance is of most importance when considering the downstream circuit-breaker fault clearance capabilities. This aspect is described in sub-sections 7.2.7 and 7.2.11. The calculation of current magnitudes may be carried out in several ways depending upon the amount and accuracy of the data available.

11.8.2 Simplest Case

Assume that only X''_d is given, and that this figure is only accurate to about ±15% accuracy. Hence, assume that the X-to-R ratio is infinity; this means that full current doubling will occur (the doubling factor from Table H.1b is 2.848).

Take the X''_d figure and deduct 15% of its value. Calculate I_f using the method of sub-section 11.5.2. This will give a safe estimate of the situation.

11.8.3 The Circuit X-to-R Ratio is Known

The method of sub-section 11.8.2 may be used, but an allowance for fault current decrement needs to be made (because the X-to-R ratio is known). Table H.1b gives the appropriate 'doubling factor' for the situation at one-quarter of a cycle for a known X-to-R ratio.

If, for example, the X-to-R ratio happened to be 25 for the numerical example in sub-section 11.8.2 then the 'doubling factor' would be 2.663 instead of 2.848.

11.8.4 Detailed Generator Data is Available

A more exact result may be obtained by using equation (7.2). However, all the necessary data must be available, e.g. X''_d, X'_d, X_d, R_a, T''_d, T'_d, T_a. It is also advisable to consider the worst-case situation where the reactances take their low tolerance values.

In this method the rms value of the asymmetrical fault current is calculated from the symmetrical rms value and the DC offset value by using the following equation:

$$\text{rms value of asymmetrical fault current} = \sqrt{\begin{array}{c}\text{(rms value of symmetrical fault current during the} \\ \text{first half-cycle)}^2 + \text{(DC offset current)}^2\end{array}}$$

Note: This equation is based on the theory used for calculating the rms value of waveforms that contain harmonic components.

The peak asymmetrical value may be found directly from (7.2) when $t = 0.005$ sec (for 50 Hz systems) or 0.00417 sec (for 60 Hz systems).

11.8.5 Motor Contribution to Fault Currents

During a fault condition, the load side of the power system can contribute currents to the fault. The origin of such contribution is motors, which can be either induction or synchronous machines.

Induction motors react as sub-transient generators during the fault. The magnitude of the sub-transient current is normally taken as the starting current or, more specifically, determined by the air-gap emf and the sub-transient impedance of the induction motor. (It is worth noting that some literature treats the rotor of an induction motor as a transient impedance rather than a sub-transient impedance. The difference is not critical but it should be recognised, see Reference 14 and 15.) Since the induction motor has no external excitation system to create flux, then during a disturbance the flux in the machine is that which is 'trapped' in it. This trapped flux decays at a rate determined by the sub-transient impedance of the machine. Hence, induction motors contribute fault current only for a very short time and, consequently, the importance of this contribution is in the fault-making duty of switchgear.

Synchronous motors behave in the same way as synchronous generators during the fault, the only difference being the pre-fault condition of the motor. The emf E'' is usually just less than unity, e.g., 0.95 pu.

Since the synchronous motor has an external source of excitation power it can maintain flux for a longer time during a fault. The rotor pole face construction and the field circuit help to maintain the air-gap flux and generated emf. The decay of flux during the fault is determined for the most part by the transient impedance of the synchronous motor.

The sub-transient impedance determines the initial decay, i.e. in the first cycle or so. Therefore the emfs E'' and E', together with the reactances X''_d and X'_d, need to be used for calculating the fault currents. In a similar way to induction motors, the synchronous motors will contribute to fault-making duty requirements. However, they will also contribute towards the fault-breaking duty because of the transient effects.

All these considerations apply to HV motors, particularly if they are fed directly from the main generator switchboard. LV motors can often be grouped together and considered as one large equivalent motor. It is sometimes possible to ignore the contributions from LV motors because their circuits often have a low X-to-R ratio, which causes the motor contribution to decay very fast. Also, the connected cables, busbars and transformers in the circuit will tend to attenuate the motor fault contribution.

LV motors can occasionally be ignored when HV switchboard faults are being calculated but this will depend upon circumstances, e.g. the number of intermediate voltages exist in the system, whether there are many small motors or a few large motors, the average route length of motor and transformer feeder cables. On offshore platforms it is advisable to seriously consider the LV network. LV motor control centres will be influenced by their motor loads, and the effect of motor contribution will mainly be determined by the fuse, contractor and circuit breaker configurations.

Induction motors can be represented by the 2-axis theory, by using the derivations for synchronous machines but deleting the field winding. In this case some of the reactances become zero, and the field resistance is infinity. Hence, the derived reactances X''_d, X''_q, etc. and the various time constants T''_d, T''_{do} etc. can be redefined for the induction motor.

11.9 THE USE OF REACTORS

Reactors are inductance coils and the name 'reactor' is used to imply their use for limiting fault current. Current limiting is often achieved by adding reactance into part of the power system. Reactors perform this function economically.

When power systems grow in size and complexity it often happens that the fault levels in some parts of the existing system become too high for the equipment. Reactors can be inserted to maintain the fault levels below the equipment limits. The most common application is in the feeders to switchgear.

In the oil industry it is often found necessary to increase the number of generators on an existing system. Sometimes this causes fault level problems at the generator switchboard. Rather than replace the switchboard it may be possible to insert one or more reactors. Several solutions are possible:-

- Insert a reactor in series with the new generator.
- Insert a reactor in series with each existing and the new generator, see Figure 11.11.
- Insert a reactor between sections of the main busbars, see Figures 11.12, 11.13 and 11.4.

The preferred solution depends on how much fault level reduction is necessary. If the change in fault level is greater than about 20% the value of the reactance may become too large and cause voltage regulation problems under normal operating conditions. A high reactance inserted into the circuit between generators may cause hunting and stability problems.

Figures 11.11 to 11.14 show different methods of installing fault limiting reactors into a power system. Figure 11.11 shows the simplest method in which one reactor is connected in series with each main generator. This is also the least expensive because no additional switchgear is required. However, it may not be the best technical solution because the value of reactance for each reactor tends to be higher than other options, and this could lead to stability problems. Also the terminal voltage of each generator under normal conditions will need to be kept slightly higher than before due to the reactive volt-drop in the reactor. This may require some modifications to the AVR set-point circuits.

The reactor systems shown in Figures 11.12 and 11.13 are very similar, one being a star-connected system and the other a delta-connected system. The star system has the advantage of

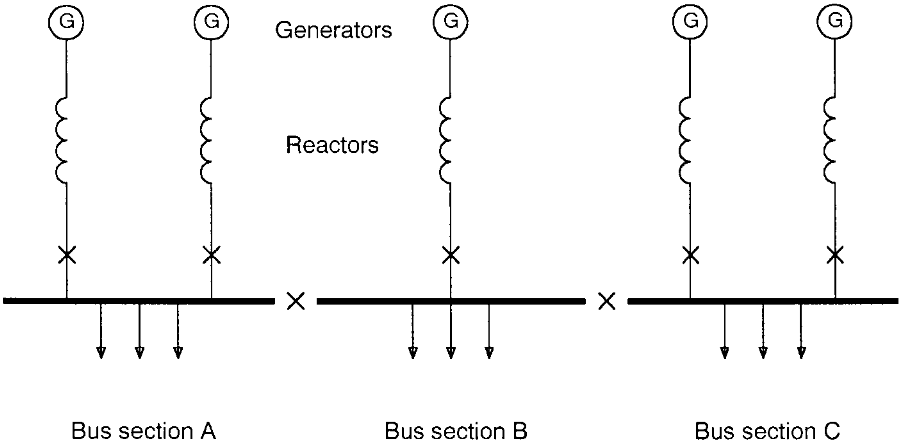


Figure 11.11 One-line diagram of a simple reactor system for reducing the fault level at the switchgear in the system.

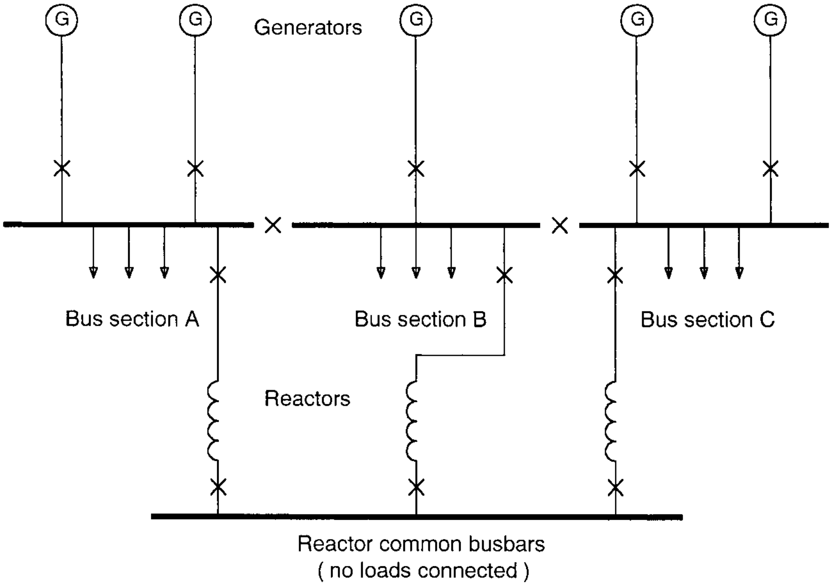


Figure 11.12 One-line diagram of a star-connected reactor system for reducing the fault level at the switchgear in the system.

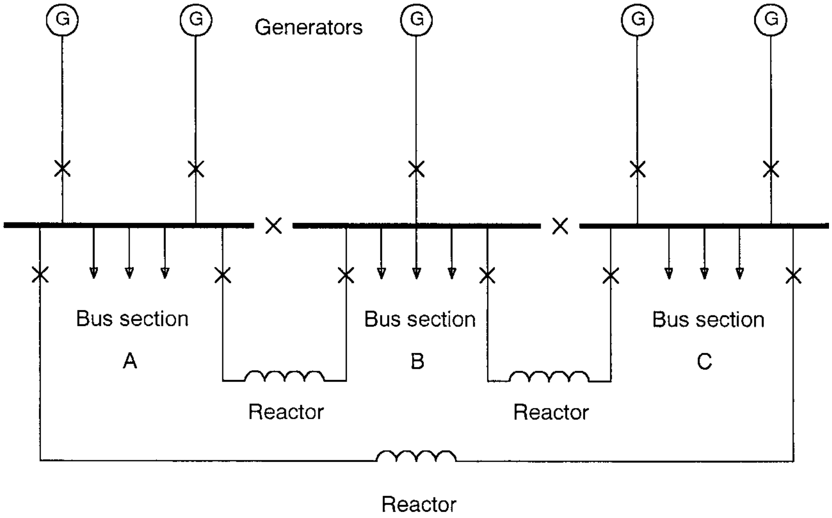


Figure 11.13 One-line diagram of a delta-connected reactor system for reducing the fault level at the switchgear in the system.

only using three circuit breakers in the existing switchgear, whereas the delta system needs six. This economises the modification of the existing switchgear in terms of cost and space, however, the star system requires a new but small switchboard for the common connections. This new switchboard could be fitted with load break switches instead of circuit breakers, with protection being given by the circuit breaker in the existing switchgear.

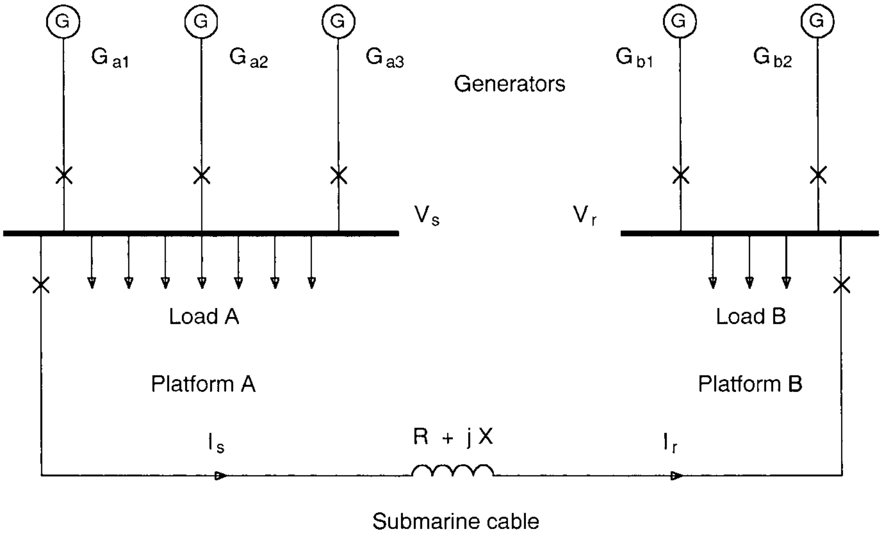


Figure 11.14 One-line diagram of a two-platform power system.

The star and delta configurations use reactors that have lower reactances than the simple method of Figure 11.11. This will give rise to better stability in both the steady state and the transient state. In addition the AVR set-point circuits should not need to be modified.

11.9.1 Worked Example

Consider the systems shown in Figures 11.11 to 11.13. Assume that all the generators are rated at 20 MVA, with sub-transient reactances of 0.15 pu and the main switchboard operates at 11 kV. The symmetrical making current duty of the switchboard is 30,000 amps. Ignore motor contribution in this example. Calculate the per-unit reactance X_r required for each reactor in the three different systems.

a) Case A: Simple system

The 1 pu current of each generator is,

$$I_1 = \frac{S}{\sqrt{3}V} = \frac{20{,}000{,}000}{\sqrt{3} \times 11{,}000} = 1049.8 \text{ amps}$$

The short-circuit current available from each generator is,

$$I_{fg} = \frac{E''I_1}{VX''_d} = \frac{1.1 \times 1049.8}{1.0 \times 0.15} = 7698.2 \text{ amps}$$

Without reactors and with five generators operating the total fault current is

$$I_{fa} = 5 \times 7698.2 = 38{,}491 \text{ amps}$$

which exceeds the duty of the switchgear by 8491 amps.

In order to reduce the total current to 30,000 amps, each generator needs to contribute 6000 amps. Therefore the following condition must be satisfied,

$$I_{fg} = \frac{E''I_1}{V(X''_d + X_r)} = \frac{1.1 \times 1049.8}{1.0 \times (0.15 + X_r)} = 6000 \text{ amps}$$

Transposing gives,

$$X_r = \frac{1.1 \times 1049.8}{1.0 \times 6000} - 0.15 = 0.0425 \text{ pu}$$

b) Case B: Star-connected reactors

From Figure 11.12 it can be seen that the left-hand side and right-hand pairs of generators contribute the same amount of fault current, because the system is symmetrical. The combined impedance of a pair of generators is $X''_d/2$. The combined impedance of two pairs of generator and their shared reactors is,

$$Z_{\text{pairs}} = \frac{X''_d}{4} + \frac{X_r}{2}$$

The fault current contributed by the four outer generators is,

$$I_{fg4} = \frac{E''I_1}{VZ_{\text{pairs}}}$$

The contribution from the centre generator is 7698.2 as found in a).

The total fault current is again 30,000 amps and is given by,

$$I_{f5} = \frac{E''I_1}{V}\left[\frac{1}{Z_{\text{pairs}} + X_r}\right] + 7698.2 = 30000.0$$

$$= \frac{1.1 \times 1049.8}{1.0}\left[\frac{1}{\dfrac{0.15}{4} + \dfrac{X_r}{2} + X_r}\right] + 7698.2 \text{ amps}$$

Transposing gives,

$$X_r = 0.00952 \text{ pu}$$

c) Case C: Delta-connected reactors

This case is similar to the star case of b) and the equivalent delta reactance values are simply three times those of the star reactance values.

Hence, $X_r = 0.02856$ pu.

It is interesting to note that in this case there will be no current flowing in the reactor that couples the two outer busbars. However, this reactor cannot be omitted because it serves its purpose when faults occur at the outer switchboards.

d) Comparison of cases

As a rough estimate it may be assumed that the cost of a reactor is directly proportional to its current rating and its value of reactance.

Table 11.5. Companion of reactor configurations

Case	No. of reactors	Reactance (pu)	Current rating (amps)	Product	Cost factor
	N	X_r	I	IX_r	NIX_r
A	5	0.0425	1049.8	44.62	223.10
B	3	0.00952	2099.6	19.99	59.97
C	3	0.02856	1049.8	29.98	89.95

Table 11.5 compares the cases in terms of cost, but without the cost of the extra switchgear being included. The cost of a circuit breaker would be in the same order of magnitude as its associated reactor.

When the cost of the switchgear is taken into account, cases B and C become closer in cost, and possibly either is more expensive than case A. Case A does not require extra switchgear.

Occasionally it is desirable to interconnect isolated power generating stations, e.g. offshore platforms or desert gathering stations. Although this often seems a good idea when considering improved power availability and minimising redundancy and spare generators, it frequently causes difficult fault level problems. However, these problems can sometimes be solved by using reactors or transformers in the interconnecting cables or overhead lines. Figure 11.14 shows an interconnection of two offshore platforms.

Even when the reactors are inserted, it may be necessary to impose operational restrictions on the system configuration, e.g. it may not be permissible to have all the generators connected when the interconnector is in service. This aspect may be overcome to some extent by introducing a system of electrical or mechanical interlocks.

Reactors are usually a solution to progressive problems. They should not be designed into a new system.

Reactors may be iron-cored or air-cored. Iron-cored units are preferred but care has to be taken in their design so that they do not become saturated when fault currents pass through them. If the fault current exceeds about three times their rated current then air-cored units become more economically attractive.

They may be of dry-type or liquid-immersed construction, the latter tending to be most common because:-

- They are more suitable for outdoor locations.
- They have a high factor of safety with regard to internal flashover.
- They have a tank, which tends to retain all magnetic fluxes inside the unit. This is important when the location of the reactor is being considered. The radiation of the flux can cause eddy current heating in adjacent steelwork and magnetic interference with other nearby electrical and electronic circuits.
- They have high thermal capacity and can therefore absorb the fault current heat more efficiently.
- The manufacturer can use standard tank and cooling designs that would normally be used for transformers.

11.10 SOME COMMENTS ON THE APPLICATION OF IEC60363 AND IEC 60909

IEC60363 was first available in 1972 and IEC60909 in 1988. IEC60363 was issued for evaluating the short circuits in power systems that are used onboard ships. It covers both the transient and sub-transient fault situations. AC power systems on modern large ships have certain similarities to those in oil industry, marine and onshore installations, e.g.

- Independent from other sources of power, i.e. 'island' operation.
- Generators connected directly to the main busbars.
- The main busbars supply induction motors that have relatively high ratings.
- Short cable routes and therefore minimal attenuation of fault currents.
- Significant contribution of sub-transient fault current from induction motor consumers.

IEC60636 is presented in two parts, the first for AC systems and the second for DC systems. The first part gives formulae and tables for calculating the steady state and dynamic fault currents at generators, near to generators and remote from generators. It takes account of the external impedance, beyond the generator terminals, that alters the values of the various time constants that are frequently used in short-circuit calculations. (This aspect is sometimes overlooked when dynamic calculations are being carried out.) The publication also uses only parameters and data that are readily available from manufacturers or databases, which is very convenient. The decrements in the fault currents are also described and illustrated by worked examples. Motor contribution to fault currents is also described and illustrated. The publication briefly addresses the effect of the generators being fully or highly loaded before the fault occurs. In recent years this subject has become more significant in the selection of equipment, relatively small variations due to loading should be considered.

IEC60909 is also presented in two parts but does not cater for DC power systems. It addresses in detail balanced and unbalanced faults near to and far away from a generator. The aspect of a loaded generator is catered for by using a factor 'c' to multiply the rated voltage U_n of the generator, see clauses 6 and 11.4, Table I therein. A second factor K_G is also introduced to modify the sub-transient impedance of the generator, as a function of the load power factor. Appendix A of the publication gives numerical examples.

11.11 STABILITY STUDIES

So far the power system has been designed to meet the steady state load distribution requirements and the steady state and transient fault currents that could occur under the worst conditions. Most power systems in the oil industry have their own generators. Consequently, the transient performance of the system and its generators is of great concern when relatively large disturbances are applied, e.g. starting large motors, switching out loaded feeders, recovery from fault clearance.

The analysis and study of the dynamic behaviour of the power system is part of what is generally called 'Stability Studies'.

The stability of a power system can be studied in several ways but, generally speaking, only two ways are important, i.e. steady state and transient stability. The results of these studies usually cause only minor changes to the system that was originally proposed provided that the system had been well thought out initially.

Typical changes would be transformer and generator reactances, limiting the maximum size of the largest motors, providing special starters for large motors (e.g. Korndorfer method), provision of special interlocks or inhibits on the switchgear. Occasionally, however, it is necessary to extend the existing power system, e.g. extra load, more generators, adding an unusually large motor, or to interconnect systems using long-distance cables or overhead lines. When this happens it is essential to carry out a stability study to ensure that the existing equipment still performs satisfactorily and that any new equipment is compatible in all respects.

11.11.1 Steady State Stability

Steady state stability relates to the ability of the synchronous source (generators) to transfer power to the synchronous sink (motors and/or other generators). This may be explained by simplifying the synchronous power system as a transmission link (cable or overhead line) of reactance X and zero resistance, a synchronous source (generator at the sending end of the link) and a synchronous sink (load at the receiving end).

The source has an internal emf E_S and the sink has an internal emf E_R,

Where phasor

$$\hat{E}_S = |E_S|\angle\delta^\circ$$

and

$$\hat{E}_{R,} = |E_R|\angle 0^\circ \quad \text{(reference phasor)}$$

The current flowing between E_S and E_R is:

$$\hat{I} = |I|\angle{-\emptyset} = \frac{\hat{E}_S - \hat{E}_R}{X}$$

Since the reactance X consumes no power, the receiving end power must equal the sending end power. (If the end voltages are not in steady state synchronism then the system is regarded as being unstable.)

Hence:-

$$\begin{aligned}
\text{Power transferred (P)} &= \text{Real part of } \hat{E}_R\hat{I} \text{ or } \hat{E}_S\hat{I} \\
&= \text{Real}\left\{\frac{(E_R\angle 0^\circ)(E_S\angle\delta^\circ - E_R\angle 0^\circ)}{X}\right\} \\
&= \text{Real}\left\{\frac{E_R(E_S\cos\delta + jE_S\sin\delta) - E_R{}^2}{jX}\right\} \\
&= \text{Real}\left\{\frac{-jE_RE_S\cos\delta + E_RE_S\sin\delta + jE_R{}^2}{X}\right\}
\end{aligned}$$

Therefore,

$$P = \frac{E_RE_S\sin\delta}{X} \tag{11.10}$$

A more detailed treatment of this aspect is given in sub-section 3.5, however, (11.10) will be used to illustrate the stability problem.

11.11.1.1 Steady state stability of a generator or motor

Equation (11.10) applies to any simple form of synchronous source and sink where E_R and E_S and the voltages at either side of the linking reactance X. δ is the phase angle between E_R and E_S. For the generator case, E_R and E_S may be replaced by V and E_g and X by X_{sg}. (For the synchronous motor case E_R and E_S may be replaced by E_m and V and X by X_{sm}.)

Hence, for the generator:

$$P = \frac{VE_g}{X_{sg}} \sin \delta_g$$

Now V is usually kept close to the system rated voltage, i.e. 1.0 pu ± 0.05 pu and X_{gs}, the synchronous reactance of the generator may be assumed constant i.e. typically 1.8 pu to 2.9 pu (depending on the generator rating).

E_q is the internal emf produced by the field winding on the rotor. Hence, for any given value of power P supplied by the generator there will be a wide range of E_g and rotor angle δ_g values.

Example:

Let $V = 1.0$ pu, $X_{sg} = 2.5$ pu and $P = 1.0$ pu (full load).

$$P = 1.0 = \frac{1.0E_g \sin \delta_g}{2.5}$$

$$\sin \delta_g = \frac{2.5}{E_g} \leq 1.0$$

It can be seen that the larger the value of E_g the smaller will be the value of δ_g.

For full-load normal operation δ_g is about 50 degrees, which would require E_g to be 3.264 pu.

Suppose E_g is reduced to 2.51 pu, then δ_g would be 85 degrees.

If E_g is reduced again, to 2.5 pu, then δ_g would be 90 degrees.

If E_g is reduced below 2.5 pu then there is not a value of δ_g to satisfy the equation and this means that the power cannot be transferred if δ_g is caused to exceed 90 degrees. The generator rotor can no longer be kept in synchronism with the terminal voltage to which it is connected. δ_g can be caused to exceed 90 degrees by either reducing the field excitation, as described above, or by allowing more power to be applied to the generator from its prime-mover, e.g. gas turbine. This can happen at any level of power loading on the generator (above zero power). When the rotor angle δ_g exceeds 90 degrees, and the generator rotor pulls out of synchronism, the condition is unstable which means the limit of steady state stability has been exceeded.

11.11.1.2 Steady state stability of an interconnected power system

As an example, consider two offshore platforms, each with its own generators and loads, operating in synchronism through an interconnecting power cable of reactance X (as shown in Figure 11.14. Assume the resistance of the interconnecting cable is zero.

In this situation it is desirable to keep both platform voltages close to their rated values, i.e. 1.0 pu ± 0.05. A particular operating condition requires one of the generators on platform B to be out of service for maintenance but the load still needs to be supplied.

This is achieved by operating an extra generator on platform A and transferring the surplus power from A to B through the interconnecting cable X.

The value of X depends upon the route length and the maximum amount of power that is ever likely to be continuously transferred under normal conditions (for example, it may be decided to size the cable to handle the rated power output of one generator on one of the platforms).

The equation for the power transferred would be:

$$P = \frac{V_s \cdot V_R}{X} \sin \delta_c$$

Where V_s is the sending end voltage on Platform A
V_R is the receiving end voltage on Platform B
δ_c is the load angle across the cable reactance X.

A typical situation could be that the cable reactance X would be 0.2 pu, and 1.0 pu of its power capability is being transferred. With V_S and V_R each about 1.0 pu then the load angle would be about 11.5 degrees. This represents a 'tight' coupling between the two platforms since the load angle is small and considerable margin exists before the 90 degree limit of steady state stability is exceeded.

In order to even approach 90 degrees, considerable current would have to flow in the cable (four to five times full-load power in this example). Therefore, a 'tightly' coupled system is unlikely to become unstable in the steady state for normal and near-normal situations.

Problems can arise when a long cable or overhead line is rated for a relatively small amount of power transfer, because its impedance will be relatively large. In this situation, the load angle will be large and a small disturbance could bring about instability. Such a system may be described as being 'loosely' coupled.

11.11.2 Transient Stability

This is a more complex subject since it is closely related to the dynamic behaviour of the generators, prime-movers, motors, loads and the control systems used with these machines. The static elements in an interconnected power system also have considerable effect on the transient responses of the machines in the system.

In an interconnected power system there will be two or more synchronous machines (or groups of machines). These machines will be coupled through their own internal reactances and through additional reactances (or impedances) due to the presence of cables, overhead lines and transformers. The system will be assumed to be stable in the steady state.

In order to change the operating conditions of the system there must be a change in the load (or loads). This may be due to starting a motor, switching in or out a cable or overhead line, changing the load on a motor or changing a static load. When a load change occurs, the relative position of the generator rotors will change, i.e. δ_g of each generator will change. This angular change of rotor position will be accompanied by an oscillatory movement of the rotors as they reposition themselves. The amplitude and duration of the oscillatory motion is mainly determined by the mechanical inertia and the damping characteristics of the generators and their prime-movers.

The inertia and damping characteristics can be represented by an accelerating power term and a frictional or damping power term in a simplified second-order differential equation for each generator. Also in the equation is a term for the electrical power generated. The right-hand side of the equation represents the mechanical power that is applied to the shaft of the generator.

Each generator prime-mover unit can be thought to be rather like a mechanical spring/mass/damper dynamic system. Once disturbed in any way, the mass will oscillate and eventually settle at a new position. The static characteristic of the spring is analogous to the electrical power generated and sent out from the generator. The inertia term includes all the rotating masses of the generator, its prime-mover and a gearbox that may be used. The damping term consists of two parts; firstly the damping due to eddy current induction in the rotor electrical circuits and, secondly, the damping due to the friction, windage and governor action at the prime-mover.

The subject of electromagnetic damping within synchronous machines is a complicated one and some of the earliest analytical work was recorded in the 1920s e.g. References 9 to 11 using mechanical analogues. A later mechanical analogue was made by Westinghouse Electrical Corporation, Reference 7, Chapter 13, based on that given in Reference 9. A comprehensive summary of the historical developments made in this subject, and automatic voltage regulation, from 1926 to 1973 can be found in Reference 12.

A typical set of system equations will now be described in their simpler form. There are many variations on the general theme, depending upon the results being sought. The analysis of fast-acting transients to match field tests would require very detailed modelling of all the dynamic components of the machinery in the system. The starting of motors or the loss of generation would not require such a detailed representation since the transients of interest take longer to manifest themselves, i.e. 20 seconds, instead of 1 second, are required to pass in order to reach a conclusion.

11.11.2.1 The equation of motion of one generator

The transient power balance equation of an individual generator prime-mover set may be written as:-

$$P_a + P_{fw} + P_{em} + P_{\text{elec}} = P_{\text{mech}}$$

Where: P_a = accelerating power for the polar moment of inertia.

P_{fw} = friction and windage power.

P_{em} = electromagnetic damping power.

P_{elec} = electrical power delivered from the generator terminals.

P_{mech} = mechanical power received by the generator at its coupling.

and $$P_a = 2\pi M \frac{d_f}{d_t}$$

$$P_{fw} = F_{fw} \cdot f$$

$$P_{em} = f_{em}(X''_d, X''_q, R_d, R_q, X_f, R_f, [f_o - f])$$

$$P_{\text{elec}} = f_{\text{elec}}(V, E, \sin\delta_c, X_{dg}, X_q, X'_d, X'_q, R_a)$$

$$P_{\text{mech}} = G_{pm(p)}\left[P_{\text{ref}} + A\left(\frac{f - f_o}{f_o}\right)\right]$$

Where: M = polar moment of inertia of the generator and its prime-mover.
f = generator shaft speed (i.e. frequency).
f_o = reference frequency of the system, e.g. 50 Hz or 60 Hz.
$F_{f\omega}$ = friction and windage coefficient.
V = terminal voltage of the generator.
E = $f_e(I_f)$ = internal emf of the generator as created by the field current I_f.
δ = rotor angle between the terminal voltage and the rotor direct axis.
X_d = direct axis synchronous reactance.
X_{qg} = quadrature axis synchronous reactance.
X'_d = direct axis transient reactance.
X'_q = quadrature axis transient reactance.
X''_d = direct axis sub-transient reactance.
X''_q = quadrature axis sub-transient reactance.
X_{fg} = rotor field leakage reactance.
R_d = direct axis rotor damper bar resistance.
R_q = quadrature axis rotor damper bar resistance.
R_f = rotor field circuit resistance.
R_a = stator resistance.
$G_{mp}(p)$ = transfer function for the dynamics of the prime mover.
(p) = general differential operator $\dfrac{\mathrm{d}()}{\mathrm{d}t}$
P_{ref} = power set-point of the prime mover.
A = governor droop setting.
f_e, f_{em} and f_{elec} are functions of the variables shown.

In some situations, the rate of change of shaft frequency is equal to the second rate of change of rotor angle, e.g. when the system frequency remains almost constant or changes slowly. Hence:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{2\pi}\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2}$$

11.11.2.2 Multi-generator situations

The equations of sub-section 11.11.2.1 can be applied to all the generators in an interconnected system. At steady state stable conditions all the generator shaft frequencies f must be equal. During disturbed conditions, the average frequency of rotation of each generator shaft will be equal, otherwise unstable operation will exist (i.e. averaged over several cycles of the alternating current delivered from the generators). The elements that connect all the generators in the equations are the electrical power terms P_{elec} (P_{mech} will change due to the governor action sensing the change of shaft speed). The P_{elec} terms are connected and balanced through algebraic equations that represent the power balance and exchange that occurs in the static electrical interconnecting network, e.g. cables, overhead lines, transformers, loads.

Hence the simultaneous solution of the generator prime-mover equations also requires the simultaneous solution of the algebraic power transfer equations of the electrical network. Digital computers must be used for the accurate solution of these complex equations. Manual solution is almost impossible, even for relatively simple situations. An excellent treatment of these complex equations for multi-machine systems is given in Reference 13, which lends itself to being reasonably easy to program in a digital computer. The reference also compares the benefits and disadvantages obtained when the mathematical modelling of the generators becomes very detailed.

11.11.2.3 Limit of transient stability

In the same way that steady state stability was assessed by concentrating on the variations of the rotor angle δ_g, so also is the limit of transient stability assessed. However, the situation is not so exact. The transient variation of δ_g for any one machine can exceed 90 degrees, and even reach 120 degrees, before unstable operation occurs. The limit of transient stability can therefore exceed 90 degrees and is influenced by several factors:

- The inertia constant (H) of the machines.
- Effectiveness of the electromagnetic rotor damping.
- The pre-disturbance operating conditions and how close they are to the rated conditions.
- The amplitude of the disturbance.
- The time function of the disturbance, e.g. step function such as a fault, slowly changing function such as a motor start.
- The ‘tightness’ or ‘looseness’ of the interconnections in the system (see sub-section 11.11.1.2).
- The time constants and gains of the control systems used in the automatic voltage regulators, governors and prime-movers.
- The non-linear limits imposed on the control systems, e.g. constraints on excitation current, valve limits on fuel valves.
- The dynamic characteristics of motor loads.
- The mixture ratio of dynamic to static loads.
- Operating power factors before the disturbance is applied.

11.11.2.4 Applications

In the oil, gas and petro-chemical industries, the need for stability studies is primarily due to the fact that most plants have their own power generation facilities which are occasionally interconnected between themselves or with a large public utility. In either case, the stable performance of the system is of great importance, otherwise unwarranted shutdowns can occur with a resulting loss of production.

Stability studies will help to minimise these possibilities. When planning a stability study the main aspects that are usually included are:-

- Application of major faults on the electrical network.
- Sudden loss of a generator, e.g. due to an unexpected failure.
- Starting large induction motors direct-on-line.
- Reduced voltage methods for the starting of motors.
- Tripping large motors.
- Switching in or out interconnecting cables or overhead lines.

The performance is assessed in terms of the following:-

- Voltage recovery throughout the system.
- Frequency recovery throughout the system.
- Synchronous operation is maintained.
- Motors recover to their normal operation.
- No prolonged overloads occur.
- Generators share load changes properly.
- Hunting oscillations do not develop.
- Transient oscillations die away within a few seconds after a sudden disturbance is applied.

11.11.2.5 Depth of study – preliminary stage

A stability study should be seriously considered necessary at an early stage of a project so that the basic configuration of the power system network may be established with confidence. This is especially applicable to remote or self-contained power plants which have a large number of motors, e.g. an offshore platform.

At the early stage it is acceptable to use typical data for particular plant items and a number of simplifications are justified:

- Use typical data for generators, motors, gas turbines, pumps and compressors. This can be obtained as ‘budget’ data when screening vendors and manufacturers for suitable machinery.
- Neglect high voltage cable impedances unless the route distances are long.
- Use simplified block models for the turbine and generator control systems.
- Represent all the low voltage motors on a typical motor control centre by one, two or perhaps three equivalent motors to cover the kilowatt range. A typical selection would be 20 kW and 100 kW. The equivalent motor would have the electrical parameters, inertia constant and pump characteristic of the typical machine, but would have the rating of the total of all the motors in the group.
- All low voltage motors would be assumed to be driving centrifugal machinery.
- Separate out any special case low voltage motors, e.g. extra large motors, large motors driving reciprocating machinery.

- Include typical transformers by their per-unit reactance. Neglect their resistance.
- Include all high voltage motors and their driven machinery.

The results of the preliminary study will enable potential problem areas to be seen ahead of the detail design stage. The results will have been obtained at a minimum cost.

11.11.2.6 Depth of study – detail design stage

As the detail design work develops, the data available for the network and individual plant items become more precisely defined. Particular manufacturers may have been selected, the cable routes and lengths fixed. The network configuration becomes more definite and the turbine and generator control systems can be precisely identified. Hence, the detail to which the network can be represented may be increased with confidence.

The preliminary studies can be re-run with a revised network and new data, and additional operational options can be considered.

11.11.2.7 Theoretical basis of a computer program

The programs used for this type of study are based on the mathematical theory of electrical machines known in various forms as:

- two-axis theory.
- d-q axis theory.
- generalised theory of machines.

The theory has been developed by many researchers over the last 70 years, e.g. H R Park, E Kimbark, C Concordia, B Adkins, G Shackshaft, G Kron, A Rankin.

The synchronous generators and motors are represented by their sub-transient, transient and synchronous reactances and time constants in both the ‘d’ and the ‘q’ axes, hence saliency is accounted for.

The control systems for the governors and automatic voltage regulators can be chosen from standard IEEE forms or can be built up separately to any degree of detail necessary.

A two-axis model is often used for the induction motors but the two axis parameters are usually created within the program from the customary impedances that are given in per-unit form.

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12

Protective Relay Coordination

12.1 INTRODUCTION TO OVERCURRENT COORDINATION

Protective devices, usually relays or fuses, are installed at supply points in a power system to accurately detect and quantify a disruptive disturbance in the system. The variable most frequently used for detection is the supply line current, and in most situations this is detected through the use of current transformers. Occasionally direct acting devices are used e.g. fuses for voltages up to about 33,000 volts or magnetic elements in low voltage moulded-case circuit breakers (MCCBs).

For special purposes other variables such as voltage, active power, impedance, admittance and frequency are used.

Most onshore oil production, petrochemical, industrial and offshore platforms use radial power generation and distribution power systems. These systems will use several voltage levels depending upon the total power demand and the kW ratings of the largest individual consumers. The transition from one voltage to the next higher one is influenced mainly by the highest normal load current that can be handled by conventional circuit breakers, busbar systems within switchgear and power cables. The 'highest' current is typically about 4000 amperes. The maximum fault currents that can be experienced within a particular power system must also be carefully considered when choosing the operating voltages. (If in any doubt, then choose a higher voltage because plants are usually extended or modified, and as such their prospective fault currents tend to increase.)

Figure 12.1 shows a typical hierarchy of switchboards and voltages for a large plant which has its own gas-turbine power generators (not all the switchboards and individual consumers are shown). The hierarchy of switchboards, for example, SB-A, SB-B, SB-C and SB-D is a typical situation, and is one in which overcurrent coordination can occasionally be difficult to achieve for all operating considerations.

There are two basic operating cases to consider:-

a) Fully loaded power system with all the main generators running. (Usually one is off-line as a standby, but periodically this generator will need to be put on-line to relieve one of the others. Hence a major fault could occur during the changeover situation.)

b) Lightly loaded power system with only one generator running. This could be during the start-up of the production plant. The fault currents throughout the system will be at their lowest levels and this will tend to cause the fault clearance times to rise, and the coordination margins to increase.

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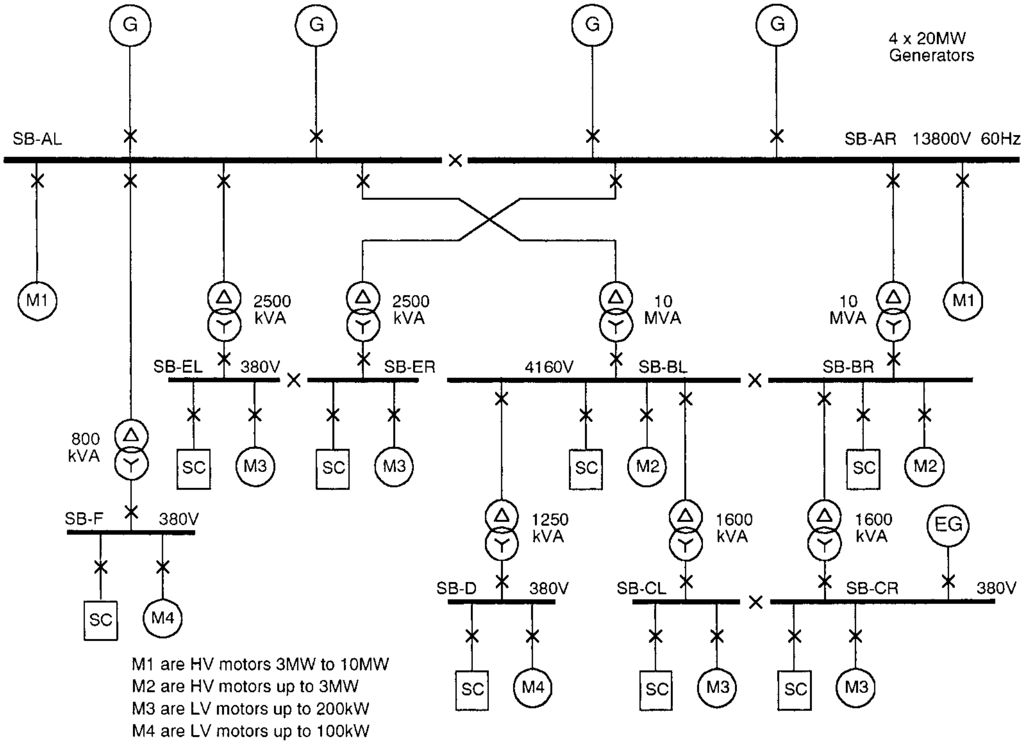

Figure 12.1 One-line diagram of an equivalent power system that has its own dedicated generators, showing the hierarchy of the switchboards.

The relay coordination is mainly based on the requirements imposed by case a) e.g. starting large motors direct-on-line, faults at switchboard busbars, faults at consumer terminal boxes. It is reasonable to assume that the plant will operate as in a) for 90% or more of its lifetime. However, the system must have satisfactory, not necessarily the best, coordination for start-up and light load operations as in case b). Operational restrictions at light load may assist the coordination calculations e.g. most large HV motors would not be running, hence their starting performances need not be considered, when switchboard feeder circuit breakers are being examined.

When all the overcurrent curves are plotted for the main generators, transformer feeders, large motors and downstream feeders, they tend to be located ‘close together’, and without much room for adjustment. This is made more difficult when there are:-

- A large number of small main generators e.g. 4, 6 or 8 as compared with 2 generators.
- The largest motors that are started direct-on-line at the main generator switchboard are large compared with the smallest generator e.g. 20% or larger.
- The largest motors that are started direct-on-line at the lower voltage switchboards are large compared with the rating of the transformers that feed the switchboard e.g. 20% or larger.
- The standing load at a switchboard is high (80% or more) compared with its feeder capacity. This is especially a problem at the main generator switchboard when b) applies, see sub-section 12.2.2.4.

- The large motors have long run-up times e.g. 10 to 20 seconds for high speed centrifugal gas compressors.

In this section the protective relays and their functions are described in a sequence that pertains to the protected equipment in a power system. The sequence begins with generators because these are usually the main source of power in the network. At the end of the sequence are the smaller power-rated equipment. The sequence is:

- Main generators.
- Emergency diesel generators.
- Feeder transformers.
- Feeder cables.
- Feeder overhead lines.
- Switchboard interconnectors.
- Switchboard busbar section circuit breakers.
- Large motors.
- Small motors.
- Static loads.

12.1.1 Relay Notation

There are two generally accepted methods of describing and notating relays and protective devices. The first and earliest system to be rationalised is that developed by the IEEE in its standard C37.2 in 1970, which has also been revised in 1991. Appendix C gives a comprehensive listing and description of each function. This method uses a simple numbering system of up to two digits, together with one or two suffixed letters, to identify the function of the device. Its simplicity is an attractive advantage and most relay and switchgear manufacturers are very familiar with the numbers.

The second system is based on the IEC60255 and its references. The symbols used are comprehensive but tend to suffer from poor clarity when photoreduced, as is often required with engineering drawings. The first method is regularly used in the oil industry and is preferred herein.

Appendix C herein gives the IEEE device numbers that are most commonly used, together with their descriptions that are typically used in the oil industry.

12.2 GENERATOR PROTECTION

12.2.1 Main Generators

For generators in the range of approximately 2 MW to 50 MW the following protection relays should be provided:-

- Overcurrent (51 V).
- Differential stator current (87).
- Field failure (40).
- Field winding earth fault (58).

- Reverse active power (32).
- Negative phase sequence (46).
- Stator earth fault current (51 G) and (64).
- Over terminal voltage, (59) Note 1.
- Under terminal voltage, (27) Note 1.
- Overfrequency, (81) Note 2.
- Underfrequency, (81) Note 2.
- Winding temperature (26).

Note 1: These can be combined in one voltage relay.

Note 2: These can be combined in one frequency relay.

A typical scheme that contains most of these relays is shown in Figure 12.2.

12.2.2 Overcurrent

12.2.2.1 Response of a generator to a major fault

When a major fault occurs externally from the generator but near to the generator stator terminals or near its switchgear, two reactions take place:-

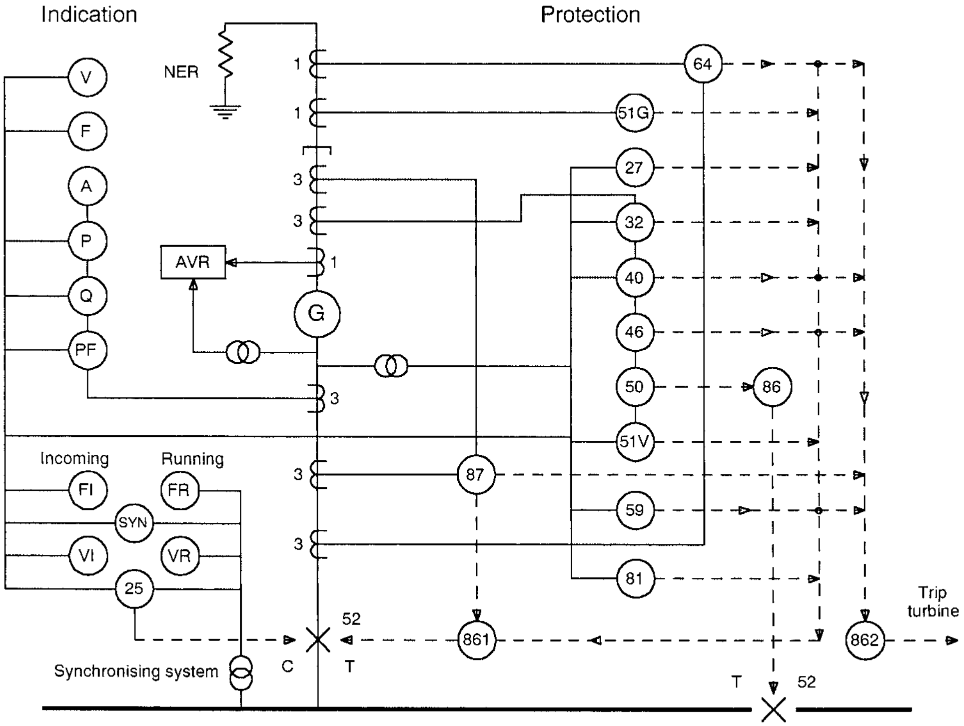

Figure 12.2 Protective devices for a high voltage generator.

a) The fault current supplied by the generator is initially high (approximately 5 to 8 times the full-load current) but decays within a few tens of cycles to a much lower value. This lower value is determined by the synchronous reactance and the maximum output current of the exciter. See Figure 12.3 which shows the stator current response to a full short circuit at its terminals. Two cases are shown, one with the AVR functioning, which is invariably the case, and the other with the excitation fixed at its pre-fault value which is a non-practical situation but emphasises the effect of the AVR. These responses are called the 'Generator Decrement Curves', and are required when relay coordination studies are being carried out, see Reference 8.

b) The terminal voltage of the generator falls to a value determined by the location and impedance of the fault circuit.

12.2.2.2 Overcurrent characteristic

The basic characteristic of the relay before it is modified by the voltage signal, as explained in sub-section 12.2.2.3, can be either a) definite time, b) inverse with a minimum time value, see Figure 12.5 or Figure 12.6 extremely inverse with a minimum time value.

12.2.2.3 Voltage restraint

A standard overcurrent relay does not have a characteristic that can give a fast enough response once the initial decay of a) above has taken place. To overcome this effect the change in terminal voltage

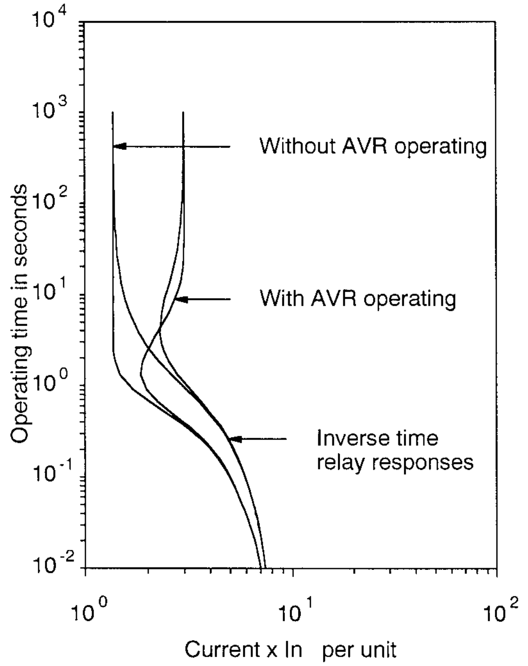

Figure 12.3 Decrement currents in a system that is fed by synchronous generators. The diagram shows the current responses where the generators are equipped with AVRs and without AVRs.

at the generator is used to measure the severity of the fault. The greater the fall in voltage the more severe is the fault. The measured voltage is used to modify the characteristic of the relay. Electronic relays use a function generator and a multiplying element to achieve the required characteristic. The voltage signal is used to automatically reduce the time setting, which is often called the 'Time Multiplier Setting'. There are several methods frequently used, two of which are:-

a) Two definite levels of voltage.

b) Continuously variable between two limiting values of voltage.

This type of relay is called a 'Voltage Restrained Overcurrent Relay' (51 V). It often has a definite minimum time limitation built into its design.

A typical multiplying function for the continuously acting voltage restraint is:-

$$K_v = \left(\frac{1.333 \times V - 6.667}{100}\right) \text{per unit}$$

For V in the range 20% to 80%, Figure 12.4 shows the voltage restraint function.

The 'unrestrained' operation of these relays is used as back-up overcurrent protection for downstream relays in case they fail to respond.

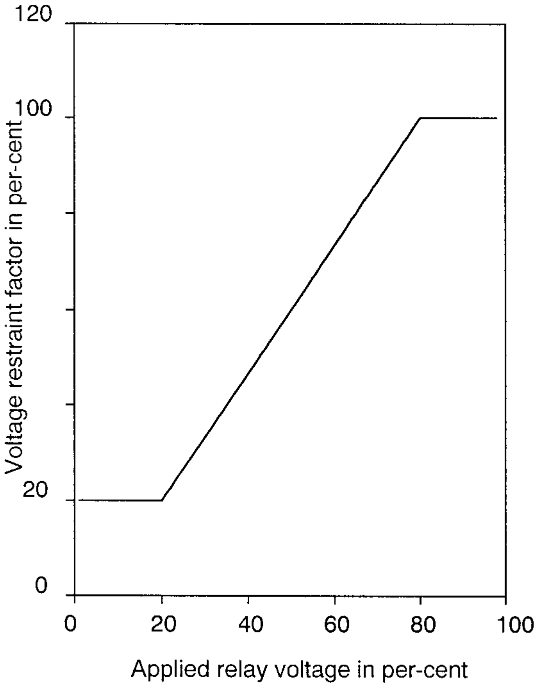

Figure 12.4 Voltage restraint characteristic for a 51 V relay.

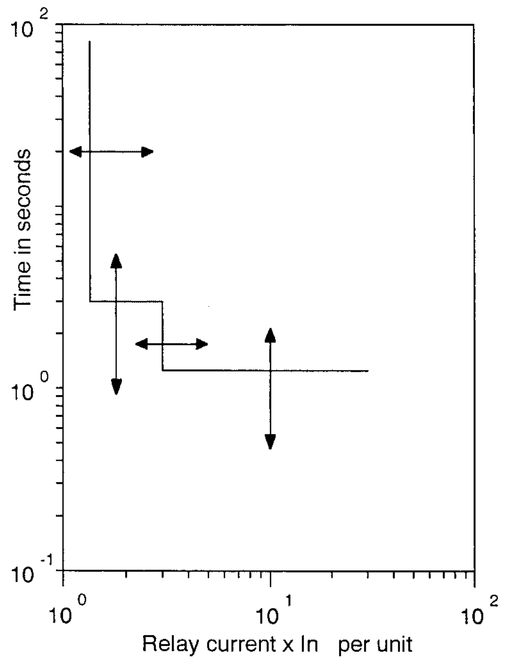

Figure 12.5 Definite time overcurrent relay with a two-stage characteristic.

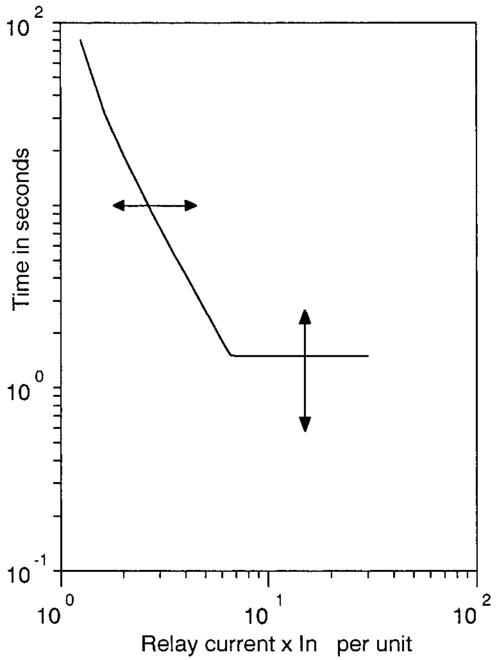

Figure 12.6 Inverse time overcurrent relay with a definite minimum time limit at high fault currents.

12.2.2.4 Influence of the load characteristics

Occasionally a power system may contain motors that have a normal continuous rating, that is large in comparison with any one of the main generators in the system. All the generators may not be of the same rating.

Direct-on-line starting of these large motors can cause several problems with the performance of the generator protection relays, for example:-

a) Voltage dip at the generator terminals during the first 100 milliseconds, or so, as the motor begins to run up to speed. This is caused by the high reactive current drawn by the motor, which remains nearly constant until the motor approaches its full-speed operation. Voltage dip can cause tripping of downstream switchgear if its control circuit supplies are taken from the AC power system e.g. switchgear voltage transformers. Prolonged voltage dip may occur if the generator excitation is not provided with sufficient ceiling voltage capability.

b) Overvoltage can occur at the end of the motor run-up period if the generator excitation has been forced to a high level. The sudden loss of the high reactive starting current will raise the generator terminal voltage significantly, which may take a second, or so, of time to recover. For high voltage systems this rise in voltage may be unacceptable for the insulation limits of equipment in the system e.g. motors, transformers, cables. This problem occurs particularly when motor run-up times exceed about 5 seconds, e.g. large high speed gas compressors.

   Undervoltage and overvoltage relays are often used on the generators to protect against prolonged overload, seen as undervoltage; and excessive stress on insulation, seen as overvoltage. These relays are usually chosen with adjustable definite time delays.

c) The high starting current of a single large motor may be sufficiently high to be seen by the generators as an overcurrent situation; particularly if a minimum number of the generators are running at the time, and each one is already heavily loaded. This situation may influence the choice of Time Multiplier Setting (TMS) or even the shape of the relay curve. This is illustrated in Figure 12.7.

High voltage generators rated above 2000 kW are usually provided with differential stator current protection (87), which is very sensitive to internal winding faults. Generators have long thermal withstand time constants and can therefore tolerate modest overcurrents for a relatively long time. For these reasons the asymptotic current (current setting) is often set fairly high when compared with other large items such as motors and transformers. Current settings up to 150% are often acceptable, but advice should be taken from the manufacturer of the generator if a high setting is to be used. The TMS of the overcurrent relay will often be set high when the kVA ratings of the downstream transformers and motors are large compared with one of the parallel generators. Overcurrent protection (51 V) of generators tends to be back-up protection to other facilities such as stator differential protection (87). It will be the last protection to operate if all the other facilities fail to respond.

12.2.3 Differential Stator Current Relay

Differential current protection (87) is used for generators to detect internal winding faults, which may develop between phase windings or between a phase and the steel core. Sensitive high-speed action is required in order to minimise the possibility of damage to the stator core laminations in particular. A current as low as 20 amps can cause significant damage if it is allowed to pass to the core

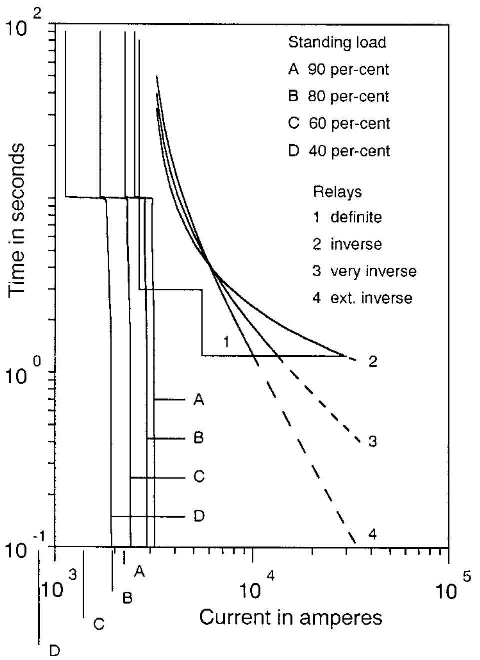

Figure 12.7 Effect of a large load variation on the response of overcurrent relays at the generators. The diagram shows the response when a large induction motor is started direct-on-line. Four different standing loads are shown.

for longer than several seconds, see Reference 2. The relay itself should function in approximately 15 milliseconds, and have a sensitivity of about 2 to 5% of the stator rated current. The nominal setting ranges are between 10 to 40% for 1amp relays and 20 to 80% for 5 amp relays. The low % settings are usually chosen initially and increased if subsequently found to be too sensitive. This type of protection is generally applied to high voltage machines above about 2 MW.

Electromagnetic differential current relays are fitted with restraining or biasing, coils in each secondary circuit of their current transformer. These restraining coils stabilise the relay when large ‘through’ fault currents are present in the windings i.e. feeding an external fault. Stabilisation is necessary because of mismatch errors and saturation effects in the current transformers, which would otherwise be large enough to activate the sensitive operating coil.

12.2.4 Field Failure Relay

If the field is lost in a generator it will attempt to generate power at a low leading power factor and with a large rotor angle. In most loading situations the generator rotor angle will increase to a critical value where unstable power transfer will occur, and the generator will no longer be able to remain in synchronism with the supply. When synchronism is lost the stator current varies in magnitude over a wide range and at the slip frequency. If this is allowed to continue then it is possible that damage will result in the stator and rotor windings, and the disturbance in voltage at the connected power network will be large enough to cause tripping and overcurrents in loads.

Since the power from the prime-mover cannot be transmitted from the generator there will be a surplus of mechanical power which will accelerate the rotor to a speed greater than the synchronous speed. Since there is also no excitation the only possible conversion of power will be a small contribution due to saliency. The generator will tend to be seen from the power system as a shunt reactor that has a varying X-to-R ratio. Therefore the generator can be shown on an impedance diagram as occupying a region of negative reactance with excursion into both the positive and negative resistance quadrants. If the condition were to be allowed to persist until steady fluctuations became established, then the shape appearing in the impedance diagram would follow a steady locus in the lower two quadrants of the diagram. Consequently a part of this region can be chosen as the response characteristic of a 'loss-of-excitation' relay. A circle is chosen as a suitable shape within the region.

When the field is lost the movement into the critical leading power factor and high rotor current regions takes a finite time, which depends upon the pre-disturbance power being generated and the moment of inertia of the generator and its prime-mover. Consequently the stator current phase angle and power factor can be monitored by a relay located in the stator current circuit, and be set to trip the generator when a critical point is reached.

A field failure relay (40) is usually an 'admittance' relay with an offset admittance zone. The tripping zone is usually determined from a circle. The relay receives a current signal and a voltage signal from the stator terminals. The 'impedance' circle of the generator is determined and located by the following features.

A circle is located in an x-y plane where the x-axis is $-R$ to the left and $+R$ to the right. The y-axis is $+X$ vertically above the x-axis and $-X$ below. The circle is centred in x-y coordinates as $+\Delta R(-(0.5 \text{ to } 0.75)X'_d - (0.5 \text{ to } 1.0))X_d$ where ΔR can be zero or a small positive value. The diameter of the circle is chosen between 0.5 to 1.0 times X_d. All points on the circle must lie in the negative y-axis region. The construction of the circular characteristic of the relay is also described in References 1, 3 and 4.

The reactance settings are converted into admittances by inversion and then used as settings for the relay. The relay setting ranges will usually exceed the requirements of the generator impedance circle. A time delay range of 0.5 to 10 seconds is usually adequate for the protection tripping setting, 3 or 4 seconds would be typical settings.

Example:

Generator details:-

Generator impedance characteristic with zero Excitation.

Rated kVA	S_{gen}	7500
Rated voltage	V_{gen}	6600 V
Rated current	I_{gen}	656 A
Synchronous reactance	X_d	250%
Transient reactance	X'_d	25%
'Sub-transient reactance	X''_d	18%
Voltage transformer ratio		6,600/110 V
Current transformer ratio		800/1 A

Conversion factor for referring the generator reactances to the CT and VT secondary circuits:-

$$X_{sec} = \frac{X_{\text{gen}}\% \times V_{\text{gen}}{}^{2} \times CT\text{ratio}}{100 \times S_{\text{gen}} \times VT\text{ratio}}$$

$$= \frac{X_{\text{gen}}\% \times 6600^{2} \times 800 \times 110}{100 \times 750{,}0000 \times 1\ 6600}$$

$$= \frac{X_{\text{gen}}\%}{100} \times 5.808 \times 13.333$$

$$X_{sec} = X_{\text{gen}}\% \times 0.7744 \text{ ohms}$$

$$X'_{\text{dsec}} = 25.0 \times 0.7744 = 19.36 \text{ ohms}$$

$$X_{\text{dsec}} = 250.0 \times 0.7744 = 193.6 \text{ ohms}$$

Choose an offset of 0.75 X'_d, a circle diameter of $0.5X_d$. This will allow the generator to run in the leading power factor zone with a large transient rotor angle (up to 120 degrees).

Relay offset = 0.75 × 19.36 = 14.52 ohms

rounded to 15.0 ohms

Relay circle diameter = 0.5 × 193.6 = 96.8 ohms

rounded to 100.0 ohms

Relay time delay, choose 4 seconds.

These results are shown in Figure 12.8.

12.2.5 Reverse Active Power Relay

Reverse active power protection (32) is required to prevent the prime mover from being driven by the generator. This can occur during transient disturbances when a generator is lightly loaded, the

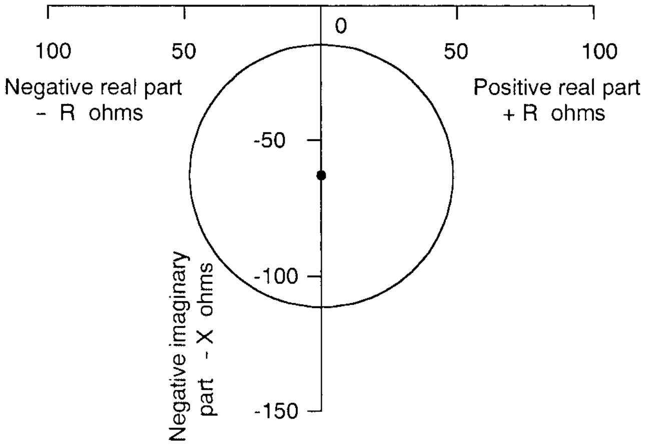

Figure 12.8 Loss of excitation characteristic of an admittance relay. The diagram is drawn in the impedance domain.

power transfer into the generator being from other generators or utility sources in the network. This can occur for example just after synchronising an incoming generator or unloading a generator prior to taking it out of service.

Reverse power protection also protects a gas turbine from failure of its governor control system to regulate its speed e.g. component failure, sluggish response to speed changes. When power is fed back to the prime mover it will tend to cause the shaft speed to rise, and the governor control system will attempt to reduce the fuel supply by closing the fuel valve to its lower limit. In these circumstances the prime mover is effectively without speed control.

Gas-turbine generators up to above 35 MW are usually driven by the prime mover with a speed-reducing gearbox, because the generators are usually 4-pole low-speed machines. The design of the gearbox and the couplings may not permit prolonged reverse power operation.

The relay is usually set for 1 to 5% of rated power and with a tripping time of up to 5 seconds.

12.2.6 Negative Phase Sequence Relay

A negative phase sequence relay (46) protects a generator against overheating of its rotor pole faces and damper bars. This form of overheating is due to the presence of unbalanced stator currents, which create a negative phase sequence (NPS) flux in the air gap. This flux rotates in the opposite direction to the rotor but at the same absolute speed. Hence the rotor poles and damper bars have double-frequency currents induced into them, which rapidly cause localised heating and eventually distortion of the rotor and slot damage. The NPS current has a heating characteristic similar to the familiar positive phase sequence overcurrents and fault currents, i.e.:-

$$K_n = I^2{}_2 t$$

Where K_n is typically 50 to 60 for air-cooled generators.

Salient pole generators used with gas-turbine drivers can tolerate NPS currents up to 40% of full-load current, when defined by:-

$$I^2{}_2 t \leq 0.4 I^2{}_1 t, \quad \text{for large values of time } t.$$

The relay characteristic therefore has a negative slope of 2 on a log-log scale, and the value of K_n is determined by biasing the sloping line up or down on the log-log scale. A setting for K_n in the relay is chosen between 5% and 30% depending upon the actual K_n value of the generator. A typical relay has an operating time of 10 seconds when 100% NPS current flows in its circuit, and the time multiplier setting (TMS) is set at 100% or 1.0 pu. The relay should be insensitive to zero sequence and third harmonic currents (otherwise externally connected star/delta interposing current transformers can be used to achieve this requirement).

12.2.7 Stator Earth Fault Relays

12.2.7.1 Standby earth fault relay

High voltage generators used in the oil industry are usually earthed by connecting an impedance, which is invariably a resistor, between its star point and the ‘ground’. Occasionally generators are unearthed; but in such cases earthing of the power system is provided artificially at the busbars to which the generators are connected.

The star-point connection to earth is provided with a current transformer and a sensitive relay. The relay (5I G) is of a definite time delay or inverse time delay type so that it can be graded as back-up protection to earth fault relays at downstream feeders and consumers.

The choice of the current setting depends upon several factors:-

- High or low impedance earthing.
- Level of continuous third harmonic current that will flow in the impedance.
- Capacitance of downstream feeders, i.e. AC charging current.
- Earth fault relay settings of downstream relays.
- Differential current relay (87) settings of the generator.

Up until about 1985 it was common practice to limit the fault current in the stator windings and neutral earthing resistor to between 50% and 100% of the full-load current. However, there has been a move away from choosing such high levels of current and it is not uncommon to choose values in the range 20 to 50 amps, and occasionally as low as 10 amps. This later approach is due to research by machine manufacturers which has shown that serious burning damage to the iron core begins to occur at about 20 amps, see References 2, 5, 6 and 7.

The thermal withstand time for the neutral earthing resistors are usually specified as 10 seconds for the duration of the fault current. This allows adequate time for main and back-up protection relays to operate and clear the fault. The standby earth fault relay (5I G) time-current characteristic must be chosen so that its I^2t curve is lower than that for the neutral earth resistor and the connecting cables. (The I^2t curve is derived directly from the I-t data, and not by integrating the curve.)

In some generating schemes e.g. drilling rigs, emergency supplies, where the nominal system voltage is less than 1000 volts, it is possible to operate them as ‘unearthed’ systems. This occasionally applies to low-voltage systems, which do not use the neutral as a 4-wire method of supplying unbalanced loads (unbalanced loads are taken between the lines, often by using a step-down transformer). However, the normal practice in these schemes is to use an earth leakage detection relay which has sensitivity between a few milliamps and 0.5 amp. The relay normally gives an alarm so that the operator of the system is aware that a fault is present somewhere in the system, and this can then be located at a convenient time. If a second earth fault occurs on a different phase then the overcurrent relays will see the fault as a phase-to-phase short circuit and will trip an appropriate circuit breaker, or a fuse in the system will operate.

12.2.7.2 Restricted earth fault relay

In order to restrict the detection of earth faults to those within the stator winding, and those from the stator terminals to the switchgear current transformers, a sensitive relay (64) is used. Three current transformers are used in the stator live lines and one in the star to NER connection. All four current transformers are connected in parallel such that any unbalance in the currents due to an ‘internal’ fault is detected by the restricted earth fault relay (64). A sensitive high impedance relay is used to achieve an instantaneous response. However, if a high impedance is connected across a current transformer it is possible that very high voltages will appear across the impedance. This is due to the action of the current transformer to balance the ampere-turns across its windings. It is the normal practice to shunt the relay with a non-linear resistor. As the voltage across the resistor and the relay rises above a predetermined value, the resistor shunts more and more current from the current transformer. In so doing the relay voltage is moderated, and the relay functions as required.

The choice of current or voltage setting for the relay will depend upon the design value of earth fault current that will pass in the NER during the specified time e.g. 20 amps for 10 seconds. If the setting is too low the relay may respond to stray and harmonic currents in the neutral circuit. The maximum expected third plus triplen currents should be determined and the relay set at say double their combined level, or higher.

It is worth noting that the stator differential relays (87) will not normally be sensitive enough to detect the low earth fault currents that are limited by a high resistance NER. With the modern practice being to limit these currents to typically 20 amps, it is necessary to install the restricted earth fault relays (64).

12.2.8 Over Terminal Voltage

If the terminal voltage of a generator persists above about 110% of its nominal value then it is possible that the automatic voltage regulator (AVR) of the generator has developed a fault within its control circuits. (An alternative cause, in the case of generators having a high neutral earth resistance, is that an earth fault on one phase is present.)

Excessive terminal voltage from the generator implies that the exciter is being forced to produce a high rotor current in the generator. Consequently both the generator itself and its exciter are being overstressed in terms of current, and therefore may become overheated.

Since the generator is supplying the power system at an elevated voltage, all the transformers and consumers near to the generator will receive an excessive voltage. In this situation transformers and motors in particular may well be overexcited and their magnetising current will rise sharply. Excessive magnetising current may be accompanied by overheating of the iron core laminations. Other consumers such as inverters, battery chargers, light fittings, electronic systems may also react unfavourably to excessive supply voltage.

If several generators are operating in parallel and one of them has a faulty AVR then the healthy generators may become underexcited as their AVRs respond to the high system voltage. This situation could lead to unstable operation if the generator rotor angles become too large.

To protect the system from prolonged high voltage it is the usual practice to install an over-voltage relay (59) in each of the generator circuit breakers or at their common busbar. The relay settings are usually set to operate at 115%, with a time delay between 0.5 and 10.0 seconds.

12.2.9 Under Terminal Voltage

Prolonged undervoltage implies that there is a fault in the AVR or that there is an excess current being drawn from the generator. An excessive current could be due to a fault in the system or an overload caused by, for example, a loss of a generator without a corresponding shedding of load. If the cause is excessive current but the voltage is still high enough to maintain the consumers, then the overcurrent protection of the generator may take too long to operate, particularly if a voltage-restrained relay is used. An undervoltage relay (27) is used to trip the generator if the voltage falls below a fixed level for a definite time. Typical settings are 90% of the nominal voltage and between 0.1 and 10.0 seconds. A longer delay may be needed if large motors with long run-up times are started directly on line at the same busbars that are fed by the generators. This relay will need to coordinate with a similar relay used at the busbars to shed consumers when an overloading situation is apparent from a prolonged low busbar voltage.

12.2.10 Under- and Overfrequency

Generators normally operate over a narrow frequency range, as determined by their prime-mover speed regulating controllers, typically 1 to 2 Hz for high loadings. Speed regulation is basically proportional control action, with a 'droop' gain giving a 4% droop of speed over the range of zero to full load. Simple situations have a fixed no-load frequency of 102 to 104% and allow the frequency to fall to 98 to 100% at full-load. Occasionally a power system is operated with its steady state frequency fixed at 100%, by the use of integral control action. This is called 'isochronous governing', and it requires special control circuits for each generator in the power system if several generators need to operate in parallel.

Under- and overfrequency relay (81) operation implies that the system frequency is outside a range of, for example, 96 to 106%. In both cases this generally will indicate that the speed-governing controllers are not functioning correctly. Underfrequency will usually be accompanied by a heavy active power demand, which will also cause the stator current to be high. If the load power factor is similar to the rated power factor of the generators (usually 0.8 lagging) then the overcurrent protection will probably function before the underfrequency protection. Most power systems have a high load power factor above 0.9 lagging, which provides some margin of operating time between overcurrent and underfrequency protection.

Underfrequency protection can operate in several stages in a progressive manner to enable the generators to recover their frequency. Several stages over a range of say 100% down to 96% would be used, initially to shed the connected loads and finally to trip the generators. Time delays of several seconds would be used at each stage, to allow the speed regulators to respond and the loads to settle to a steady state. This subject is discussed in more detail in Appendix D.

12.3 EMERGENCY DIESEL GENERATORS

Emergency diesel generators occasionally operate at high voltage e.g. 3300, 4160, 6600 volts. They are used in plants that consume high levels of power and which are sensitive to the loss of supply. Liquified natural gas (LNG) plants are typical examples where high voltage emergency generators are installed. The refrigeration processes and storage tank facilities need to be maintained in an operating state until they can be carefully shutdown.

Low voltage is most commonly used for emergency power services. Emergency generators need to operate in difficult situations and may be called upon to continue until fuel is exhausted or until physical destruction takes place. The second scenario is occasionally adopted for offshore facilities, where safety of personnel is paramount. Personnel need to be evacuated under all weather conditions and when there is a dangerous situation onboard the facility. Hence lighting, public address, navigational aids, radio etc. need to be kept operating for as long as possible.

In view of the need to continue operation it is possible to tolerate some relaxation in the protective relays that are provided for emergency generators, especially low voltage offshore machines. The following relays in sub-section 12.2.1 may therefore be deleted for low voltage generators:-

- Negative phase sequence (46).
- Differential stator current (87).
- Field winding earth fault (58).

In addition the current setting of the overcurrent relay (51) may need to be higher than for a 'normal service' generator. The voltage-restraining element of a 51 V relay may not prove to be particularly beneficial for low voltage emergency generators.

12.4 FEEDER TRANSFORMER PROTECTION

Power systems for offshore platforms and onshore plants, which have their own generators seldom have feeder transformers with ratings greater than about 10 MVA. These transformers usually feed radially to the consumer switchboards. Several levels of operating voltages are used in these situations, for example:

a) Generators and main distribution HV switchboards.

Voltages: 13,800, 11,000, 10,000, 6600, 6000 volts,
occasionally 4160 and 3000 volts.

b) Secondary distribution HV and LV switchboards.

Voltages: 6600, 6000, 4160, 3000, 600, 440, 400, 380 volts.

c) Sub-circuits

Voltages: 254, 240, 230, 220, 120, 110 volts.

The power system frequency is either 50 or 60 Hz.

The construction of transformers will be either liquid insulated in a steel tank or cast resin in a safety enclosure. Either type can be used for outdoor and indoor services, although additional weatherproofing will be needed for cast resin units.

For transformers having ratings up to 10 MVA the following protection schemes would normally be provided:

Typically schemes for different transformer configurations that contain most of the following relays are shown in Figures 12.9, 12.10 and 12.11.

- Overcurrent.
- High-set or instantaneous current.
- Primary earth fault current.
- Secondary earth fault current.
- Differential current.
- Winding and core high temperature.
- Buchholz oil tank surge protection.

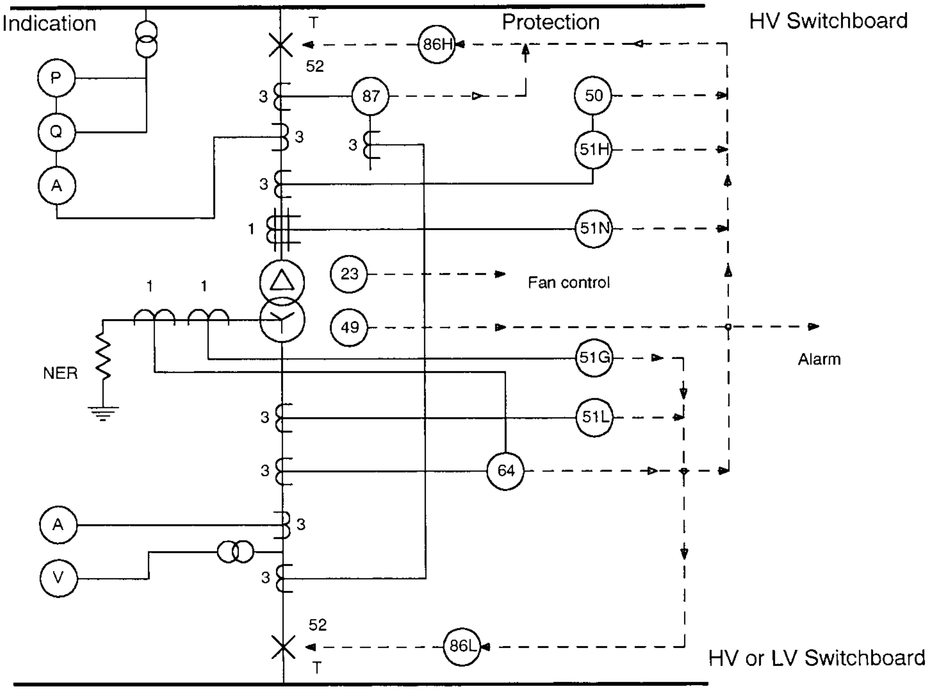

Figure 12.9 Protection devices for a two-winding transformer with NER.

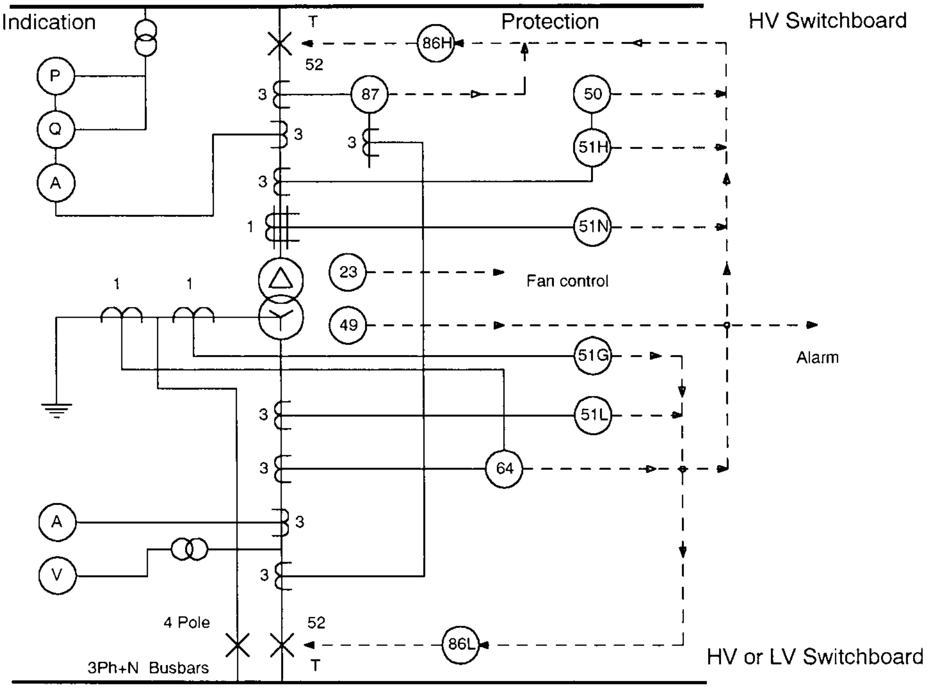

Figure 12.10 Protection devices for a two-winding transformer with solid neutral.

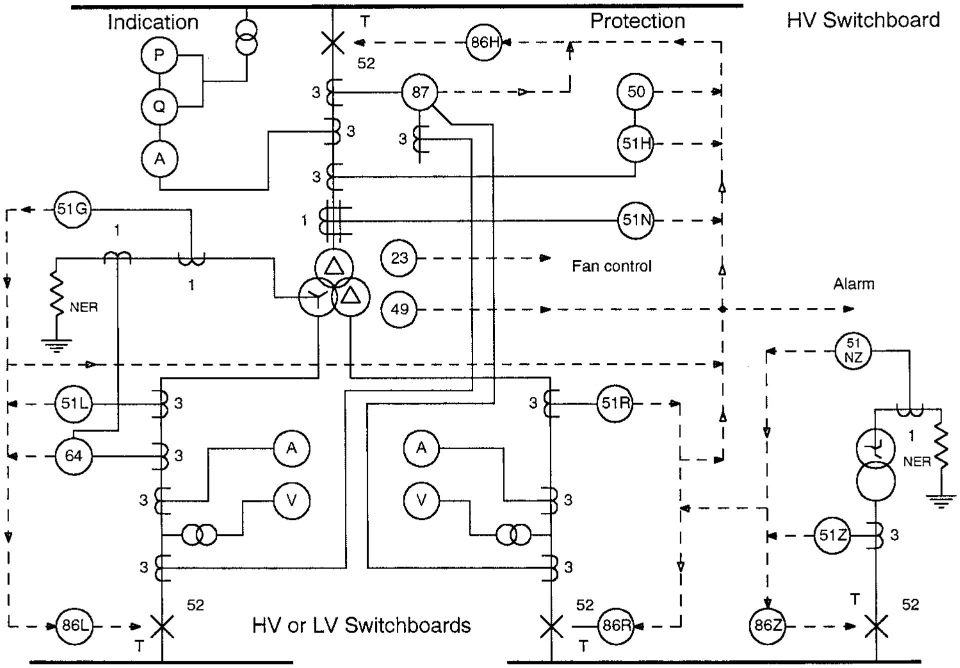

Figure 12.11 Protection devices for a three-winding transformer.

The number of these protection schemes applied to a particular transformer depends upon several factors e.g.:-

- Critical nature of the load e.g. emergency, essential, normal production.
- Single or duplicated feeder.
- Nominal kVA rating of the transformer.
- Secondary winding voltage.
- Primary winding switching device.
- Physical location and availability of spare complete units or parts.

Figure 12.9 applies to a delta-star transformer that feeds a high or low voltage switchboard. In this case the secondary winding star point is earthed through an impedance, shown as a resistance. The NER could also be an earthing inductor or a transformer with a secondary winding feeding a resistance load, as explained in sub-section 13.3.1. The use of earthing transformers in the oil industry is seldom encountered, it is more commonly found in EHV systems operated by power utility companies.

Figure 12.10 is almost the same as Figure 12.9, the difference being that the star point of the secondary winding is solidly earthed, which is usually the case with low voltage secondary systems.

Figure 12.11 is again similar to Figure 12.9 but applies to a three-winding transformer. Three-winding transformers are occasionally used in the oil industry. The most common application is with drilling rigs that are located at offshore production platforms, where they share the power generated by the production facility. Drilling rig DC systems are fed from a 600 V unearthed system, which makes the use of a delta winding attractive. This delta winding acts like a tertiary winding in that it helps to suppress harmonics from being transferred to the primary winding and HV system.

Transformers used for offshore services will generally have more protection schemes applied, than those for onshore services. This is due to the cost of lost production caused by failure of main power supplies, and the difficulties that arise when a failed unit needs to be replaced. Cast resin transformers are often preferred for offshore services because of their higher reliability, simpler and safer construction and ease of maintenance.

12.4.1 Overcurrent

An overcurrent situation is more likely to be caused by excessive secondary load or a serious fault at the downstream switchboard than an internal fault. Overcurrent protection can be regarded as currents that are above 100% but below about 500% rated current. Currents above about 500% rated current can be regarded as 'high-set' or 'instantaneous' currents, and these are protected in a different manner than for overcurrents. It is feasible, therefore, to treat the overcurrents as a 'through-fault' condition and detect them in either the primary or the secondary winding switchgear, but not necessarily at both windings. Detecting overcurrents at both windings would appear to be a desirable requirement, but it can introduce the need to coordinate the protection curves of the two relays. These could often be different types of relays or even be made by different manufacturers, in which case their curves may not match satisfactorily. Alternatively the relays, or their curves, could be chosen to be the same, or nearly the same. In this case their settings could be made the same and whichever relay operates first can be used to trip the circuit breakers in both windings, either directly or through intertripping circuits.

The characteristic curve of the overcurrent relay(s) can be chosen from several standard shapes:-

- Definite time.
- Standard inverse time.
- Very inverse time
- Extremely inverse time.

Definite time relays are chosen when the individual secondary loads are small when compared with the transformer rating, and when motor run-up times are small i.e. up to 1 second. Care must be taken to match the current–time settings to the thermal characteristic (I^2T) of the transformer. (A good guide to estimating the I^2t characteristic for a liquid insulated transformer, when data from the manufacturer are not available, is the ANSI/IEEE standard C57.12–1980 which takes into account the probability of frequent through faults and the ratings of the transformers. Note, in this connection plants which do not use or are not fed from overhead power lines would be regarded as having infrequent through faults.) Definite time relays are the least expensive of the four types and easy to set up. They are seldom used for offshore platform applications.

When an individual load is a large induction motor which is started direct-on-line and has a long run-up time, then the standard or very inverse time relays are often chosen.

Very and extremely inverse relays are used in systems where the fault level downstream is low when compared with that available at the point of main supply, e.g. a main generator switchboard. They are also used where coordination with upstream or downstream fuses is necessary.

Extremely inverse relays have an inverse square law characteristic, which predominates at high fault currents. It therefore closely matches the I^2t characteristics of cables, motors, transformers, NERs etc.

12.4.1.1 Comparison of inverse time curves

Before electronic relays were developed the standard inverse characteristic was taken as the reference e.g. in BS142 for UK practice. A point on the characteristic was chosen for the comparison with others, e.g. extremely inverse. The reference point was 10 times the nominal relay current and an operating time of 3 seconds.

Most literature for modern relays, and the IEC60255, do not compare the characteristics in this manner. Instead they use a standardised formula for each relay,

Inverse time

$$t = \frac{0.14}{\left(\frac{I}{I_n}\right)^{0.02} - 1} \quad \text{seconds}$$

Very inverse

$$t = \frac{13.5}{\left(\frac{I}{I_n}\right)^{1.0} - 1} \quad \text{seconds}$$

Extremely inverse

$$t = \frac{80}{\left(\frac{I}{I_n}\right)^{2} - 1} \quad \text{seconds}$$

Where the numerator is a constant that falls within the range of the time multiplier of the relay. If the numerator is ‘temporarily’ modified then the characteristics can be compared in a similar manner to the older method of BS142. A good pictorial comparison can be made by choosing the common point to be at 5 times nominal current and 5 seconds operating time. The modified numerators are 0.1636, 20.0 and 120.0 respectively. The three characteristics are shown in Figure 12.12. It is feasible with modern electronic relays to use any value for the exponent in the denominator. Figure 12.13 shows a family of curves in which intermediate values of the exponent are included, i.e. 0.5, 1.5 and 3.0.

12.4.2 High-Set or Instantaneous Current

12.4.2.1 Basic considerations

The use of high-set or instantaneous current protection for the primary winding, or the secondary winding, is determined by several factors, which differ for either winding. Consider the primary

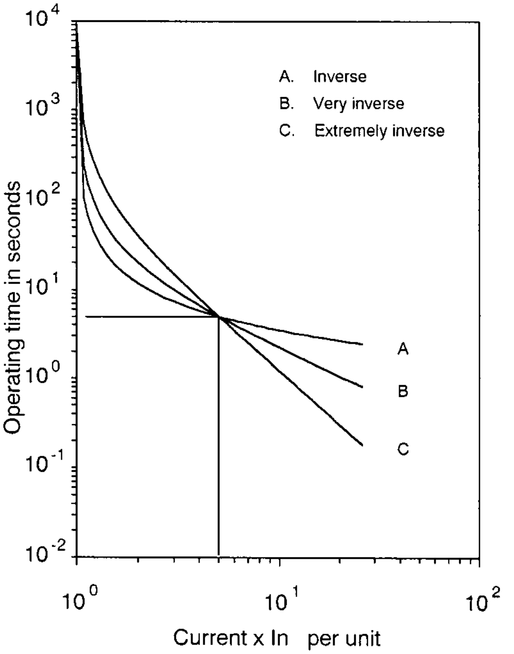

Figure 12.12 Various standard inverse time characteristics of a time-dependent overcurrent relay.

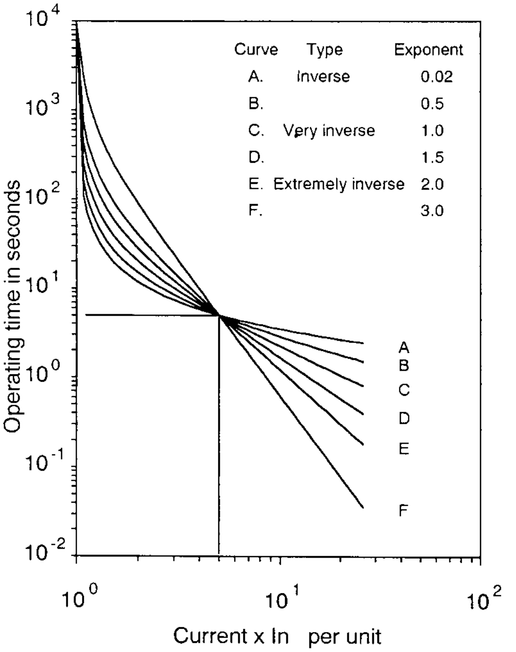

Figure 12.13 Various non-standard inverse time characteristics of a relay.

winding. Instantaneous protection is applied to respond to major three-phase faults at or near to the primary terminals e.g. in the main terminal box or chamber. It should not be used to detect major faults in the secondary winding or its downstream circuit. The settings for the primary instantaneous protection can therefore be chosen to be relatively high. However, the choice may be influenced by the upstream source of fault current e.g. the number of generators, another transformer, a utility connection, as explained in sub-section 12.5.2.2.

The situation for the secondary circuit is different. The purpose of instantaneous protection is to detect major faults at or near to the secondary terminals and at the downstream switchgear e.g. busbar fault. This protection must also be coordinated with the instantaneous protection settings of downstream circuits e.g. static loads, motors. The settings chosen are much less sensitive to the upstream source characteristics than those of the primary protection, because of the inclusion of the leakage impedance of the transformer in the faulted circuit.

12.4.3 Characteristics of the Upstream Source

Where the upstream source is another transformer, or a utility connection, the calculation of the three-phase fault current is straightforward and it will not usually vary significantly with the operating configuration of the upstream network.

If the upstream source is one or more generators then the situation is more complicated, especially for the transformer primary protection. When a major fault is applied near to generators they respond in a complicated manner due to the sub-transient and transient dynamics of their windings and to the dynamic response of their voltage regulators. The response from their windings is also modified by the impedance connected between the generator terminals and the point where the fault is applied. The sub-transient and transient direct-axis time constants, governing the decay of fault current, change with the amount of impedance added to the fault circuit. As this impedance increases from zero to a large value, the time constants change from their short-circuit values to their open-circuit values, see 7.2.11 and 20.3.2. The inclusion of the impedance reduces the fault current, which is more significant when only one generator is operating. The decrement of fault current can be plotted on the coordination graphs for the various operating situations. In the example of sub-section 11.9 and 12.1 there are four or more generators and therefore the two main situations to consider are four generators running and only one generator running.

12.5 FEEDER CABLE PROTECTION

The type of feeder cables described in this section are those between switchboards within an oil industry site, rather than those between a utility power plant and an oil industry site. These feeders may be described as primary feeders as opposed to secondary feeders downstream in the system. Feeders from a utility power plant or a transmission network have protective relaying systems that are more sophisticated than those described herein, e.g. multi-zone distance protection, admittance relays, carrier protection schemes.

Two basic requirements apply to feeder cables, firstly to protect the cable from overcurrents, which may be related to the connected load, and secondly to detect faults along the length of the cable.

12.5.1 Overcurrent Protection

Overcurrent protection is usually provided by a (51) relay, which has separate elements for each phase. The overcurrent curve should be chosen with a margin below the I^2t characteristic of the cable, and to coordinate with the protective devices downstream e.g. an exceptionally large consumer at the switchboard being fed by the cable. The type of curve may be inverse, very inverse or extremely inverse, depending upon the coordination required downstream and the margin between the current rating of the cable and its expected loading.

For cables having long route lengths the associated volt-drop may cause the margin in current capacity to be reasonably high, especially with low voltage feeders.

12.5.2 Short-Circuit Protection

Short circuits that do not involve earth, and which are within the length of the cable, can be detected by setting the instantaneous elements of the overcurrent relays to a value of current calculated at the receiving end of the cable that flows into a zero-impedance fault. Customarily this fault is a three-phase fault for which the calculations are straightforward. If the fault is beyond the cable for example in a consumer then the fault current will be less and should be cleared by the consumer protective device. The feeder cable relays will then act as a back up to the consumer relays.

If the feeder cable is protected by fuses then these should be chosen to rapidly clear an internal line-to-line or three-phase fault. They should be supplemented with a (51) relay to provide overcurrent protection.

High voltage cables that provide a critical service, that are to be operated in parallel or will have a long route length in an area of high risk of damage, should be protected by a high speed differential current scheme. The most commonly used is the Merz–Price scheme. Each sending end and receiving end line of each cable is equipped with a matched current transformer. At the sending end switchgear is placed the (87) relay to detect an out-of-balance current due to a fault within the cable. The operating time for this scheme is typically 5 or 6 cycles of fundamental frequency current.

An alternative and less expensive scheme uses a core-balance current transformer at the sending end of each cable. Such a scheme is shown in Figure 12.14.

12.5.3 Earth Fault Protection

When a cable is damaged accidentally from external means, such as digging in a trench, it will nearly always cause an earth fault. The earth fault current may flow in the surrounding earth or in the armouring metal; or a combination of both routes. The magnitude of the earth fault current will depend to a large extent on how the sending end star-point upstream of the cable is earthed. For most high voltage systems the star-point is earthed through an NER that limits the current to between 10 and 100 amps. Most low voltage systems are solidly earthed at the star-point of the supply. There are the occasional exceptions to these methods. The usual method of detecting an earth fault in a cable feeder is to use a core balance current transformer in conjunction with a sensitive 50 N relay.

A time delayed 51 N relay may be preferred so that some coordination and back up can be provided to downstream devices. The primary feeder should not trip in response to a fault in a consumer circuit. The consumer circuit should have its own fast-acting earth fault 50 N relay or element.

Often the earth fault 50 N or 51 N relay is an integral part of the overcurrent relay. These integral relays usually have various options which can be simply switched into the scheme as required.

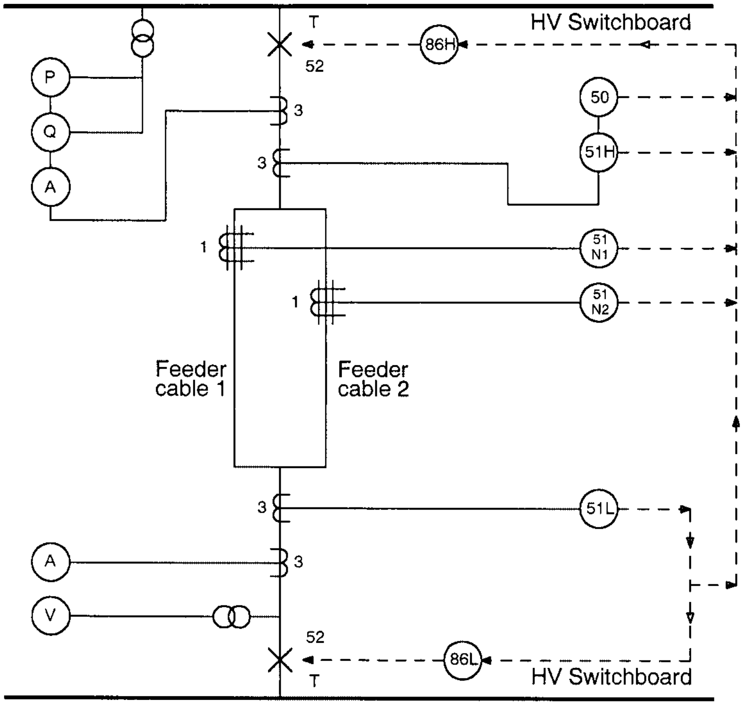

Figure 12.14 Protection devices for a high voltage feeder cables.

12.6 BUSBAR PROTECTION IN SWITCHBOARDS

Faults can occur within the busbar and riser compartments of switchboards. However, modern switchgear is very reliable and such faults are rare. Many purchasers of switchgear specify insulated and segregated busbars and risers, with all the connectors, clamps, nuts and bolts to be fully shrouded with flame retardant material, see sub-section 7.2.4.

12.6.1 Busbar Zone Protection

For switchboards to be operated at voltages up to approximately 15 kV it is common practice to avoid using differential busbar zone protection. If it is necessary to provide the maximum practical availability of supply then busbar zone protection should be considered.

If the fault level at the high voltage busbars is high and close to the rating of the switchgear then busbar zone protection should be given serious consideration. Busbar zone protection is usually based on the Merz–Price circulating current scheme, with high impedance (87) relays.

Where a bus-section circuit breaker is used to divide the busbars (during abnormal operating conditions) each set of busbars is protected as a separate zone. Each zone consists of the incomers, the outgoing circuits and the bus-section circuit breaker(s). An accurate current transformer is connected in each line of each circuit. All the current leaving the zone must be balanced by current from the incomer circuits. A fault in the zone will be detected by the (87) relay. Rapid operation is required to open the incomer and bus-section circuit breakers so that the fault does not develop and spread as a fire or blast along the busbars.

12.6.2 Overcurrent Protection

It is not normally necessary to provide overcurrent protection in the bus-section circuit because the presence of overcurrent, not caused by an in-zone fault, would be detected by an outgoing circuit relay. For the busbar to be overloaded the outgoing system must also be overloaded. Introducing an overcurrent relay in the bus-section circuit will add complication to the coordination of the incoming and outgoing relays, since a time margin is necessary between each relay. In systems where there are large induction motors the coordination can already be awkward to achieve.

12.6.3 Undervoltage Protection

If the busbars are being operated at an unusually low voltage then the consumers may attempt to consume their full power. If this happens they will take in more than their rated current, which is a potentially damaging condition. If the switchboard supplies one or more large induction motors then during their starting process they will draw a heavy current. Should the motor experience difficulty during starting then a prolonged period of high current will occur and this could cause a depression in the busbar voltage. Such a depression may adversely affect other consumers.

Undervoltage operation is undesirable and therefore a suitable relay (27) with a time delay is often used, especially in high voltage switchboards. A similar problem can arise with main generator switchboards. If a generator is suddenly tripped then the remaining generators must try and supply the load. Each of these generators will experience a sudden increase in current and a drop in terminal voltage. The load will react to the drop in voltage. The automatic voltage regulators will try and restore the voltage. If the load is predominately induction motors then they will all try and accelerate back to their normal speed. The acceleration will be accompanied by an increase in their reactive current which will aggravate the volt-drop and delay the voltage recovery. If the depression is more than at least 20% and lasts for more than 0.2 to 0.5 seconds then there is a risk that the system of induction motors will fail to recover, see also sub-section 7.6.1.

The (27) relays should have an adjustable voltage range to cover for the 80% voltage condition, typically 50% to 100%. The relay should have a time delay that is adjustable up to at least 0.5 second.

The relay may be set to trip all the outgoing circuits on its section of busbars. Alternatively a more selective method can be used in which the largest consumers are tripped initially. If the initial tripping fails to produce a good recovery then a second level of tripping may be used for the remaining consumers.

During the studies that are usually carried out for system stability, starting large motors, loosing a generator etc., a study of undervoltage (and overvoltage) should be included. Several scenarios should be considered so that a good compromise between voltage depression and its duration can be found for setting the (27) relays.

Undervoltage schemes are often included in the reacceleration control systems of individual motors or groups of motors. However, these are more appropriately considered in motor protection rather than busbar protection schemes.

12.7 HIGH VOLTAGE INDUCTION MOTOR PROTECTION

Most oil industry plants use high voltage induction motors to drive pumps and compressors. Unlike industries that take power from a utility the oil industry usually generates its own power. Most utility companies restrict the size of induction motors that are to be started direct-on-line. This restriction seldom applies in the oil industry. There are some applications where direct-on-line starting is avoided e.g. large compressors in LNG plants, but these may be regarded as special cases. The starting time for high voltage induction motors varies typically from one second to as long as 30 seconds. Pumps and low speed machines tend to have the shorter times. A high-speed compressor driven through a gearbox will usually have a long starting time.

High starting currents and long starting times can give rise to difficulties in choosing suitable protective relays for the motor. Not all motor relays have a wide enough range of settings to adequately protect the motor during the starting time.

High voltage induction motors are normally provided with the following protective devices, some or all of which may be incorporated in the one device (occasionally called a motor managing relay). Modern motor relays are based on microcomputer technology and these relays not only provide most of the protection functions but also provide a full range of measurements, indications and alarms. They also communicate by media such as fibre optics through networks to management and SCADA computers, see also sub-section 7.6.2.

a) Main functions:
   - Overloading or thermal image (49).
   - Instantaneous or high-set overcurrent (50).
   - Negative phase sequence (46).
   - Core balance earth fault (51N).
   - Differential stator current (87).

b) Additional functions:
   - Stalling current.
   - Limitation to the number of successive starts.
   - Undercurrent (37).
   - High winding temperature.
   - High bearing temperature.
   - Excessive vibration.

Figure 12.15 shows the application of the above functions to small and large high voltage motors.

Most modern electronic motor relays are designed to meet the requirements of IEC60255 Part 8. This standard defines the thermal image or overloading curves of the relay. Some modern motor relays are very sophisticated and their literature needs to be studied carefully in order to ensure that the relay chosen fully satisfies the characteristics of the motor. Not all manufacturers use the same terminology to describe the functions of their relays. This makes the process of comparing different makes and models of relays somewhat difficult.

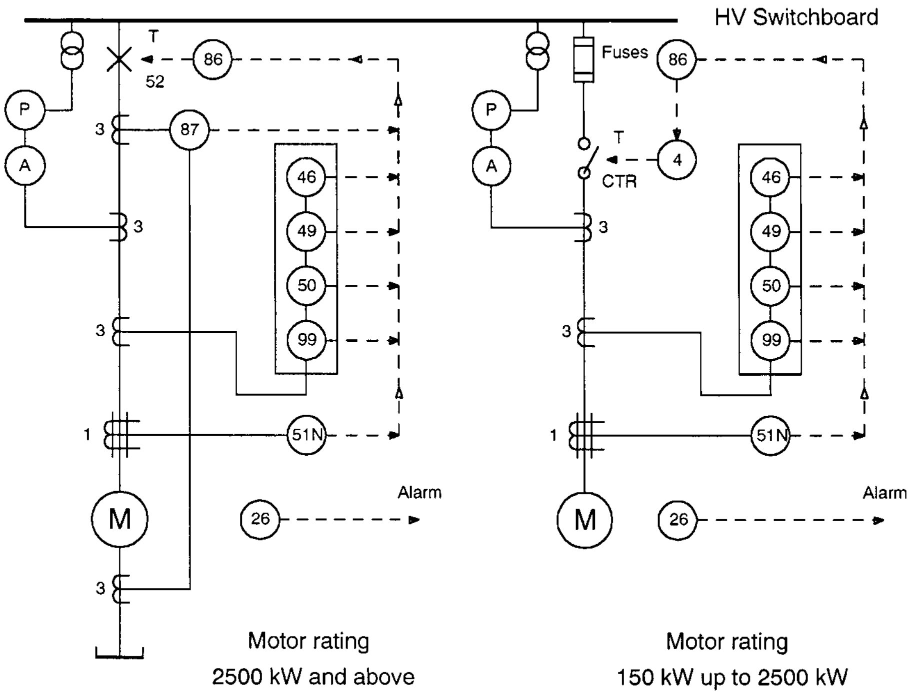

Figure 12.15 Protection devices for high voltage motors.

12.7.1 Overloading or Thermal Image

As with most electrical power equipment the thermal characteristic is based on an I^2t law. The equation for the thermal image as given by IEC60255 Part 8 when the motor is cold is,

$$t_c = T_{\text{th}} \log_e \left[\frac{I^2}{I^2 - I_o^2} \right] \text{ seconds}$$

Where I = Relay current as a multiple of the nominal current, pu.

I_o = Reference current in pu that determines the position of the asymptote, e.g.

at $t_c \rightarrow$ 10,000 seconds. I_o has a typical value between 1.015 and 1.065.

T_{th} = Thermal time constant in seconds, usually given in minutes for a particular motor.

Note: The equation is only valid for $I > I_o$.

A similar equation is used for the hot condition of the motor,

$$t_h = T_{\text{th}} \log_e \left[\frac{I^2 - I_p^2}{I^2 - I_o^2} \right] \text{ seconds}$$

Where I_p = motor load current before the overload, pu.

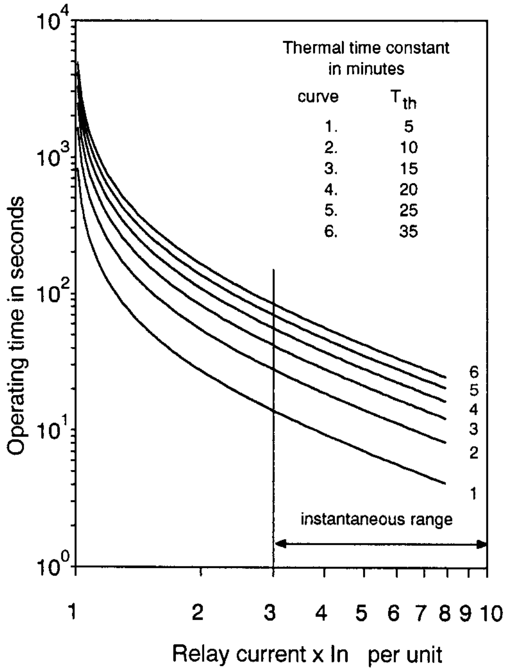

Figure 12.16 Operating time of a motor thermal image relay. The motor is assumed to be running fully loaded before the fault occurs.

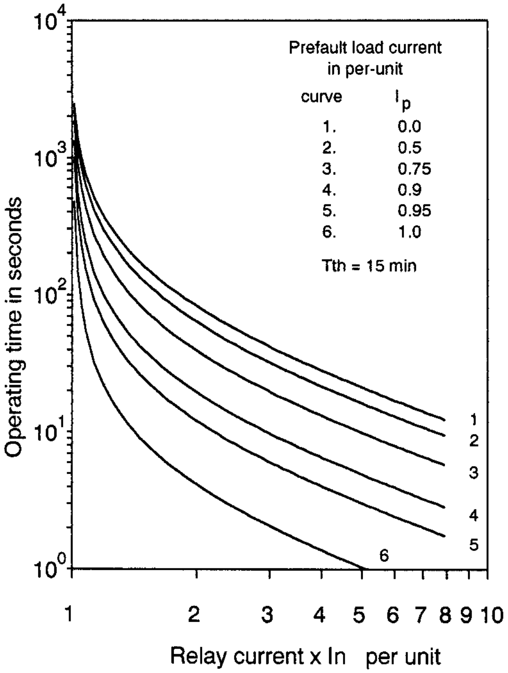

Figure 12.17 Operating time of a motor thermal image relay. The effect of the motor being partly loaded is shown.

When the t_c and the t_h functions are plotted with log-log scales they exhibit slight curvature at the higher multiples of nominal current. Figures 12.16 and 12.17 show the thermal image and the effect of pre-fault load current. Some manufacturers incorporate a feature where this curvature is removed at the high currents, and follows at the conventional I^2t straight line when plotted on log-log scales. For a given relay current the hot time t_h for a fully preloaded motor will be approximately one-sixth to one-tenth the value of t_c. Some relays allow this ratio to be preset over a wider range.

12.7.2 Instantaneous or High-Set Overcurrent

In order to protect against prolonged winding or terminal box faults it is the usual practice to include an instantaneous tripping function. The range of the setting is typically 3 to 10 times the relay nominal current.

High voltage motors are often controlled by a contactor (CTR in Figure 12.15) that has a high-speed fuse just upstream and mounted in the same compartment of the switchboard. The contactor must have sufficient I^2t capacity to handle the let-through fault current until the fuse completes its function. It is necessary under this situation to delay the opening of the contactor. Consequently the relay should either have an adjustable delay for contactor services, or it can send its tripping signal to a separate self-resetting timer (2). Upon timing out the timer trips the contactor (4). The minimum delay setting is typically 0.2 seconds. Advice should be taken from the switchgear manufacturer for the actual delay to use for a particular motor circuit. (Small kW rated low voltage motors are also controlled by contactors and the same precaution is necessary.) The contactor may be overstressed during the passage of fault current, and in order to minimise the stressing the requirements of IEC60632 Part1 Appendix B, Type C, should be adopted when specifying the switchgear, see sub-section 7.3.2.

12.7.3 Negative Phase Sequence

As with the rotors of generators the presence of negative phase sequence currents in the rotor of an induction motor causes detrimental heating. The cause of the negative phase sequence currents could be an internal or an external malfunction. An internal malfunction may be a minor or major phase-to-phase fault in the stator windings. An external malfunction could be a depression in one of the incoming phase-to-neutral or phase-to-phase voltages. The motor will then be fed from an unbalanced source of voltage, and will respond by creating unbalanced currents in its stator and rotor conductors.

Modern relays include a function for detecting the negative phase sequence currents, with settings typically in the range of 10% to 50% of the nominal relay positive sequence current. High power rating motors may need a lower limit than 10%.

Since rotor heating can be caused by excessive positive sequence current as well as the presence of negative sequence current it has become the practice in some relay designs to combine these heating causes.

The shape of the curve for negative phase sequence current operations varies with the manufacturer. Some prefer an $I_2{}^2t$ whilst others an inverse time characteristic. Time settings are typically in the range of 10 to 120 seconds.

12.7.4 Core Balance Earth Fault

Earth faults that occur within the stator windings will usually involve the iron laminations. Such faults can cause a considerable burning type of damage to the iron and windings if not either limited in magnitude by the supply NER or by tripping the motor rapidly. The discussion given in sub-section 12.2.3 for generators applies in the same manner for high voltage motors.

It is therefore necessary to provide a sensitive method for detecting earth fault currents. The most common method is to provide a core balance current transformer at the circuit breaker or contactor. This current transformer has a current or turns ratio, which is independent of the ratios used by the transformers connected in the three-phase conductors. This is because a particular level of current is to be detected rather than a fraction or multiple of the stator load current. The switchgear manufacturer will normally recommend the ratio of the core balance transformer and the matching relay. The relay will be either instantaneous 50 N or an inverse time 51 N type depending upon whether the motor is controlled by a circuit breaker or a contactor.

A core balance current transformer functions more reliably and is more sensitive than a set of three current transformers connected in parallel. A three-transformer system is prone to responding to the initial inrush current of the motor. To avoid this the current setting needs to be higher than would be preferred.

The setting ranges of the relay are often given as 10% to 40% of nominal relay current with up to 0.5 second delay. Some designs have wider ranges of current and time settings.

Long motor feeder cables have enough capacitance to require a significant charging current. During some earth fault conditions the charging current is seen by the relay and so the relay setting should be made higher than the charging current. A reasonable upper margin is between 1.5 and 2.0 times the charging current.

12.7.5 Differential Stator Current

High voltage motors rated above a range of approximately 2 to 4 MW are usually provided with a Merz–Price differential current protection scheme. The range of kW ratings covers the requirements of many companies in the oil industry. The protection scheme is essentially the same as that applied to generators and large transformers. The instantaneous setting of the three-element (87) relay is typically in the range 10% to 40% of the nominal relay current for 1 amp circuits, see also sub-section 12.2.3 for generator protection.

12.7.6 Stalling Current

If the motor fails to run up to full speed during the starting period or is suddenly forced to run at a low or zero speed then the stator current will be at or near its starting value. This will cause overheating of the stator and rotor conductors and the much reduced cooling airflow will aggravate the problem. Protection is required to discriminate between a normal starting period and a stalling condition. Stalling is determined by checking that the current is at or near its stalling value and the tripping time is between the cold and hot thermal times for this current. Therefore the thermal image is used for this purpose, see Figure 12.18.

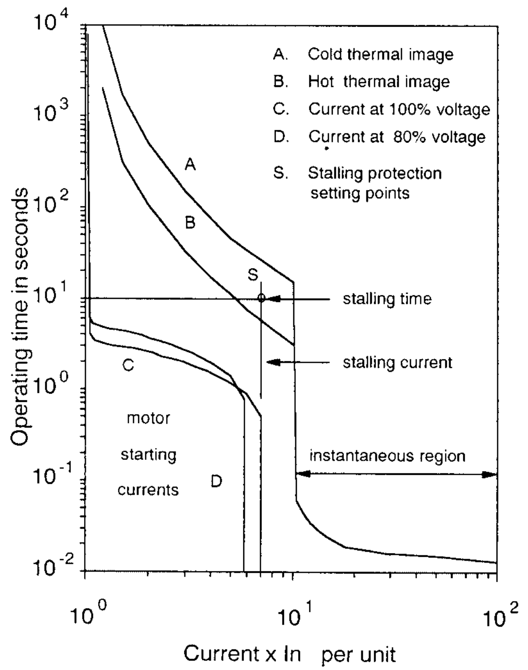

Figure 12.18 Motor run-up, thermal and instantaneous relay curves. The cold and hot thermal images of the relay are presented. The stalling conditions are indicated. The increase in the motor run-up time due to a reduction in terminal voltage is shown.

Should the stalling time be less than the corresponding cold thermal image time for the same stalling current then the relay will not detect the condition. Either the relay thermal settings will need to be reduced, if possible, or a separate special timing relay used instead.

12.7.7 Limitation to the Number of Successive Starts

Repeated starting of a motor in close succession will cause the accumulation of heat in the conductors and body of the motor. To safeguard against damage it is desirable to limit the number of starting attempts that are made in a predetermined time period. A well-specified motor will have a prescribed number of starting attempts, e.g. 2 to 5, and a rest period before the same attempts are repeated. The rest period is typically 0.5 to 1.0 hour. This should apply especially to motors that have long starting periods, such as motors that drive high-speed compressors.

Modern microcomputer based relays are easily able to provide this function.

12.7.8 Undercurrent

Most high voltage motors used in the oil industry operate at steady loads between 75% and 90% of their rated power capability. Should the motor suddenly find itself underloaded then it is possible that the driven machine has inadvertently lost its load, e.g. a pump loses liquid at its suction port. This may not present a problem to the motor but the driven machine could be damaged if it is allowed to operate continuously in this state.

Undercurrent protection is often specified as a back up to the process control systems. It has a typical setting range of 30% to 80% of the nominal relay current. A time delay is incorporated into the relay and its range is typically 2 to 120 seconds.

12.7.9 High Winding Temperature

Resistance temperature detectors e.g. 100 ohm platinum elements, or thermocouples are usually embedded in the three-stator phase windings to detect overheating in the vicinity of the conductors. A set of three is normally used, and a second set of three specified as spare detectors. The active elements are wired to a simple threshold relay that gives an alarm when the temperature is exceeded.

12.7.10 High Bearing Temperature

Similar detectors and relays as those in sub-section 12.7.9 are used to detect excessive temperature in the bearings of the motor. The relay gives an alarm when the temperature is exceeded.

12.7.11 Excessive Vibration

Excessive vibration in the shaft of a motor can be caused by several functions:

- Damaged rotor conductors.
- Damaged bearings, especially rolling element bearings.
- Low oil pressure in the bearings.
- Unbalance in the driven machine e.g. vane damage in a pump, blade damage in a compressor.
- Loose coupling or gearbox components.

The measurement of vibration should be made by a non-contacting transducer, i.e. it should not make direct contact with the rotating shaft.

12.8 LOW VOLTAGE INDUCTION MOTOR PROTECTION

In general a large amount of the theoretical aspects of the protection of high voltage motors applies to low voltage motors. However, some functions are not normally required, in particular, core balance earth faults (50 N and 51 N) see the note below:-

- Differential stator current (87).
- Undercurrent (37).
- High winding temperature.
- High bearing temperature.
- Excessive vibration.

Note: For small motors, e.g. 22 kW and below, the earth loop impedance including the feeder cable armouring may be too high. When this is the situation a risk of electric shock exists during a short circuit at or near to the motor. To reduce the exposure to the risk it is necessary to use a 51 N or a 50 N core balance current transformer and relay at the motor control centre. The choice of a 50 N is preferred subject to the contactor being properly coordinated with its upstream fuses.

Figure 12.19 shows the application of the above functions for a wide range of low voltage motor kW ratings.

Many modern installations favour the use of moulded case circuit breakers instead of fuses and separate relays. Moulded case circuit breakers are available with basic functions for small motors and more sophisticated functions for large motors.

12.8.1 Overloading or Thermal Image

It is common practice to use a bi-metal strip in each line of the protective device to create the thermal image of the low voltage motor. The protective device may be a moulded case circuit breaker or a time dependent relay. The thermal time constant of low voltage motors does not vary so widely as with high voltage motors. It is therefore reasonably easy to modify the shape of the thermal curves by changing the physical dimensions and properties of the bi-metal strip. The bi-metal strip is mechanically connected to the circuit breaker mechanism, or to an auxiliary switch in the case of a relay.

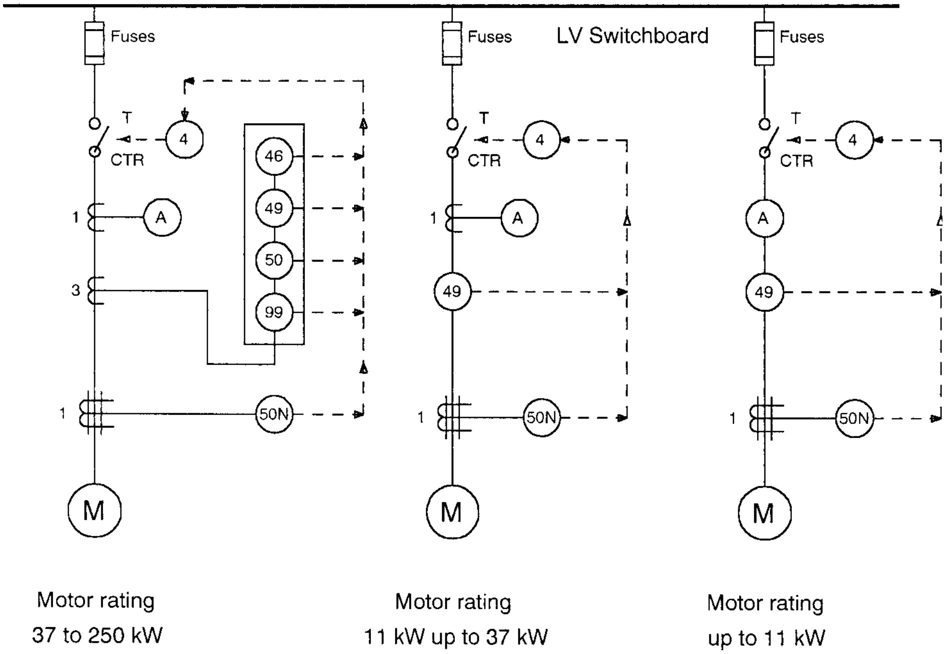

Figure 12.19 Protection devices for low voltage motors.

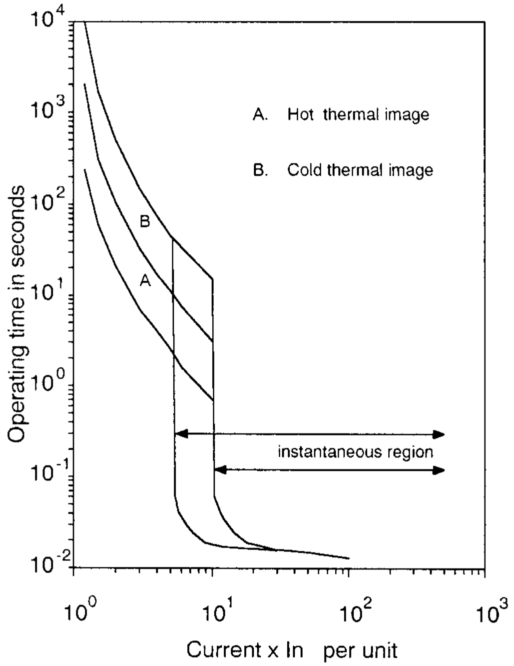

Figure 12.20 Thermal and instantaneous curves of a motor relay.

Hot and cold characteristics are usually available for circuit breakers having ratings from a few amps up to 500 amps. For a given frame size it is usually possible to fit different ratings of thermal elements. Each rating of a thermal element has a narrow or nominal current, see Figure 12.20.

12.8.2 Instantaneous or High-Set Overcurrent

The necessity for an instantaneous tripping function is the same as for a high voltage motor. This function can be provided by a magnetic repulsion device within the moulded case circuit breaker, by a (50) relay or by upstream fuses. If fuses are used then the contactor must be capable of carrying the I^2t duty until the fuse completes its function. To minimise the stressing of the contactor it should be coordinated with the fuses as recommended in IEC60947 Part 2, as a Type 2 requirement.

The range of settings for moulded case circuit breakers is typically between 5 and 30 times the nominal current. The lower values e.g. 5, 7.5 and 10 are often fixed for a particular circuit breaker, whilst the higher values are adjustable.

12.8.3 Negative Phase Sequence

The purpose of negative phase sequence protection is the same as for high voltage motors. It is not normally needed for motor ratings less than approximately 22 kW. In the simpler designs of moulded case circuit breakers and relays the negative phase sequence detection is more in the form of single-phase protection, wherein a phase is completely lost.

12.8.4 Core Balance Earth Fault

This function is occasionally required because the earth loop impedance is too high. Most of the impedance is in the armouring of the cable if the armouring is chosen to be braiding rather than wires. If the route length is short then the problem may not arise, but for good design practice it is not worth making exceptions for short routes. Core balance protection is normally required in these circumstances for motor ratings above approximately 18.5 kW. A core balance current transformer and a 50 N relay is used with a circuit breaker, or a 51 N relay with a contactor–fuse combination.

The sensitivity of the scheme should allow an earth fault current in the order of 30 mA to be detected and reliably tripped.

12.8.5 Stalling Current

Low voltage motors used in the oil industry usually have modest starting times, since the majority of their driven machines are pumps. Reciprocating compressors and ventilation fans can have reasonably long starting times. It is therefore not normally necessary to provide special relays to detect the stalling condition.

12.8.6 Limitation to the Number of Successive Starts

Low voltage motors are robust machines and can tolerate being restarted several times in succession. It is not normal practice to provide special facilities to limit the number of starts in a predetermined period of time. Modern motor control centres often have more sophisticated ‘motor management’ features than older equipment. It is reasonably easy to provide this requirement if the ‘motor management’ approach is adopted for the motor control centre.

12.9 LOW VOLTAGE STATIC LOAD PROTECTION

Static loads encompass heaters, battery chargers, uninterruptible power supplies, lighting distribution boards, socket outlets, cathodic protection, navigational aids, computers, public address, radio communication and the like. Excluded are loads that are not predominantly composed of motors. The load may have fractional kW motors for cooling fans.

They are essentially constant current loads that have a power factor near or equal to unity.

The protection required is usually kept as simple as possible, consisting of,

- Time-delayed overcurrent.
- Instantaneous or high-set overcurrent.
- Core balance earth fault.

The circuit may be controlled by a circuit breaker or a combination of a contactor and fuses. In some circuits that are controlled frequently as in the case of heaters controlled by thermostats or thermometers, the main protection may be incorporated into a circuit breaker whilst the control would be given by a contactor.

12.9.1 Time-delayed Overcurrent

A time-delayed overcurrent (51) relay would normally be used for a static load. The choice of the characteristic would depend to some extent on the nature of the load. A standard inverse characteristic would normally be adequate. Its pick-up current would be set at between 105% and 115% of the rated current of the load.

12.9.2 Instantaneous or High-Set Overcurrent

Instantaneous overcurrent protection would detect short circuits in the load and along its feeder cable. It would usually be practical to set the instantaneous elements of a moulded case circuit breaker to their lowest value e.g. five times the nominal current. If the protection is provided by a set of fuses then the fusing factor would be marginally above unity, the nearest fuse rating above the load current would be chosen. The protection must fully cover the I^2t capacity of the feeder cable.

12.9.3 Core Balance Earth Fault

The theoretical requirements for applying core balance earth fault protection are the same as those for low voltage motors. Some additional requirements often apply.

The requirement for a sensitivity of 30 mA should generally apply to final sub-circuits; see BS7671: 1992 Sections 412, 413 and 471 for further guidance.

In some situations the sensitivity may need to be reduced and a higher tripping current used e.g. 100 mA or 300 mA. Fluorescent lighting systems and welding socket feeders are subject to a poor quality of current waveform due to non-linear characteristics of their loads. The distortion superimposed on the fundamental current may be sufficient to cause spurious tripping of a fast-acting 30 mA relay.

12.10 MATHEMATICAL EQUATIONS FOR REPRESENTING STANDARD, VERY AND EXTREMELY INVERSE RELAYS

Since 1976 many relays have generally followed the recommendations of the IEC255-4, Clause 3.5.2, regarding the shape of their time–current curves. The general function recommended has the form:-

$$t = \frac{k}{\left(\dfrac{I^a}{I_n}\right) - u} \quad \text{seconds} \tag{12.1}$$

Where t = theoretical operating time, seconds.
I = relay current in pu or amps.
I_n = nominal current in pu or amps.
a = exponential constant.
k = constant for the particular relay.
u = constant for a particular relay determined from the time asymptote in the region of the rated current I_n. It usually has the value close to 1.0, in the range of 0.95 to 1.3. For

Table 12.1. The value of the exponent '*a*' for different relay curves

Type	Range of a	Preferred value of a
Standard	0 to 0.5	0.02
Very	0.5 to 1.5	1.0
Extremely	greater than 1.5	2.0

negative phase sequence relays u has a value equal to K_2^2 where K_2 has the value between 0.02 and 0.2.

The three basic types, standard, very and extremely inverse, are approximately represented by three ranges in which the exponential constant (a) should fall:-

If the values of 'k' and 'a' are not known then a suitable curve can be fitted to a set of values taken from the manufacturer's published curves. In some cases the standard and thermal curves may require a modified function in order to give a good fit over a wide range of I/I$_n$. A suitable function for such purposes is:-

$$t = \frac{k_m}{\left(\dfrac{I^a}{I_n}\right) - k_b\left(\dfrac{I^b}{I_n}\right) - u} \quad \text{seconds}$$

Where k_m = modified form of k.
k_b = small auxiliary constant for the particular relay.
u = constant for a particular relay determined from the time asymptote in the region of the rated current I_n it usually has the value close to 1.0, in the range of 0.95 to 1.3. For negative phase sequence relays u has a value equal to K_2^2 where K_2 has the value between 0.02 and 0.2.
b = an auxiliary exponent to be formed by trial and error.

Note: This function is only applicable to currents 'within' the range of data used to determine the curve, and so it is important to include a pair of points at the largest per unit-current in the range.

From about 1975 to 1995 the various types of inverse curves were generated within the relays by electronic 'function generators'. Function generators are analogue devices that rely on the non-linear voltage-current characteristics of devices such as diodes, zener diodes and transistors. These are used in conjunction with analogue amplifiers and integrators to derive the required relay curves. Since the introduction of digital microelectronics the use of analogue methods has been gradually superseded. The curves produced by digital devices are more accurate, stable and repeatable. Almost any practical curve can be easily programmed into the microcomputer 'chips'. Hence the constant 'a' in equation (12.1) can be programmed as integers, 1, 2, 3, 4 etc. or as fractional values in between the integers e.g. 0.5, 1.1, 1.5.

By virtue of modern electronic techniques, especially microcomputer chips, it is possible to provide additional characteristics to inverse relays in particular. At the high multiples of current one or more instantaneous limits can be provided. These can be adjusted by the user to create a type

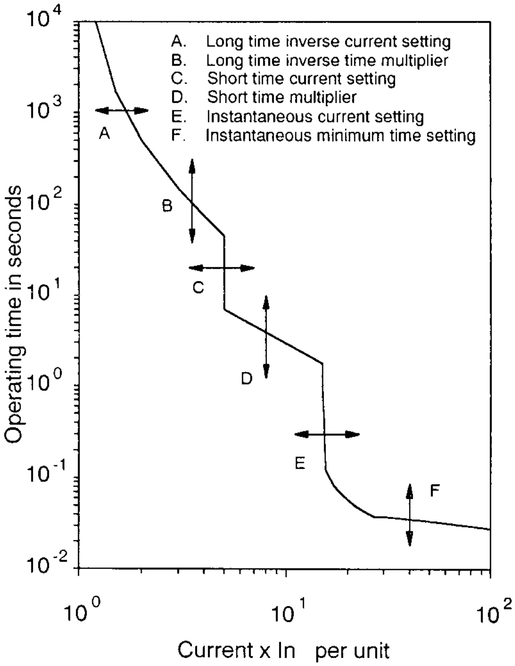

Figure 12.21 Operating time of a composite inverse time relay.

of staircase or stepped shape. Such additions are very useful in the coordination of incomer and interconnector relays at switchboards, with other devices downstream and upstream. The descriptions of these features occasionally vary between manufacturers, but generally they are called:

- Long delay setting, $\times I_n$
  or current plug setting
  symbol $I >$ (or I_1)
- Long delay time, seconds
  or time multiplier setting
  symbol $T(I >)$
- Short delay setting, $\times I_n$
  symbol $I \gg$ (or I_2)
- Short delay time, seconds
  symbol $T(I \gg)$
- Instantaneous or high-set setting, $\times I_n$
  symbol $I \gg$ or $I \ggg$ or (I_3)

Where I_n is the nominal current of the relay e.g. 1.0 per unit, 1 amp, 5 amps. Also the symbol I_o is used.

Note: The use of I_o, I_1 and I_2 should not be confused with their symmetrical component counterparts.

Some relays, for example as used with low voltage high current air circuit breakers and moulded case circuit breakers, have many adjustments to their parameters. Manufacturers often publish their curves showing the tolerances in the performance of their relays. These tolerances are shown as a band or range about a nominal curve. From a recent survey of relays and circuit breakers it was found that the tolerances and adjustments can be illustrated as shown in Figure 12.21.

Note: The characteristic between points A and B may be a horizontal line, a straight sloping line or an inverse curve.

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13

Earthing and Screening

13.1 PURPOSE OF EARTHING

There are three main reasons why it is necessary to earth, or to ground, electrical equipment:-

- To prevent electric shock to human operators, maintenance personnel and persons in the vicinity of electrical equipment.
- To minimise damage to equipment when excessive current passes between the conductors and the casing or frame during an internal fault condition.
- To provide a point of zero reference potential in the power system for the conductors.

13.1.1 Electric Shock

Electric shock occurs when two factors exist:-

- Two points in an electrical circuit that have unequal potentials are in contact with the human body.
- The difference in these two potentials exceeds a lower threshold value.

At the threshold limit slight perception of pain or 'tingling' near to the points of contact will occur. A continuous alternating current at a power system frequency, e.g. 50 or 60 Hz, of approximately 1 mA will cause this slight reaction. Increasing the current causes a greater intensity of reaction. At approximately 12 mA the muscles become very difficult to control, i.e. almost unable to 'let go' of the contact. Between approximately 20 mA and 50 mA the current tends to cause difficulty in breathing, but not to an irreversible extent. A continuous current above 50 mA and up to 100 mA will tend to cause ventricular fibrillation and may lead to heart failure and death.

Some of the early detailed work on this subject was published in 1936 by Ferris, King, Spence and Williams. Much work has been published by Dalziel and his co-authors from about 1941 and 1972, see Reference 1, Chapter 20 'Bibliography' for details. In this reference [B26] and [B29] showed that the current threshold withstand versus time duration characteristic has an 'I-squared-t' form, as follows:-

$$\surd t_n = \frac{K_h}{I_h} \tag{13.1}$$

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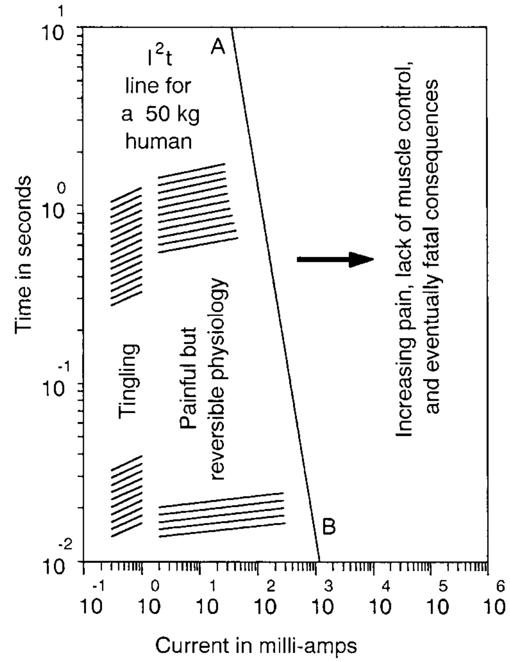

Figure 13.1 Intensity of electric shock for human beings.

Where $K_h = 0.116$ for a human body weighing 50 kg.
$I_h =$ non-fibrillating current tolerable by a human body, in amperes.
$t_n =$ non-fibrillating time duration of tolerance, in seconds.

Figure 13.1 shows the form of the characteristic as the line A-B, and the approximate regions of increasing danger. IEC60479 part 1 shows a similar figure with its Figure 14 providing numerical data.

In a practical situation the value of t_n will be equal to the fault current clearance time of the device protecting the circuit. The current I_h may be assumed to be limited by the resistance of the human body as it makes contact with two different potentials. In Reference 2 Ryder recommended in 1949 that a resistance of 500 ohms could be used to represent the resistance between both hands. In more recent times the IEEE80, in its Chapter 5 uses 1000 ohms generally in relation to the design of substation grounding grid and rod systems. The assumption used by Ryder was that the hands were thoroughly wet, which is still a reasonable assumption. The IEC60479 (1994 edition), part 1, clause 2.6 also uses 500 ohms as the appropriate value for hand-to-hand and hand-to-foot when the contact area is large, and notes that it does not vary significantly with the contact area unless it is very small, i.e. a few square millimetres. Ryder also recommends a limiting current that a human should be subjected to without fatal consequences as 100 mA, at a power frequency of 50 to 60 Hz. IEC60479, part 1, and Reference 3 describe the impedances of different parts of the human body and how they form a complete electrical circuit.

It is on the basis of a body resistance of 500 ohms and a current of 100 mA that the hand-to-hand maximum voltage limit of 50 volts (root-mean-square alternating voltage) has been established and used in the international literature, e.g. IEC60364. The corresponding hand-to-hand direct voltage is usually taken as 110 volts. If a resistance of 1000 ohms is used as a standard value then from equation (13.1) the threshold voltage E_{shock} will be:-

$$E_{\text{shock}} = 1000 \times \frac{0.116}{\sqrt{t_s}} \quad \text{volts} \tag{13.2}$$

Where t_s is the time duration of the shock in seconds. This voltage can be withstood by 99.5% of human bodies weighing 50 kg.

13.1.2 Damage to Equipment

Occasionally an electrical fault will occur inside a piece of equipment such as a switchboard or motor that causes a conductor to touch the casing or frame. In most power systems this type of fault would cause a much larger than normal current to flow in the conductors. This current would flow through the casing or frame and in so doing would usually cause serious damage to the conductors, their insulation and casing metalwork due to sparking or arcing. The damage will usually increase with time and can only be minimised by a careful design of the electrical protective relaying schemes that detect the fault current, see Chapters 11 and 12.

13.1.3 Zero Reference Potential

Most power systems comprise several different three-phase voltage levels, e.g. 11,000 V, 6600 V and 440 V. They are isolated from one another by the use of transformers. Each isolated sub-section is invariably ‘earthed’ or ‘grounded’ at one or more points. (The term ‘earthed’ will be used hereinafter.) The purpose of this is to ensure that the voltage difference between any conductor and its casing cannot rise above a predetermined amount. The voltage difference can increase due to several causes.

Static charge builds up across the insulation and causes the conductor potential to rise. This is more of a problem with high voltage equipment because the dielectric properties of the insulation are more pure. The insulation resistance is extremely high and does not discharge the accumulated charge.

If a fault occurs between the primary and the secondary windings of a transformer, the lower voltage winding may experience a high voltage being impressed upon it.

If a three-phase sub-system is unearthed and a line-to-casing fault occurs, then the two ‘healthy’ lines will have their voltage-to-casing raised by a factor of $\sqrt{3}$. Normally the insulation of machines and cables can withstand this increase for a long period of time without harm. It is good practice to specify that the insulation systems of transformers, motors, generators and cables should be able to withstand an overvoltage of this type continuously.

13.2 SITE LOCATIONS

The environment in which the power system is located will have an impact on how the methods of earthing equipment are applied. The environments can be broadly grouped as:-

- Steel structures.
- Land-based plants.
- Concrete and brick-built structures.

13.2.1 Steel Structures

Some processing plants are constructed predominantly from steel, e.g. ships, offshore platforms, drilling vessels, compact refineries and chemical plants. In these plants the superstructures and processing equipment are generally made of steel beams, steel plating, steel flooring, steel vessels and pipe-work. These items are either welded or bolted together, and by so doing they tend to form a continuous electrical circuit as far as the passage of 'earth' currents are concerned. In some situations where bolting is used it is necessary to provide additional copper bonding conductors across the bolted surfaces, e.g. piping flanges, cable racking, machinery footings. It is essential to maintain a low impedance continuous circuit, in order to minimise the risk of electric shock when fault currents pass in the steelwork.

In certain parts of a power system it can be seen that very large earth currents can flow in adjacent steel-work, e.g. generator frames, high power switchboards. These locations are often provided with a specially designed sub-system of interconnected copper busbars and common reference earth points. The principle behind this sub-system is to provide what is in effect a set of very low impedance conductors in parallel with the steelwork. The sub-system has the effect of forcing the earth currents to pass in well-defined routes, in which the interconnecting conductors are situated. This occurs because the impedance of each 'copper route' is designed to be much lower than the 'steel route'. In general it is extremely difficult to calculate the impedance between any two points in a typical steelwork electric circuit because of its three-dimensional nature. Even calculating the low frequency impedance of a simple steel plate or 'H' section beam to the passage of alternating current is difficult due to the creation of eddy currents, skin effect and local magnetic saturation of the steel. The impedance would be a complicated function of the current magnitude. Consequently the calculation of the sizes of earthing busbars and their interconnectors is based on assuming that all the current flows in the copper and none in the parallel steel. This leads to a conservative and safe result.

The method of calculating the cross-sectional area of busbars, interconnectors and bonding conductors is given in 9.4.3.5.

13.2.2 Land-Based Plants

Processing plants located on land frequently have the benefit of space, wherein the plant is subdivided into discrete units. Each unit occupies a separate plot of land. Hence the plant is horizontally distributed as opposed to an offshore platform in which the plant is both vertically and horizontally distributed.

Each discrete unit is usually supplied with power from one or two main circuits, called feeders, from a central high voltage source, e.g. local captive generators, supply authority overhead line intake. The high voltage supply is used in two forms. Firstly to supply a few large consumers such as large gas compressors, oil transporting pumps or large cooling water pumps. Secondly it is transformed down to a lower voltage for all the small process motors, heaters, utilities, lighting and small power.

This two-fold situation requires the earthing to be dealt with in two distinct ways, one for the high voltage feeders and one for the low voltage distributors. With a land-based plant the high voltage feeders may be routed over reasonably long distances, i.e. 0.5 km to 2.0 km, at voltages between 3000 V and 13,800 V (longer distances may require voltages up to 66,000 V).

13.2.2.1 High voltage feeders

Long distances make it impractical to route earthing interconnectors to carry the full earth current for the high voltage feeders. In such situations advantage is taken of the conductivity of the surrounding soil, sand, clay or rocks (the material hereinafter called the ‘ground’). The notation adopted is that a power system is ‘earthed’ in some manner to the ‘ground’. Nearly all ‘grounds’ have some moisture content at some depth, even rocky ground, and thereby provides a satisfactory low impedance circuit over a long distance. It can be shown mathematically that if for example two separate earthing rods are driven into the ground and that they are separated by a distance much greater than their depth, then by assuming that the physical structure of the ground is uniform it is found that the potential difference over most of the horizontal distance is negligible. Most of the potential difference caused by the fault current occurs close to the vertical rods, as shown in Reference 2, Chapter XI. It declines approximately as an inverse function of the distance from the rod. In such circumstances the potential gradient across most of the surface of the ground between the rods is very small and is not sufficient to cause an electric shock to a person standing anywhere along a direct route between the rods. Some precautions need to be taken near to the rods for high voltage and high power situations, e.g. erection of a fence at a suitable radius from each rod.

It is common practice to earth a high voltage system through a high impedance, usually a resistance bank, so that the maximum earth current is limited to between 20 A and 200 A. If the line voltage of the star winding exceeds approximately 15 kV then an earthing transformer may be used, in which the earthing impedance is connected to the lower voltage secondary winding. This enables the design of the earthing impedance to be more robust, with thicker conductors. When this is done the risk of electric shock is negligible, even close to the rods. The deliberate limitation of the prospective earth current is also implemented in order to minimise the physical damage that could occur in the source equipment, e.g. supply transformer windings, generator windings, or even in the consumer equipment such as motor windings and switchboards. The reduction of current magnitude will reduce the mechanical forces in windings by a quadratic factor, and will also greatly reduce burning or arcing damage in the laminations of iron cores of machines. For further discussion on the choice of the current magnitude that should be used, see References 4 to 8.

13.2.2.2 Low voltage local consumers

The local power system at a processing unit usually derives its source of voltage from one or two local power transformers, e.g. 11,000 V/440 V step-down ratio. Each of these transformers usually has a star-connected low voltage winding to provide a four-wire supply. The star point is usually connected directly to a ground rod or grid, and a neutral connection is brought to the switchgear. An earthing impedance is not generally used. However, there are some exceptions that will be described later. Such a connection is described as a ‘solidly earthed system’. This type is preferred because in systems where the neutral is used for single-phase loads it is necessary to have the neutral potential maintained as close to the ‘zero’ earth potential as possible. This minimises the risk of electric shock, and ensures that the upstream earth fault protection devices clear the fault current very quickly. In most plants where both high and low voltages are present, it is generally the case that the operating personnel have more direct physical contact with low voltage equipment than with high voltage equipment. Extra measures are taken with low voltage systems to further reduce the risk of electric shock. Often the high voltage equipment such as switchboards and neutral earthing resistors (NERs) are located in rooms that are only accessible by specially qualified operating staff, who are trained in high voltage switching practices and procedures. For safety reasons high voltage switchgear is often operated nowadays by remote control, i.e. from a central control room.

The local processing equipment will be similar to that described in sub-section 13.2.1, and therefore the earthing practices will be similar, for example the use of copper interconnected busbars and bonding conductors. However, if the plant is mounted on concrete foundations then extra earthing rods will usually be needed at each foundation site. All reinforcing steelwork in concrete should be earthed to busbars or through their own rods.

13.2.3 Concrete and Brick-Built Structures

Concrete buildings such as offices and storehouses contain reinforcing steel rods and bars inside the concrete columns, walls, floors and ceilings. Steel beams are used to carry the structural loads of the building, and these beams are either encased in concrete or exposed. Brick-built structures also use steel beams in a similar manner. In all cases the unseen steel should be bonded to the earthing system. This is carried out at the footings and foundations, either by using local earth rods or an interconnecting cable to a nearby point in the earth system.

All electrical equipment and appliances inside the building must be earthed, including metal luminairs, socket outlets, MCB and MCCB panels, cooking appliances and the like. Earthing is achieved by routing separate earthing conductors to each appliance, from a central earth point that is usually at the main power intake at the building. References 9 and 10 give full details of earthing practices for buildings.

It has become standard practice in recent years to use sensitive earth leakage current detectors in circuit breakers to further protect against electric shock. The current sensitivity can be chosen from a range of standard current values, e.g. 30, 100, 500 and 1000 mA. The 30 mA sensitivity is used at individual consumer sub-circuits, e.g. feeders to domestic and small power socket outlets, feeders to luminairs. The higher sensitivities are used in the upstream circuit breakers so that protection discrimination is achieved.

13.3 DESIGN OF EARTHING SYSTEMS

This section covers the design of high voltage and low voltage earthing systems and highlights some difficulties that can be experienced in practical installations. The concepts and practical requirements of References 9 and 10 will be discussed.

13.3.1 High Voltage Systems

A plant requiring more than about 1000 kW of power will normally receive a supply at a high voltage, drilling rigs are often an exception because they tend to use captive diesel engine driven generators. The primary source of high voltage power will be generators or supply authority transformers. The supply authority voltage could range from typically 3000 V to 132,000 V depending upon the total and future power demands of the plant, and to some extent the distance from the ‘point of connection’ to the central grid or power station. The supply of power would be transmitted through overhead lines or cables. The authority would take care of the earthing requirements for the supply, in a manner similar to that described later.

High voltage supplies within a plant are invariably arranged as three-phase star-connected systems. The star point of the transformer secondary winding or the generator stator winding is

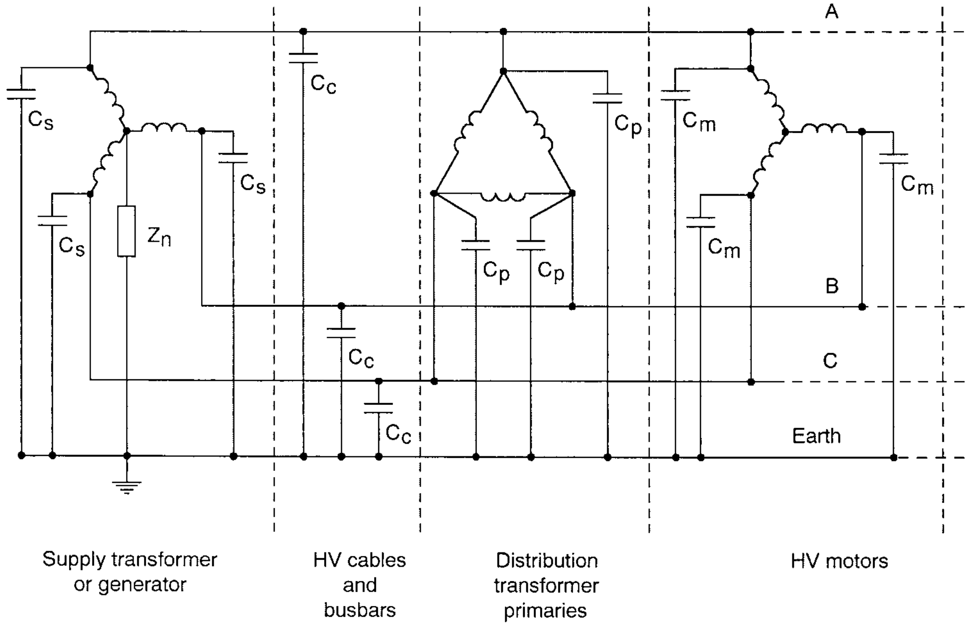

Figure 13.2 Earthing circuit of leakage capacitance in a high voltage system.

earthed locally through an impedance. This impedance is large enough to reduce the prospective earth current to a much lower level than would be the case if solid earthing were to be used. It has become the practice over the last 20 years or so to restrict the current to between 20 A and 200 A, as explained in 13.2.2. The lowest current is recommended but there is a restriction on the minimum value that can be reliably used. This restriction is due to the total capacitive charging, or shunt, current caused by all the insulation systems in the high voltage network. All the components in the network will have an amount of capacitive charging current, e.g. cables, motors, transformers, generators, switchboard busbars. Cables are the main source of charging current. Each component can be represented by a single capacitor connected between each phase and the earthed neutral reference or the ground plane, see Figure 13.2.

All the capacitors in each phase can be considered as being connected in parallel, and so the total charging current can be reasonably easy to calculate. An industrial standard practice is to choose the impedance Z_n to be less than one-third of the reactance of the total parallel capacitance in one phase of the system to earth. The impedance Z_n is usually chosen to be a resistance R_n for oil industry networks, see Reference 6. Reference 11, Chapters 14 and 19, and Reference 12 gives discussions on the various types of neutral earthing methods where the capacitive reactance between the lines and ground are involved. The possibility of overvoltages occurring when a fault is cleared, and the power dissipation from NERs are discussed. Reference 9 recommends References 13 and 14 for further reading on this subject.

13.3.2 Low Voltage Three-Phase Systems

A low voltage in this context is the lowest three-phase voltage that is commonly used for plant motors, heaters and general utilities, e.g. 380 V, 400 V, 415 V, 440 V and for drilling systems

600 V. In general there are two approaches used for earthing low voltage three-phase networks in the oil industry:-

- Solidly earthed star points.
- High impedance earth points.

Most power systems use the solidly earthed star points. High impedance earthing may be preferred for ships, occasionally for offshore platforms, and frequently for emergency and uninterruptible supplies in all locations.

a) Solidly earthed star points.

A low voltage secondary winding of a transformer, or a generator winding, has a star point solidly earthed, i.e. no intermediate impedance. Most solidly earthed systems are designed for four-wire operation and so the neutral conductor of the associated switchgear is also connected to the star point. There are several alternative methods used to make the earth connection to the ground for transformers and generators, and the choice depends upon various factors:-

- The distance between the windings and the switchgear.
- Whether the transformer or generator is located outdoors or indoors.
- The type of connection between the windings and the switchgear, e.g. cables, bus-ducting.
- The ground material, e.g. soil, steel decking.
- Whether a circuit breaker is used at the incoming side of the switchgear.
- Whether there are one, two or more feeders to the switchgear.
- The design of the earth fault relay protection scheme for the winding.
- Whether earthing connections and neutral busbars need to be isolated during maintenance, e.g. as may be required when two transformers feed a common switchboard.
- Whether three-pole or four-pole circuit breakers are used in the switchgear.
- Whether the system supplies consumers in a hazardous area.

See also sub-section 13.3.3 for a description of the IEC standardised earthing circuits for low and high voltage systems.

b) High impedance earthed star points.

It is possible to design three-wire and four-wire systems that do not need to be solidly earthed. Instead a high impedance is inserted between the star point connection and earth, as shown in Figure 13.3. Alternatively an artificial star point is created and again a high resistance is connected to earth as shown in Figure 13.4.

The high impedance is usually a resistance chosen to limit the earth current to about 20 mA. A current detector is used in conjunction with the resistance to raise an alarm if a line-to-earth fault occurs. A zig-zag transformer, or reactor, is sometimes used with three-wire supplies such as used in drilling rigs and emergency systems. It is specially designed and internally connected to create a very low zero sequence impedance to earth currents. Therefore, the current is limited only by the resistance of the neutral earthing resistor. Some special purpose earth current alarm systems are available that inject a small DC current into the three-phase system, which is used to identify the actual location of the fault.

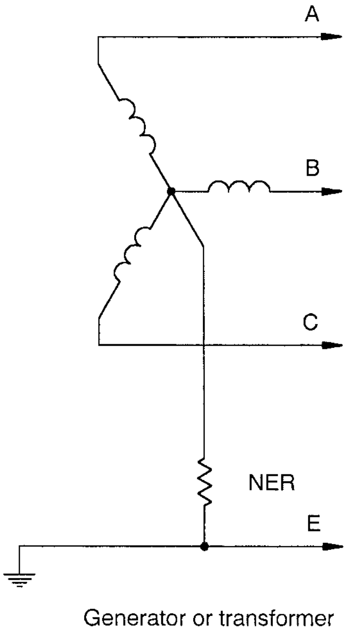

Figure 13.3 Earthing a high voltage system by using a neutral earthing resistor.

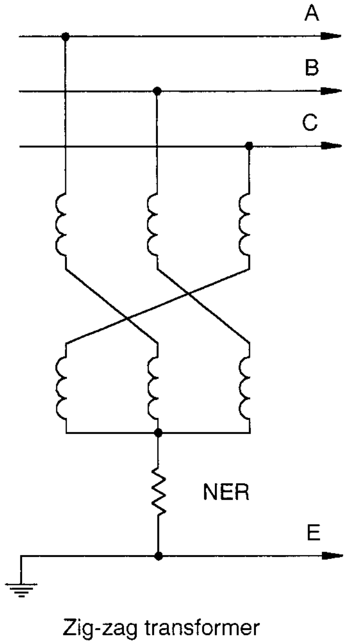

Figure 13.4 Earthing a high voltage system by using a zig-zag transformer and a neutral earthing resistor.

The main advantage of using a high impedance is that the system will function satisfactorily if only one line is faulted to earth. This is highly beneficial for emergency and essential services such as process shut-down supplies, computer supplies, fire protection systems, telecommunications and public address systems. These consumers must be maintained whenever possible. The earth fault would be detected and the operating staff alerted. The staff would then be in a position to decide whether or not to defer the shutting down of the supply to a later more convenient time. The single fault cannot develop into an explosive or damaging state because the current is far too small. A solidly earthed system does not have this benefit.

Reference 9 recommends Reference 15 for further reading on this subject.

13.3.3 IEC Types of Earthing Systems

The international standards IEC60364, part 4, and Reference 10 use a set of diagrams to clarify five basic methods of earthing and providing the neutral where it is required. Three of these methods are most commonly applied to oil industry installations. The five methods are abbreviated TNC, TNS, TNCS, TT and IT, and are shown in Figures 13.5 to 13.9. The three common ones are TN, TT and IT. The first letter is T or I. The second letter is N or T.

- The first letter denotes the source of power from a star-connected winding. T denotes that the star point of the source is solidly connected to earth, which is usually at a location very near to the winding. I denotes that the star point and the winding are isolated from earth by their design and

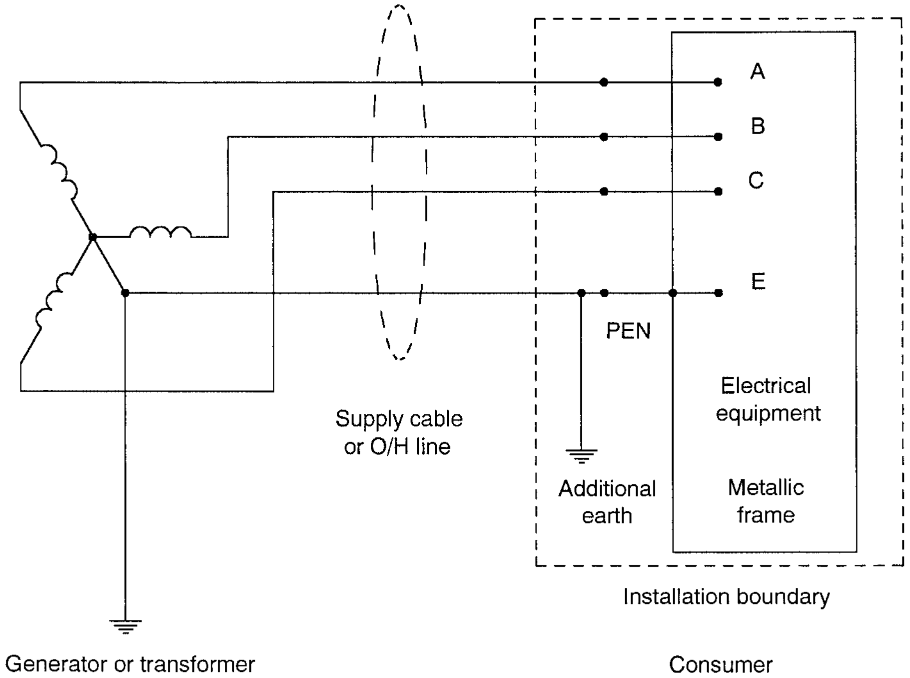

Figure 13.5 IEC earthing system type TNC.

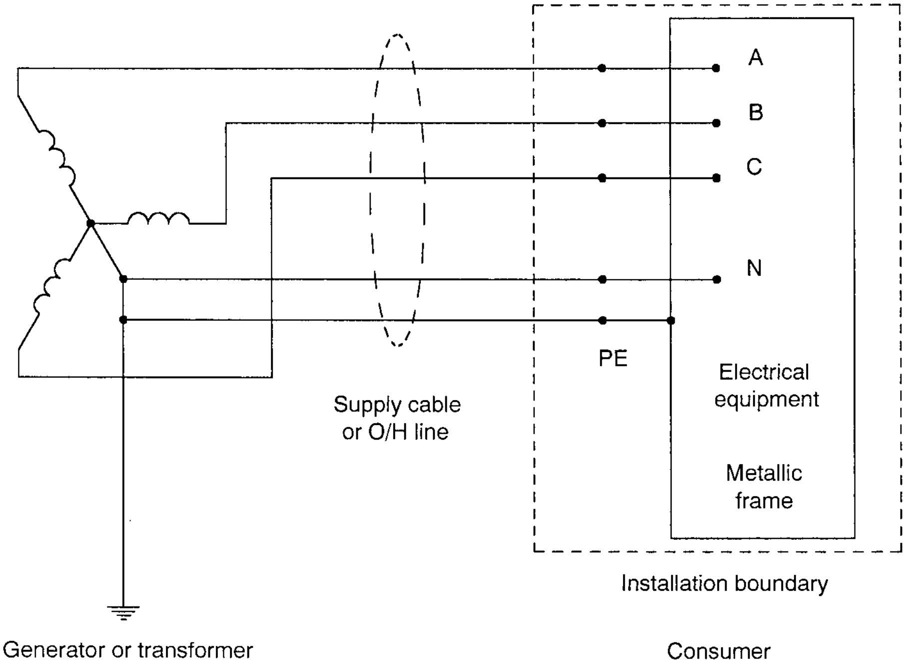

Figure 13.6 IEC earthing system type TNS.

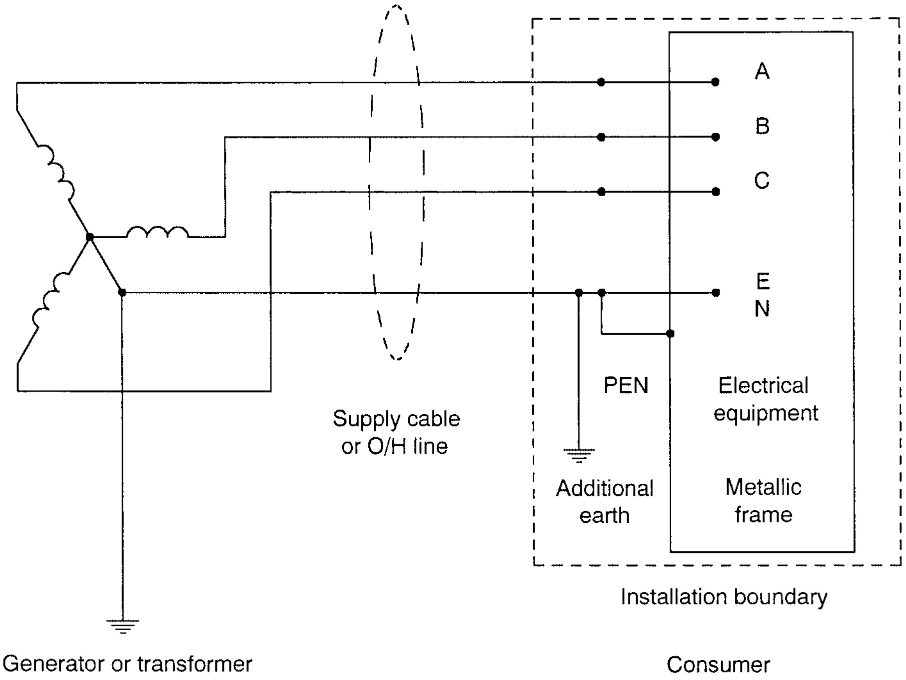

Figure 13.7 IEC earthing system type TNCS.

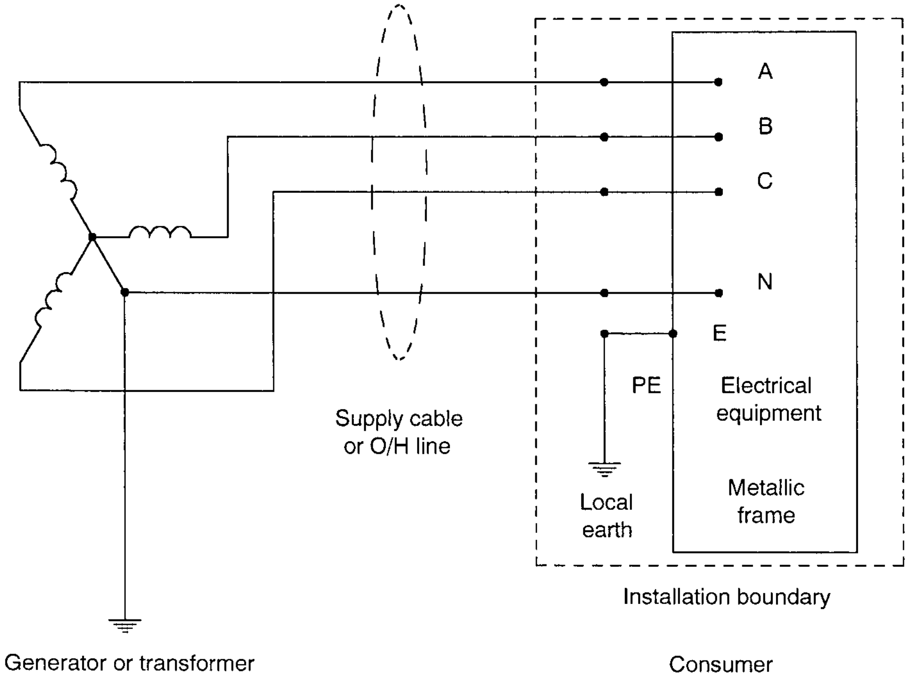

Figure 13.8 IEC earthing system type TT.

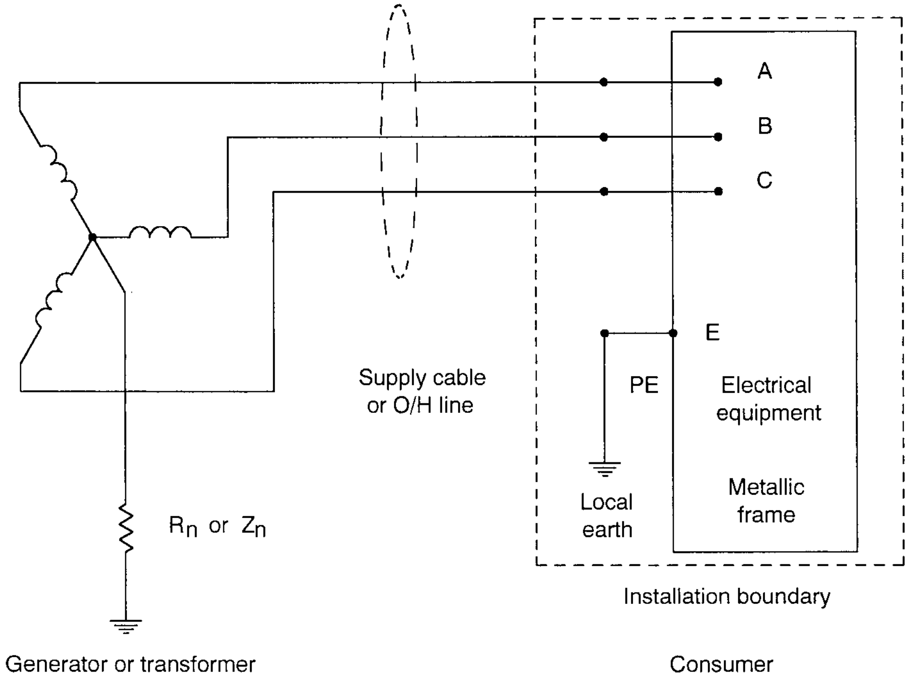

Figure 13.9 IEC earthing system type IT.

construction, but it is accessible by a proper terminal. The star point is usually connected to an inductive impedance or resistance. Capacitive impedance is not used.

- The second letter denotes the consumer. The consuming equipment needs to be earthed. There are two basic methods that can be used to earth frames, cubicles, panels and the like. The letters are T and N. The letter N is sub-divided into other letters, S and C, thus giving NS and NC and the composite NCS. T denotes that the consumer is solidly earthed independently of the source earthing method. N denotes that a low impedance conductor is taken from the earth connection at the source and routed directly to the consumer for the specific purpose of earthing the consuming equipment. S denotes that the neutral conductor routed from the source is separate from the protective earthing conductor, which is also routed from the source. This means that five conductors need to be routed for a three-phase consumer. C denotes that the neutral conductor and the protective earthing conductor are one and the same conductor. This means that four conductors need to be routed for a three-phase consumer.

Oil industry installations can generally be described in terms of the two-letter code as follows:-

- Land-based installations.
  The high voltage network is IT.
  The low voltage network is TT (or TNC or TNS) for four-wire systems.
  (A motor feeder could be regarded as a TT system with neutral not present.)
- Offshore and marine installations.
  The high voltage network is IT.
  The low voltage network is TT due to the abundance of interconnected steelwork.
  (A motor feeder could be regarded as a TT system with neutral not present.)

13.3.3.1 Influence of hazardous area classification

Where a site is classified as being Zone 1 or Zone 2, with regard to explosion ignition of flammable gases and vapours, it is necessary to take special precautions when installing live conductors. In some situations these conductors may be bare having no sheathing or insulation provided. It should not be possible to make intentional or accidental contact with bare live conductors, because a spark may occur. The energy of a spark that is needed to ignite an explosive mixture of air and gas is surprisingly small, see IEC60079 parts 11 and 15.

The term ‘live conductors’ in this context means any conductor that can carry current in the steady state, or in the transient state such as when a line-to-ground fault occurs. Therefore all forms of earthing conductors can be included. An important aspect in the design of earthing systems for hazardous areas is to maintain an ‘equi-potential’ conducting system within the area. In this sense ‘equi-potential’ means as far as is practically and economically possible. Only a few millivolts of difference should occur in the event of fault currents flowing in the conductor system. This is usually achieved by adequately sizing and positioning the earthing busbars, bonding cables, terminal systems and connections for a prospectively high I-squared-t duty, see Chapter 9. This aspect came to the attention of engineers in 1989 when several serious accidents that occurred offshore were reported, which resulted in Safety Notices being issued by the Department of Energy in the UK, see for example References 16 and 17 in particular, and Reference 18 as further reading of an allied subject. Investigations were carried out in the UK by the leading manufacturers of large motors, and recommendations were subsequently made.

IEC60079, part 14, clause 6.2 draws attention to the methods of earthing the neutrals, and to the use of neutral conductors and protective earthing conductors. The three methods, TN, TT and IT, discussed above and the use of 'Safety Extra Low Voltage' (SELV) and 'Protective Extra Low Voltage' (PELV) systems and equipment as defined in IEC60364 (or identically in Reference 10), part 4, chapter 41, require the following features when hazardous areas are being considered.

- Type TN earthing.

  The type TNS method should be used, TNC and TNCS are not recommended. The neutral conductor and the protective earth conductor shall only be connected together at the star point of the source. A transition from TNS to TNC or from TNC to TNS should be avoided otherwise the design may become too complicated.

- Type TT earthing.

  This method is commonly used in the oil industry because of the predominance of steelwork in a typical installation. In this method the power system is earthed separately from the equipment frames and cubicles. The star point at the source is the only common earthing point. The IEC standard requires the circuit to be protected by a residual earth fault current device at the switchboard or motor control centre, where the consumer is located in a Zone 1 area.

- Type IT earthing.

  In this method the occurrence of a line-to-ground fault will normally cause a small earth return current to flow. Its magnitude will be determined by the impedance of the neutral earthing device, which will be a resistor or inductor. A device for detecting this current should be fitted in the switchboard or motor control centre, where the consumer is located in a Zone 1 or a Zone 2 area. Note that a solidly earthed low voltage three-wire system will normally have a very small current flowing in the insulation materials of all the line conductors in the network. If the insulation degrades or is damaged then an increase in the insulation current will occur, which will give rise to an unbalanced distribution of currents in the three lines. A sensitive core-balance device should be fitted in the switchgear to detect this current and to isolate the circuit. This precaution should be used for Zone 1 and Zone 2 areas.

13.3.3.2 SELV and PELV systems and equipment

The definitions of SELV and PELV as given in Reference 10 are:-

A SELV system is an extra-low voltage system (50 Vac or 120 Vdc free of ripple when measured between any two conductors), which is electrically separated from the earth (or ground) and other systems (such as the primary winding of an isolating transformer) in such a way that a single fault cannot give rise to the risk of electric shock. A PELV system is also an extra-low voltage system, but is one that is not electrically separated from earth. In all other respects it must satisfy the requirements of a SELV system.

SELV systems generally consist of double-wound isolating transformers where the secondary winding is not connected in any manner to earth, motor-generator sets where the mechanical coupling serves the same purpose as two windings of an isolating transformer, batteries that are isolated from the low or high voltage source of their chargers, and certain types of electronic supply units that have high speed control of overvoltages. (See clause 411-02-02 for the actual wording and cross-referencing to other clauses.) In general the practical significance of PELV versus SELV is unnecessarily complicated and a suitable SELV should be chosen in preference to a PELV alternative.

13.3.3.3 Four-pole circuit breakers and isolators

Where a four-wire supply is needed in a hazardous area it is necessary to use four-pole circuit breakers and isolators so that the neutral is completely isolated when maintenance work is required to be undertaken. If the neutral is not electrically separated and a fault occurs elsewhere in the same network then the neutral in the hazardous area could have its potential elevated sufficiently above zero to cause a spark (or even an electric shock). This aspect is especially important when a switchboard or motor control centre is supplied from more than one source such as two parallel transformers.

13.3.4 Earth Loop Impedance

A key factor in the design and choice of earth continuity conductors, e.g. cable armouring, bonding straps, and fault current protective devices is the 'earth loop impedance'. This is especially the case for solidly earthed low voltage systems, whether they be three-phase, single-phase or even direct current systems.

The earth loop impedance is the total impedance seen by the source of voltage in a faulted circuit which involves the earthing conductors. Figure 13.10 shows the situation for a three-phase cable supplying a load such as a motor or static load.

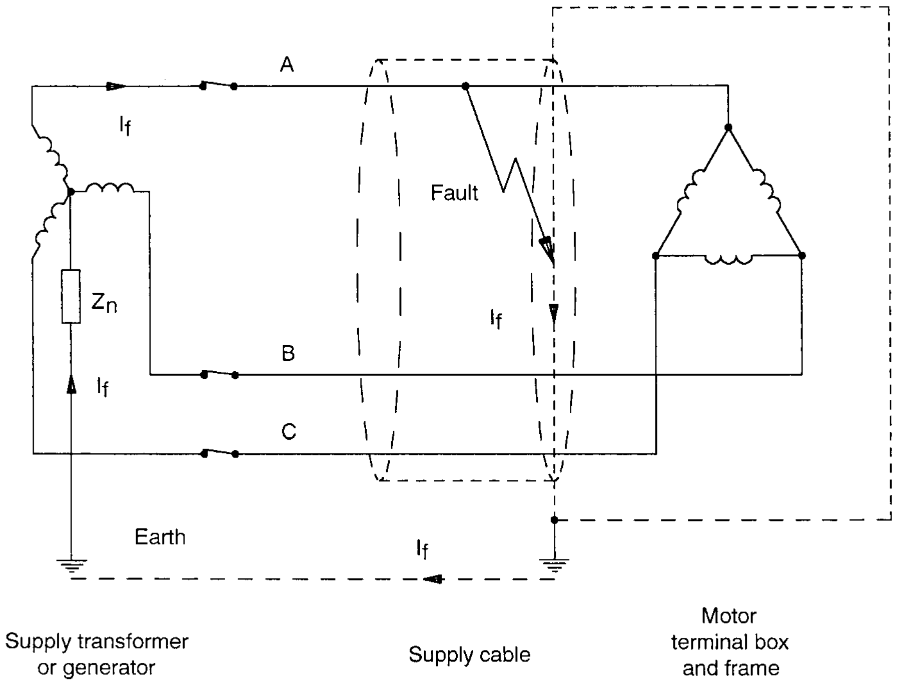

Figure 13.10 Earth loop impedance of a three-phase circuit.

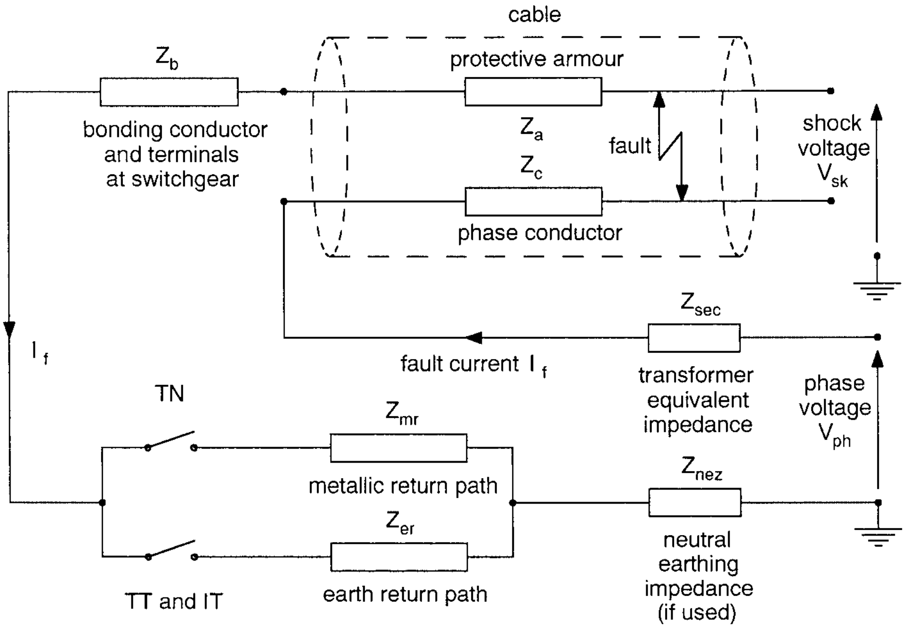

Figure 13.11 Equivalent circuit of the earth return paths in the earth loop impedance circuit involving a cable and its armouring. This is an interpretation of BS7430 Clause 3.13.

The worst design case is shown wherein the fault occurs at the far end of the cable. The fault is assumed to be a line-to-earth fault having zero fault impedance. The equivalent circuit for this example is shown in Figure 13.11.

A pessimistic assumption can be made that the steelwork impedance Z_e between the fault and the source is large compared with the parallel-connected cable armouring impedance Z_a. This implies that the current will only return to the source through the cable armouring and the copper bonding connection, of impedance Z_b, at the source-end of the cable. The impedance Z_b includes the local steelwork at the source. The bonding is assumed to be in tact and of very low impedance compared with Z_a. Hence Z_b can be ignored, and so earth loop impedance Z_{loop} simply becomes:-

$$Z_{\text{loop}} = Z_s + Z_c + Z_a \quad \text{ohms}$$

The driving voltage is the phase voltage. The source impedance Z_s is fixed and is usually that of the upstream supply cables and transformers, or generators (or the output impedance of supplies such as a UPS). Z_s can often but not always be neglected. The cable conductor impedance Z_c is easily calculated from the cable data for one phase conductor and its route length. Similarly the armouring impedance Z_a can be calculated from the data, which is predominantly resistive for most types of power cables. For typical cable data see the tables in Chapter 9.

In order to safeguard against electric shock at the far end of the cable, where the AC root mean square voltage may exceed 50 V, the earth loop impedance must be limited to a particular value. This value is such that the fault current should only be passed by the protective device at the supply for a specific period of time, i.e. to satisfy the I-squared-t criterion given in sub-section 13.1.1. The correlation of loop impedance, current and time varies with the type of protective device, e.g. fuse, moulded case circuit breaker, miniature circuit breaker. The international standards such as IEC 60364 and Reference 10 give tables for the limiting values of the earth loop impedance for common ratings of fuses and circuit breakers. Once the limiting value for the circuit is determined from these tables it is a simple calculation procedure to find the maximum length of the cable that can be allowed, as demonstrated in 9.4.3.6.

13.3.5 Earthing Rods and Grids

An essential aspect in the design of earthing systems for land-based plants in particular is the minimisation of the risk of electric shock due to the creation of potential along the surface of the ground and between the ground and metallic structures such as switchgear, overhead line poles and fences. The creation of potential along the surface of the ground gives rise to what is defined as the ‘step potential or voltage’, and between the ground and metallic structures, the ‘touch potential or voltage’.

13.3.5.1 Touch and step voltages

Situations arise where the soil resistivity (ρ) is very high, for example in desert locations. In these situations the concepts of ‘touch’ and ‘step’ voltages are important, see the international standard IEEE80, section 5. A person may be standing on a conductive surface and touching electrical equipment with one or both hands. At the same time a fault occurs and its current passes through the equipment casing to the ground, thereby creating a potential difference across the person. This is the touch potential difference or touch voltage. In a second type of fault situation a person is standing on conductive ground with his feet spread one metre apart. The fault current, or part of it, passes horizontally at or near the surface of the ground. The local resistance of the ground in the path of the current creates a potential difference across the feet of the person. This is the step potential difference or voltage.

The magnitude and duration of these voltages, together with the resistance of the person between his points of contact, will determine whether the person receives a minor or even a fatal shock. If the surface layer of the ground can be reduced in conductivity by a significant amount then the current along the surface will be small, and most of the fault current will be forced down to a lower level in the ground. A small level of surface current and an inherently high source resistance will tend to restrict the amount of the surface current that can be shunted into the person, thereby reducing the risk of shock. The surface layer may be the addition of dry crushed rocks or stones, and it should be kept reasonably shallow, e.g. 100 to 150 mm or rubber mats as used in switchrooms. Chapter six in Reference 3 gives an excellent coverage of the subject of earthing, mathematic derivations of complex formulae and the topics of step and touch voltages. The equations presented are well suited to hand calculations or simple computer programming.

IEEE80 sub-divides the touch and step voltages into two categories, one for heavier persons of typical weight 70 kg and one for lighter persons at 50 kg. The reference illustrates the fact that the heavier the body the higher the threshold of fibrillation of the heart. For calculation purposes it is conservative to use the 50 kg equations. The results will be about 25% lower, which will eventually require a little more conductive material in the ground for a given situation. The reference also introduces an additional term to the standard body resistance of 1000 ohms, which takes account of the ‘crushed rock layer’ and the resistivities of the crushed rock (ρ_s) and the main mass of earth below that has the resistivity (ρ). This term is:-

$$R_{2Fs} = 6(\rho_s)C_s(h_s, K) \text{ for use in the step voltage case, and}$$

$$R_{2Fp} = 1.5(\rho_s)C_s(h_s, K) \text{ for use in the touch voltage case}$$

Where : − h_s = the thickness of the crushed rock layer
$K = (\rho - \rho_s)/(\rho + \rho_s)$.

Which is negative when the upper layer is more resistive then the lower layer. If no crushed rock is used then $C_s(h_s, K) = 1$. The resistances R_{2Fs} and R_{2Fp} are added to the 1000 ohms in equation (13.2) and the resulting threshold voltages are then denoted as E_{step50} and as E_{touch50} (using the same notation as in IEEE80). The function $C_s(h_s, K)$ is derived from a convergent infinite series and can be expressed as:-

$$C_s(h_s, K) = \frac{1}{0.96}\left[1 + 2\sum_{n=1}^{n=\infty} \frac{K^n}{u_s}\right] \tag{13.3}$$

Where

$$u_s = \sqrt{1 + \left(\frac{2nh_s}{0.08}\right)^2}$$

13.3.5.2 *Soil resistivity*

Soil resistivity varies greatly with the material, e.g. rocks, sand, clay, and its moisture content, as in coastal areas, high annual rainfall, dry deserts. Table 1 of BS7430 gives comprehensive values for these variations. For dry desert conditions a value of 1000 ohm-metres is generally considered acceptable for design calculations, unless site measurement data are available. Table 3 of IEEE80 gives typical values of crushed rock that would be used as a surface layer, and recommends in its sub-section 10.5 a value of 3000 ohm-metres for a wetted layer. Hence a dry layer would be very much higher e.g. 10^6 to 10^7 ohm-metres.

13.3.5.3 *Resistance to earth*

The resistance to earth R_e as measured or calculated for a conductor buried in the ground depends upon its shape, volume and orientation in the ground. In favourable conditions the resistance should be less than one ohm. With unfavourable conditions and small sites such as the bases of pylons a value between 1 and 5 ohms should be considered. For simple shapes such as uniform rods, strips and plates, there are formulae available for calculating the resistance. For example a vertical round rod or hollow pipe the resistance is:-

$$R_e = \frac{\rho}{2\pi L}\left[\log_e \frac{8L}{d} - 1\right] \quad \text{ohms} \tag{13.4}$$

Where ρ is the soil resistivity in ohm-metres
L is the buried length of the rod or pipe in metres
d is the diameter of the rod or pipe in metres.

Annex A of BS7430 gives formulae for various shapes of buried conductors. See also Appendix H of Reference 1. Reference 2 shows the mathematical derivations of some basic cases. Reference 3 provides much useful information regarding buried materials. If the rod or pipe is surrounded by a casing or backfill of more conductive material such as Bentonite, then a lower resistance is obtained for the same depth, the formula is:-

$$R_e = \frac{1}{2\pi L}\left[(\rho - \rho_c)\left(\log_e\left(\frac{8L}{d}\right) - 1\right) + \left(\rho_c \log_e\left(\frac{8L}{d}\right) - 1\right)\right] \text{ ohms} \tag{13.5}$$

Where ρ_c is the back fill resistivity in ohm-metres
d is the diameter of the back fill or casing in metres.

This equation can also applied to reinforced concrete in which a steel rod is encased. A single rectangular strip of width (ω) buried horizontally has a resistance to earth of:-

$$R_e = \frac{\rho}{2\pi L}\left[\log_e\left(\frac{2L^2}{\omega h}\right) - 1\right] \text{ ohms} \tag{13.6}$$

Where L is the horizontal length of the strip in metres
h is the depth of burial in metres.

One difficulty with a small site such as a ring main station with an overhead line pole, a transformer and a switchgear unit is the spacing between the vertical rods tends to be small compared with their buried length. This reduces the effectiveness of each rod due to its proximity to the adjacent rods, see sub-section 10.2 of BS7430. The best results are obtained when the rod spacing is approximately equal to the depth of the rod.

An arrangement of conductors for a difficult site would generally consist of a grid of horizontal strips with vertical rods connected at the corners and sides of the grid. Hence the overall resistance will then be a function of equations (13.4) and (13.6) (or (13.5) if necessary).

Malhothra in Reference 3, sub-section 6.12, comments that in a system comprising rods and a horizontal grid, the rods can in some situations be deleted because they have little effect compared with the grid acting on its own.

The current that passes into the earth causes a voltage difference across the resistance. Since a point or region a long way from the connection to the conductor is at zero reference potential, the connection must be at an elevated potential. This potential is called the ‘ground potential rise or GPR’. At distances close to the point of connection the potential will be high, but further away it will be much lower. When the earthing conductor includes a horizontal grid buried near to the surface, the surface voltage decays in a more complicated manner. Within the grid itself are squares or rectangles of conductors. Consequently the potential at the centre of a square or rectangle is less than at their metallic sides. Outside the frame of the grid the decay is greater, and this creates a region if high risk of shock. It is therefore necessary to calculate the potential at the corner of the frame as a percentage of the full potential due to the total resistance. Two potentials are needed, the ‘corner mesh voltage or E_m’ and the ‘corner step voltage E_s’. E_m and E_s are obtained by calculating per-unit or percentage factors that relate to the grid geometry. These are then used to scale down the GPR by simple multiplication. The mesh voltage E_m is usually more of a constraint on the design than the step voltage E_s. The IEEE80 standard provides graphs of E_m and E_s for different mesh configurations, (Figures B1 to B5 therein).

In Reference 3 a typical design of a grid of large area would be to bury it to about 0.5 m and choose each mesh in the grid to have sides of length about 5 or 6 m. This would give a good starting point for a series of calculations.

13.3.5.4 Fault current entering the ground

For most practical designs the calculation of a 'single line-to-ground or L-G' fault current should be adequate. Assume the fault occurs at the pole location and that the pole is at a long distance from the source of power. Assume for a simple example that the overhead line is a simple radial circuit fed only from one end, and that the line is furnished with an overhead earthing conductor. To be conservative assume that the earthing conductor is only bonded to the pole in question and to the neutral earthing point at the source end. The source is considered to be earthed through a neutral earthing resistor (NER) having a resistance R_n.

The overhead earthing conductor will divert some of the L-G fault current from entering the ground at the foot of the pole. The extent of diversion will be in proportion to the impedance of the overhead line compared with that of the earth resistance path back to the source. The calculations required for determining the fault current and its diverted amounts are shown in Appendix H by way of an example, and Figure 13.12.

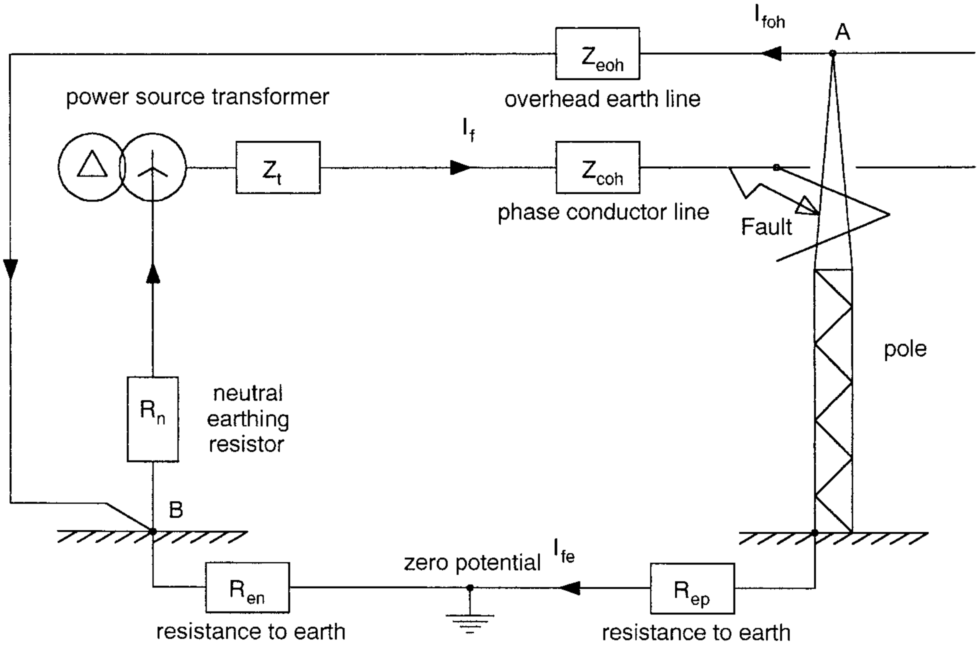

Figure 13.12 Earthing circuit of an overhead transmission route.

13.4 CONSTRUCTION DETAILS RELATING TO EARTHING

This section describes some of the practical construction and installation details that are required with metallic frames, casings, cubicles, terminal boxes and cables.

13.4.1 Frames, Casings and Cubicle Steelwork

Frames and casings are the steel or cast iron enclosures of motors and generators in particular. Frames can also include the base plate of machines and transformers, and these are often channel iron-welded fabrications. Cubicles are usually fabricated sheet steel box type enclosures used for switchgear, distribution boards, control panels, fuse boards and terminal chambers.

In all locations these constructions must be connected to the earthing system. Most frames and casings are bolted to the supporting structure, e.g. steel deck beams, concrete foundation block or plinth. They are usually fitted with at least two large earthing bosses, which are welded or cast into the fabrication, separated as far apart from each other as possible, and having threaded entries for bolts of typically 10 to 15 mm diameter. The size of the bolts is related to the maximum fault current that can flow in the fabrication. Copper bonding straps are connected to these bosses and similar ones welded nearby on the deck beams, or onto nearby earth rods or busbars. In some situations the frames are welded to the deck beams and so the use of bosses may not be necessary. Casings of machines are seldom welded because the machine will need to be removed for major maintenance, repair or re-alignment.

Cubicle steelwork is invariably bolted to the floor, a floor frame or to a wall structure, and therefore bolted bonding straps are used in a similar manner as described above. Most cubicles are fitted with an internal copper busbar which is bonded internally to the steel. The busbar is used to receive the bonding connections from internal components, partitions, screening panels, cable glands, cable armouring, cable screens and gland plates.

13.4.2 Screwed and Clearance Hole Entries

A major part of any power system installation is the termination of all the cables. Cables are terminated at equipment by the use of cable glands. There are many different types of cable glands, and they must be carefully chosen to suit their function and environment. Factors influencing their choice are:-

- Indoor or outdoor installation.
- Power or instrumentation cables.
- Weather and particle ingress proofing.
- Mechanical vibration or movement of the equipment.
- Non-hazardous or hazardous environment.
- Corrosive atmosphere.
- Internal construction of the cable, e.g. type of armour, use of core screens.
- Equipment submerged in liquids, e.g. sump pumps, down-hole pumps.
- Gland material, e.g. brass, stainless steel, plastic.
- Total length and type of the entry thread.

Cubicles and light duty terminal or junction boxes often use stainless steel or painted mild steel gland plates for receiving cable glands, occasionally brass plates are used for single-phase and DC cables. Stainless steel may also be used for special services. These plates are chosen to be between about 2 and 5 mm thick, to provide adequate rigidity and resistance to the ingress of dust and liquids, as defined for example in the international standard IEC60529, see also Chapter 10. The glands pass through plain or clearance holes and are secured by lock-nuts and spring washers on the inside surface. Since the entry is a plain hole with a painted surface, it is necessary to use earthing tabs. Each cable should have a tab and all the tabs should be bonded to a common earthing boss nearby. The tabs may be on either the outer or the inner surface, depending on the type of equipment and its environment. Care must be taken to ensure that water and other liquids cannot pass along the entry hole.

Casings and heavy-duty terminal boxes are often made of cast iron or fabricated from thick steel plates. Occasionally cast bronze may be used, in services offshore where sea water corrosion may be a problem. In these cases the entry is usually threaded. The gland is screwed into the threaded hole. A washer may be required between the outer surface of the box and the gland, to satisfy the requirements for ingress of liquids and particles, and for the hazardous area. When Ex (d) glands are used with Ex (d) boxes it is necessary to ensure that the prescribed number of threads on the gland enter the hole.

Most casings, terminal boxes and gland plates are provided with one or two earthing studs for bonding them to the earthing system. If a terminal box is cast integral with the frame or casing of a motor, a generator or other machine, then an earthing stud is not necessary at the box, but the frame will have one or two studs or bosses for the same purpose.

13.4.3 Earthing Only One End of a Cable

Multi-core cables used for control, instrumentation, computers and telecommunications carry very small currents in their conductors, when compared with power cables, and these currents feed into very sensitive electronic circuits. The system design of these electronic circuits must take account of interference that can be induced or circulated in the cable conductors. Screens are provided around groups of typically two, three or four conductors, which are mainly intended to discharge static charges that can otherwise accumulate and create noise or damage at the terminal equipment. Screens are also provided around all the conductors in the cable for a similar reason.

If a screen is earthed at both ends of its cable then a ‘stray’ current may be caused to flow in the screen. This is because the earth potential at each end of the cable may not be exactly the same or both zero. A few millivolts difference due to random stray currents, or worst still fault currents, in the local earth or steelwork is enough to cause difficulties with the electronic signals. The stray current flowing along the screen will magnetically induce currents into the core conductors. It is therefore common practice to earth the cable screens only at one end of the cable. The bonding of each screen is made at a specially designed ‘clean earth’ busbar mounted inside, for example, a control panel or marshalling box.

High voltage power cables that operate at voltages above about 3000 V are provided with graphite semiconducting screens at the surface of the conductor and on the outside surface of the insulation. The purpose of the screen around the conductor is to control the potential gradient, or electric stress, in the insulation that is close to the conductor. The high surface voltage is accompanied with a very rapid fall in potential just inside the insulation (measured or defined in volts/mm). The natural insulating property of the insulating material is limited by the maximum potential gradient at any point within its structure. If the maximum gradient is exceeded then local breakdown and discharge will occur at the site, which is sometimes called 'partial discharging'. If this is allowed to continue for a long time the insulation will eventually fail. In a cable the stress is greatest at the surface of the conductor. This screen is not earthed. It must be bonded to the inner surface of the insulation very carefully so that no pockets or gaps exist, which could also promote local discharges.

A similar screen is placed around the outer surface of the insulation, especially with multi-core high voltage cables so as to maintain a radial stress pattern in each core. A metallic tape is placed over the semiconducting screen. The tape may be made of tinned copper, bronze or aluminium. The semiconducting screen is used to ensure a good electrical contact is made with both the insulation and the tape. This is necessary to avoid local highly stressed areas on the surface of the insulation, so that it is not weakened. The tape is usually bonded to earth at the switchgear end of the cable. At the switchgear the bonding will be taken to the internal earth busbar.

13.5 SCREENING AND EARTHING OF CABLES USED IN ELECTRONIC CIRCUITS

Since about 1980 power system switchgear, control panels, uninterruptible power supplies, power management systems, variable speed drives, protective relays, SCADA, and the like, invariably use instrumentation cables to transfer low level signals between equipment. These cables can 'pick-up' stray signals by interference from nearby sources. These stray signals will be called 'noise' hereinafter, and they occur due to several different forms of coupling:-

- Common circuit conduction.
- Electrostatic or capacitive coupling.
- Electromagnetic or mutual inductive coupling.

Reference 19 gives a comprehensive coverage of these complex subjects. References 20 to 24 are recommended as further reading. Reference 23 gives a full descriptive treatment of these subjects together with useful numerical data, and a reference list of over 160 articles, books and papers. A few of these topics that relate to oil industry practice and equipment are described below.

Instrumentation cables used for power system signal transmission are usually of two basic types, multi-core twisted pairs, triples and quadruples, and coaxial cables.

13.5.1 Capacitance and Inductance Mechanisms

There are three basic conductor configurations to consider; a single conductor located above a flat plane, two conductors running in parallel with each other, and a conductor running inside a cylindrical screen or shield. Let the following notation be used for the inductances and capacitances that will be referred to later. See Reference 19 for formulae that relate these inductances and capacitances to the physical dimensions of the conductors. Reference 25, chapters 10 and 11 give full details of how to calculate the magnetic and electric field patterns of simple and complex shapes, such as,

a) Single conductor above a flat plane.

Leakage capacitance.

Self-inductance.

b) Two conductors in parallel.

Coupling capacitance between the conductors.

Self-inductance of each conductor.

Mutual inductance between the conductors.

b) One screened conductor in a cylinder.

Coupling capacitance.

Self-inductance of the conductor.

Mutual inductance between the conductor and the cylinder.

Invariably the cable length is very much greater than the radius of a conductor and its separation from other conductors in the cable or its screening. Therefore all the capacitances and inductances are distributed along the length of the cable. The conductor resistance and the insulation leakage resistance are also distributed. For practical calculations it is adequate to 'lump' these parameters into single elements of inductance, capacitance and resistance.

13.5.2 Screening against External Interference

Instrumentation cables frequently run in parallel along the same routes as heavy current power cables. The routing is designed in such a manner that a prespecified spacing is used between power cables and instrument cables. Table 13.1 gives typical minimum spacings between the cables that run in the same trench or set of racks. There are situations where a power cable can radiate interference, particularly in the form of mutually induced currents, for example:-

- Single-core cables run in groups.
- Cables carrying unbalanced currents.
- Cables carrying harmonic currents, e.g. drilling power systems.
- Cables carrying surge currents, e.g. starting large motors direct-on-line.
- Cables carrying fault currents of high magnitude, particularly if they flow in the armouring.

Table 13.1. Separation of electronic and power cables

Power cables and control cables	Minimum Separation of cables (mm)
110 V or 10 A	300
240 V or 50 A	450
415 V or 500 A	600
3300 V to 33,000 V	1000
Currents above 200 A	1000

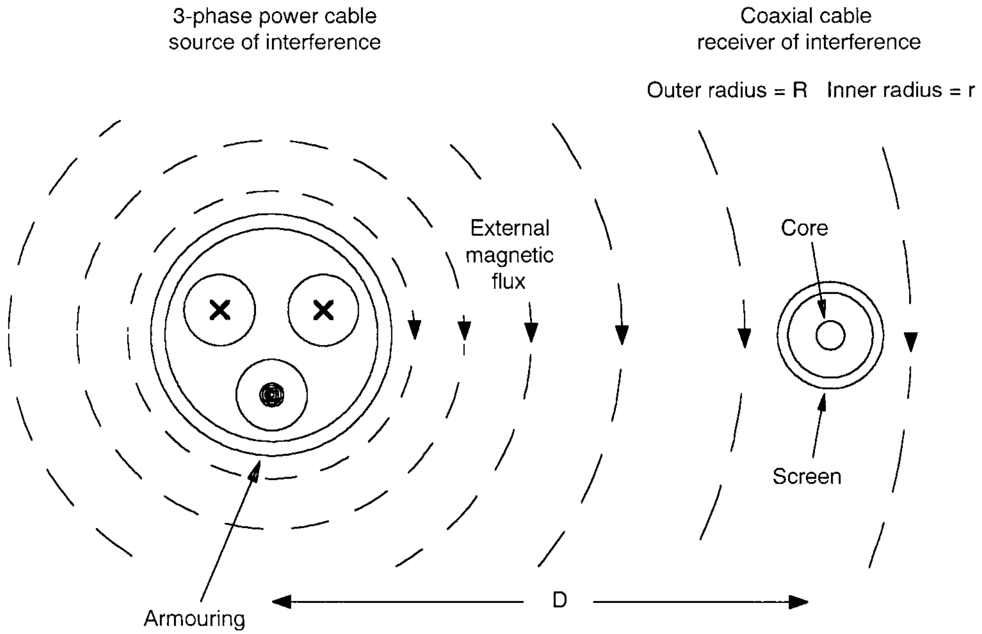

Figure 13.13 Mutual coupling between spaced out cables.

In these examples the situation of interest is a combination of a single conductor above a plane and another single conductor above the same plane but running in a cylinder or screen, as shown in Figure 13.13.

The source of interference in the example is a three-phase cable in which unbalanced currents flow. The currents that are unbalanced can be replaced by one equivalent current, which is the sum or resultant of all the three phase currents. The three-phase cable is assumed to be armoured, which is generally the case, and the armouring is assumed to be earthed at one or both ends. Earthing the armour reduces the external electric field to zero, and so only mutual inductive coupling needs to be considered.

The equivalent circuit of the various conductors and screening is shown in Figure 13.14.

Where:

For the interference source cable

I_3 is the three-phase resultant interference current source.
R_3 is the resistance of the source circuit.
L_3 is the self-inductance of the source circuit.

For the signal instrumentation cable

R_s is the resistance of the cable screen.
L_s is the self-inductance of the cable screen.
R_s is the resistance of the cable core.

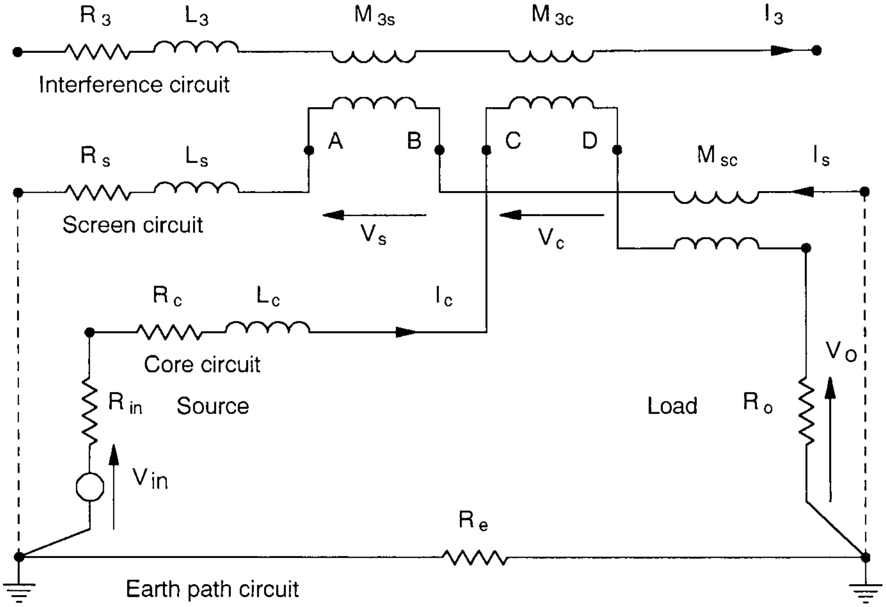

Figure 13.14 Interference and screening circuit of cables that are run in parallel with each other.

L_s is the self-inductance of the cable core.
M_{sc} is the mutual inductance between the screen and the core.

For the couplings between the cables

M_{3s} is the mutual inductance between the interference cable and the screen of the signal cable.
M_{3c} is the mutual inductance between the interference cable and the core of the signal cable.

For the components connected to the cables

R_{in} is the internal resistance of the signal source.
R_o is the output or load resistance on the signal source.
R_e is the resistance of the common earth path of the signal cable.

Consider two cases, firstly a cable without a screen and secondly one with a screen. The two cases will then be compared.

Case A. Signal cable without a screen.
The summation of voltages and emfs in the signal cable is:-

$$V_{\text{in}} = (R_{\text{in}} + R_c + j\omega L_c)I_c + j\omega M_{3c}I_3 + (R_o + R_e)I_c$$

Find I_c in terms of I_3. Assume $V_{\text{in}} = 0$ in order to determine the amount of current induced from I_3. Let this amount be called I_{co}.

$$I_{co} = \frac{-j\omega M_{3c} \cdot I_3}{R_{in} + R_c + R_o + R_e + j\omega L_c} \quad \text{amps} \tag{13.7}$$

Let the voltage appearing across the load be V_{oo}:-

$$V_{oo} = \frac{-j\omega M_{3c} - R_o \cdot I_3}{R_{\text{in}} + R_c + R_o + R_e + j\omega L_c} \quad \text{volts} \tag{13.8}$$

Let the core loop resistance be called R_{cc}:-

$$R_{cc} = R_{\text{in}} + R_c + R_o + R_e \quad \text{ohms} \tag{13.9}$$

Note that the components R_3 and L_3 of the source are not included in this result because the interference is a current source, which is known.

Case B. Signal cable with a screen.
Assume that the screen is earthed at both ends at the same points as the signal source and the output load. Hence the common earth resistance R_e is shared by both the screen and the core circuits. Again assume that V_{in} is zero for the same reason as above.

The summation of voltages and emfs in the core loop of the signal cable is:-

$$\begin{aligned} V_{\text{in}} &= (R_{\text{in}} + R_c + j\omega L_c)I_c + (R_o + R_e)I_c \\ &\quad + j\omega M_{3c}I_3 - j\omega M_{sc}I_s = 0, \text{ which upon rearranging is,} \\ &\quad - j\omega M_{3c}I_3 = (R_{cc} + j\omega L_c)I_c - j\omega M_{sc}I_s \end{aligned}$$

This has the form:-

$$y_1 = a_{11}I_c + a_{12}I_s \tag{13.10}$$

Where

$$\begin{aligned} y_1 &= -j\omega M_{3c}I_3 \\ a_{11} &= +(R_{cc} + j\omega L_c) \\ a_{12} &= -j\omega M_{sc} \end{aligned}$$

The summation of voltages and emfs in the screen loop of the signal cable is:-

$$0 = (R_s + j\omega L_s)I_s - j\omega M_{3s}I_3 - j\omega M_{sc}I_c + R_e I_s$$

which upon rearranging is,

$$-j\omega M_{3s}I_3 = +j\omega M_{sc}I_c - (R_{ss} + j\omega L_s)I_s$$

This has the form:-

$$y_2 = a_{21}I_c + a_{22}I_s \tag{13.11}$$

Where

$$\begin{aligned} y_2 &= -j\omega M_{3s}I_3 \\ a_{21} &= +j\omega M_{sc} \\ a_{22} &= -(R_{ss} + j\omega L_s) \\ R_{ss} &= +R_s + R_e \end{aligned}$$

The solution of the simultaneous equations (13.10) and (13.11) for the two currents I_s and I_c is:-

$$I_s = \frac{y_1a_{21} - y_2a_{11}}{a_{12}a_{21} - a_{11}a_{22}} \quad \text{amps} \tag{13.12}$$

and

$$I_c = \frac{y_2a_{12} - y_1a_{22}}{a_{12}a_{21} - a_{11}a_{22}} \text{ amps} \tag{13.13}$$

Some simplifications can be made after comparing the various mutual and self-inductances. The following assumptions are valid:-

$M_{sc} = L_s$ because the majority of the flux between the screen and the core couples the screen and the core.

Let $M = M_{3s} \approx M_{3c}$

And $M_{sc} \gg M_{3s}$ or M_{3c} because of the relative dimensions and separation distances.

The denominator of (13.12) and (13.13) becomes:-

$$a_{12}a_{21} - a_{11}a_{22} = R_{ss}R_{cc} + j\omega(R_{cc}L_s + R_{ss}L_c) + \omega^2(L_s(L_s - L_c))$$

In which the extreme right-hand term is very small in the range of frequencies of interest, and can be ignored. Therefore the denominator becomes:-

$$a_{12}a_{21} - a_{11}a_{22} = R_{ss}R_{cc} + j\omega(R_{cc}L_s + R_{ss}L_c)$$

The I_s numerator of (13.12) becomes:-

$$y_1a_{21} - y_2a_{11} = (+\omega^2M(L_s - L_c) + j\omega MR_{cc})I_3$$

The I_c numerator of (13.13) becomes:-

$$y_2a_{12} - y_1a_{22} = (-\omega^2M(L_s - M) + j\omega MR_{ss})I_3$$

If the cable core terminates at a high impedance device such as the input channel of an operational amplifier, then R_o is large when compared with R_c, R_{in}, R_e and R_s.

Therefore $R_{cc} \gg R_{ss}$ unless the cable is extremely long.

Let the voltage appearing across the load be V_{os}:-

$$V_{os} = I_c R_o = \frac{-j\omega M R_{ss} I_3}{R_{ss} + j\omega L_s} \quad \text{volts}$$
$$= \frac{-j\omega M I_3}{1 + j\omega \dfrac{L_s}{R_{ss}}} \quad \text{volts}$$

And revising the expression for V_{oo}:-

$$V_{oo} = \frac{-j\omega M R_{cc} I_3}{R_{cc} + j\omega L_c} \quad \text{volts}$$
$$= \frac{-j\omega M I_3}{1 + j\omega \dfrac{L_c}{R_{cc}}} \quad \text{volts}$$

It can be seen from these two expressions that the screening effectiveness is mainly determined by the separation of the signal cable from the interference cable, which is not surprising and supports the standard practice of laying these cables. It is also seen that at low frequencies the screen and the core have the same magnitude of induced current and load voltage. Attenuation begins at a high frequency for both the screen and the core. The cut-off (or 3 db) frequency is typically in the range 0.5 kHz to 2.0 kHz for coaxial and twisted pair screened cables.

The overall armouring of a typical offshore signal cable is phosphor-bronze, copper or galvanised steel braid. Steel wire armouring is used where extra mechanical protection is required. The armouring provides some of the screening effect. An inner overall tinned copper, copper or aluminium tape is also frequently used. Paired, tripled and quadrupled conductors are often screened with similar tapes. However, all these various layers of screening are not very effective against low frequency interference from sources such as adjacent power cables.

13.5.3 Earthing of Screens

In some situations the core of a coaxial cable and the screen are used as a two-wire circuit, e.g. antenna cables, computer cables. In this case the signal current flows in one direction along the inner core and returns in the opposite direction in the screen. In this way the induced noise is reduced.

It is often necessary to earth one end of the screen for practical reasons. If the end at A_e in Figure 13.15 is earthed then the earth path resistance R_e shunts the screen completely and some of the screen current will flow along the earth path. This will unbalance the core and screen currents and so noise cancellation will not occur. A noise voltage will appear in the core circuit. Earthing the screen at the end B_e overcomes this difficulty because the positive channel of the amplifier is a virtual earth. In some cases the connection at B_e is made at a 'clean' or 'instrument' earth if the receiving device has only one channel or input terminal (the chassis or framework would be the second channel or

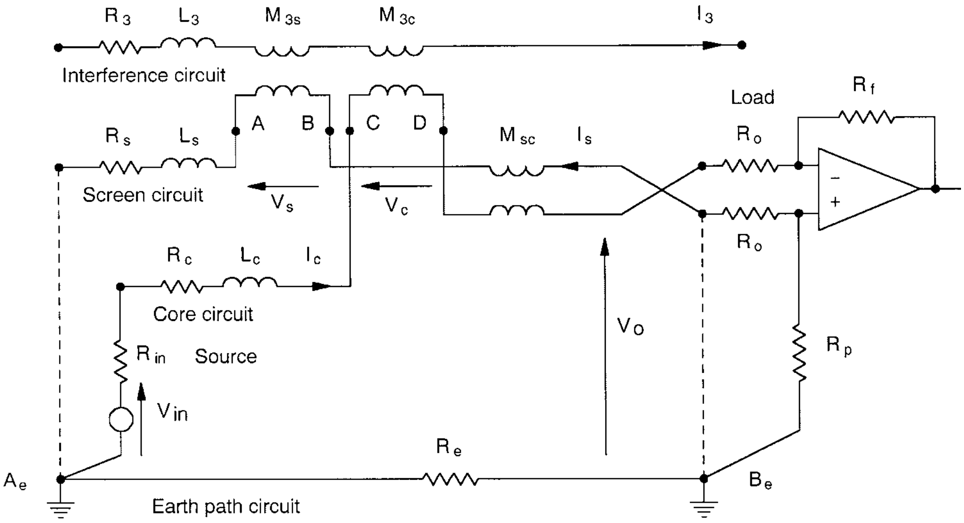

Figure 13.15 Interference and screening circuit of cables that are run in parallel with each other. The signal cable is terminated by an amplifier at the far end.

terminal). The connection at A_e also has the disadvantage that stray currents frequently flow in earth paths and so a conductive noise voltage can appear between points A_e and B_e, and will therefore add to the signal voltage V_{in}. The same principles of cancellation can be used with twisted pairs (triples and quadruples). The use of a screen around the pairs slightly improves the attenuation of induced noise, but this depends upon which end or both are earthed. Earthing the screen at the receiving device end has the best attenuation due to the same reasoning as for the two-wire coaxial circuit. Earthing the screen also discharges any electrostatic charge that may build up in the insulation, which will also appear as noise at the receiving device.

13.5.4 Screening of High Frequencies

It was mentioned in sub-section 13.5.2 that the cut-off frequency for effective screening is in the range of 0.5 kHz to 2.0 kHz for external interference. At frequencies higher than about 1 MHz it is useful to consider the coupling between the screen and the core as an impedance that relates the screen current to the core open-circuit voltage. In such a case it is not specified how the current appears in the screen. It could be by mutual induction from nearby cables, but more often by radio waves received from local radio transmitters, radio telephones, or a radar antenna. The impedance is called the 'shield transfer impedance Z_T' and it can be measured by a relatively simple test procedure. The expression for the impedance Z_T is:-

$$Z_T = \frac{V_{o/c}}{I_s l} \quad \text{ohms}$$

Where $V_{o/c}$ is the open-circuit voltage seen between the screen and the core
I_s is the screen current
and l is the length of the cable

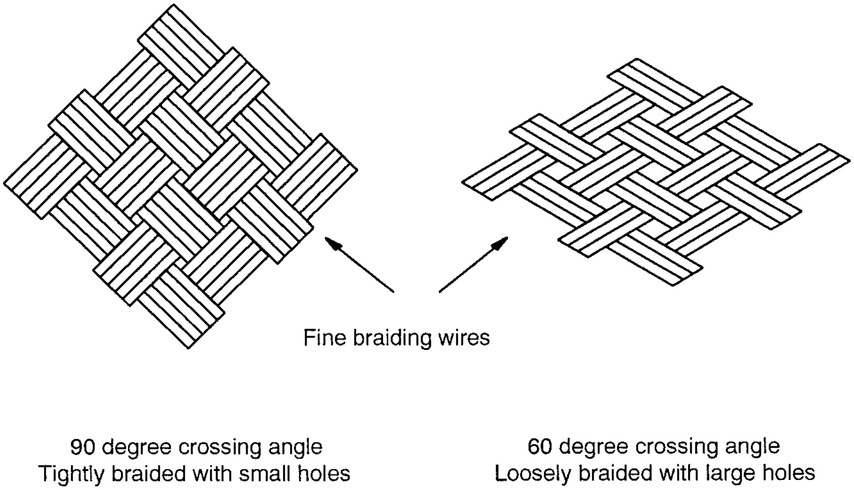

Figure 13.16 Holes in the braided armouring of instrumentation cables.

This impedance can be used to analyse the effect of laying cores close together in a multi-core cable, and whether or not to use individual screens for pairs, triples and quadruples. The impedance is a complex function of skin effect in the screen and wave propagation through the holes or gaps in a screen material such as braiding. As the frequency rises the skin effect causes the screen current to flow on the outer surface of the screen and not to penetrate towards the core. This lack of penetration prevents the currents from being mutually induced into the core. The effect is similar to placing a non-linear resistance in the primary or secondary terminals A-B and C-D of the mutual inductances shown in Figures 13.14 and 13.15. This resistance would decrease in value as the frequency increases due to the increased presence of eddy currents. The effectiveness of the screen due to skin effect reaches a maximum at about 1 MHz for typical braided screens, and about 5 MHz for aluminium foil screens. Braids vary in construction as shown in Figure 13.16. It is almost impossible to avoid ‘holes’ or gaps in the braiding. Even an amount as low as 2% to 5% for the area of holes in the braiding will have a significant effect on the transfer impedance and will cause it to rise when the frequency is above about 1 MHz. The effectiveness of the screen will therefore decrease significantly and VHF and UHF radiation will penetrate to the cores of the cable. If it is anticipated that the electronic equipment in a plant may be influenced by VHF or UHF radiation, for example from a local transmitting station, then the screens should be made of tightly meshed braid or non-ferrous overlapped tape.

13.5.5 Power Earths, Cubicle and Clean Earths

Plants frequently have areas where large motors, switchgear, control panels and SCADA panels are located in close proximity, especially in offshore platforms. In such cases the equipment and its internal electronic circuits needs to be earthed. If all the earthing connections are to be made locally at each item of equipment, e.g. to an earthing boss next to a control panel, then there is a possibility that control and signal circuits will pick up noise due to stray currents in the common earth circuit. This possibility can be minimised by taking special precautions in the design of the earthing systems.

a) Switchboards and motor control centres

It is the normal practice to provide a copper busbar at the base of the switchboard or motor control centre for earthing all the high power circuits, e.g. cable armouring, motor earthing cables, and low power circuits that are not sensitive to noise pick-up. This busbar is insulated from the frame, and at one or both ends there is an isolating link with bolts that bonds the busbar to the steel frame. The steel frame is bonded to the local earthing system, e.g. steel decking in a marine installation, earthing conductor or rod in a land-based installation. The isolating link can be opened for checking the earth-loop impedance or for making measurements of the noise voltages. It is often the practice to install one or two external earthing busbars in the locality of the switchgear. For example in a switchroom a busbar would be located near to each of the two opposite walls, and in reasonable proximity to the switchgear. Equipment such as switchgear, neutral earthing resistors, transformers, have their internal earth busbars or star points connected by single cables of large cross-sectional area to the external earthing busbars described above. These external earthing busbars are often mounted on insulators or bushings and fitted with bolted isolating links that are again used for testing purposes.

A typical offshore platform will have several modules or large equipment rooms and so all the external earthing busbars will be interconnected by single-core insulated cables of large cross-sectional area. The interconnections are preferably made in the form of a ring circuit so that continuity is highly assured. A similar ring circuit approach can be used for land-based plants where the items of equipment are located near to each other, otherwise a radial interconnection system or one with local grids and rods would be more economical.

b) Earthing within cubicles and panels

Instrumentation cubicles, SCADA cubicles, control panels, computer equipment and the like require to be earthed in a particular manner so as to avoid or minimise the pick up of noise. Some of the internal circuits may be very sensitive to noise pick-up from earth sources, e.g. input amplifiers, signal conditioning units. These circuits may have their own special noise elimination devices, as described in References 20 and 22, but it is better to assume that they have not for the purposes of designing a good earthing system in the first place. It is common practice therefore to provide two separate internal earthing busbars, one for general earthing and the other for the special circuits. These will be isolated and insulated from each other.

The general earthing busbar would be used for earthing the framework, chassis metalwork and cable armouring. The special earthing busbar, often called the ‘clean earth’ busbar, would be used for signal core screens, earth reference points of input circuits, and earth reference points of output circuits. Both the ‘general’ and the ‘clean’ earthing busbars would be mounted near the cable gland plate on insulated bushes. The level of insulation need not be high because in practical testing the potential to earth with the links removed would only be a few volts. (It is more governed by the expected level of cleanliness in the area at ground level, which may contaminate the bushings and cause a leakage current to pass and upset the measurements taken.) If the plant is not prone to earth pick-up noise then the general busbar could be bonded to the same local earthing boss as the main frame or cubicle. However, where earth pick-up is a problem then the clean earth busbar would be interconnected by a large section cable to the copper ring system. The general and clean busbars serve as ‘single-point’ earths, thereby eliminating pick up between distributed earthing points due to conducted noise.

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14

Variable Speed Electrical Drivers

14.1 INTRODUCTION

Due to an increasing concern about conserving energy there has become a requirement for variable speed drivers in the oil industry. The most common requirement is for compressors where the gas composition may not be well known or it may vary in composition and desire throughout, which is often the case in the production industry. Occasionally, benefits may be obtained by driving pumps with variable speed motors, especially large oil loading and pipeline pumps.

An important area where variable speed is used is in the drilling of wells where accurate control of speed and torque is essential. In recent years some attention has been focused on the application of variable speed motors in the down-hole pumping of oil, as discussed in sub-section 14.4.2.

Speed variation can be obtained by using two alternative types of electric motors.

- AC motors
- DC motors

AC methods include standard squirrel-cage induction motors, wound rotor induction motors, synchronous motors and commutator motors. Speed variation is obtained by the control of applied voltage to the stator or the control of current and voltage in the rotor by external circuit connections.

Before thyristors and power transistors were introduced for AC to DC and AC to DC to AC converter systems, there were a number of special designs of AC motors that gave better performance than standard squirrel-cage motors. These motors required connections to the rotor windings. They had better speed control, superior torque versus speed characteristics and some methods were energy efficient. However, they were more complicated and hence more expensive.

Much depends upon the performance required, e.g. accuracy, energy efficiency, standstill and low speed torque control. External equipment such as extra switchgear, controllers, instrumentation and protection is required and this increases the overall cost of the system. Also required will be extra maintenance and stocking of spare parts.

DC methods mostly use shunt or compound wound motors. Occasionally series wound motors are used when high torque at low speeds is required. These machines are fed with DC voltage derived from a three-phase AC source using a thyristor converter. The thyristor converter rectifies the AC into DC but with control over the magnitude of the average DC voltage. Thyristors are also called ‘silicon controlled rectifiers’.

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DC motors have a widely variable drooping torque versus speed characteristic and so, for any given torque and speed within its rating, the motor can be controlled to give a chosen speed and torque. Hence a DC motor can be controlled to accurately match and operate the characteristics of its driven machine from zero to beyond rated speed.

References 1, 2 and 3 give a good description of the operation and the characteristics of the motors used in traditional variable speed systems. When considering using variable speed motors the environment, the power supply and the economics should be carefully investigated.

14.1.1 Environment

The application of variable speed motors in the oil and gas industries tends to be for the larger pumps and compressors in the several thousands of kilowatt range. In such cases the motor and driven machine unit would often be located in a hazardous area or zone.

This greatly restricts the options available because it may not be permissible to have a motor which has slip-rings or a commutator. The only option in such cases is the squirrel-cage induction motor which would be fed from a variable frequency supply remote from the motor. There are notable exceptions, however, and one in particular is a drilling rig. Under most operating conditions on a drilling rig, the environment is actually non-hazardous, even though the area is classified Zone 2 or Zone 1. Hence for most of the time there will be no gas or vapour present in uncontrolled or unknown amounts and so the possibility of fire or explosion is negligibly small.

Drilling rigs require DC motors in the range of 500 to 800 kilowatts to drive the rotary table, draw-works, mud-pumps, winches and the propulsion system in the case of semi-submersibles. To reduce the danger of fire or explosion to even smaller levels, special ‘safe air’ purging systems are used. Safe air is continuously passed into the commutator end of the motor and vented from the drive end via appropriate fans and ducts. Even large induction motors above about 750 kilowatts will present problems for use in hazardous areas. In such cases an air purging system will be needed and the motor will be specified as a type Ex (p), see Chapter 10. Whether the motor is AC or DC it will also need to withstand, and be specified for, the full range of weather and climatic variations envisaged, e.g. hot and dry, cold and wet, high humidity, corrosive atmosphere, high winds and storms. These aspects are also addressed in Chapter 10 under the subject of types of protection against the ingress of water and solid particles.

14.1.2 Power Supply

Most power systems in the oil industry do not have variable speed drives and so the AC supply is a highly dependable and simple source of sinusoidal voltage and current. Little or no harmonics are present. If a large variable speed drive is required, and an inverter or thyristor controller of some form is used, then the combination of these equipments will cause harmonic currents to be drawn from the supply.

These harmonics will cause two secondary problems. Firstly, the harmonic currents will flow in cables, transformers and generator windings and in so doing will immediately produce harmonic volt-drops in these series circuits. This in turn will cause the voltages at various points in the system to contain harmonic components, e.g. either side of a transformer, at motor control centres and switchboards, other driving motors. Hence the voltages throughout the system will be contaminated by harmonics, a condition which is sometimes called ‘noise’. This can be troublesome and difficult to accommodate or remove. In some situations, the current drawn from the supply by the inverter or controller can be filtered and smoothed to an almost pure sine wave but this requires extra equipment which can be large, bulky and expensive.

The second effect of the harmonic currents is to induce harmonic emfs by mutual coupling, and consequently additional harmonic currents, into cables that are run close to the power cables feeding the driving motor or its controller. This is particularly troublesome for low power cabling e.g. computer cables, instrument cables, telemetry systems, telephones and communications cables, electronic circuit cables.

These induced harmonic currents and emfs can be damaging to electronic equipment in particular and troublesome to computer systems. Often the induced emfs and currents contain very ‘spikey’ components that have large peak values, and these can be difficult to remove or suppress.

14.1.3 Economics

A clear operational advantage must be obtained to justify the use of a large, variable speed motor when compared to the conventional methods of operation and design. The problems of environment and technical complexity introduced by the variable speed approach will add significantly to the unit capital costs and to the on-going maintenance costs. Since the system is bound to be more complicated and will have additional rather sophisticated equipments, the possibility of longer system down-time exists. The extra down-time will have two associated costs, one for loss of production and one for increased maintenance. The cost associated with obtaining high reliability should not be overlooked. A manufacturer that has a good ‘track record’ should eventually be chosen. Well-established technology should be used unless there is a very good reason to try out some new technology.

AC methods can be broadly divided into two groups:

a) Group 1.

A conventional AC power system is used in which the motors consume sinusoidal currents and do not produce harmonics.

Various standard types AC motors are used e.g. squirrel-cage and wound rotor induction motors, variable speed commutator AC motors.

b) Group 2.

A special AC power system is required that will contain thyristor controllers, inverters or the like, that will produce harmonics.

The system must be designed to ‘absorb’ the harmonics and the problems they could cause. The motors could be AC or DC, however, the degree of control and the scope of performance of these systems tends to be better than the more conventional approach of Group 1 above. Some very sophisticated control systems are now available. Some of the methods used in Group 1, although interesting and have been successful in the past, are now obsolete.

14.2 GROUP 1 METHODS

In this group there are three alternative possibilities that are practical. The first possibility uses an intermediate device between the sinusoidal supply and the motor to vary the magnitude of the voltage applied to the motor. Secondly, simple switching methods are available when two or three discrete speeds are required. These are usually obtained by special stator winding arrangements for squirrel-cage induction motors.

Examples in this sub-group are:-

- Star-delta stator winding.
- Pole-changing motors, e.g. PAM and NS motors.
- Special motors that have connections made to their rotor windings.

References 4 and 5 give descriptions of the PAM and other switched winding methods.

These methods find little application in the oil industry.

The third possibility includes systems that allow the speed to be continuously varied over part or all of the torque-speed characteristic of the motor. This is achieved by making special connections to the rotor or secondary circuit of the motor. Examples in this sub-group are:

- Wound rotor induction motors.
- AC commutator motors, e.g.
  - Schrage motor
  - Double-fed motor
  - Three-phase series motor
- Special combinations of machines that use the slip frequency energy of the rotor circuit e.g.
  - Kramer combination
  - Scherbius machine

All of these possibilities have become obsolete due to the availability of highly reliable electronic controllers.

14.2.1 Simple Variable Voltage Supplies

These methods provide continuously variable control of the speed over part or all of the torque-speed characteristic of the motor. One of the simplest ways of causing an induction motor speed to change is by altering the magnitude of the applied voltage to its stator. This will cause the motor torque to change in proportion to the square of the voltage, i.e. $T \alpha V^2$.

Thus, at the new voltage a new torque will be produced and this will match the load requirements at some new value of speed. The shape of the torque-slip (speed) curve of the motor will be

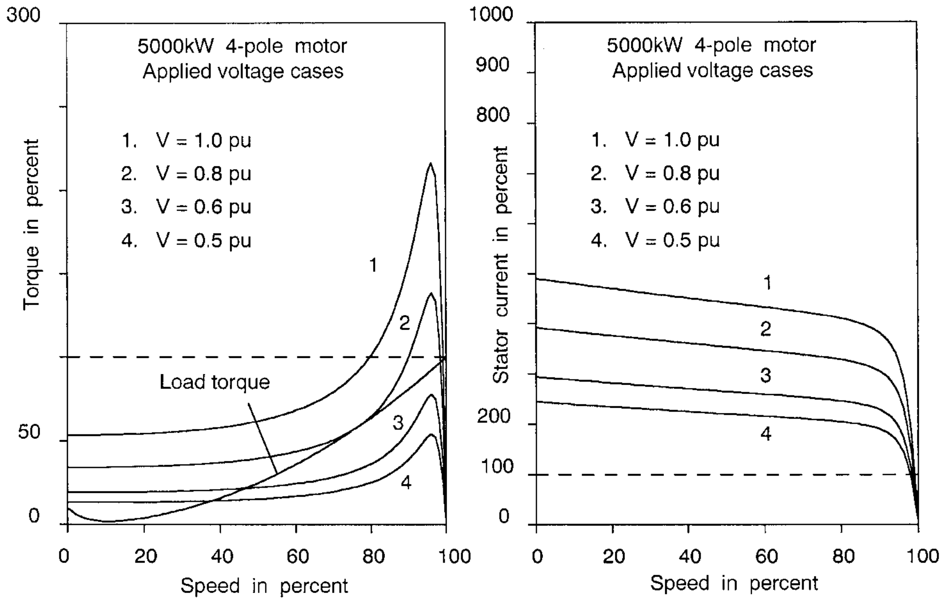

Figure 14.1 Variable applied voltage with a normal design of an induction motor.

the same as that for full voltage operation, but scaled up or down by the ratio $(V/V_r)^2$ where V is the applied voltage for the new speed and V_r is the rated voltage, see Figure 14.1.

It may be seen that if this method is used to control the speed of a standard, almost constant-speed type of induction motor, then the actual range of speed control obtained will, in fact, be small before stalling occurs. The situation could be improved by using a motor with a high rotor resistance as shown in Figure 14.2. The rotor resistance at full-load has been increased by a factor of 10 in order to demonstrate the effect on the torque-speed characteristic.

However, this method is not used for medium and large industrial drives, because of the practical difficulty in designing a high resistance rotor. If a slip-ring wound rotor design is used then an external high resistance can be added, but this method is seldom acceptable in the oil industry because of restrictions imposed by hazardous area classification.

The voltage applied to the stator can be varied in two ways:

- In steps using a transformer that has various taps on its secondary winding. This gives a course control and is used for ‘open loop’ control, i.e. no feedback regulation is used.
- Continuously by using some form of thyristor controller which will allow feedback action in the form of ‘closed loop’ control to be used to accurately regulate the speed. However, if such a scheme is used then it is the customary practice to adjust the applied frequency so as to maintain a constant air-gap flux, see 14.3.2 and 14.6.

14.2.2 Pole-changing of the Stator Winding

If an induction motor has more than two poles, e.g. four or eight, then it can be arranged to operate at two different synchronous speeds, one being half of the other. This technique is one of several which

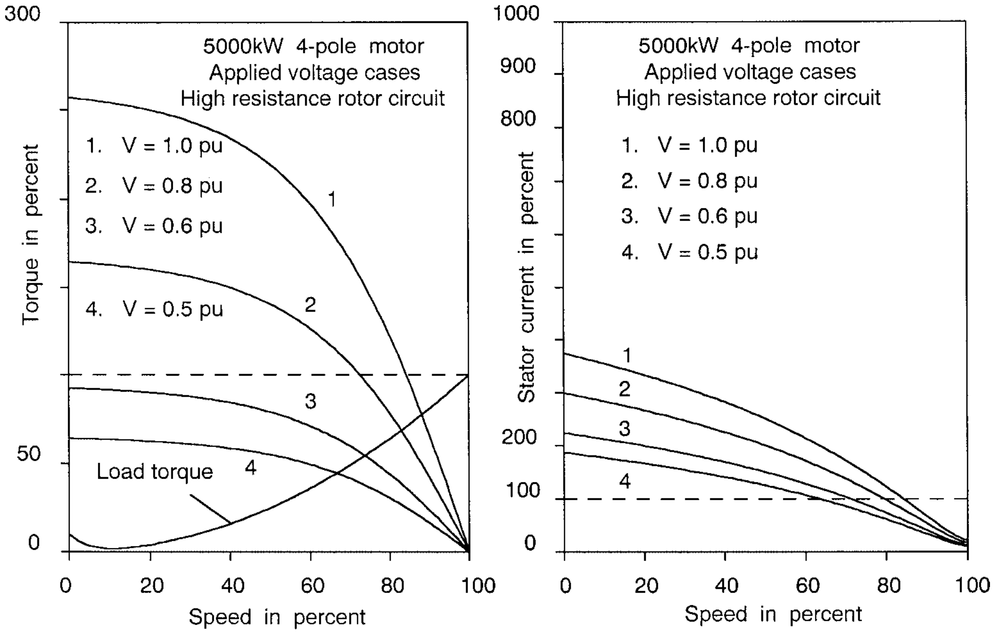

Figure 14.2 Variable applied voltage with a high resistance rotor design for an induction motor.

come under the general heading of ‘pole-changing’ motors. The method just outlined is applied to squirrel-cage motors but not to wound rotor motors.

In a multi-pole motor for eight-pole operation, the adjacent poles change in polarity from North to South around the air gap.

If half of the pole windings have their connections reversed so that the current flows in the opposite direction around the windings, then those windings will produce poles of opposite polarity. Hence each pair of adjacent poles will have the same polarity.

Therefore the resulting number of effective North and South poles will be halved and so the synchronous speed will be doubled.

Care should be taken when specifying the duty of multi-speed motors to ensure that the windings are appropriately rated for continuous or short-term duty since this may affect the amount of heat and temperature rise produced in the windings and also the effectiveness of any shaft-mounted cooling fans that may be employed.

14.2.3 Pole Amplitude Modulated Motors

A variation on the theme of pole changing is a particular type of squirrel-cage induction motor, called the Pole Amplitude Modulated (PAM) motor. PAM motors should be used for low speed applications thereby requiring many poles e.g. 10, 12, 16. In addition, the various speeds required should not be widely different. This means that the number of effective poles will not be too dissimilar, e.g. 8-pole and 10-pole operation. Commonly used two-speed pole ratios are 4/6, 6/8, 6/10, 6/12, 8/10, 10/12, 12/14, 12/16, 16/20 and 16/40. Low speed motors have many poles e.g. 16 and 24, and so complicated winding reconnections can be devised to produce more than just two speeds from the motor, as described in Reference 4. However, this is mainly of academic interest since the demand in the oil industry for such motors is rare. Three-speed ratios are 4/6/8, 6/8/10 and 8/10/12. Fractional ratios of speeds can be obtained by reversing and reconnecting only a small number of the poles or leaving some poles unexcited. Hence, an irregular distribution of poles around the stator is produced and this tends to produce harmonic torques throughout torque-slip characteristics.

Occasionally in refineries there is a need for large gas compressors to operate at two different speeds for long periods of time. If these two speeds can be matched to the pole arrangements of a multi-pole motor, then pole changing can be used satisfactorily.

These motors have been used successfully on large multi-speed air fans for power plant steam boilers. Most of the research on PAM motors took place between about 1958 and 1975 and is well documented in the proceedings of the IEE of the UK during this period.

14.2.4 Wound Rotor Induction Motors

A more versatile and satisfactory method of speed control of an induction motor is to make use of the rotor impedance. There are two basic approaches, firstly by simply adding resistance into the circuit by means of rotor slip-rings and an external static resistance bank or, secondly, by injecting a slip frequency AC voltage into the rotor circuit in such a way that the rotor current can be changed in magnitude or phase angle for any particular speed. The second method can be achieved by using rotor slip-rings or a rotor commutator, which looks and functions rather like those used on DC machines. In both approaches the essential effect is that the time phase of the flux produced by the rotor current, relative to the main flux produced by the applied voltage to the stator, is reduced to a minimum. Maximum torque is produced when this effect is achieved. If the rotor circuit is made predominantly resistive at any particular slip then the desired effect is achieved.

The simplest method of achieving the effect is to insert extra resistance into the rotor circuit. The rotor of the induction motor has to be specially wound so the winding can be split into three sections. Each section is connected to shaft-mounted slip-rings. The conductors of the rotor winding are carefully insulated from the iron core and from each other. The extra resistance is an external static unit mounted near to the motor.

If, for example, a water pump needs to be run at reduced flow rate for much of its operating time then a reasonably accurate method is to use a wound rotor motor with an external resistance. The resistance can be in the form of wire elements with various fixed tappings (for coarse control and starting) or an electrolytic tank using a water and caustic soda solution (for fine control and starting). In practice, the tendency is for this electrolytic tank to be preferred for large motors. A wide range of speed control with good torque performance is obtained by this method.

Until the introduction of thyristor and power transistor controllers a wound rotor motor with added resistance was one of the most common and simplest methods of speed control and is used for motors up to 10 MW. The main disadvantage is that the resistance bank is wasteful of energy, and the removal of the heat produced can prove difficult. The stability of the resistance of the electrolyte is also a problem since the resistance varies considerably with temperature and chemical composition of the electrolyte. Reasonably good speed regulation can be obtained by closed loop control, even though the stability of the electrolyte can introduce complications. Precise regulation is obtainable by other, more sophisticated, methods as will be described in following pages. However, now that power electronic controllers are available for even the largest motors, the use of wound rotor motors has been largely superseded and no longer used in the oil industry.

14.3 GROUP 2 METHODS

In this group there are several systems that use power electronics to provide a variable magnitude voltage at a variable frequency. Most of the systems use rectifiers and thyristors in the form of converters and inverters.

Examples are:-

- Thyristor rectifier for variable voltage but constant frequency.
- Thyristor rectifier-inverter for variable voltage and variable frequency.

These systems can be used to supply either induction or synchronous motors, although the first method is mainly used for small induction motors up to about 20 kW. The second method is suitable for motors up to about 30,000 kW. In all cases standard motor designs are used but some attention to the effects of harmonic currents and voltages is necessary on the part of the motor manufacturer.

14.3.1 Variable Voltage Constant Frequency Supply

A thyristor circuit is placed in series with the stator windings of the motor.

In each phase winding circuit there are two thyristors which are connected in parallel but with opposite polarities. This allows controlled conduction in the windings and allows the current to flow in both directions through the winding. The phase voltage is varied by delaying the firing of the thyristors and so only part of the sinusoidal waveform is applied to the motor. The average and rms values of the applied voltage are therefore reduced.

The torque produced by the motor is therefore reduced in proportion to the square of the rms value of the applied voltage. Circuits are available for both star and delta connected motors. Closed loop feedback control may be used to adjust the firing of the thyristors, thereby making accurate speed regulation possible. These systems are only used for small machines, e.g. up to 20 kW because they tend to produce many harmonic currents and voltages in the supply.

14.3.2 Variable Frequency Variable Voltage Supply

A typical basic circuit is shown in Figure 14.3 which consists of two main parts, a three-phase bridge-connected thyristor rectifier and a three-phase bridge-connected thyristor inverter.

The rectifier produces a variable magnitude DC voltage by applying control signals to the thyristor gates. The output current from the rectifier is specially filtered by a series inductance so that it is almost a pure DC current which passes through the three branches of the bridge-connected inverter in such a way that the three currents are caused to flow into the motor. This is achieved by cyclically firing the gates of the inverter and the frequency of the cyclic firing determines the AC fundamental frequency at the motor. A variable frequency oscillator is used to generate the firing pulses for the inverter thyristors. It is possible to arrange for the oscillator to accept feedback signals

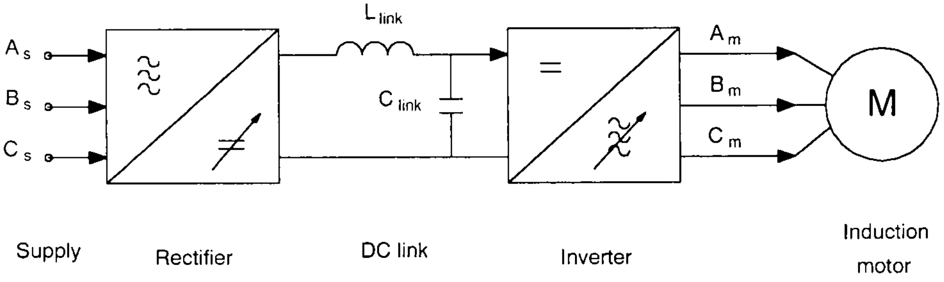

Figure 14.3 Schematic diagram of a variable voltage and variable frequency rectifier inverter system for an induction motor.

for accurate speed control and other signals for protection purposes, e.g. short circuit, and stalling, current limiting.

If an induction motor is run at a frequency below its normal operating frequency, the air-gap flux will rise if the supply voltage magnitude is kept constant. The rise in flux will cause magnetic saturation in the iron circuit of the motor and this in turn will cause a very large increase in magnetising current in the X_m branch shown in Figures 5.1 or 15.11.

The applied voltage must be reduced almost in proportion to the frequency so that the flux remains almost constant. The control of the flux is achieved by using a frequency sensing circuit to fire the rectifier thyristors. As the frequency is reduced the X-to-R ratio of the complete circuit is reduced and therefore the shape of the torque-speed curve becomes less peaked. Figure 14.4 shows the

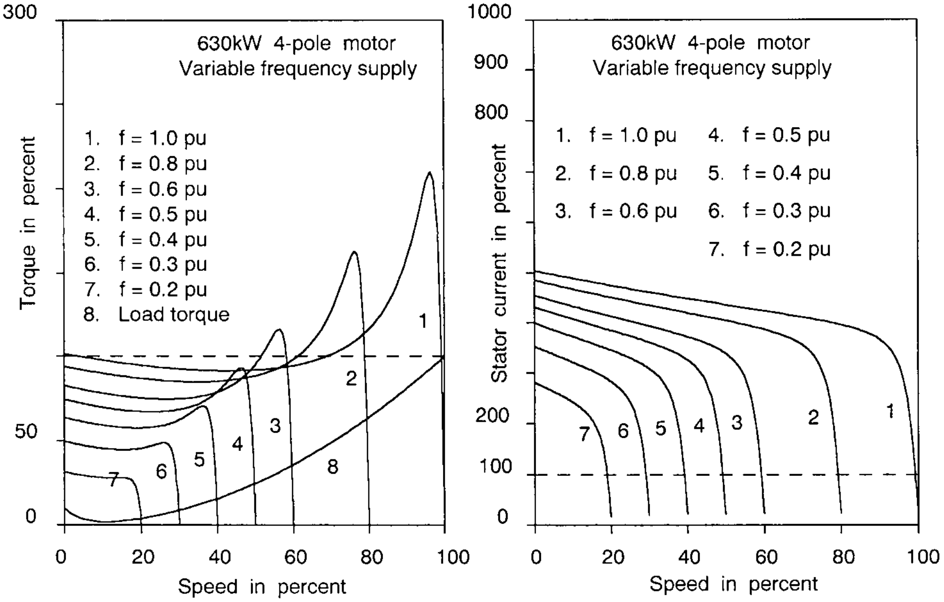

Figure 14.4 Torque and current versus speed curves of a 630 kW four-pole motor that is fed from a variable voltage and variable frequency supply. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

torque-slip characteristic for operation at various supply frequencies. This method, and its variants, is applied to the largest induction motors used in the oil industry. The method is also applied to submersible motors for 'down-hole' pumping in oil and water wells.

14.4 VARIABLE SPEED DC MOTORS

In the oil industries, DC motors are used for driving drilling rig systems, e.g. rotary table, draw-works, mud pumps and winches. Modern drilling rigs use thyristor rectifiers to supply DC power to the motors which are in the range of 700 to 800 kW. Drilling rigs do not normally require very fast reversal of speed and so reversal by means of field control is usually adequate, or if a series motor is used than a reversing switch will need to be used at zero speed and zero current.

Often the driven machine requires to be braked e.g. draw-works, anchor winches. It is possible, although not yet common practice, to use the motor as a brake for the mechanical load. This is achieved by using the load to drive the motor as a generator and to pass its current through the thyristors in their inversion mode. This requires the thyristor bridge circuit to have six thyristors and some additional electronic control circuits. Thus the motor 'supplies the supply' with energy during the braking period. The transition from motoring to braking, and from braking to motoring can be arranged to be fully automatic, without any kind of surge or disturbance at the point of changeover. The electronic circuit makes this possible.

The very flexible nature of the thyristor controller allows the motor to have accurate control plus excellent overload protection. Most thyristor controllers are furnished with maximum current limits for motor armature current and for short-circuit current protection. During conditions of rapid acceleration or heavy load the armature current will rapidly become high and so the maximum current limiter will automatically hold the armature current until the duty is reduced. Thyristor controllers also make it possible to gain accurate control of the torque or load at zero speed. This is very desirable when handling anchors and the drill string.

14.5 ELECTRICAL SUBMERSIBLE PUMPS

14.5.1 Introduction

There are many methods by which well-bore fluids can be raised to the platform or land level. In situations where high flow rates are required, the main options are:-

i) Gas lift, assuming adequate gas supply.
ii) Water flood.
iii) Electric submersible pumping (ESP).

Gas lift and water flood systems give higher reliability over ESP systems (by virtue of their operating environment at ground level or on a platform deck) but are disadvantaged by equipment weight and space requirements plus the large power demands involved. Moreover, gas lift cannot easily be installed gradually across a field on a well-to-well basis.

Electrical submersible pumps, albeit less reliable than gas and water flood systems, are utilised worldwide due to the major advantages of minimum topside weight and space requirements. The units, when properly selected, operated and maintained, provide an acceptably economic means of lifting well-bore fluids.

This sub-section deals briefly with the basic mechanical and electrical components that form the pump unit. The mechanical and electrical aspects are reviewed in this section with attention being paid to methods of speed control.

14.5.2 Electrical Submersible Pump Construction

The basic components involved are:

- Motor.
- Seal or protector.
- Pump.
- Gas separator.
- Feeder cable.
- Controller.

The pump unit must be designed to operate at very onerous levels of pressure, temperature and in the presence of contaminates such as sand, acids etc. Moreover, the unit must be suitable for lowering into a well-bore which can vary from only 150 to 300 mm in diameter. Due to diametral limitations and the necessary power requirements the motor pump unit itself becomes extensive in length, e.g. up to 10 metres. See Reference 6 for an overview of the subject of submersible pumps.

14.5.2.1 Pump motor parameters are varied

The following list provides some basic data that are applicable to ESP motors:

- Power range 20 to 700 kW.
- Applied voltage 415 to 3000 volts.
- Squirrel-cage induction motor in cascaded sections.
- Number of poles is usually two.
- The insulation needs to be superior to Class H (epoxy impregnation system).
- High grade insulating oil is used.
- Variable frequency speed control is used.

The motor can be expected to operate at a depth of 5 km or more in an hostile and acidic environment with temperatures of up to 150°C.

The oil insulant provides the means of heat transfer from motor internal components to the motor casing.

To provide the necessary power requirements within severe diametrical limits, the motor length can be up to 10 metres.

14.5.2.2 The seal or protector

The seal (or protector) operates, as its name implies, to provide a barrier between the well-base fluids and the motor. The seal is normally multi-chamber and is additionally designed to equalise the internal motor pressure and to enable the motor insulant to either expand or contract.

14.5.2.3 The separator

Depending upon the gas to oil ratio (GOR) of the well fluid and possibly pump damage, a need may arise to separate out the gas prior to pumping the well fluid to the surface.

14.5.2.4 The pump

The pump is of the centrifugal type, consisting of a multi-stage impeller and fixed diffuser. The lift and volume requirements of the pump determine the number of stages, the length of the pump and the power rating of the motor.

14.5.2.5 The cable

Cables for supplying power to the pump motor are of a specialised design and must conform to stringent requirements due to the severe operating conditions. Typically, the cable must:

- Possess ‘breath ability’ to allow trapped gases to escape during decompression when the pump is raised for maintenance.
- Use materials suitable for use in temperatures up to 200°C.
- Have smooth and flexible wire armouring.

14.5.2.6 The controller

The controller is of the variable voltage, variable frequency type, thereby providing a complete speed range for the motor at constant torque. The system inherently provides soft start which is necessary to alleviate high torsional stresses within the motor-pump unit, that may otherwise damage the shaft and couplings.

The controller, being typically designed for 2 to 3 kV, is usually supplied via a unit transformer. Because of the multi-stage nature of the motor the terminal voltage required for the motor may be non-standard and so a transformer must be used to match the motor to the power system.

The major advantages of variable frequency controllers for submersible motors are:-

- Soft start.
- Variable torque.
- Variable pumping capability to suit change in fluid pressure and flow parameters.
- System frequency up to 75 Hz, giving 25% extra motor power output.

14.6 CONTROL SYSTEMS FOR AC MOTORS

In the oil industry the use of variable speed AC motors has become a requirement for several reasons:

- Availability of economical high power inverter systems.
- Improved reliability of power electronic control systems.
- Availability of micro-computers for intelligent control and protection of the rectifier-inverter motor system.
- The modern emphasis on the conservation of energy.
- Control performance that is superior to non-electrical fluid controllers such as throttle value control and fluid couplings.
- Standard or ‘near standard’ motors can be used.

The application of speed control to a large AC motor is generally for one of two reasons, or less frequently a combination of both:

- Steady state speed control over a significant range e.g. 10% to 100%, 50% to 100%, 75% to 110%.
- To restrict the starting and reacceleration currents that the motor requires.

The steady state speed control can be easily achieved by modern control systems and the regulation about a set speed can be as low as 1% or less. In addition rapid and adequately damped responses to changes in set points or to process disturbances are standard features of most systems. The high performance of modern electronic control systems enables the sharing of loads and process duties between parallel pumps or compressors to be accurately achieved without much difficulty. These systems also allow scheduling and the admission into or the removal from service of motors to be achieved in a smooth manner. Modern protective systems for the power electronics and the motor are very comprehensive, and fast to react if required to do so.

Most oil industry power systems permit, and indeed encourage, direct-on-line starting of motors. This becomes difficult as the motor ratings are large in relation to the capacity of the main power source e.g. several gas-turbine driven generators. In large installations such as LNG plants and refineries, and along bulk oil or gas pipe lines, it is common to find motors with ratings up to 10 MW. In order to start such large motors it has become the practice to use a variable speed rectifier-inverter system as a starting device, which is sometimes referred to as a ‘soft start’ system. Whilst the starting problem has been solved by such a system, it is then a simple matter to take advantage of the variable speed controls to adjust the motor speed during its normal running operations.

The basic elements of variable speed control systems for an AC motor are shown in Figure 14.5. In practice there are several variations to the basic system, see Reference 7, Chapters 4 and 6, and Reference 8, Chapter 9. Some of the devices and signal lines, e.g. A or B, may not be used in all practical systems.

The following comments apply to the various blocks ( ) in the diagram.

The system receives its main power from a circuit breaker (6) or contactor in the upstream switchboard or motor control centre. This switchgear will contain the main power protective relays

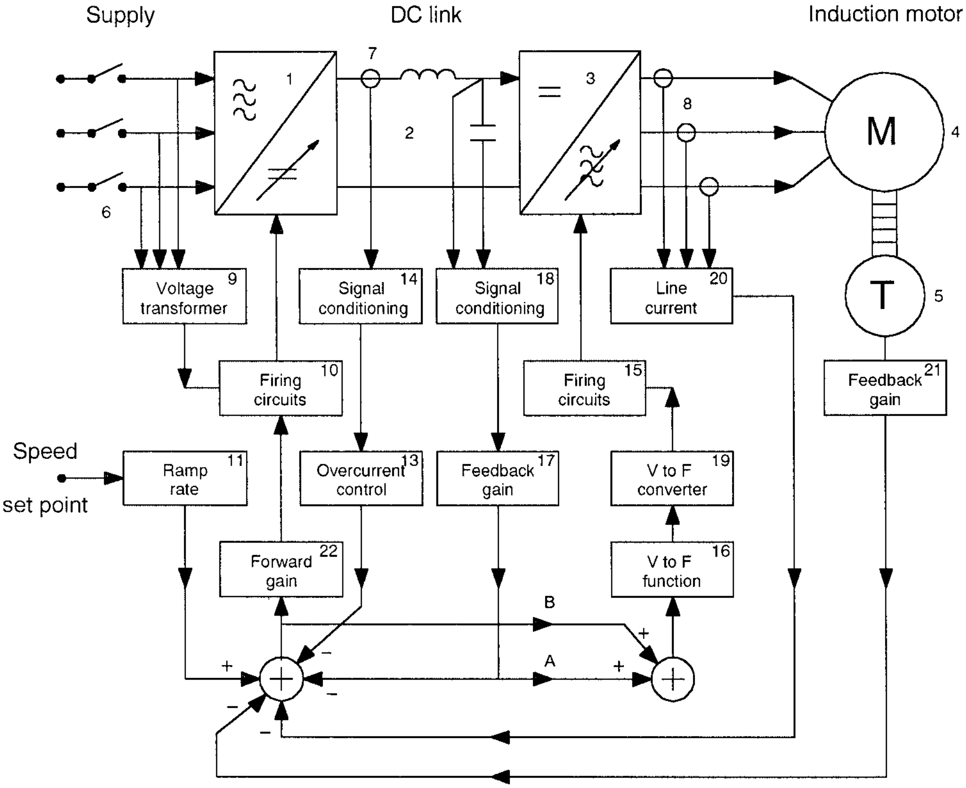

Figure 14.5 Block diagram of the control system for an induction motor fed from a variable voltage and variable frequency.

such as overcurrent, undervoltage, earth fault, and fuses if appropriate. These will protect the power circuit up to rectifier input terminals including its transformer. The transformer may be fitted with additional devices such as winding temperature detectors and a Buchholz relay which will send their alarm and tripping signals back to the switchgear. The switchgear will also receive alarm and tripping signals derived from the rectifier-DC link-inverter motor system. For example a major fault may develop in the motor which should be de-energised as quickly as possible. Failure of power diodes, thyristors and power transistors is usually taken care of by high speed fuses, whereupon fuse failure can be detected and a signal sent back to the switchgear.

Modern switchgear and variable speed controllers are available with micro-computer based control, protective and indication facilities. These can communicate between each other and to external networks by such links as fibre optics and digital hardwire networks.

The rectifier (1) may be of the 6 or 12-pulse type. The choice mainly depends upon the tolerance that is available for the harmonics, which will be injected into the upstream power system. The rectifier will be designed to provide a source of variable voltage to the DC link. The 12-pulse type will usually be necessary for the highly rated motors within their voltage level. Inside the rectifier compartment will be a set of voltage transformers (9) which will be used to derive a set of firing pulses (10) for the rectifier elements. These pulses will be in synchronism with the power supply.

The control of motor speed essentially requires two components, one for varying the terminal voltage of the motor and one for varying the frequency of this voltage. Part of the control system will contain a function generator that will convert a voltage signal into a frequency signal. As the voltage is changed so will the frequency be changed in sympathy. Above about 10% of rated voltage the characteristic of this sympathetic control will be linear dependency. Below 10% the voltage-to-frequency ratio will need to be slightly increased so as to avoid over-fluxing the iron core of the motor. Block (16) contains the appropriate characteristic. However, controlling the speed in such a low range is seldom required. During the starting sequence the motor will initially receive at least 10% of its rated voltage and frequency, thereafter it will be ramped upwards to the required steady state conditions. The ramp rate (11) will depend upon the response characteristics of the mechanical load, e.g. static torque versus speed curve, low or high moment of inertia. The ramp rate should be slower than the speed response of the driven load otherwise the operating point on the torque versus speed curve of the motor will more towards the peak value, and in the extreme situation move to the left of the peak value. During these undesirable situations the current drawn by the motor may exceed its full load value. If an overcurrent limiter (13) is incorporated then the motor will be forced to operate in the stable right-hand side of its torque-speed curve. In practice the setting of the current limiter should be a reasonable margin above the full-load current of the motor e.g. +20%, but not too high as to require an unnecessarily high current rating for the rectifier and inverter power semiconductors. The manufacture of the rectifier-inverter will often be able to advise what the upper limit should be to suit a particular driven load. The current signal taken in the DC link at (7) could alternatively be taken from current transformer in the AC supply circuit, i.e. in the switchgear or the rectifier cubicle. The voltage control of the rectifier should be of a closed-loop type which should have a reasonably high degree of regulation. The control loop can be closed by feedback (A) from the DC link voltage (17) or the inverter output (20). Signal (B) which is used to control the rectifier firing circuits (10) can also be used as an alternative to (A) for controlling the frequency of the inverter. If the cables are long then some compensation for volt-drop could be incorporated into the voltage controller. If a very small speed regulation is required e.g. less than 1% then a tacho-generator (5) will be needed, which will to some extent override the voltage feedback provided by the DC link voltage measurement blocks (17) and (18). The regulation can be adjusted by the feedback gain (21), the more the feedback the lower the regulation. However, the system has time constants in most of the blocks and so the overall transfer function is likely to become unstable if the feedback gain (21) or the forward path gain (22) is too high. Without the tacho-generator the inverter-motor system is open-loop unless a frequency signal is derived from the measurement of current or voltage in block (20).

Block (19) is an oscillator in which its frequency is controlled to be directly proportional to its input DC signal from the characteristic block (16).

Some manufacturers recommend using a filter at the output of the inverter to smooth the waveform applied to the motor and to reduce the sharp rise and fall in the notches that may be present, as in the case of current-fed motors. Steep sided notches cause a high dV/dt across the insulation of the motor, which can reduce the life expectation of the insulation. The filter may also be required to reduce electromagnetic interference (EMI).

Modern fast-acting micro-computers are capable of storing and manipulating a reasonably detailed mathematical model of the motor. It is therefore possible to compute the model in ‘parallel’ with the actual motor and compare the computed variables with those measured at the output of the inverter. An algorithm can be developed that will adjust the rectifier and inverter set-points so that the actual motor responds more like the mathematical model. An advantage of such a scheme is the ability of the model to store the non-linear parameters of the motor e.g. stator and rotor resistances as functions of slip, saturation of the magnetising reactance, stator and rotor reactances also as functions of slip. Hence the 'deep-bar' effects in the rotor can be taken into account. In such a scheme the use of a tacho-generator may not be needed to improve the speed regulation. The necessary parameters, with their non-linearities, can be obtained from factory tests near to the time when the motor is to be delivered to site.

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15

Harmonic Voltages and Currents

15.1 INTRODUCTION

It is generally understood that the voltages and currents in industrial power systems are sinusoidal quantities with a frequency of usually 50 Hz or 60 Hz. The design of these systems is based on an assumption that the voltages and currents are not distorted by harmonic components. In the majority of power systems this assumption is true and the effects of harmonics can be ignored.

However, occasions do arise when the design must take account of harmonics. Such consideration may be necessary at the beginning of a new project, or for a plant that already exists. In the first case the minimisation of the bad effects of harmonics is reasonably easy to accomplish. The second case for existing plants it is usually more difficult due to constraints that may not be removable or reducible.

The main sources of harmonics in power systems are:-

- Magnetic saturation in the stators and rotors of generators.
- Geometry of the windings in the stators and rotors of generators.
- Magnetic saturation in transformer cores.
- Non-linear consumers such as battery chargers, uninterruptible power supplies, fluorescent light fittings.
- Rectifiers and inverters for major consumers such as DC and AC motors.

The presence of harmonics caused by magnetic saturation and winding geometry of generators and transformers can be minimised from the outset by carefully specifying the design requirements of these equipments before they are purchased. Such specification may incur some small extra cost at the purchasing stage. For example if the operating flux density in these equipments is kept near to or below the knee-point of their saturation characteristics, then this will usually require a greater volume of iron in their magnetic circuits. This in turn will tend to make the equipment larger in its principal dimensions, and therefore more expensive.

The creation of harmonics by minor consumers can usually by minimised or eliminated by the use of shunt-connected capacitors, simple internal filters or smoothing circuits. This is again a matter of specification before purchasing the equipment.

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The use of rectifiers and inverters for variable speed motor drives is becoming common in the oil industry, especially for large gas compressors and oil pumps. Adding these to an existing power system can create problems that are difficult to solve, even if they are furnished with harmonic filters. Power systems that have long high-voltage feeder cables, such as submarine cables between platforms, are particularly sensitive to harmonic currents created by rectifiers-inverter loads. The amount of shunt capacitance in these cables can be enough to cause a resonant condition at a low multiple of the fundamental e.g. 5, 7, 11, 13. These low frequency harmonics usually exist at a magnitude that cannot be ignored in such situations. This can present the power system engineer with a difficult task in designing a suitable anti-resonant filter. The remainder of this chapter is concerned only with harmonics caused by variable speed motor drives.

The theoretical operations of rectifiers and inverters under steady state and transient conditions are described in many publications, for example References 1 to 6.

Reference 2 also describes the ‘on-off’ characteristics of the power semiconductors used in the bridges e.g. diodes, thyristors, triads, gate turn-off thyristors and bipolar power transistors. Only the steady state operations of bridges are described herein. For such operations it is assumed that the load is well matched to the rating of the bridge. The remainder of this section is an introduction to the subject of harmonic voltages and currents that are caused by variable speed systems for DC and AC motors. It emphasises the main aspects that affect the supply power systems.

15.2 RECTIFIERS

15.2.1 Diode Bridges

Power rectifiers rated above a few kVA are usually three-phase units and occasionally six-phase units. The bridge elements may be diodes, thyristors (silicon controlled rectifiers) or power transistors operated as switches.

Diode bridges are the simplest and are suitable where the output DC voltage is constant and related to the input AC voltage by a fixed factor. They are well suited to battery chargers, uninterruptible power supplies and cathodic protection units. Figure 15.1 shows the basic element of a three-phase diode bridge, in this case the rectifier elements R_1 to R_6 and diodes, not thyristors as shown.

15.2.1.1 Commutation

The transfer of the load current from one diode to the next is called ‘commutation’. This takes place when the potential at the anode of the first diode has fallen to a value equal to the rising potential at the anode of the second diode. Shortly after the transfer is initiated both diodes conduct the current and a temporary short circuit exists across the two phases supplying the diodes. Since the short circuit contains the leakage reactance of the supply transformer, plus the impedance upstream of the transformer, there is sufficient inductance to delay the rise in current in the second diode. Hence the current rises exponentially from zero to a value equal to the DC load current. At this point the commutation is complete and the first diode ceases to conduct. The finite time taken by the commutation process is related to the periodic time of the supply voltage by defining an angle ‘u’ called the commutation angle. As the load current is increased the commutation time is increased and so the angle u increases. At no-load the angle u is zero. At full-load the angle u is between zero and 60° for properly designed bridges, and in practice u will be in the order of 10° if a good power factor is to be obtained, as shown in Table 15.1.

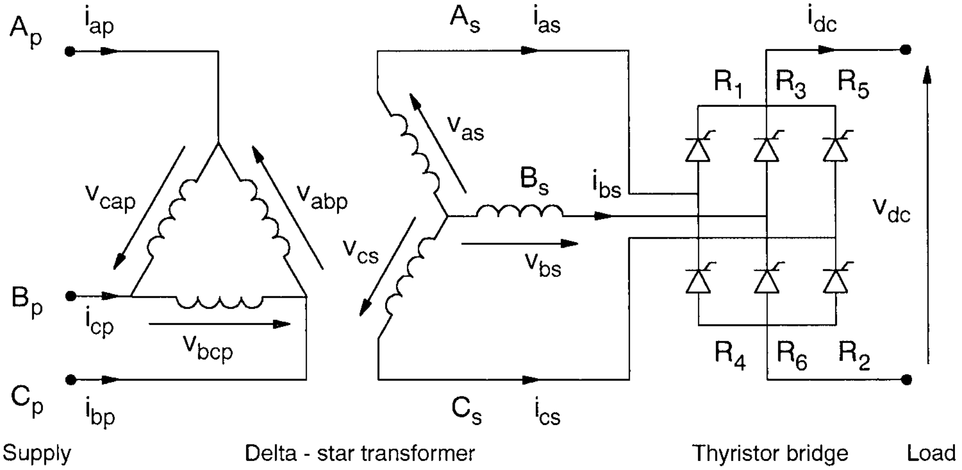


Figure 15.1 Circuit diagram of a six-pulse thyristor bridge.

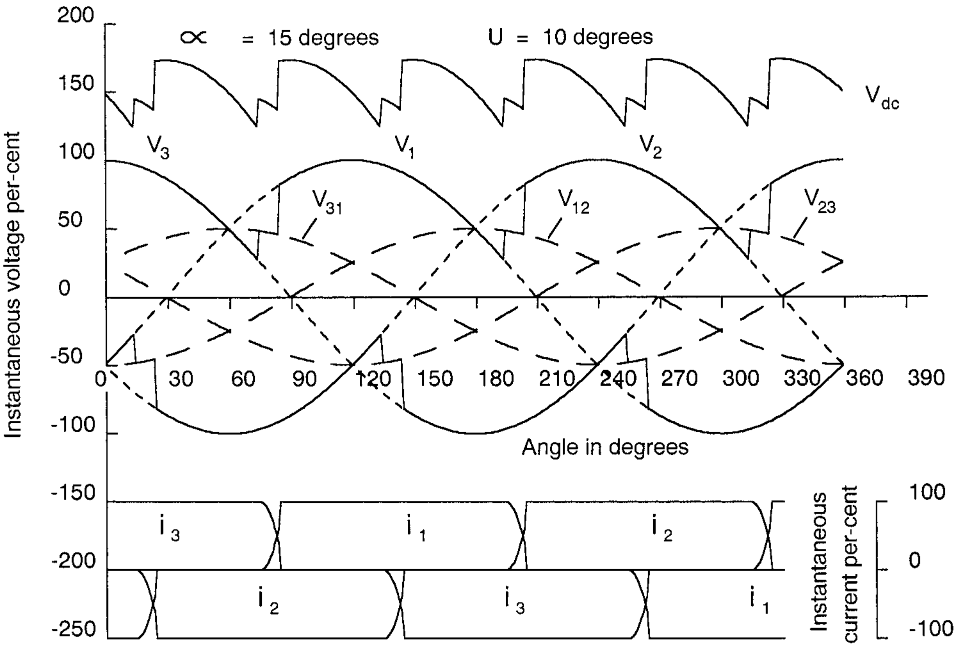


Figure 15.2 Voltage and current in six-pulse thyristor bridge.

When the angle *u* is within the range of zero to 60° the current in each phase of the supply is discontinuous as it crosses over at its zero value, and is almost trapezoidal, as shown in Figure 15.2.

This type of operation is often called 'Mode 1' and includes load currents that are within the rating of the bridge and its supply transformer. If the bridge needs to carry a higher current then the commutation is modified. The maximum commutation angle *u* is 60° and thereafter the commutation occurs in the negative half of the bridge because the decaying current has not yet reached zero.

A time delay is incurred until the zero is reached, and the corresponding angle is 'α' which is called the 'delay angle'. This angle occurs from zero to 30°, and the type of operation is called 'Mode 2'.

If the load current is further increased a new condition arises, called 'Mode 3' operation. The decaying current requires more time to reach zero. During this extra time there is a short-term three-phase short circuit and the output voltage is discontinuous at zero for this period. The output voltage appears as a train of saw-toothed pulses. The average value of this voltage is capable of driving more current into the load. As this occurs the delay or 'retardation angle γ' increases until it eventually reaches 60°, at which angle there is a complete three-phase short circuit and the output voltage is zero. During the increase in retardation angle the AC phase currents change their shape from a quazi-trapezium to a pure fundamental sine wave. The AC current is then limited only by the impedance of the transformer and any impedance upstream.

References 7 and 8 describes these commutation process in relation to the use of diode bridges in the main rotor circuits of synchronous generators.

15.2.1.2 Harmonic components

The waveform of the current in the secondary winding, phase AS of Figure 15.1 is shown in Figure 15.2 in relation to its phase voltage. The operating condition is for angle $u = 10°$ in Mode 1, when the delay angles α has a nominal value 15°.

As the three angles u, α and γ increase the current waveform moves to the right of the phase voltage waveform. The centre of the current waveform is approximately the position of the peak value of the fundamental current component. Consequently as the current increases the power factor of the fundamental current decreases. Table 15.1 shows values of the harmonic components of current and the power factor as the retardation angle u is increased from zero to 60°. The fundamental component is taken as unity reference at each value of u.

15.2.2 Thyristor Bridges

Thyristors used in rectifier and inverter bridges are usually of two types. The first type is a three-terminal semiconductor that can only be turned 'on' by a control or 'firing' signal applied to its

Table 15.1. Operating modes of a three-phase diode bridge

Mode	Rectifier angles			Approximate	
	u	α	γ	Power factor angle ϕ	Power factor $\cos\phi$
1	0	0	0	0	1.0
1	20	0	0	13.1	0.974
1	45	0	0	29.6	0.870
1	60	0	0	39.1	0.776
2	60	15	0	50.3	0.639
2	60	30	0	63.0	0.454
3	60	30	15	74.6	0.266
3	60	30	30	82.9	0.124
3	60	30	60	90.0	0.0

'gate'. It cannot be turned 'off' by the control signal. It can only be turned 'off' by forcing the anode current to zero, which is achieved by a special circuit that is connected across the anode and cathode, see References 6 and 9. This was the first type to be developed. In recent years a second type has been developed that can be turned 'off' by applying a reversed polarity control signal to the gate. This device is usually called a 'gate turn off' thyristor or GTO. Both devices are either in their fully 'on' state or their fully 'off' state when operating in normal bridge circuits. There is not an intermediate state such as found with transistors.

Thyristor bridges are used where the DC output voltage needs to be varied. For example for control purposes such as varying the speed of motors or for protective purposes such as limiting the maximum DC output current that can flow when an external short circuit occurs.

The basic circuit of a thyristor bridge is almost the same as that for a diode bridge. The essential differences are the replacement of the diode elements by thyristor elements, the inclusion of a controlled firing system for the thyristor gates, and in some cases the application of forced commutation circuits, see Figure 15.1.

15.2.2.1 Commutation

The commutation processes for Mode 1 operation of delay and current transfer are essentially the same as the diode bridge, except that the delay angle α is now controlled instead of occurring naturally and can be extended to 90° from 60°. The current transfer occurs in the same manner and gives rise to the same angle u.

Control of the triggering pulses to the thyristors needs to be carefully managed when the commutation is in Modes 2 and 3, otherwise the operation of the bridge may become unstable, see Chapter 7 of Reference 1.

The normal control range of the delay angle α is from zero to 90°, over which the average DC output voltage decreases from its maximum value to zero. In a good design of the bridge, with an appropriate reactance in the supply transformer and enough inductance in the DC load circuit, the practical operating region is ensured to be within the Mode 1 operating range. If the load is a motor then it will produce an emf that has a magnitude roughly in proportion to the shaft speed. During transient disturbances there may be a wide mismatch between the output voltage of the bridge and the emf within the motor. The mismatch will cause a large current to flow, e.g. if the motor suddenly stalls, which may drive the bridge into a Mode 2 or 3 operation unless the protective control circuits rapidly take corrective action to prevent such operation.

15.2.2.2 Harmonic components

The shape of the waveform for the AC current in the supply lines to the bridge will be the same as that for the diode bridge. Hence the harmonic analysis will yield the same results for practical operating conditions. Table 15.2 shows the harmonic components for the range of u between zero and 60°. The fundamental component is taken as reference.

15.2.2.3 Distortion upstream of the bridge

The installation of a rectifier bridge that has a relatively high power rating with respect to its supply will cause significant distortion to the supply line currents and line voltages.

Table 15.2. Variation of harmonic coefficients with the commutation angle u

Harmonic number	Magnitude of the coefficient b_n at different values of u in degrees							
u	0.01	0.25	1.0	5.0	10.0	20.0	40.0	60.0
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	0.2001	0.2001	0.2001	0.1986	0.1941	0.1766	0.1152	0.0400
7	0.1429	0.1429	0.1429	0.1409	0.1345	0.1106	0.0384	0.0204
11	0.0911	0.0910	0.0910	0.0878	0.0779	0.0449	0.0156	0.0083
13	0.0771	0.0771	0.0771	0.0732	0.0618	0.0262	0.0171	0.059
17	0.0591	0.0590	0.0590	0.0540	0.0398	0.0035	0.0035	0.035
19	0.0529	0.0529	0.0529	0.0473	0.0320	0.0028	0.0028	0.0028
23	0.0438	0.0438	0.0438	0.0370	0.0199	0.0085	0.0055	0.0019
25	0.0403	0.0403	0.0403	0.0331	0.0153	0.0088	0.0031	0.0016
29	0.0349	0.0349	0.0344	0.0266	0.080	0.0066	0.0023	0.0012
31	0.0326	0.0327	0.0327	0.0239	0.0052	0.0047	0.0031	0.0011

The near-rectangular line currents will produce volt-drops in the series resistance-reactance cables, overhead lines and transformers. These volt-drops will be non-sinusoidal and will distort the waveform at their intermediate points of connection. At such points there may be a switchboard or distribution board and the loads connected to them will experience the distorted voltage waveform.

The line voltage waveform at the primary terminals of the transformer that feeds the bridge will be distorted by the short commutation pulses. These are often called ‘notches’. At the thyristors or diodes the notches have a near-zero base due to the temporary short circuit during the commutation. Immediately upstream of these elements is the impedance of the transformer, and beyond that the impedance to the main source of supply. A potential divider circuit exists between the bridge elements and the source of supply. Consequently the higher the transformer impedance the lower will be the impact of the commutation notches. Suppose the bridge is fed from a motor control centre that has its own feeder transformer. Since the feeder transformer and its upstream circuit has a finite impedance, there will be a certain amount of distortion to the voltages at the busbars of the motor control centre. The notching distortion injects high frequency currents into all the loads and instrumentation connected to the busbars. In many situations the loads are not sensitive to this form of distortion, but a few in a particular situation may be adversely affected, especially power factor correction capacitors and capacitors in fluorescent light fittings (if fitted). Retrofitting filters to an existing set of loads on a switchboard or motor control centre may be a difficult task to complete satisfactorily. Some instrumentation within or supplied from the switchgear may be requiring timings pulses or triggering signals that are derived from the busbar voltages. These signals may be disrupted by the presence of notching distortion.

The presence of high frequency harmonics in the power supply lines leaving the switchgear can cause mutual coupling to electronic and telecommunication cables if they are routed in close proximity to the power cables. This can occur especially if the cable racks run parallel to each other over an appreciable distance. As a ‘rule-of-thumb’ guide, derived from Table 13.1, the spacing (d) between power and electronic cables should be at least,

$$d \geq 300 + 1.75 I_n \text{ millimetres}$$

Where I_n is the current rating of the power cable.

The spacing need not be greater than about 1000 mm unless the parallel route length is very long.

15.2.3 Power Transistor Bridges

In recent times there has been a rapid development in the design of high-power transistors, to such an extent that they are feasible alternatives to thyristors for many applications. The main advantage of transistors is that they can be switched ‘on’ and ‘off’ at any point in the conducting half-cycle that can appear across their emitter and collector terminals. They must be protected against the reversal of voltage when the second half-cycle appears across the terminals. It is therefore possible to synthesise the waveforms in such a manner as to reduce the harmonic distortion at the supply terminals to a low level.

Although a power transistor can be controlled over its whole operating range from being fully ‘off’ to being fully ‘on’, it is not usually operated in the intermediate state. This is because the inherent resistance of the device in the intermediate state causes a very large amount of heat to be developed in the transistor itself, which if not properly conducted away from the transistor will cause thermal instability and permanent damage. In the ‘off’ state the current in the transistor is negligibly small and its collector-to-emitter voltage will be high. Hence the product of voltage and current will be very small. When the transistor is fully ‘on’ the current will be high and the collector-to-emitter voltage will be small, but not negligible. Hence the power dissipated by the product of a high current and a small voltage will again be small, but a definite amount of heat will be dissipated. This amount can normally be conducted away by using standard designs of air fins or ‘heat sinks’. See also Reference 9.

15.2.4 DC Motors

15.2.4.1 Voltages and currents

Variable speed DC motors are mainly used in the oil industry for driving drilling equipment such as the drill string, draw-works, mud pumps, cement pumps, winches and the propulsion systems in semi-submersible rigs and barges. They are typically rated at approximately 800 kW, 750 volts, and several motors may be operated mechanically in parallel e.g. the draw-works motors. Each bridge that supplies a motor has a typical current rating of 2250 amps. Within its control system is a manually adjustable current limiting potentiometer to safeguard the bridge and to limit the torque produced by the motor. The bridges are fed from a three-phase 600 volt power source which is usually earthed by a high resistance fault detection device, that gives an alarm but does not trip the source.

Assume that the secondary phase-to-neutral emf of the supply transformer is E and the fundamental reactance of each phase winding is X_l, and the DC load current is I_d, then for Mode 1 operation the DC output voltage V_d is,

$$V_d = \frac{3\sqrt{6}E}{\pi}\cos\alpha - \frac{3X_c I_d}{\pi} = I_d R + E_m \qquad (15.1)$$

Where R is the DC circuit resistance.
E_m is the emf in the motor armature.
$X_c = 2X_l$ is the commutating reactance.

An alternative expression for V_d in terms of the commutation angle u, is,

$$V_d = \frac{3\sqrt{6}E}{2\pi}(\cos\alpha - \cos(\alpha + u)) \tag{15.2}$$

Hence it can be seen that u is a function of I_d, as will be shown below.

The factor $3\sqrt{6}/\pi$ applies to a three-phase bridge and is derived from,

$$V_{do} = 2E\left(1 - \cos\left(\frac{4\pi}{n}\right)\right)^{1/2}\left(\frac{n}{\pi}\right)\sin\left(\frac{\pi}{n}\right)$$

Where n is the ripple number, in the above case $n = 3$

and V_{do} is the average ripple voltage at no-load.

The current I_d can also be given as a function of α and u,

$$I_d = \frac{\sqrt{6}E}{2X_c}(\cos\alpha - \cos(\alpha + u)) \tag{15.3}$$

It can be seen from (15.1) that for a given delay angle α the output voltage has declining or 'drooping' value as the DC current rises, for example as the load on a motor is increased causing it to slow down and to reduce its emf. Figure 15.3 shows a family of curves of output voltage against current, as a function of angle α.

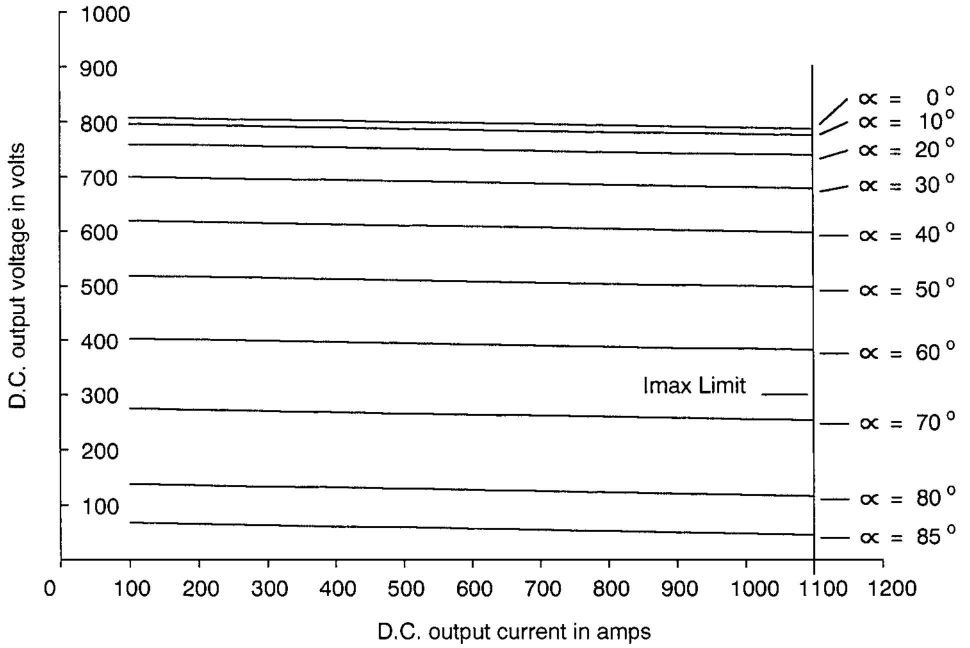


Figure 15.3 Voltage versus current regulation of DC thyristor bridge used for a drilling system DC motor.

The power factor of the fundamental phase current in the reference phase of the secondary winding can be found from the in-phase and quadrature Fourier coefficients of the current. Let these be a_1 and b_1 respectively. Hence the fundamental instantaneous current is,

$$\begin{aligned} i_1 &= \hat{I}_1(a_1 \sin \omega t + b_1 \cos \omega t) \\ &= \hat{I}_1 c_1 \sin(\omega t + \varnothing_1) \end{aligned}$$

Where the power factor is $\cos \varnothing_1$, and the suffix 1 refers to the fundament component.

Reference 4 gives an expression for a_1 and b_1 in terms of the angles α and u that is suitable for Mode 1 operation,

$$a_1 = \cos \alpha + \cos(u + \alpha) \tag{15.4}$$

and

$$b_1 = \frac{\sin(2\alpha + 2u) - \sin 2\alpha - 2u}{2[\cos \alpha - \cos(u + \alpha)]} \tag{15.5}$$

where α and u are in radians.

From which,

$$c_1 = \sqrt{{a_1}^2 + {b_1}^2} \tag{15.6}$$

and

$$\cos \varnothing_1 = \frac{a_1}{c_1}$$

and

$$u = \cos^{-1}\left(\frac{\pi R - 3X_c}{\pi R + 3X_c}\right) \text{ radians} \tag{15.7}$$

The fundamental components of the rms current I in the phases of the secondary winding are,

Real part,

$$I_r = \frac{I_d}{\pi}\sqrt{\frac{3}{2}}a_1 \tag{15.8}$$

and

Imaginary part,

$$I_i = \frac{I_d}{\pi}\sqrt{\frac{3}{2}}b_1 \tag{15.9}$$

and the rms magnitude is,

$$I = \frac{I_d}{\pi}\sqrt{\frac{3}{2}}c_1 \tag{15.10}$$

The coefficient c_1 has a maximum value of 2 when α is zero and the commutation angle u is assumed to be negligibly small.

In this case the maximum rms value of I is,

$$I_{\max} = \frac{I_d}{\pi}\sqrt{\frac{3}{2}2} = \frac{\sqrt{6}}{\pi}I_d \qquad (15.11)$$

15.2.4.2 Active and reactive power

The rectifying elements of the bridge are assumed to be free of ohmic power losses. Therefore the power input to the DC motor must be equal to the AC power input to the bridge. Hence the sum of the active power in each phase of the supply transformer must equal the motor input power.

The input power P_d to the motor is,

$$P_d = V_d I_d \qquad (15.12)$$

The output volt-amperes of the transformer is,

$$S_{\text{sec}} = 3EI = \frac{3EI_d}{\pi}\sqrt{\frac{3}{2}}c_1 \qquad (15.13)$$

The active and reactive powers at the output of the transformer are,

$$P_{\text{sec}} = \frac{3EI_d}{\pi}\sqrt{\frac{3}{2}}a_1 \qquad (15.14)$$

and

$$Q_{\text{sec}} = \frac{3EI_d}{\pi}\sqrt{\frac{3}{2}}b_1 \qquad (15.15)$$

The power factor of the fundamental current I is,

$$\cos \emptyset_1 = \frac{P_{\text{sec}}}{S_{\text{sec}}} = \frac{a_1}{c_1} \qquad (15.16)$$

15.2.4.2.1 Worked example

Certain operations that take place when drilling oil wells require the DC motors to operate at reduced speed and to produce a moderate or high torque, e.g. reaming holes, running casing, stuck pipe removal, working over a well. Consider an example where a draw-works is running casing and several series-wound motors operate in parallel to drive the line drum.

The motor design details are

Rated output power	750 kW
Rated efficiency	93%
Rated voltage	750 volts
Rated current	1075 amps
Rated speed	975 rev/min
Rated torque	7350 nm
Armature and field circuit resistance (hot)	0.0488 ohms
Armature and field circuit inductance	0.006 henry

The motor running details are,

Running output power	217.8 kW
Running voltage	323.3 volts
Running current	761.1 amps
Running speed	400 rev/min
Running torque	5200 nm
Running input power	246.1 kW

The transformer that feeds the bridge has the following ratings,

Rated kVA	6000
Voltage ratio, volts/volts	11,000/600
Leakage reactance in per-unit	0.04
Leakage reactance at 346 volts/phase	0.0024 ohms

Commutating reactance $= 2 \times 0.0024 = 0.0048$ ohms.

For (15.1) the variables and parameters are,

$$\begin{aligned} V_d &= 323.1 \text{ volts} \\ E &= 346.0 \text{ volts} \\ I_d &= 761.1 \text{ amps} \\ X &= 0.0048 \text{ ohms} \end{aligned}$$

Therefore,

$$\begin{aligned} 323.1 &= \frac{3\sqrt{6} \times 346}{\pi} \cos\alpha - \frac{3 \times 0.0048 \times 761.1}{\pi} \\ &= 810.285 \cos\alpha - 3.4886 \\ \cos\alpha &= \frac{326.59}{810.29} = 0.4033 \\ \alpha &= 66.215 \text{ degrees} \end{aligned}$$

From (15.2)

$$\begin{aligned} 323.1 &= \frac{3\sqrt{6} \times 346}{2\pi} (0.4033 + \cos(66.215 + u)) \\ 0.7975 &= 0.4033 + \cos(66.215 + u) \\ u &= 66.215 - 65.677 = 0.538 \text{ degrees} \\ &\qquad\qquad\qquad\quad = 0.00939 \text{ radians} \end{aligned}$$

From (15.4)

$$\begin{aligned} a_1 &= \cos 66.215 + \cos 66.753 \\ &= 0.4033 + 0.3947 = 0.7980 \end{aligned}$$

$$\begin{aligned}
b_1 &= \frac{\sin(2\times 66.753) - \sin(2\times 66.215) - 2\times 0.00939}{2(0.4033 - 0.3947)}\\
&= \frac{0.7253 - 0.7381 - 0.01878}{0.0172}\\
&= -1.834 \text{ indicating a lagging power factor}
\end{aligned}$$

From (15.8), (15.9) and (15.10)

$$\begin{aligned}
I_r &= +\frac{761.1}{\pi}\sqrt{\frac{3}{2}}\quad 0.798 = +236.8 \text{ amps}\\
I_i &= -\frac{761.1}{\pi}\sqrt{\frac{3}{2}}\quad 1.834 = -544.2 \text{ amps}
\end{aligned}$$

and

$$\begin{aligned}
I &= \frac{761.1}{\pi}\sqrt{\frac{3}{2}}\quad (0.7680^2 + 1.834^2)^{1/2}\\
&= 593.46 \text{ amps per phase}
\end{aligned}$$

From (15.13), (15.14) and (15.15) the volt-amperes at the bridge AC terminals are,

$$S_{\text{sec}} = P_{\text{sec}} + jQ_{\text{sec}}$$

Where

$$\begin{aligned}
P_{\text{sec}} &= \frac{3\times 346.0\times 761.1\times 0.7980\times 1.2247}{3.1415926}\\
&= 246.09 \text{ kW}
\end{aligned}$$

and

$$\begin{aligned}
Q_{\text{sec}} &= \frac{3\times 346.0\times 761.1\times 1.834\times 1.2247}{3.1415926}\\
&= 565.52 \text{ kVA}_r
\end{aligned}$$

and

$$S_{\text{sec}} = 616.75 \text{ kVA}$$

The power factor of the fundamental current is,

$$\cos \varnothing_1 = \frac{246.09}{616.75} = 0.3990 \text{ lagging}$$

or

$$\frac{a_1}{c_1} = \frac{0.7980}{\sqrt{0.7980^2 + 1.834^2}} = 0.3990 \text{ lagging}$$

Note, a 'rule-of-thumb' expression for the power factor is,

$$\cos \text{Ø}_1 \simeq 0.7\frac{\omega_o}{\omega_n} + 0.2$$

Where ω_o is the running speed of the motor and ω_n is the rated speed of the motor.

Hence,

$$\begin{aligned}\cos \text{Ø}_1 &\simeq \left(0.7 \times \frac{400}{975}\right) + 0.2\\ &= 0.4872 \quad \text{which is a little optimistic but a satisfactory estimate.}\end{aligned}$$

15.3 HARMONIC CONTENT OF THE SUPPLY SIDE CURRENTS

15.3.1 Simplified Waveform of a Six-pulse Bridge

In a well-designed rectifier-load system the inductance in the DC circuit may be assumed to be sufficiently large to completely smooth the DC current. In practice the smoothing is not perfect but adequate for the performance of the bridge. In the ideal situation the shape of the current in the three lines that supply the bridge are rectangular in shape, when the commutation angle u is assumed to be zero. A positive rectangle of duration 120° is followed by a pause of zero value and a duration of 60°. A second rectangle of negative magnitude follows in the same form as the positive rectangle. In this simplified situation only the magnitude of the rectangle changes with loading of the bridge, the sides of the rectangles do not change shape or position relative to each other. Hence the harmonic components of the AC currents remain constant with loading.

For the simplified situation the harmonic coefficients of the AC currents are only odd coefficients, and all triple coefficients are absent. The coefficients may be summarised as,

$$\begin{aligned}\frac{I_n}{I_1} &= \frac{1}{n}, \quad \text{for } n = 5, 7, 11, 13, 17, 19 \text{ etc.}\\ n &= 6k \pm 1\end{aligned}$$

Where $k = 1, 2, 3, \ldots, \infty$. The lowest harmonic present is the fifth.

For the purpose of Fourier analysis assume that the positive 120° rectangle is placed with the centre at $\pi/2$ on the x-axis, and the centre of the negative rectangle at $3\pi/2$. The analysis will yield only coefficients for the sine terms. Assume the amplitude $i_{\max}$ of the rectangle is 1.0. The Fourier integration yields the harmonic coefficients as,

$$b_n = \frac{1}{n\pi}\left(\cos\frac{\pi n}{6} - \cos\frac{5\pi n}{6} - \cos\frac{7\pi n}{6} + \cos\frac{11\pi n}{6}\right) \text{ and } a_n = 0$$

$$i(\omega t) = i_{\max}\sum_{n=1}^{n=\infty} b_n \sin \omega t \tag{15.17}$$

Let b_n be denoted as b_{n120} for use in sub-section 15.3.4.

The lowest harmonic present is the fifth.

The value of the fundamental coefficient b_1 is,

$$b_1 = \frac{1}{\pi}\left(4\frac{\sqrt{3}}{2}\right) = \frac{2\sqrt{3}}{\pi}$$

15.3.2 Simplified Commutation Delay

In practice the commutation delay angle is in the order of a few degrees. When the waveform of AC current is drawn it is difficult to distinguish a difference between a sloping straight line and an exponential line for the 'vertical' faces of the waveform. For this reason it is acceptable to assume a straight line and treat the waveform as a trapezium, as for example, in Reference 1, Chapter 9. Figures 15.4 and 15.5 show a trapezoidal waveform for two values of commutation angle $u = 20^\circ$ and $u = 50^\circ$. It can be seen that as u increases from zero the right-hand side face moves to the right and reduces the zero valued gap from 60° to zero. As a result the coefficient of each harmonic component diminishes from $1/n$ to $1/n^2$, which may be expected because a trapezium is a closer approximation to a sine wave than the rectangular pulse. Table 15.2 shows the reduction in coefficient magnitudes as the commutation angle u increases over its theoretical range. The method of calculation was by numerical integration, as described for example in References 10 and 11, which is sufficiently accurate for practical purposes. It can be seen that for practical values of u the approximation of commutation by a sloping straight line can even be ignored, and the simple rectangle pulse is adequate for all practical steady state loading of the bridge.

15.3.3 Fourier Coefficients of the Line Current Waveform

The Fourier coefficients of the line current waveform for the sine and cosine components can be found by integrating the waveform over any period of π, or 360°. The waveform is shown in Figure 15.4 or

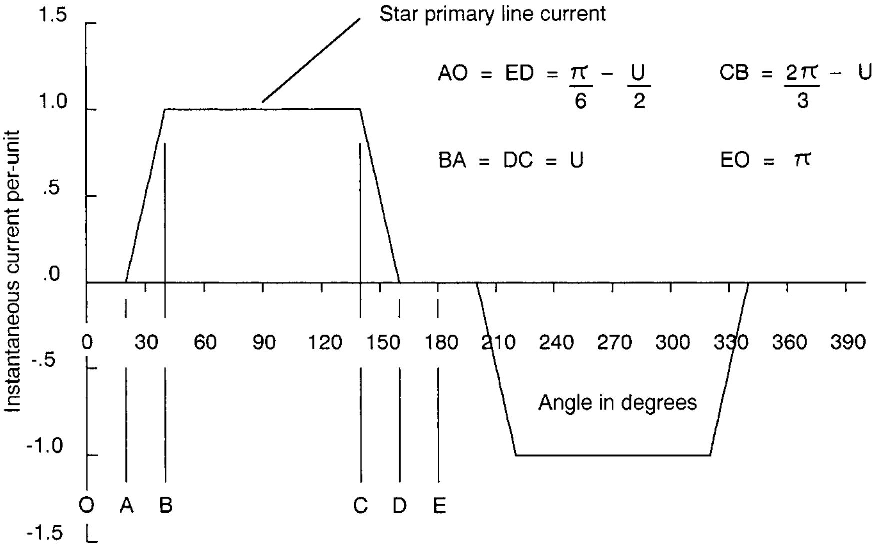


Figure 15.4 Trapezoidal current in the supply side of a six-pulse thyristor bridge, with the commutation angle $u = 20^\circ$.

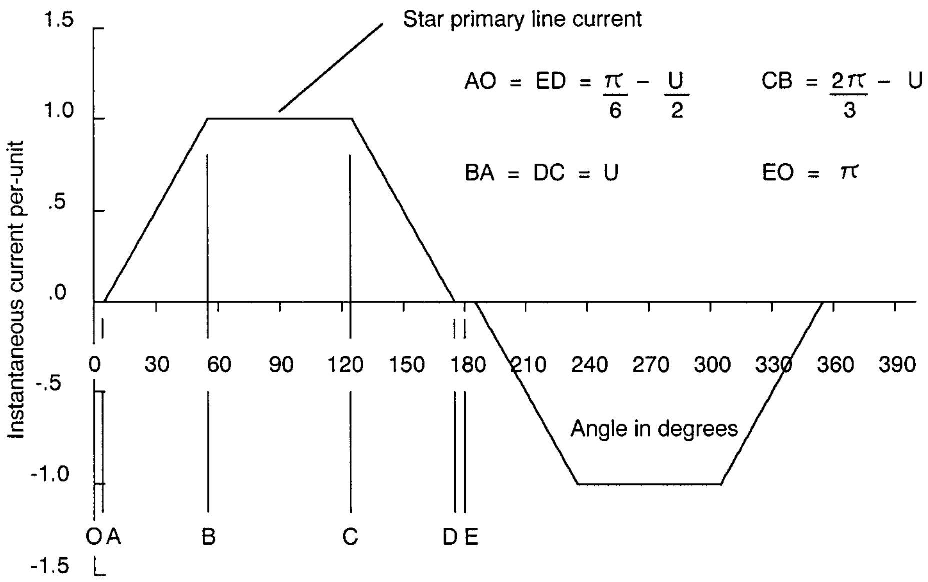


Figure 15.5 Trapezoidal current in the supply side of a six-pulse thyristor bridge, with the commutation angle $u = 50°$.

15.5 for a value of the commutation angle u between zero and 60°. This is the current in the phase A terminal of the bridge. If the first point on the waveform is placed at the origin of the X-Y axes then the waveform will contain both sine and cosine terms. Alternatively the waveform can be advanced, so that the centre of the positive half-wave coincides with $\pi/2$ or 90°, and the centre of the negative half-wave coincides with $3\pi/2$ or 270°. This simplifies the analysis and yields only coefficients for the sine terms.

The Fourier integration is carried out as six sequential parts along the X-axis, i.e. A to B, B to C, C to D for the positive half-wave and similarly for the negative half-wave. If the maximum instantaneous value of the current is $i_{\max}$ then the result of the integration yields the following expression for the sine coefficients.

$$b_{nu} = \frac{2}{un^2\pi}\left(\sin\frac{un}{2}\right)\left(\cos\frac{n\pi}{6} - \cos\frac{5n\pi}{6} - \cos\frac{7n\pi}{6} + \cos\frac{11n\pi}{6}\right) \tag{15.18}$$

$$a_{nu} = 0$$

For which,

$$i_a(\omega t) = i_{\max}\sum_{j=1}^{n} b_{ju}\sin j\omega t$$

It is found from the integration that all even harmonics and those multiples of three are not present in the waveform. Hence n has the following value for a six-phase bridge:

$$n = 1, 5, 7, 11, 13, 17, 19 \text{ etc.}$$

$$\text{or } 1, 6k \pm 1 \text{ for } k = 1 \text{ to infinity.} \tag{15.19}$$

The average value of the waveform is zero because it is symmetrical about the Y-axis, and so the coefficient a_o for the average value is zero. The sinusoidal function in the coefficient a_n varies with the commutation angle u and approaches a limiting value when u is small,

$$\text{As } u \to 0, \quad \frac{2\sin\dfrac{un}{2}}{un^2} \to \frac{1}{n}$$

Which applies to a rectangular waveform. When u is 60° the sinusoidal function has an absolute value of,

$$u = 60^\circ, \quad \left|\frac{2\sin\dfrac{un}{2}}{un^2}\right| = \frac{3}{\pi n^2}$$

$$= \frac{0.9549}{n^2}$$

Therefore the magnitude of all the harmonics decrease as u increases, which is a reasonable expectation since the waveform more closely resembles a sine wave.

The magnitude of the sum of the four cosine terms in (15.18) is $2\sqrt{3}$ for all values of k in (15.19), otherwise the magnitude is zero.

Table 15.2 shows the magnitudes of b_n after scaling them by $1/b_1$, i.e. creating $b_1 = 1.0$ as reference.

15.3.3.1 *Worked example*

Consider a 250 kW DC motor fed by a rectifier system. The line voltage is 415 volts at 50 Hz. The rectifier is fed by a 400 kVA transformer which has an unusually high impedance of $0.0 + 24.5\%$. Assume the motor rated efficiency is 0.9 per unit. Assume the motor terminal voltage is 262.3 volts and its total current is 425 amps.

Phase voltage of the supply $E = \dfrac{415}{\sqrt{3}} = 239.6$ volts.

Open-circuit DC voltage of the rectifier $V_{do} = \dfrac{3\sqrt{6}}{\pi}(239.6) = 560.45$ volts.

The supply current

$$I_{ac} = \frac{2I_d}{\pi}\sqrt{\frac{3}{2}} = 0.7797\ I_d$$
$$= 0.7797 \times 425 = 331.37 \text{ amps}$$

The transformer rated current $= \dfrac{400{,}000}{\sqrt{3} \times 415} = 556.48$ amps

1 pu impedance $= \dfrac{239.6}{556.48} = 0.4306$ ohms/phase

Therefore the commutating reactance = 2.0 × 0.245 × 0.4306 = 0.211 ohms/phase = X_c

$$\begin{aligned}
V_d &= V_{do}\cos\alpha - \frac{3X_cI_d}{\pi}\\
262.3 &= 560.45\cos\alpha - \frac{3\times 0.211\times 425.0}{\pi}\\
&= 560.45\cos\alpha - 43.685
\end{aligned}$$

Therefore

$$\begin{aligned}
\cos\alpha &= \frac{262.3 + 85.623}{560.45} = 0.6208\\
\alpha &= 51.63^\circ
\end{aligned}$$

Also

$$\begin{aligned}
V_d &= \frac{V_{do}}{2}(\cos\alpha + \cos(\alpha + u))\\
262.3 &= \frac{560.45}{2}(0.6208 + \cos(51.63 + u))\\
\cos(51.63 + u) &= 0.3152\\
51.63 + u &= 71.626\\
u &= 20^\circ
\end{aligned}$$

The resulting waveform is shown in Figure 15.4.

15.3.4 Simplified Waveform of a 12-pulse Bridge

The six-pulse rectifier bridges can be connected in such a manner as to produce a 12-pulse DC output voltage. The average value of DC ripple voltage is thereby reduced. From the AC power system point of view the magnitude of the harmonic components is reduced and some harmonics are eliminated. Figure 15.6 shows a typical circuit of a 12-pulse bridge.

The upper bridge is fed by a Dyll delta-star transformer T_u which has a 30° phase shift between the primary and secondary line currents. The lower transformer T_l has zero phase shift. See sub-section 6.4 for an explanation of phase shifts in transformer windings.

The primary currents for transformer T_u are added as follows,

$$\begin{aligned}
I_{12} &= I_1 - I_2\\
I_{23} &= I_2 - I_3\\
I_{31} &= I_3 - I_1
\end{aligned}$$

Where, I_{12} etc. can be either the rms values or the instantaneous values, but displaced by their appropriate phase angles, i.e. 0°, −120° and −240°.

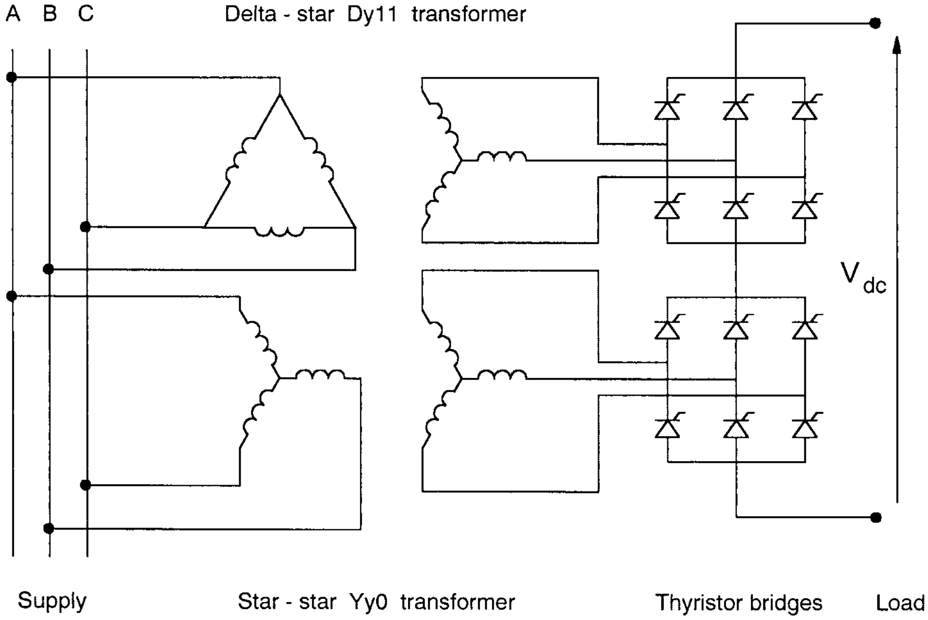


Figure 15.6 Circuit diagram of a 12-pulse thyristor bridge.

For example, let $i_1 = I \sin \omega t$ and $i_2 = I \sin(\omega t - 120^\circ)$ be the fundamental instantaneous currents, then i_{12} becomes,

$$\begin{aligned}
i_{12} &= I(\sin \omega t - \sin(\omega t - 120^\circ)) \\
&= I(\sin \omega t - \sin \omega t \cos(-120^\circ) - \cos \omega t \sin(-120^\circ)) \\
&= I(\sin \omega t + 0.866 \cos \omega t + 0.5 \sin \omega t) \\
&= I(+1.5 \sin \omega t + 0.866 \cos \omega t) \\
&= \sqrt{3} I \sin(\omega t + 30^\circ)
\end{aligned}$$

In order to obtain the full benefit of harmonic cancellation the two bridges must be controlled in a common manner. The control system will enable the fundamental current in both supply lines of the same phase to be in-phase, i.e. the star primary line current must be in-phase with the delta primary line current. See Reference 12, Chapter 3 which emphasises this aspect. The controlled firing of the delta-star bridge T_u cancels the 30° degree phase shift of the transformer. From the Fourier analysis point of view this can be achieved by adding $a + 30^\circ$ phase shift to the delta primary line current.

In sub-section 15.3.1 the line current of the star-star bridge T_l was the same as the phase current, both having the shape of the 120° rectangle wave form. When the phase currents are combined to produce the delta line current the waveform consists of two parts. The first part is a full, rectangular wave, which can be called the '180° rectangle waveform'. The second part is a narrow rectangular wave. The width of this rectangle is 60°, hence call this the '60° rectangle waveform'. The two parts have the same magnitude, which is 1.0 per unit for the analysis. In both waveforms the rectangles are centred at $\pi/2$ and $3\pi/2$, as described in sub-section 15.3.1. The harmonic coefficients for the two parts are,

Part 1. For the 180° rectangle waveform,

$$b_{n180} = \frac{4}{\pi n}, \text{ the fundamental } b_{1180} = \frac{4}{\pi}$$

Part 2. For the 60° rectangle waveform,

$$b_{n60} = \frac{2}{\pi n}\left(\cos\frac{2\pi n}{6} - \cos\frac{4\pi n}{6} - \cos\frac{8\pi n}{6} + \cos\frac{10\pi n}{6}\right)$$

The value of the fundamental coefficient b_{160} is,

$$b_{160} = \frac{1}{\pi}(4)\frac{1}{2} = \frac{2}{\pi}$$

The magnitude of the two parts is divided by $\surd 3$ to obtain the primary line current of the delta-star transformer. The result is then added to the line current of the star-star transformer. The total magnitude of the supply line harmonic coefficient b_{nsum} is given by,

$$\begin{aligned} b_{\text{nsum}} = \frac{1}{\pi n}\Bigg[& \frac{4}{\surd 3} + \cos\frac{\pi n}{6} + \frac{1}{\surd 3}\cos\frac{2\pi n}{6} \\ & - \frac{1}{\surd 3}\cos\frac{4\pi n}{6} - \cos\frac{5\pi n}{6} - \cos\frac{7\pi n}{6} \\ & - \frac{1}{\surd 3}\cos\frac{8\pi n}{6} + \frac{1}{\surd 3}\cos\frac{10\pi n}{6} + \cos\frac{11\pi n}{6}\Bigg] \end{aligned}$$

and

$$i_{\text{sum}}(\omega t) = i_{\max}\sum_{n=1}^{n=\infty} b_{\text{nsum}} \sin n\,\omega t$$

The value of the fundamental coefficient $b_{1\text{sum}}$ is,

$$b_{1\text{sum}} = \frac{1}{\pi}\left(\frac{4}{\surd 3} + \frac{4\surd 3}{2} + \frac{2}{\surd 3}\right) = \frac{4\surd 3}{\pi}$$

The fundamental coefficients from the 180°, 120° and 60° waveforms are found to be in the ratio 2:$\surd$3:1 respectively. The fundamental coefficient of the supply current is double the magnitude of the 120° waveform coefficient, which is the desired result.

The 180° waveform contains triplen harmonics for n taking odd values. The 60° waveform also contains the same triplen harmonics but with opposite signs, which therefore cancel those in the 180° waveform. None of the waveforms contain even harmonics.

The following harmonics are contained in the waveform,

$$n = 12\,k \pm 1$$

Where $k = 1, 2, 3, \ldots, \infty$. The lowest harmonic present is the eleventh.

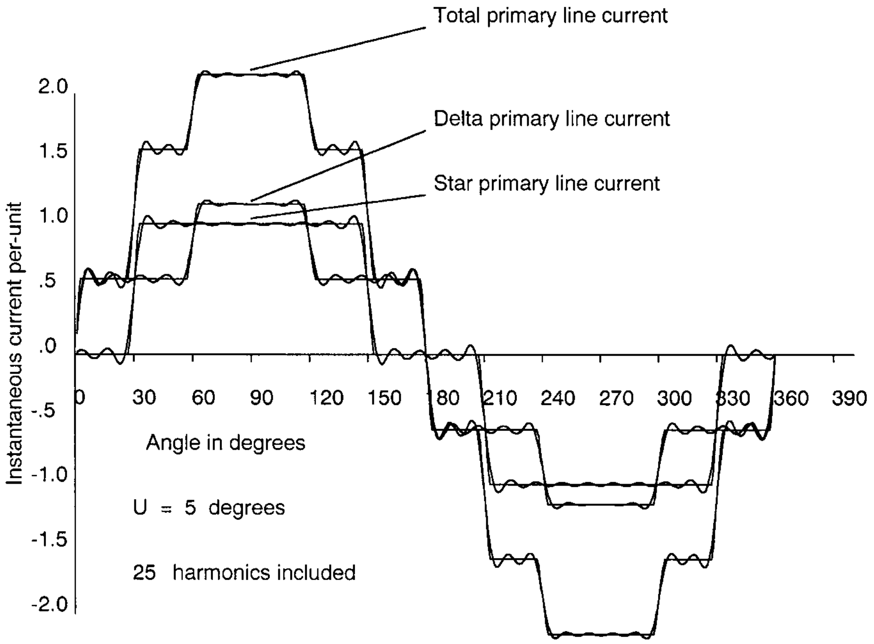


Figure 15.7 Primary line currents in the transformers feeding a 12-pulse thyristor bridge, with the commutation angle $u = 5°$. The waveforms are composed of 25 harmonics, some of which are zero in magnitude.

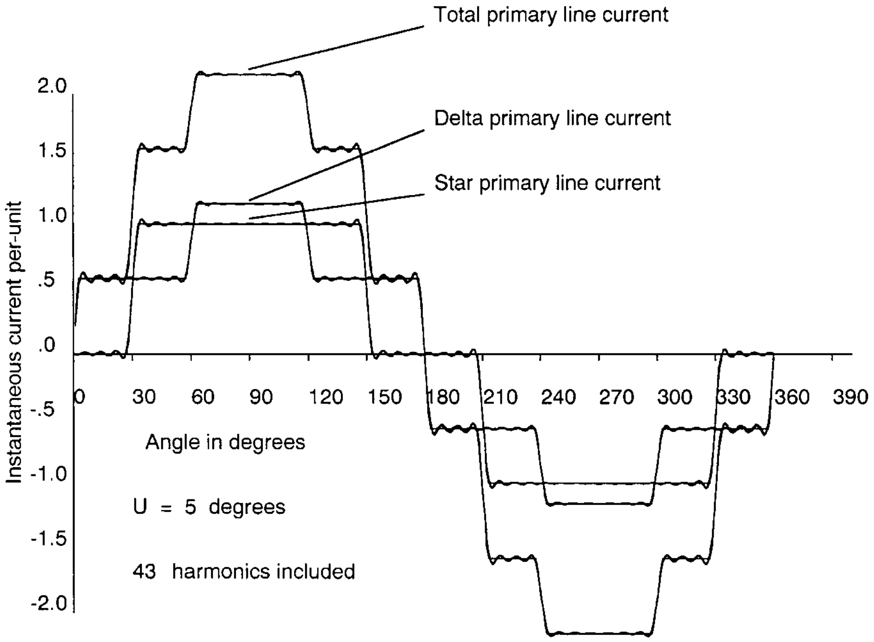


Figure 15.8 Primary line currents in the transformers feeding a 12-pulse thyristor bridge, with the commutation angle $u = 5°$. The waveforms are composed of 43 harmonics, some of which are zero in magnitude.

The effect of the commutation angle u on the 180°, 60° and supply current waveforms is the same as found in sub-section 15.3.2 for the 120° waveform. Therefore each coefficient b_n becomes,

$$b_{nu} = \frac{2b_n}{un} \quad \sin\left(\frac{un}{2}\right)$$

Figures 15.7 and 15.8 show the following waveforms for $u = 5°$ for the first 25 and 43 harmonics included, some being naturally zero.

- Star primary line current or 120° waveform.
- Delta primary line current or the sum of the 180° and 60° waveforms.
- Total primary line current.

15.4 INVERTERS

15.4.1 Basic Method of Operation

Inversion is the process by which a DC voltage is changed into an AC voltage by the use of a set of switches. The following illustrates the method of operation of a simple single-phase 'square-wave' inverter. Consider Figure 15.9.

The four switches T_1, T_2, T_3 and T_4, are controlled in their fully 'on' and fully 'off' modes, in a sequence that causes the current I_{ac} and hence voltage V_{ac} to flow in one direction, to fall to zero, to flow in the opposite direction and again to fall to zero. The conduction of current in the load from A to B is achieved by closing T_1 and T_2, and keeping T_3 and T_4 open. The conduction from B to A is the reversed process, T_3 and T_4 are closed and T_1 and T_2 are kept open. The capacitors, diodes

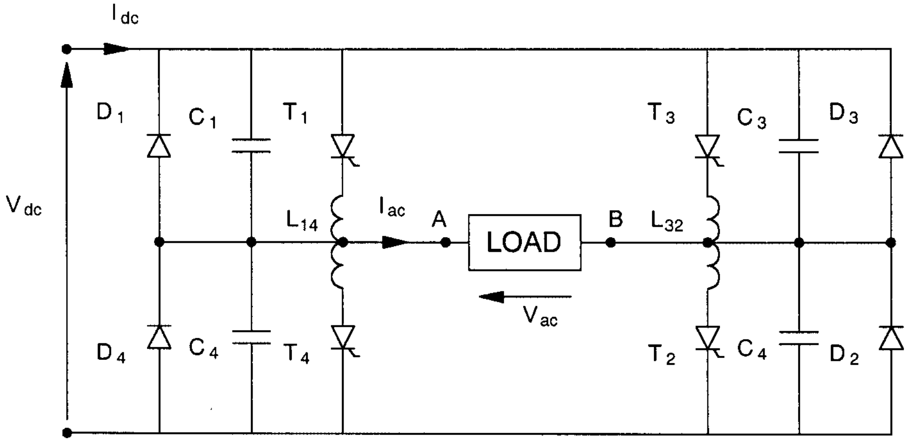


Figure 15.9 Circuit diagram of a single-phase square-wave inverter.

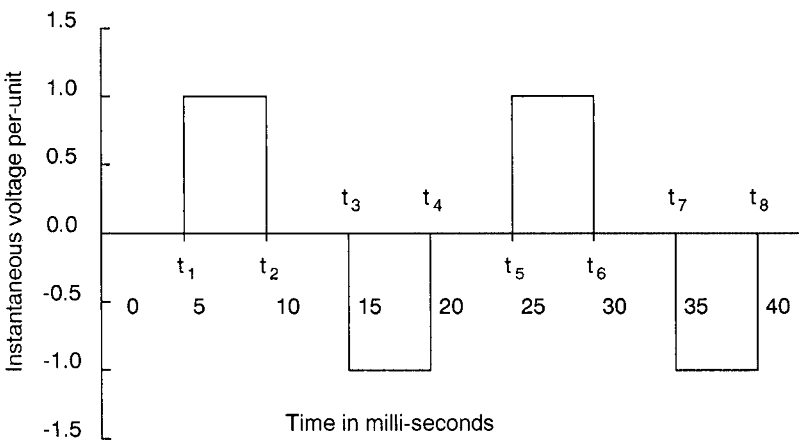


Figure 15.10 Waveform of the load current in a single-phase quazi-square-wave inverter.

and the centre-tapped inductor are used to provide forced commutation where the 'off' state is not controllable. Figure 15.10 shows the voltage applied to the load.

The method described above can be modified to operate as a three-phase inverter. Single and three-phase inverters operating in this manner form the basis for many types of uninterruptible power supplies (UPSs), and variable speed drives for AC motors.

15.4.2 Three-phase Power Inversion

High-power inverters were initially developed for the long-distance transmission of power from a three-phase source to a remote three-phase sink using a DC overhead transmission line or cable. Early DC power transmission used mercury arc thyratrons (gas-filled values or tubes), which functioned in a manner very similar to the early types of thyristors. The 'on' state of the valves was controllable, but the 'off' state was determined by natural commutation made available by the sinusoidal voltages of the sink power system, see Reference 13. A brief description of three-phase inverters follows.

There are two basic types of high-power inverters that are used to supply AC induction or synchronous motors, see References 2 and 9.

- Voltage source inverter.
- Current source inverter.

The voltage source inverter was the first to be developed for the control of induction motors. It consists of a supply rectifier, a DC link inductor, a DC link capacitor and an inverter for the motor. The inductor provides some smoothing of the DC current and short-circuit current limiting for the supply rectifier elements. The capacitor is relatively large and stores sufficient charge to provide current into the inverter. It also provides smoothing of the DC current. Figure 14.3 shows the basic configuration.

The inverter bridge switches the DC voltage across the lines of the motor. The waveform appearing across the lines is a 120° rectangle, similar to the current waveform described in sub-section 15.3.2 for the star-star rectifier transformer, but with vertical sides. Hence the voltage is switched and the load current responds. The Fourier coefficients for this waveform are the same as for (15.17) except that V replaces I and $V_{\max}$ replaces $I_{\max}$. The harmonic content is,

- Lowest harmonic is the fifth.
- Zero even harmonics.
- Zero triplen harmonics.

Current source inverters differ from voltage source inverters in two basic ways, the DC link inductor is made large enough to provide an almost constant current, and there is no DC link capacitor. The inverter therefore switches the current and the load voltage responds. The switching of current requires a commutation process to take place, and so the current waveform for each line current to the load has approximately a trapezoidal shape. The shaping of the waveform is described in sub-section 15.2.1. The commutation angle u is therefore inherent in the inverter operation. The line current waveforms are shown in Figure 15.4. It can be seen that these are 120° trapeziums and therefore the harmonic analysis is the same as that applied in sub-section 15.3.2 for a six-phase rectifier bridge for its line currents. Since the currents appearing at the lines of the motor are switched by the commutation process the inductances of the motor create a rapid 'rate of rise' of voltage across themselves. The terminal voltage of the motor will therefore contain a proportion of these 'noisy voltages', and some form of suppression of overvoltages may be necessary.

15.4.3 Induction Motor Fed from a Voltage Source Inverter

If an induction motor is running in a stable steady state with a low slip, then the various fundamental currents and voltages within the motor can be calculated from the conventional equivalent circuit. When the motor is supplied from a source of harmonic voltages the impedance elements in the circuit need to be modified to account for the frequency of each harmonic that is present. The various reactances are directly proportional to the harmonic frequency. The stator and rotor resistances may be assumed constant, although in practice they will increase with the frequency, the rotor more than the stator, see Reference 9, Figure 1.26 therein.

If the harmonic content of the applied voltage is known in terms of magnitudes and phase shifts of the components, then the circuit can be solved for each frequency. The result for each branch current or voltage will be the sum of all their harmonic components plus their fundamentals.

Before the calculation can be made the slip for each frequency needs to be found when the shaft is running at its normally loaded conditions i.e. near to the synchronous speed of the fundamental frequency. The slip s_n for the harmonic frequency nf_1 is given by,

$$s_n = \frac{n - (1 - s_1)}{n} \quad \text{for } n = 1,7,13 \text{ etc.}$$

$$s_n = \frac{n + (1 - s_1)}{n} \quad \text{for } n = 5,11,17 \text{ etc.}$$

As explained in Reference 2, Chapter 6.

For motors that normally operate at slips in the order of 0.5% to 3.0% the values of s_n for n, greater than unity are approximately given by,

$$\begin{aligned} s_n &\simeq \frac{n-1}{n} \text{ for } n = 7, 13, 19 \text{ etc.} \\ &= 0.8571, 0.9231, 0.9474 \text{ etc.} \\ s_n &\simeq \frac{n+1}{n} \text{ for } n = 5, 11, 17 \text{ etc.} \\ &= 1.2, 1.0909, 1.0588 \text{ etc.} \end{aligned}$$

The rotor resistance that represents the winding and the load is R_2/s_1 for the fundamental. For the harmonic resistance to be found simply replace s_1 by s_n.

15.4.3.1 Worked example

A 250 kW three-phase, four-pole, 50 Hz, 415 V, induction motor is fed from a voltage source inverter. The motor has the following parameters for its star-wound windings. Find the currents and air-gap voltage in the circuit.

R_1	Stator resistance	0.0053 ohms
X_1	Stator leakage reactance	0.0470 ohms
R_2	Rotor resistance at full-load	0.0045 ohms
X_2	Rotor reactance at full-load	0.1113 ohms
X_m	Magnetising reactance	2.9310 ohms
s_1	Full-load slip	0.00738 pu
	Full-load efficiency	0.983 pu
	Full-load power factor	0.902 pu
	Full-load current	392.26 amps

The equivalent circuit fed from a Thevenin voltage source is shown in Figure 15.11.

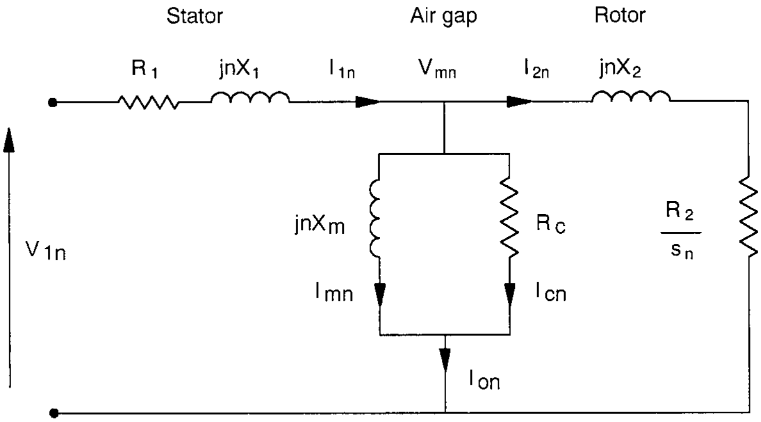


Figure 15.11 Equivalent circuit of an induction motor when fed from a voltage source that contains harmonics.

Assume the inverter equivalent output phase-to-neutral voltage consists of a 180° rectangle waveform plus a 60° rectangle waveform. The complete waveform has a harmonic content of,

$$\begin{aligned}
b_n &= \frac{4}{\pi n} + \frac{2}{\pi n}\left(\cos\frac{2\pi n}{6} - \cos\frac{4\pi n}{6} - \cos\frac{8\pi n}{6} + \cos\frac{10\pi n}{6}\right) \\
&= \frac{4}{\pi n} + \frac{2}{\pi n}(1.155) \qquad \text{for } n = 1, 5, 7, 11, 13, \text{ etc.} \\
&= \frac{6.31}{\pi n} = \frac{2.0085}{n} \\
\text{And} \qquad &= \frac{4}{\pi n} + \frac{2}{\pi n}(-2.309) \qquad \text{for } n = 3, 9, 15, 21 \text{ etc.} \\
&= \frac{-0.618}{\pi n} = \frac{-0.1967}{n}
\end{aligned}$$

The rms value of the fundamental phase-to-neutral voltage is $415/\sqrt{3} = 239.6$ volts. Therefore its peak value is $239.6\sqrt{2} = 338.85$ volts which corresponds to b_1 having a value of 2.0085. The peak values of the first 17 harmonic components of the phase-to-neutral voltage are given below in Table 15.3.

The triplen harmonics can be ignored because the motor has a star-wound stator winding.

Consider the fifth harmonic situation

The rotor resistance becomes	$0.0045/1.2 = 0.00375$
The rotor reactance becomes	$0.1113 \times 5 = 0.5565$
The stator reactance becomes	$0.0470 \times 5 = 0.2350$
The magnetising reactance becomes	$2.9310 \times 5 = 14.655$

Assume the stator resistance to be constant.

Table 15.3. Peak values of harmonic voltage components

Harmonic number	Peak value and sign of the component voltage
1	338.85
3	−11.06
5	67.77
7	48.41
9	−3.69
11	30.80
13	26.06
15	−2.21
17	19.93
19	17.83

The combined admittance of the rotor and magnetising impedances become,

$$\begin{aligned}Y_{m2} &= \frac{-j}{nX_m} + \frac{\dfrac{R_2}{S_n} - jnX_2}{\left(\dfrac{R_2}{s_n}\right)^2 + n^2{X_2}^2}\\ &= 0.01211 - j\ 1.8650 \text{ ohms}\\ Z_{m2} &= \frac{1}{Y_{m2}} = 0.00348 + j\ 0.5362 \text{ ohms}\end{aligned}$$

Add the stator impedance.

$$Z_{1m2} = R_1 + jnX_1 + Z_{m2} = 0.00878 + j\ 0.7711 \text{ ohms}$$

All the harmonics of the supply voltage have zero phase shift (except the triplens which are anti-phase). The fifth harmonic supply voltage V_{5n} is $67.77/\sqrt{2}$ volts (rms). Supply this voltage to the circuit. The supply current is,

$$\begin{aligned}I_{15} &= \frac{V_5}{Z_{1m2}} = \frac{67.77 + j\ 0.0}{\sqrt{2}(0.00878 + j\ 0.7711)}\\ &= 0.7075 - j\ 62.1377 \quad \text{amps}\end{aligned}$$

The volt-drop across the stator impedance is,

$$\begin{aligned}V_{1m5} &= (0.0053 + j\ 0.2350)(0.7075 - j\ 62.1377)\\ &= 14.606 - j\ 0.163 \quad \text{volts}\end{aligned}$$

The air-gap voltage V_{m5} becomes,

$$\begin{aligned}V_{m5} &= V_{15} - V_{1m5}\\ &= 47.921 - 14.606 + j\ 0.163\\ &= 33.315 + j\ 0.163 \quad \text{volts}\end{aligned}$$

The magnetising current I_{m5} is,

$$\begin{aligned}I_{m5} &= \frac{V_{m5}}{j_n X_m} = \frac{33.315 + j\ 0.163}{0.0 + j\ 14.665}\\ &= 0.0111 - j\ 2.272 \quad \text{amps}\end{aligned}$$

Hence the rotor current I_{25} becomes,

$$\begin{aligned}I_{25} &= I_{15} - I_{m5}\\ &= 0.7075 - j\ 62.1377 - 0.0111 + j\ 2.272\\ &= 0.6964 - j\ 59.866 \quad \text{amps}\end{aligned}$$

Table 15.4. Harmonic rms currents and voltages in a star-wound induction motor that is fed from a voltage source inverter

Harmonic number	Stator current		Rotor current		Magnetising current		Air-gap voltage	
	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)
1	392.28	−25.60	371.51	−14.27	78.56	−89.07	230.27	−3.93
5	62.14	−89.35	59.86	−89.33	2.27	−89.72	33.32	0.28
7	31.70	−89.46	30.54	−89.45	1.16	−89.83	23.80	0.17
11	12.84	−89.69	12.37	−89.69	0.47	−89.88	15.14	0.12
13	9.19	−89.72	8.86	−89.71	0.37	−89.90	12.81	0.09
17	5.38	−89.80	5.18	−89.79	0.20	−89.92	9.80	0.08
19	4.30	−89.81	4.14	−89.80	0.16	−89.93	8.77	0.07
23	2.94	−89.85	2.83	−89.85	0.11	−89.94	7.24	0.06
25	2.49	−89.86	2.40	−89.85	0.09	−89.95	6.66	0.05
29	1.85	−89.88	1.78	−89.88	0.07	−89.96	5.74	0.05
31	1.62	−89.89	1.56	−89.88	0.06	−89.96	5.37	0.04

If the above calculations are made for all the active harmonics then their results can be added and the waveforms synthesised. Table 15.4 summarises the results.

Figure 15.12 shows the synthesised currents and air-gap voltage using the first 61 harmonics.

15.4.3.2 Worked example

The same motor as used in the 'worked example' of sub-section 15.4.3.1 is fed from a current source inverter. Find the currents and air-gap voltage in the circuit.

The equivalent circuit fed from a constant current source is shown in Figure 15.11, wherein I_{1n} is the source current instead of V_{1n}.

Assume the inverter output line current consists of a 120° rectangle wave and that the commutation angle u is small enough to be ignored. The complete waveform has a harmonic content of,

$$\begin{aligned} b_n &= \frac{1}{\pi n}\left(\cos\frac{\pi n}{6} - \cos\frac{5\pi n}{6} - \cos\frac{7\pi n}{6} + \cos\frac{11\pi n}{6}\right) \\ &= \frac{3.464}{n\pi} \quad \text{for } n = 1, 5, 7, 11, 13 \text{ etc.} \\ &= \frac{1.1026}{n} \end{aligned}$$

The rms value of the fundamental line current is 392.26 amps. Therefore its peak value is $392.26\sqrt{2} = 554.74$ amps which corresponds to b_1 having a value of 1.1026. The peak values of the harmonic components of the line current are given below in Table 15.5.

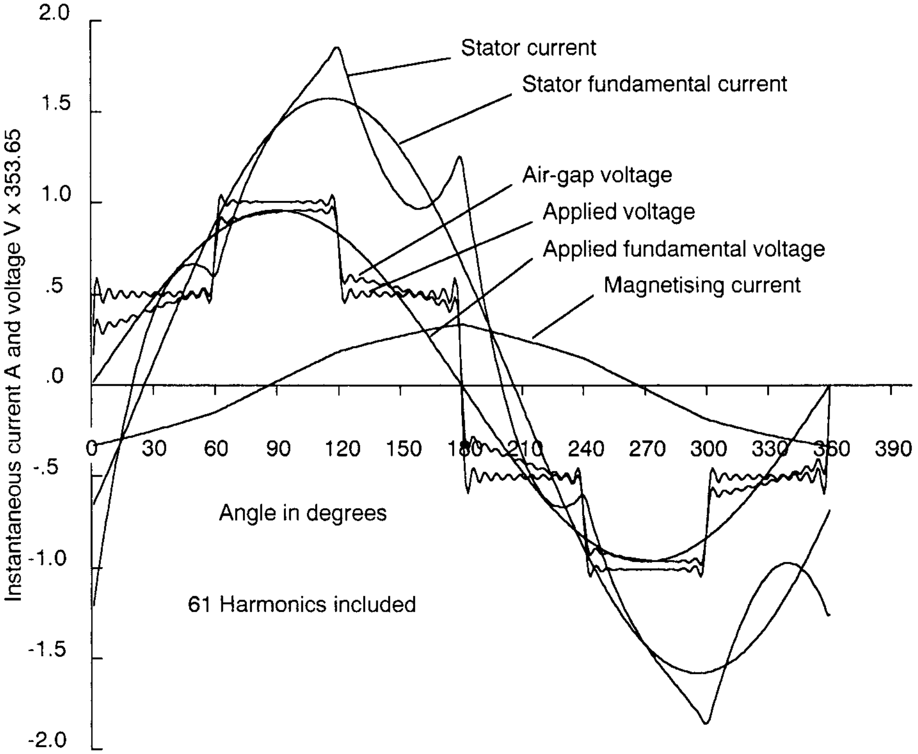


Figure 15.12 Instantaneous voltages and currents in an induction motor supplied from a voltage source inverter.

Table 15.5. Peak values of harmonic current components

Harmonic number	Peak value and sign of the component current
1	+554.74
5	−110.95
7	−79.25
11	+50.43
13	+42.67
17	−32.63
19	−29.20

From the Worked Example 15.4.3.1 the combined impedance of the rotor and magnetising branches is $Z_{m2} = 0.00348 + j\ 0.5362$ ohms. Adding the stator impedance gives,

$$Z_{1m2} = 0.00878 + j\ 0.7711 \quad \text{ohms}$$

All the harmonics of the supply current have either zero or 180° phase shift as seen in Table 15.5. The fifth harmonic supply current I_{15} is $-110.95/\sqrt{2}$ amps (rms). Inject this current into the circuit.

The supply voltage becomes,

$$\begin{aligned} V_{15} &= I_{15} Z_{1m2} \\ &= -\frac{110.95}{\sqrt{2}}(0.00878 + j\ 0.7711) \\ &= -0.6888 - j\ 60.496 \text{ volts} \end{aligned}$$

The voltage across the stator impedance is,

$$\begin{aligned} V_{1m5} &= (0.0053 + j\ 0.2350)(-78.453 - j\ 0) \\ &= -0.4158 - j\ 18.4365 \end{aligned}$$

The air-gap voltage V_{m5} becomes,

$$\begin{aligned} V_{m5} &= V_{15} - V_{1m5} \\ &= -0.6888 - j\ 60.496 + 0.4158 + j\ 18.4365 \\ &= -0.273 - j\ 42.059 \quad \text{volts} \end{aligned}$$

The magnetising current I_{m5} is,

$$\begin{aligned} I_{m5} &= \frac{V_{m5}}{j_n X_m} = \frac{-0.273 - j\ 42.059}{0.0 + j\ 14.655} \\ &= -2.8699 + j\ 0.0186 \quad \text{amps} \end{aligned}$$

Hence the rotor current I_{25} becomes,

$$\begin{aligned} I_{25} &= I_{15} - I_{m5} \\ &= -78.453 + j\ 0 + 2.8699 - j\ 0.0186 \\ &= -75.565 - j\ 0.0186 \quad \text{amps} \end{aligned}$$

If the above calculations are made for all the active harmonics then their results can be added and the waveforms synthesised. Table 15.6 summarises the results.

Figure 15.13 shows the synthesised currents and air-gap voltage using the first 91 harmonics.

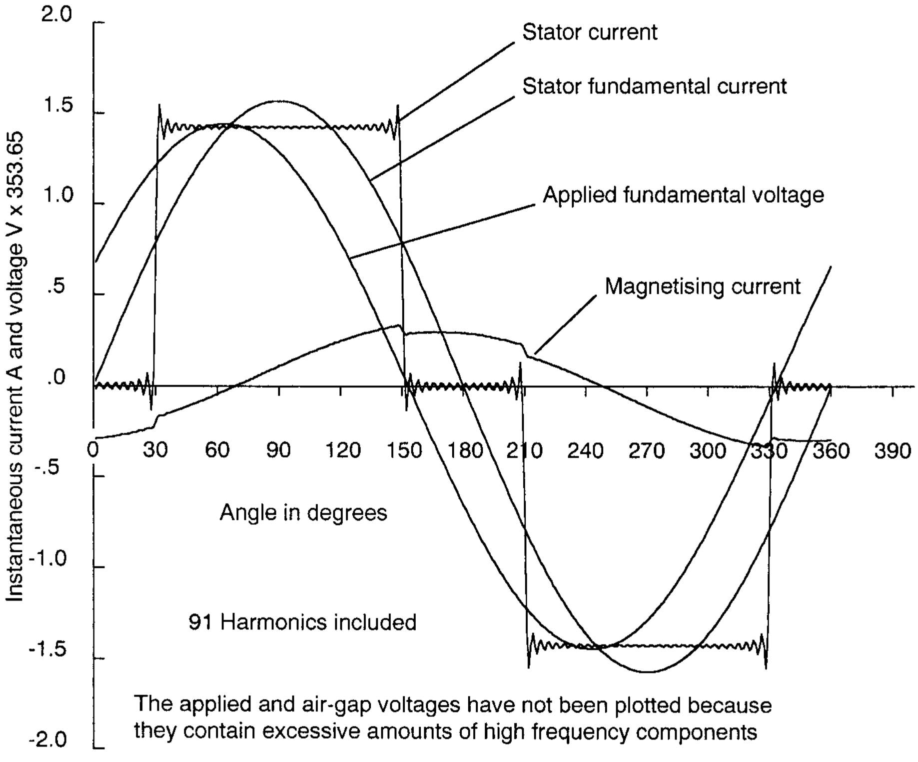
15.5 FILTERING OF POWER LINE HARMONICS

In modern oil industry power systems there is a probability that one or more variable speed systems will be present. When the system engineer designs or modifies a power system he will need to take full account of the effect of the harmonics that will be injected into the system from the rectifier part of the variable speed drive, see also sub-section 15.1.

The most frequently used reference document based on European practice that makes recommendations on the levels of harmonics that can be tolerated in LV and HV systems is Reference 14,

Table 15.6. Harmonic rms currents and voltages in a star-wound induction motor that is fed from a current source inverter

Harmonic number	Stator current		Rotor current		Magnetising current		Air-gap voltage	
	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)	Mag. (Amps)	Angle (Degrees)
1	392.28	0	370.54	11.33	78.36	−68.32	229.67	21.68
5	78.45	180.0	75.58	180.014	2.87	179.63	42.06	269.63
7	56.01	180.0	53.99	180.014	2.05	179.63	42.06	269.63
11	35.66	0	34.35	0.007	1.30	−0.186	42.06	89.81
13	30.67	0	29.07	0.007	1.10	−0.186	42.06	89.81
17	23.07	180.0	22.23	180.005	0.84	179.88	42.06	269.88
19	20.65	180.0	19.89	180.005	0.76	179.88	42.06	269.88
23	17.05	0	16.43	0.004	0.62	−0.093	42.06	89.91
25	15.69	0	15.12	0.004	0.57	−0.093	42.06	89.91
29	13.53	180.0	13.03	180.003	0.49	179.93	42.76	269.93
31	12.65	180.0	12.19	180.003	0.46	179.93	42.76	269.93



The applied and air-gap voltages have not been plotted because they contain excessive amounts of high frequency components

Figure 15.13 Instantaneous voltages and currents in an induction motor supplied from a current source inverter.

which at the time of preparing this book was still in its original form. In addition the Reference 15 is used. When an oil company owns or operates a power system, which is independent of other power systems such as a 'national grid', it may prepare its own specifications to cover the tolerable levels of harmonic voltages and currents. Such specifications may be more or less as strict as the recommendations made in References 14 and 15. In Reference 12 there is a comprehensive description of national standards that apply in various European countries, USA, Scandinavia, Australia and New Zealand. Most of these standards refer to six-pulse and 12-pulse converters and applied in 1985 when the reference was published. Some but not all of these standards have been revised since 1985, e.g. IEEE519 was revised in 1997. The standards described in Reference 12 are not directly comparable with each other because different criteria are used e.g. current in amps, current in percent, kVA converter ratings, individual harmonics, odd and even harmonics, total harmonic distortion and short-circuit rating. These criteria have been applied to public or 'national grid' power systems. For smaller self-contained power systems such as those used in offshore platforms the criteria that use actual current or kVA levels, rather than percentage levels, may prove to be too generous for the HV parts of the system. The G5/3 document offers recommendations for both actual currents in amps and voltages in percent. The recommendations based on percentage voltage are a popular choice in the oil industry. Table 15.7 summarises these recommendations to cover typical voltages in the oil industry.

The design of filters to reduce or eliminate harmonics from the system connected upstream of the source of harmonics is a specialised subject and the results will depend on many factors such as,

a) Proximity of the harmonic source to the source of main power, e.g. an HV converter connected onto the main generation busbars of an oil and gas gathering plant.
b) The type of converter i.e. six or 12 pulse. (Drilling rigs usually have six-pulse converters.)
c) The number of converters that will be operating at the same time.
d) The likely variations in the fundamental frequency during typical operating conditions of the plant.
e) Whether there are long HV feeder cables, e.g. an offshore platform supplied by power from the shore base or another platform some reasonable distance away. The cable capacitance may be sufficient to accentuate the effect of one or more of the lower order harmonics, see Reference 16.
f) Power dissipation from the filter may be a significant factor if it is to be placed indoors in a confined space.

Factors a) and d) are interrelated due to the scheduling for the number of generators that will be needed to operate for a particular plant condition. Generators and motors can be represented by their sub-transient impedance when harmonic studies are being carried out. These impedances and those of

Table 15.7. Recommended harmonic levels in relation to the system voltage level

Switchgear rated voltage (volts)	Total harmonic voltage distortion (%)	Individual harmonic voltage distortion (%)	
		Odd	Even
300 to 1000	5.0	4.0	2.0
1000 to 15,000	4.0	3.0	1.75
5000 to 40,000	3.5	2.5	1.5
40,000 to 80,000	3.0	2.0	1.0
80,000 to 132,000	1.5	1.0	0.5

Table 15.8. Protection alarms and indications for a high-voltage variable speed drive

Function	Protection	Alarm	Indication
1. Open circuit, short circuit and earth faults in the rectifier including the faults in the rectifier including the DC link	X		
2. Open circuit, short circuit and earth faults in the inverter including the cable and motor	X		
3. Overcurrent due to commutation failure in the rectifier	X		
4. Overcurrent due to commutation failure in the inverter	X		
5. Undervoltage at the output of the inverter	X		
6. Overfrequency at the output of the inverter	X		
7. Undervoltage at the input of the rectifier	X		
8. Enclosure over-temperatures		X	
9. Control system faults	X	X	
10. Harmonic filter faults	X	X	
11. Single-phase operation of the motor	X	X	
12. Overcurrent of the motor	X	X	X
13. Winding temperature of the motor	X	X	X
14. Winding temperature of power transformers	X	X	X
15. Supply line voltages			X
16. Supply line currents			X
17. DC link voltage			X
18. DC link current			X
19. Motor line voltages			X
20. Motor line current			X
21. Set-point frequency of inverter			X
22. Actual frequency of inverter			X
23. Motor speed			X

local transformers may be sufficient to cause sensitivity in the performance of the filter with variations in system loading. This is less of a problem where the plant is supplied from an overhead transmission line, and the upstream MVA capacity is large compared with the total demand of the plant.

Drilling rigs and low capacity AC variable speed drives are usually six-phase systems. If these are known to be needed at the conceptual stage of a project then their effects on other equipment can be taken into account reasonably easily. For example the specifications that are prepared for equipment connected to the 'distorted' network can include a full description of the harmonics that will be present. In most cases the manufacturer will be able to include some form of local filtering or add some extra capacity to the equipment offered e.g. larger motor rating so that the extra heat can be accommodated.

Droop governed generators will give a system frequency that varies with the power loading on their network. Some generating plants do not have the generator set-points available for manual or automatic adjustment. Consider a 50 Hz system with 4% droop governing at no-load the frequency may be preset to 51 Hz for each generator. As the loading is increased the frequency will fall to 49 Hz when all the connected generators are fully loaded. If there is another generator available and it is then switched into the system it will take its share of the common load and the frequency will settle at some value above 49 Hz. It can be seen that in this situation a variation of 1 Hz is very likely to be experienced.

If a sharply tuned filter system is used wherein the 'Q-factor' in each series resonant branch is high e.g. 30 or more, then a variation of $n \times 1$ Hz either side of the tuned frequency f_n may be unacceptable.

In practice the filter elements could be tapped with small increments but this would be expensive if some form of automatic control of the tappings were to be used. A more practical solution would be to control the governor set-points at the generator in a simultaneous manner, by using a form of integral control to maintain the system frequency within a narrower band. Reducing the droop settings would not achieve the desired result.

15.6 PROTECTION, ALARMS AND INDICATION

A high-voltage variable speed motor will usually drive an important pump or compressor which must remain in a serviceable condition, and not be subject to lengthy shut downs due to poor performance or serious failure of its major components. Modern systems will usually contain a micro-computer to process alarms, to give visual information, to communicate to external facilities and to safely shut down the system in the event of a serious or progressive fault being detected.

Table 15.8 lists the typical protection, alarms and indications that would be provided in the system.

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16

Computer Based Power Management Systems

16.1 INTRODUCTION

Modern power systems that are self-sufficient with their own turbine generators are often equipped with a computer based power management system (PMS). The main purpose of this system is to enable the generators to be operated at high load factors i.e. 85 to 90%. Operating the generators at high load factors has two main advantages:

- The most economic fuel consumption is obtained.
- In some situations less generators need to be installed, especially in old plants where load growth has occurred.

In addition there are other benefits which become available when a PMS is included in the power system:

- Improved range and accuracy of plant measurements and display.
- Improved range and types of alarms, messages and event recording.
- Better control by the control room personnel.
- Greater confidence in the performance of the plant.
- Addition of special technical facilities, e.g. auto-synchronising, condition monitoring, managing the tap-changing of transformers.
- Communication with SCADA systems.
- Data logging, trending and archiving.

The power system is the 'life-blood' of the whole plant and therefore it must have high availability and high reliability. A well-designed PMS will enable the highest performance to be achieved in these respects. A PMS should be considered as an essential requirement in a modern plant.

16.2 TYPICAL CONFIGURATIONS

The PMS central computer and its input and output signal interfaces should all be located in one self-contained unit. If for some reason this cannot be achieved then these functions could be included in

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a SCADA sub-system, but its operation should be kept as independent from other general operations as possible. The reasons for this will be discussed later in more detail.

If the PMS is a part of a SCADA system then faults within the SCADA system could shut down the PMS and thereby put the power system at risk e.g. cascade shut down following the tripping of one generator.

16.3 MAIN FUNCTIONS

A comprehensive PMS would incorporate at least the following functions, those marked with an asterisk* can be regarded as the most necessary:-

a)* High-speed load shedding.
b)* Low-speed load shedding.
c)* Inhibiting the starting of large motors.
d)* VDU display of one-line diagrams.
e)* Alarms, messages and reporting of status at the VDU and printers.
f) Active power sharing for generators.
g) Isochronous control of system frequency.
h) Reactive power sharing for generators.
i) Isochronous control of system main busbar voltage.
j) Condition monitoring of the gas turbines.
k) Scheduling the starting up and shutting down of the main generators.
l) Control of the reacceleration of motor loads.
m) Auto-synchronising of the main generators.
n) Data logging and archiving of data.
o) Trending display.
p) Control of peripheral hardware e.g. VDUs, keyboards, printers.
q) Communication with the SCADA systems.

16.3.1 High-speed Load Shedding

Of all the functions the high-speed load shedding is usually the most important. The objective is to shed a predetermined amount of less essential load simultaneously with the loss of a generator (or utility supply transformer). When a generator, or its driving engine, experiences a fault, a sequence of signals is created within its control panel and main circuit breaker panel to cause the machine to shut down quickly and safely. Within the generator control and protection systems there is usually a ‘lock-out relay’ (86-G, G for generator). All the different trip signals from fault detection devices are wired to the lockout relay, which is the master trip relay for the circuit breaker. It is usually a manually reset relay with an indicating flag or lamp. A similar philosophy of tripping is used in the engine control panel in which all the mechanical failure signals are received at the engine lockout relay (86-T, T for turbine). This lockout relay also trips the generator circuit breaker. Hence any fault

Table 16.1. Relay devices and switchgear mechanism delay times

Device	Circuit breaker delay (millisec)	Motor starter (contactor) delay (millisec)
Lockout relay	5	5
Trip coil	5 to 10	5 to 10
Circuit breaker Clearance time	80 to 120	–
Contractor Clearance time	–	50 to 100
Total delay	90 to 135	60 to 115

detected by either the 86-G or the 86-T relay will trip the circuit breaker quickly and in about the same time duration.

When either the 86-G or the 86-T relay sends its signal to the circuit-breaker trip coil, time is taken before the circuit breaker begins to move and finally reach its fully open state. Table 16.1 shows the accumulation of time for typical high-voltage circuit breakers and motor contractor starters.

The PMS should be designed to monitor the status of all the main circuits in the system, the generator currents and powers, and all the outgoing currents and powers. The monitoring should be a cycle updating process, with a cycle period of at least five cycles of fundamental frequency e.g. 100 to 250 millisec, to allow power transients to decay.

The monitoring process can be approached in two ways:-

16.3.1.1 Precision approach

Every circuit breaker, contactor and switching device in the high-voltage network is monitored for open and close status. In addition each circuit is provided with accurate active power transducers. Hence the PMS will be continually checking the active power balance in the network, and the actual consumption of each load. The PMS will be able to calculate exactly how much, and which, loads to shed when a generator trips due to a fault. The PMS can also add a small margin of power to each load to be shed so that the remaining generators are able to settle at a level similar to that before the faulted generator tripped. This is important when the pre-fault load factor of the generators is high i.e. approximately 90 to 95%, and it will prevent the transient power change in the remaining generators from causing a rise in gas-turbine power turbine temperature (frequently called the ‘operating temperature’).

This approach is the most accurate in terms of selecting which loads to shed and safeguarding the remaining generators.

16.3.1.2 Approximate approach

Every circuit breaker, contractor and switching device in the high-voltage network is monitored for open and close status. Each generator circuit is provided with an accurate active power transducer. Each load will be assigned an active power value from knowledge of the plant operating conditions and the nameplate rating of the load. The power transducers in the generator circuits are necessary because in practice generators seldom share power accurately, as measured and indicated, unless a special load sharing control scheme is used, see sub-sections 2.5.4 and 2.5.5. This is important when the pre-fault load factor of the generator is high, for the reasons given in a).

When a generator trips the precalculated number of loads are also tripped. In this approach there will always be the possibility that one or two loads more than theoretically necessary will be tripped. This is because some of the running loads will have been operating at a power lower than that assigned. This inherent source of error can be minimised if current transducers are fitted to the shedable loads. In this case the assigned power can be modified by the ratio of measured current to the assigned current.

This approach is the most economical in terms of the hardware necessary for load shedding. The PMS can be arranged to detect the fault at the 86-G and 86-T relays, in one of two methods:

a) From the input terminals (operating coil) of the 86 relay, or
b) From the output contacts of the 86 relay.

Method (a) is preferred for a new plant where a high-speed auxiliary relay can be used in parallel with the 86 relay coil.

Method (b) can be used for an established plant where spare contacts are available in the 86 relays, otherwise method (a) can be used.

Upon detection of the signal at an 86 relay the PMS will call from its memory the list of loads to shed, and then send tripping signals to each load simultaneously. In the meantime the generator circuit breaker will have received its tripping signal and its mechanism will have started to separate the main contacts. When the generator circuit breaker has reached its fully open position the load shed circuit breaker and contractor mechanisms will be part way through their travels. It can be seen that the time delay between the generator and the load-shed circuit breakers is approximately equal to the computing time needed by the PMS to create the tripping signals to the loads. This computing time is typically 40 to 60 msec. The whole process takes between 100 and 175 msec. It can be considered that the remaining generators only need to take up the lost power of the faulty generator for approximately the time it takes the PMS to compute the loads to be tripped, i.e. 40 to 60 msec.

If there are N generators operating, each at a load factor F_b per unit, then after one generator is tripped each remaining generator will be operating at a new load factor of F_a, where:

$$F_a = \frac{F_b N}{N-1} \quad \text{p.u.}$$

If the remaining generators are assumed to be able to ride through the disturbance and tolerate an overload of 5% for a long time then the pre-fault critical load factor F_{bc} is:

$$F_{bc} = 1.05\left(\frac{N-1}{N}\right)$$

Table 16.2 shows the critical pre-fault load factor for plants with different numbers of generators.

If the load factor F_b is less than or equal to F_{bc} then load shedding will not be necessary. Most plants that have their own power generation use two, three or four generators. With only two

Table 16.2. Critical load factor versus number of generators

Critical pre-fault load factor (%)	Number of operating generators before the fault
52.5	2
70.0	3
78.8	4
84.0	5
87.5	6

generators it is essential to have a load shedding system. On the other hand a plant with six or more generators operating should not need to have a load shedding system. These are usually plants that have grown in stages over a long period of time.

16.3.2 Load Shedding Priority Table

The consumers in the high-voltage network can be examined for their importance in the operation of the whole plant. Hence each consumer can be placed in a table that identifies its order of importance. This is called the load shedding priority table. Such a table will vary considerably from plant to plant because of the nature of the processes therein. In some exceptional situations it may be necessary to include some of the low-voltage loads.

Table 16.3 shows a typical priority table for an offshore platform that produces oil and gas.

The table as shown applies to a fully loaded platform with all four 4 MW generators running at a load factor of approximately 80%. At first sight it may appear that too many items are included in the table. However, as the platform becomes loaded from its start-up condition the number of items in their 'on' state increases from a small number, and each item may be only partially loaded. Once the total load requires two generators to be on-line, then the PMS can be enabled to take load shedding action.

The priorities shown are typical for an offshore platform, but each project should be considered on its own merits and the table prepared from discussions with the process, mechanical and facilities engineers, see sub-section 1.8.

The priority table is stored in the PMS memory and therefore it can be easily modified or rearranged as the plant ages. As plants become established their various processes often need to be modified, especially offshore platforms where the gas-to-oil ratio changes with time.

It may not be necessary to put all the high-voltage consumers in the priority table. The most economical approach is to select enough consumers such that their total nameplate power, when multiplied by a factor (K), is equal to the rated output of one generator when it is operating at its highest ambient temperature in its 'dirty state'. In Table 16.3 this would apply to the group of items numbered approximately 16 to 23, such that the motor control centres are not included. The factor K will therefore need to take account of:

- Dirty engine conditions.
- Highest ambient temperature.

Table 16.3. Priority table for a power management system on an offshore oil and gas platform

Load shedding priority (1 = low)	Description	Rated load (kW)	Consumed load (kW)	Status (ON or OFF)	Remaining load (kW)	No. of running generators (approx.)
	Generation on-line				16,000	4
	Total load				12,825	4
1	HP compressor A	1,200	1,020	on	11,805	4
2	HP compressor B	1,200	1,020	on	10,785	4
3	IP compressor A	1,000	860	on	9,925	3
4	IP compressor B	1,000	860	on	9,065	3
5	IP compressor C	1,000	0	off	9,065	3
6	LP compressor A	800	700	on	8,365	3
7	LP compressor B	800	700	on	7,665	3
8	LP compressor C	800	0	off	7,665	3
9	Seawater lift pump A	500	420	on	7,245	3
10	Seawater lift pump B	500	420	on	6,825	3
11	Seawater lift pump C	500	0	off	6,825	3
12	Refrigeration Compressor A	350	265	on	6,560	3
13	Refrigeration Compressor B	350	0	off	6,560	3
14	Main oil-line pump A	900	720	on	5,840	2
15	Main oil-line pump B	900	720	on	5,120	2
16	Process MCC LHS A		670	on	4,450	2
17	Process MCC RHS A		630	on	3,820	2
18	Process MCC LHS B		590	on	3,230	1
19	Process MCC RHS B		610	on	2,620	1
20	Utility MCC LHS		750	on	1,870	1
21	Utility MCC RHS		720	on	1,150	1
22	Accommodation MCC		310	on	840	1
23	Emergency MCC LHS		450	on	390	1
24	Emergency MCC RHS		390	on	0	1
25	Spare		0	off		1
26	Spare		0	off		1

- Highest load factor of the generators.
- Operating level of each load shedding consumer.
- A contingency if felt necessary.
- Reappraisal of importance with ageing of the plant.
- Spare and future consumers.
- Base and peak loading of the plant.

16.3.3 Low-speed Load Shedding

Low-speed load shedding takes account of long-term drifting and trending towards an overloaded state. It is applied to each turbine generator individually. The overloading can be detected directly or indirectly as follows:

- Measurement of active power at the generator terminals.
- Measurement of gas-turbine operating temperature.
- Measurement of the power system frequency.

When a plant is heavily loaded with a load factor above 90% it is necessary to ensure that all the generators are equally loaded. The equalisation of load is often left to the droop settings of each governor, or by manual trimming if suitable controls are available. Automatic load sharing can also be included in the PMS, see sub-sections 2.5.4 and 2.5.5. It is also necessary to maintain the gas turbines in a 'clean' state and not let them become widely mismatched in this respect. If mismatches in operating electrical power and engine cleanliness exist at the same time, then it is possible that, for example, say one of the gas-turbine generators will be operating very close to its upper limits. This will be seen as an excessively high operating temperature. Under very steady load conditions this excessive temperature could be tolerated for a long time. If the plant has a number of large motors, comparable in rating to that of one of the generators, then the starting of such a motor will cause a significant power disturbance at the main busbars. It is common practice with offshore platforms to start these motors direct-on-line. It is less common to do this with onshore plants. The disturbance will be shared amongst the generators, and may last for 0.5 to 20 seconds, depending upon the run-up time of the motor. The disturbance will consist of the static power characteristic of the driven machine and the necessary accelerating power for the rotating inertia. Hence the disturbance may be large enough and long enough to cause the operating temperature of the highest loaded generator to exceed its tripping limit. This generator will then shut down.

The PMS will receive this shut-down signal from one of the 86 lock-out relays, and will respond in exactly the same way as with the high-speed load shedding, see sub-section 16.3.1.

The low-speed load shedding will be more active when the ambient temperature is high i.e. near to the site high limit.

16.3.4 Inhibiting the Starting of Large Motors

The volt-drop ΔV at the main busbars can be given by the approximation:

$$|\Delta V| = \frac{X_g(K S_m{}^2 - S_g S_L \sin\phi_L)}{S_g + K S_m{}^2 X_g} \quad \text{per unit} \tag{16.1}$$

Where the prestarting busbar voltage V is unity, and

X_g is the transient reactance X'_d in per unit of the generator
S_g is the KVA rating in per unit of the generator
S_m is the KVA rating in per unit of the motor
S_L is the KVA rating in per unit of the standing load
$\cos\phi_L$ is the power factor of the standing load
ϕ_L is the power factor angle, hence $\sin\phi_L$ can be found.
K is the starting current to running current ratio of the motor

Equation (16.1) can be rearranged to determine the largest motor rating for a given volt-drop limit:

$$S_m{}^2 = \frac{S_g(X_g S_L \sin\phi_L \Delta V)}{K\ X_g(1 - \Delta V)} \tag{16.2}$$

Table 16.4 shows the largest motor rating allowed for different system conditions and designs, where $S_g = 1$ pu.

It can be seen that the most restricting factors are a low standing load or a standing load with a power factor near to unity. In these cases the motor rating is limited to approximately 27% of the total generator kVA capacity. If an allowance is also made for additional volt-drop in the generator and motor cables then the 27% limit would be reduced to between 20 and 22%. Thus a ‘rule-of-thumb’ ratio of 5:1 between the kW or kVA ratings of the generators and the motor to be started is reasonable for quickly assessing a satisfactory system performance, see also Appendix G.

In view of the above findings it would be reasonable to have the PMS inhibit the starting of the large motors when there is insufficient kW capacity of running generators. The PMS would raise an alarm and advise that an extra generator should be brought on-line so that the particular motor can be started. The PMS could incorporate an equation such as (16.2) since all the constants are known from the nameplate data and the variables can be found from the system measurements received at the PMS for other uses.

16.3.5 VDU Display of One-line Diagrams

A PMS can be programmed to display the status of the power system in the form of one-line diagrams. The one-line diagrams can be displayed in colour, where different colours can be used for different functions, such as:-

- Green busbars and feeders are alive.
- Red busbars and feeders are de-energised.

Table 16.4. Relative magnitudes of different parameters that effect the amount of volt-drop experienced during the starting of a large induction motor

Case	S_m	ΔV	K	X_g	S_L	$\sin\phi_L$
a	0.34	0.1	6	0.25	0.5	0.436
b	0.40	0.15	6	0.25	0.5	0.436
c	0.46	0.2	6	0.25	0.5	0.436
d	0.41	0.1	4	0.25	0.5	0.436
e	0.37	0.1	5	0.25	0.5	0.436
f	0.40	0.1	6	0.15	0.5	0.436
g	0.36	0.1	6	0.2	0.5	0.436
h	0.39	0.1	6	0.25	1.0	0.436
i	0.27	0.1	6	0.25	0.0	0.436
j	0.27	0.1	6	0.25	0.5	0.0
k	0.36	0.1	6	0.25	0.5	0.6

- White devices withdrawn from service.
- Yellow devices tripped due to a fault.

Each switchboard in the main distribution network can have its own one-line diagram displayed, and for the more complicated switchboards each busbar section can be displayed. The active and reactive power flows and current flows can be shown for each item where suitable analogue transducers have been fitted. This is particularly beneficial for the main power generation switchboard. All names and tag numbers can be shown for clarity. A diagram similar to Figure 16.1 can be displayed.

16.3.6 Active Power Sharing for Generators

As explained in sub-section 2.5.3 it is possible to compensate for the mismatching of active power delivered by each generator. The PMS can be programmed to calculate the average power of each generator and thereby to determine the power mismatch of each generator. The PMS can then use each mismatch to iteratively readjust the set point of the corresponding governor without changing the common frequency. All the generators must be operating in their droop-governing mode for such adjustments to be applied.

16.3.7 Isochronous Control of System Frequency

As explained in sub-section 2.5.3 it is possible to superimpose an integral controller on to the set point controls of the individual governors. The master integral controller will have a master frequency

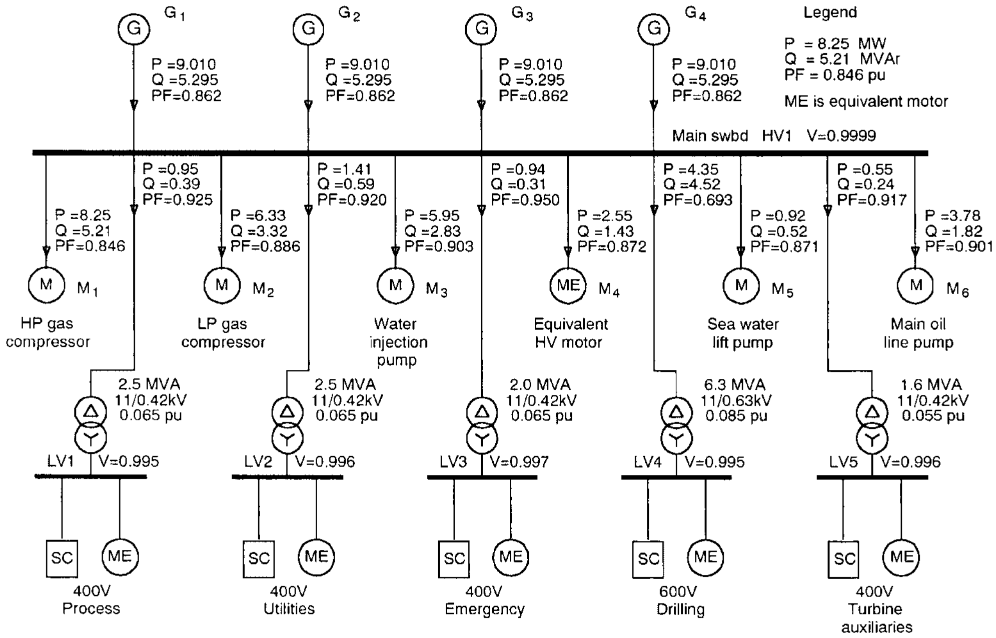

Figure 16.1 One-line diagram of a power system that has its own dedicated generators, showing the load flows between the switchboards.

set point. Such a scheme can be easily incorporated into the PMS because all the measurements and output signals exist if a load-sharing scheme is present. The master integral controller must be slow acting relative to the time response of the governor control action. For a 50 Hz power system, for example, the master set point frequency could be set at 50 Hz or some other frequency to suit the operating conditions.

If it is necessary to switch off the isochronous controller when the plant is heavily loaded, then the PMS should calculate what the individual governor set points should be for a system frequency to suit the overall droop. It should send these signals shortly after the isochronous controller is switched off. This feature will prevent the system frequency rising too high when the plant is lightly loaded. As the frequency rises each motor will run at a higher speed and thus consume a little more power and current. If a motor normally runs close to its nameplate rating, rather than at its originally designed load, then it is possible that the higher current could activate the overcurrent protection of the motor. After some length of time such a motor may trip. Alternatively the PMS could allow the frequency to rise to a predetermined maximum value before the corrective isochronous signals are sent to the governor set points. This would give the benefit of maintaining a good frequency for most operating levels of the plant.

16.3.8 Reactive Power Sharing for Generators

As explained in sub-section 2.5.3 for speed governing it is possible to compensate for the mismatching of reactive power delivered by each generator in a similar manner. If this is achieved together with reducing the mismatch of active power, then each generator will be operating at the same current. This will eliminate the possibility of an overcurrent occurring at one of the generators when a high load factor exists. The method described in sub-section 2.5.3 can be used with frequency being replaced by busbar voltage, and the set points to be adjusted will be those of the automatic voltage regulators (AVRs).

16.3.9 Isochronous Control of Busbar Voltage

Likewise as explained in sub-section 2.5.3 it is possible to superimpose an integral controller on to the set point controls of the individual AVRs. The master set point will be the busbar voltage. The master controller must be slow acting relative to the time response of the AVR control action, so as to avoid the possibility of oscillatory or even unstable operation.

Safeguarding against over-frequency was explained in sub-section 16.3.7. The same concept can be used to safeguard against overvoltage at light loads.

The sharing of active and reactive power and the isochronous control of the system frequency and main busbar voltage can be displayed on the VDU using a diagram similar to that shown in Figure 16.2.

16.3.10 Condition Monitoring of the Gas Turbines

The power output from a gas turbine is greatly influenced by changes in ambient temperature and the state of cleanliness of the combustion equipment and power turbine blades.

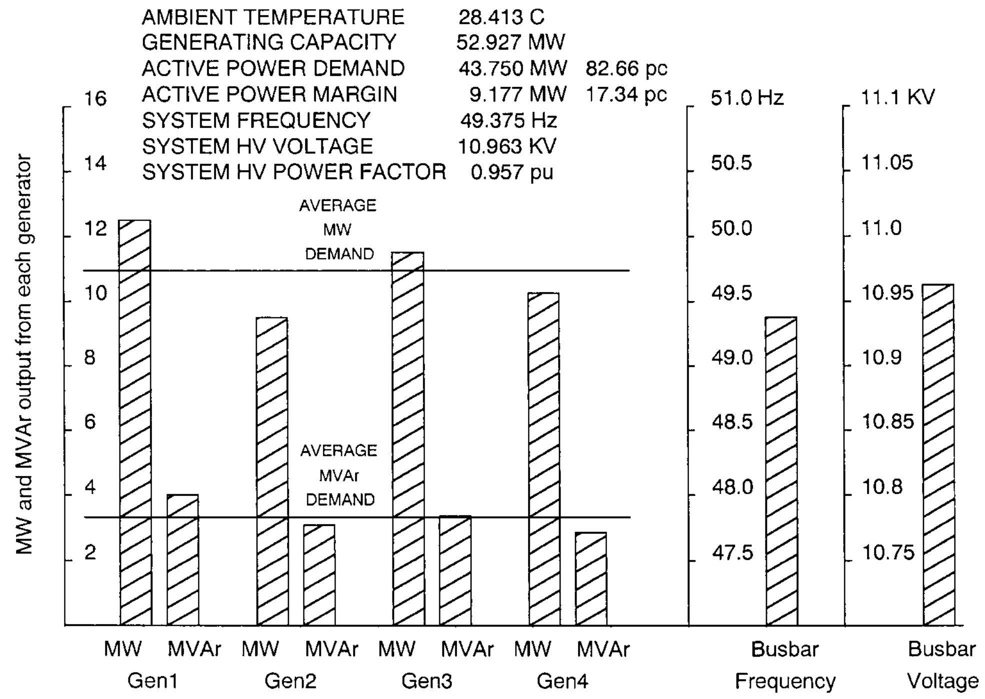

Figure 16.2 Screen page of a power management visual display unit.

The PMS can be programmed to take account of the ambient temperature by storing the ‘new’ engine power versus ambient temperature characteristic, as referred to the generator terminals i.e. gear-box and generator losses deducted from the shaft power, see Figure 2.10.

The ‘dirty’ engine reduction in power can be assessed by measuring the electrical power at a particular ambient temperature and the corresponding operating temperature. As the engine becomes more dirty the operating temperature will rise for a given electrical power and ambient temperature. This rise in temperature can be found from site tests on engines that have been running for different periods, since a major maintenance. The longest period would be similar to the figure recommended by the manufacturer. Hence an approximate linear correlation between running time, and hence dirtiness, against excessive operating temperature can be found. This correlation can be applied by the PMS for operating load factors above 70% to ensure that the operating temperature is kept below a predetermined value, which could be ‘close to alarm limit’. The correlation can be applied by biasing the power versus ambient temperature characteristic downwards.

The PMS can be programmed to give a message to the control room operator that the engine is in need of being cleaned.

16.3.11 Scheduling the Starting Up and Shutting Down of the Main Generators

The PMS can be used to schedule the starting up and shutting down of the main generators. A simple method can be used as follows. Set the upper load factor of each generator to be say 75% and the lower load factor to be say 60%. As the plant load increases from zero one generator would be used initially until the upper load factor is reached. At this point the PMS should give a message to start up the second generator. The same sequence is used until all the generators are on-line and the plant is at full load.

As the plant load decreases the generators operate at a decreasing load factor. When each generator has become unloaded to the level set by the lower load factor then the PMS should advise the operator to shut down one generator. This sequence can be repeated until only one generator is running.

There needs to be a margin between the upper and lower settings of the generator load factors, otherwise the scheduling will become too frequent and the messages will be subject to short-term fluctuations of load. In addition to the fairly wide margin needed for the above situation it is recommended that the PMS calculates average loading information over say a 30 minute period before a message is given. This will ensure that the fluctuations due to starting and stopping large motors will not create an unacceptable effect.

Figure 16.3 shows the scheduling profile as the load increases from zero to full plant load, and decreases back to zero. The lines shown are based on a 75% upper load factor and a 60% lower load factor.

16.3.12 Control of the Reacceleration of Motor Loads

Some motor control centres are designed to allow the motor starters to reclose upon the restoration of the main busbar voltage following a supply disturbance. This is especially necessary for emergency and essential loads, e.g. cooling water pumps and lube oil pumps for engine-driven generators. If the

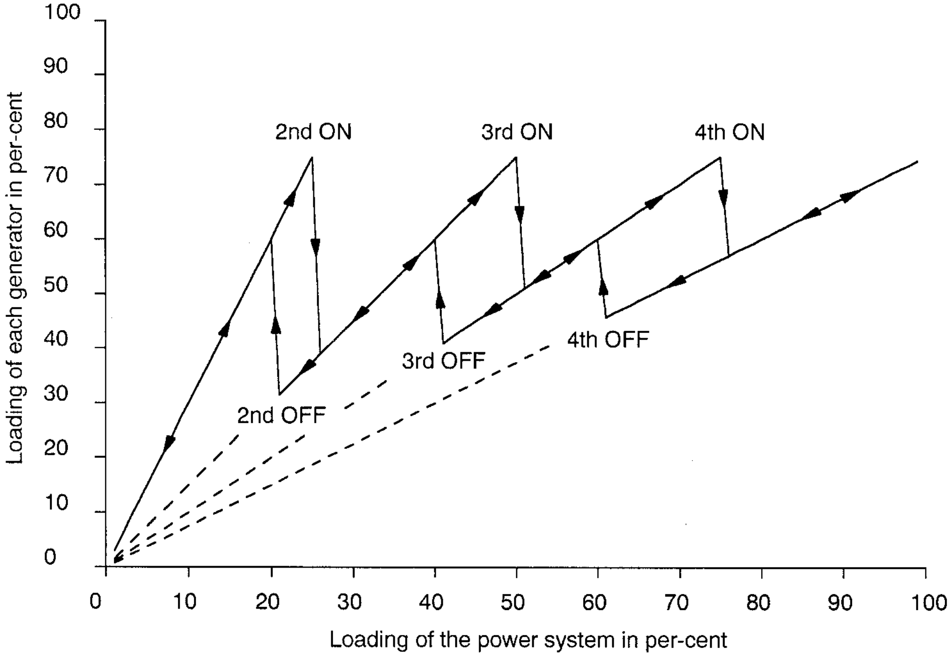

Figure 16.3 Scheduling the starting up and shutting down of generators.

supply is lost for a short time, or even a long time, then these loads should be allowed to restart without the need for operators to manually intervene.

If there is a large number of motors to restart (or also called reaccelerate) then there will be a large surge of main feeder current if they all start at the same time. This will cause a severe volt-drop at the common busbars, which will cause the run-up times to be extended and the possibility of the overcurrent protection relay at the main feeder circuit breaker to trip. Similarly if there is a group of motor control centres all in the same state of restarting their motors, then their common busbar e.g. main generator switchboard, will experience a significant volt-drop which may not be acceptable.

It is therefore necessary to plan the restarting process of all the motor loads by introducing time delays into each motor starter or groups of starters. There are many methods of achieving this, some of which are peculiar to the type of plant and whether it is offshore or onshore.

In general it is better to first restart the smaller motors and those with short run-up times. The larger and long run-up motors should be started towards the end of the planned sequence. This may not be possible in all cases because of plant operational constraints. However, the reason for attempting this is that if the supply is from a generator(s) then the driving emf of the generator increases as the load increases. The initial starting of small motors will gradually increase the emf. Consequently, when the larger motors are started later, the higher emf will benefit the volt-drop, the motors will receive a slightly higher terminal voltage throughout their run-up times.

The restarting process is usually initiated by using a voltage-sensing relay or transducer to detect the return of busbar voltage. The detection also checks that the magnitude of the voltage received is high enough to allow motors to be started e.g. greater than 90%, and a time delay may be included to ensure that the supply settles and is not a transient quantity.

All the functions required for restarting motors can be programmed in a PMS, or in a purpose designed programmable device built into each motor control centre, see also sub-section 7.6.

16.3.13 Auto-synchronising of the Main Generators

If the PMS incorporates active and reactive power sharing facilities, then it is reasonably simple to add an auto-synchronising system for the generators. The generator to be synchronised would be started and run up through its normal sequences, as furnished by its manufacturer, one for the turbine and one for the generator excitation. At the end of these sequences the generator speed and terminal voltage would be close to their busbar running values.

The PMS would then be signalled to start the auto-synchronising process, either by a signal from the turbine-generator control panel or from the operator. The PMS would use a comparator for the frequency and another comparator for the terminal voltage. The terminal voltage of the generator will be checked for nearly equal magnitude and phase angle against the switchboard busbar voltage. Three error signals will be created:-

- Voltage magnitude error.
- Voltage phase angle error.
- Frequency error.

The PMS can use these signals to adjust the AVR set point to reduce the voltage magnitude error, and the governor set point to firstly reduce the frequency error, and secondly to reduce the phase angle error. The PMS would then send a synchronising signal via a Synchronisation Check relay (25) to close the generator circuit breaker, as soon as the following incoming generator conditions are satisfied:-

• Voltage magnitude error	±0.15%
• Voltage phase angle error	-30° to 0°
• Frequency error	$+0.05\%$

Once the circuit breaker has closed the PMS should slightly increase the governor set point to ensure that the generator delivers a small amount of power. This will avoid the possibility that a reverse power situation will develop to a level that could cause the reverse power relay to trip. The PMS will then switch off the auto-synchronising facility.

16.3.14 Data Logging, Archiving, Trending Display, Alarms, Messages and Status Reporting

These facilities are typically incorporated into SCADA systems where all kinds of plant data are collected, time stamped, stored, displayed and printed out.

However, the PMS can be used to handle special electrical power system data in the same way, either as a self-contained PMS or by communicating the data to associated SCADA equipment. The following list gives typical data that would be collected and reported:-

- Change of status of main circuit breakers, motor starters, transformer feeders, busbar bustie circuit breakers, switchboard interconnectors, earthing switches, withdrawn devices.
- Variables such as busbar voltages, system frequency, load flow and current flow in main circuits and interconnectors, generator power factor, ambient conditions.
- Operation of individual protection relays at main circuits and feeders.
- Alarm and trips of engine and generator parameters.
- Trending of engine and generator parameters.
- Trending of active and reactive total power.

Note, the data associated with each consumer e.g. pumps, heaters, compressors and fans would normally be collected and reported by the SCADA system as individual process items.

The data collected will normally be displayed in several forms on the VDU and as printed out information. The operator will be able to choose tabular output of, for example:-

- Chronological alarms and trips received.
- Alarms and trips acknowledged (or not).
- Chronological messages and events.

Note: Once an alarm or trip has been reset it often disappears from the tables, but the time and date of its disappearance can be logged as an event. Colour-coding can be used for unacknowledged and acknowledged data.

17

Uninterruptible Power Supplies

17.1 AC UNINTERRUPTIBLE POWER SUPPLIES

17.1.1 The Inverter

Static inverters are used to convert DC voltage into AC voltage. The simplest forms of inverters produce an output waveform that is rectangular, as a result of the simple switching process described in sub-section 15.4.1. A rectangular waveform can be used to feed some types of AC equipment e.g. incandescent lamps, domestic equipment such as kitchen mixers and kettles. Equipment that contains electronic devices may not function properly if their supply waveform is non-sinusoidal. Their timing circuits and pulse generating systems may be disturbed by the shape of the waveform or its derivative.

Harmonics in the voltage waveform may create harmonic currents in the equipment that could give rise to excessive heat dissipation and ultimately damage may be caused.

All but the smaller ratings of inverters used in the oil industry require a sinusoidal output waveform. The quality of the waveform is typically defined as, being that no greater than 5% total harmonic distortion should be present. In order to achieve a sinusoidal output it is necessary to include a filter in the output circuit. The output of the inverter usually has a double wound transformer so that the required line voltage is obtained. The filter is placed on the load side of the transformer, its leakage reactance of the transformer contributes to the filtering process.

Inverters are fed from a battery bank that has sufficient cells to optimise the output voltage of the inverter and the performance of the rectifier or charger. The inverter is shown in Figure 17.1, which provides an uninterruptible supply (UPS) that also has an off-load bypass supply.

Some of the equipment in a plant requires a source of power that is extremely reliable and does not become interrupted during an emergency. For example if all the main generators on a production platform trip for some emergency reason then it is necessary to maintain supplies to vital services such as communications, public address, emergency lighting, navigational panels, fire and gas systems, see sub-section 1.2. Many of these loads can tolerate a short break and can be supplied by the emergency diesel generator once it is ready for service. Some loads cannot tolerate an interruption at all e.g. data processing systems, instrument panels, safety shut-down systems.

Inverters can be arranged to operate in various ways to provide an uninterruptible supply.

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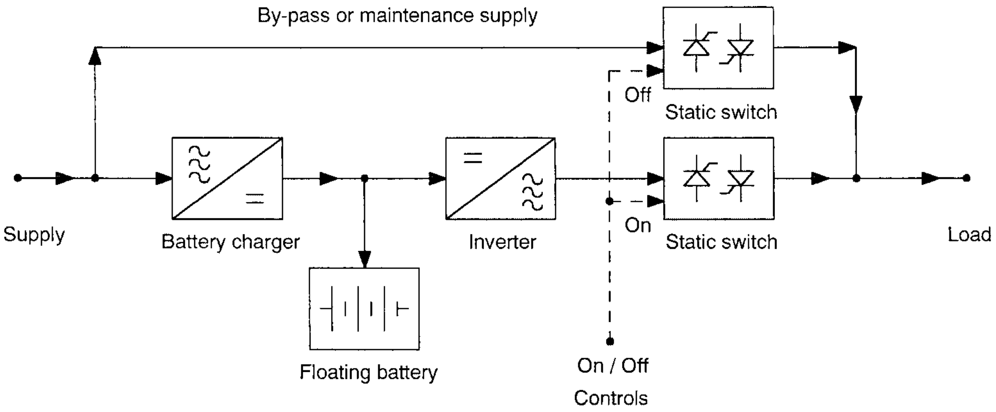

Figure 17.1 Single UPS with a bypass supply and static switches.

17.1.2 Coordination of the Sub-circuit Rated Current with the Inverter Rated Current

The output current of an inverter must not be allowed to exceed the maximum rated current of the inversion power thyristors or transistors for more than a few fractions of a second, otherwise permanent damage will be made. Consequently the inverter bridge is provided with a current limiting circuit that detects the output line total current and modifies the firing delay angle so that the bridge then functions as a constant current source. Upon detection the inverter will raise a suitable alarm and shut down. When the bridge operates in its current limiting mode the output voltage will fall to a value determined by the downstream impedance.

This situation raises an important problem with overcurrent protection. From the above explanation of current limiting it is clear that a circuit breaker or a fuse placed in the inverter output circuit lines will serve no useful protection purpose. At best the circuit breaker could be used as a switch. In practice an isolating switch is preferred especially where dual inverters feed a common load or distribution board.

The maximum rating of any one of the loads must be limited by the rapid tripping or fusing time of the device that protects the circuit. Fuses function better than moulded case circuit breakers in these situations because they are not limited by a definite minimum time constraint. To ensure that the protective device functions rapidly the rated current of this device must be limited to about 30% of the rated current of the inverter upstream. Hence the ratio of load kVA to inverter kVA of each load sub-circuit will be a maximum of about 25%.

Any fuses or moulded case circuit breakers downstream of the above mentioned protective devices should have complete coordination, as described in sub-section 7.7.5. The operating region of the upstream device should have a narrow region to the left of the asymptotic part of its curve. As the rating of the downstream device falls in value, its right-hand side characteristic will begin to come within a region to the left of the curve for the upstream device. When this occurs a degree of coordination will result. Ideally the current cut-off region of the downstream device should lie to the left of the upstream device asymptotic region. In calculating or estimating the necessary margin for coordination it is essential to account for the practical tolerances that accompany the 'nominal' curves of the devices involved. A margin must be added between the upper tolerance curve of the downstream device and the lower tolerance of the upstream device. If the two cascaded devices are of the same type, range of products from the same manufacturer, and similar shapes of curves then the margin of coordination can be relatively low. Often these cascaded devices are different, e.g. fuses upstream with circuit breakers downstream or vice versa, and their manufacturers are different. This will generally result in requiring a wider margin for coordination. A 'rule-of-thumb' guide can be based on the normal rated currents of these devices. For a good situation where the type of the two devices is the same, e.g. both are fuses or both are circuit breakers, the marginal factor should be no less than 2.5. For the poor situation with dissimilar devices the marginal factor may need to be at least 3.0. In the above discussion it is assumed that the protective devices do not have a definite minimum time at currents within the range of fault current being considered. This is a different situation from one in which the prospective fault currents are much greater than full-load currents, see sub-sections 7.7.5 and 7.7.6.

It should be noted that a UPS on an important plant, such as a production platform, is in a critical situation. It must function in a very reliable manner otherwise the cost of lost oil or gas production will be very high in relation to the cost of all the components in the UPS system that are unreliable. If the unreliability is due to poor coordinations of protective devices then the marginal factors described above may need to be reviewed, or better still applied in the early stages of the power system design.

Reference 1 gives a good description of the coordination of protective devices and their protected equipment, a diagrammatic procedure and a worked example consisting of miniature circuit breakers and an upstream fuse in a 415 V three-phase system. See also sub-section 13.3.2 for a brief discussion on the use of a high impedance to earth a low-voltage emergency or drilling power system.

Reference 2 discusses the difficulties that can be experienced with coordinating cascaded protective devices, plus a comprehensive description of all aspects of NiCd charger-battery-inverter systems.

17.1.3 Earth Fault Leakage Detection

Short circuits often develop from faults of a leakage nature. It is therefore advisable to provide each sub-circuit with an earth leakage current relay or alarm unit, which has a sensitivity that adequately coordinates with other devices. Indeed this is a necessary requirement for sub-circuits that feed power to hazardous area equipment. The use of these earth leakage current relays and detectors will greatly increase the confidence that can be placed on the overall performance of the system of protective devices in the UPS.

17.2 DC UNINTERRUPTIBLE POWER SUPPLIES

A DC uninterruptible power supply is basically a battery bank and a charger. However, it differs from a simple battery and charger system that may be associated with starting diesel engines, or similar rugged functions, because the output voltage must be maintained within a close tolerance of the nominal DC voltage.

DC uninterruptible power supplies are used for:

- Closing and tripping of circuit breakers and contactors in switchboards.
- Switchboard indicating lamps.

- Radio communication equipment.
- Emergency generator control panels.
- Start-up and shut-down lubricating oil pumps and auxiliary systems for gas turbines, large pumps and compressors.

When specifying the battery and charger system the following points should be considered.

- Rated voltage and current.
- Rated ampere-hour capacity.
- Rate of discharge
- Type of cell i.e. lead-acid or nickel-cadmium
- Ventilated batteries. Some types of cells can be non-venting but this greatly influences the charging process.
- Type of charger e.g. rectifier or thyristor.
- Boost, float and trickle charging requirements.
- Duty and standby units, and their interlocking and control philosophy.
- Volt-drop considerations in the DC outgoing cables.
- Overload and short-circuit protection.
- Tolerance on the DC output voltage during all load and charging conditions.
- Ambient temperature and appropriate derating factors for the cells and the charger.

17.2.1 UPS Battery Chargers

Battery charger technology for AC and DC UPSs can be simple as in the case of a domestic car battery charger, or complex as in instrumentation or fire and gas battery chargers. Complex battery chargers are designed to have:-

- Predetermined current and voltage versus time charging characteristics.
- Electronic protection against overloads and short circuits.
- Minimum supervision and maintenance.
- Occasionally a form of automatic duty-standby change over facility is required.

Modern chargers use fast acting and accurate electronic devices to control the desired output characteristics. The rectifying device can be diodes or thyristors.

The rectifying device is usually in the form of a single phase for units up to about 25 kVA, or a three-phase bridge-connected device for larger units. The rectifying device is fed by a single-phase or three-phase transformer. The output from the rectifier is passed through a current detection circuit (a resistance shunt or special magnetic device) and a smoothing reactor (or choke). Signals are taken from the current detector and from the output terminals, are fed back to a control circuit which produces the desired current and voltage characteristics. The control circuit also incorporates overcurrent and overvoltage protection so that the battery and its load are not damaged during abnormal conditions. Some loads cannot tolerate overvoltages, not even for a short time.

Battery chargers have an energy conversion efficiency of about 85% and a typical power factor of 0.75 to 0.85 lagging.

17.2.1.1 Charging rates

The basic method of charging batteries depends upon the type of cell i.e. lead-acid (Pb) or nickel-cadmium (NiCd). The basic method for Pb cells is 'constant voltage' where the current varies as the state of charge changes. Conversely the method for NiCd cells is 'constant current' where the cell voltage varies as the state of charge changes.

When charging Pb cells from a constant voltage source the charging current starts high and slowly decreases to a constant value when the cells become fully charged. The constancy of the current is an approximate indication that the cells are fully charged.

However, this is not the case with NiCd cells since constant current charging is preferred. The best indication with NiCd cells is the specific gravity of the electrolyte. The specific gravity should ideally be checked before and after charging, but this is not practical on a routine basis.

If batteries are kept in good condition then it is possible to predetermine a charging pattern to suit the particular battery. This is the basis upon which battery charger manufacturers are able to design their equipment. Manufacturers will provide charging and discharging diagrams for their batteries and chargers, see Figure 17.2, which shows the typical requirements for Pb cells.

It is possible to overcharge batteries and this is wasteful on electricity, causes gassing and can cause internal damage if the current is too high.

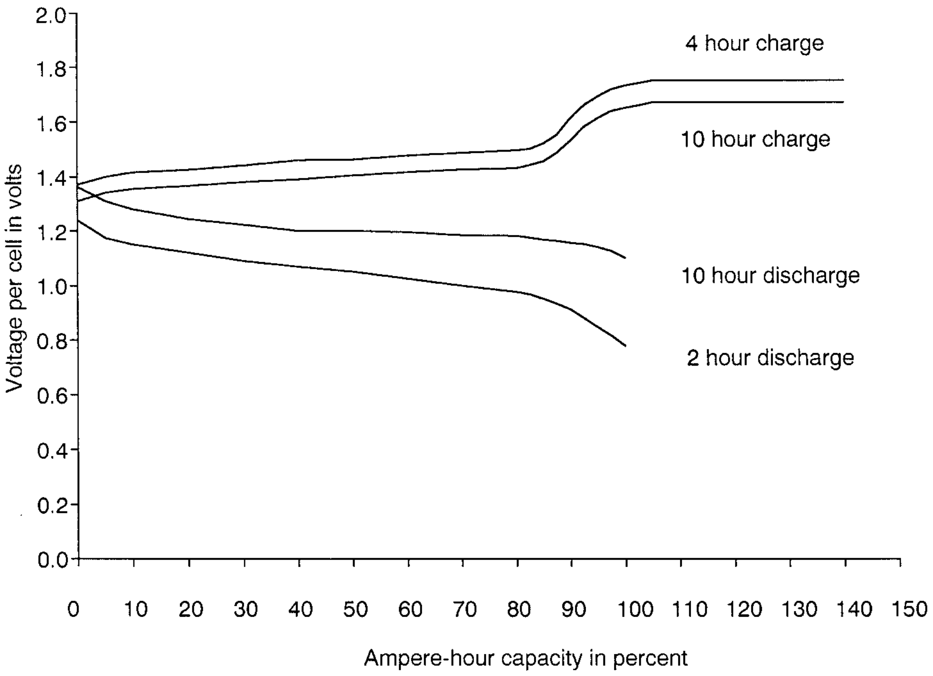

Figure 17.2 Charging and discharging of a lead-acid battery.

A 'rule-of-thumb' guide to the appropriate slow charging current is to divide the ampere-hour (AH) capacity of the battery (at a 10 hour rate) by about 7, e.g. a 100 AH battery would require a charging current of about 15 amps for 10 hours.

Modern chargers are usually designed to charge a battery in one or more of the following ways:-

- Float charge – for Pb and NiCd cells.
- Boost charge – for Pb and NiCd cells.
- Trickel charge – for Pb cells only.

The transfer from one method to another may be automatically or manually achieved during the charging period.

17.2.1.2 Float charge

With this method the battery is connected to its load during charging. The charger must be designed to supply sufficient current for the battery and the load. The charger operates in an almost constant voltage manner with its voltage normally just above the battery voltage. When a sudden demand of current occurs the battery and the charger attempt to share the current. However, the demand from the charger may exceed its rating and so the mode of operation then changes to constant current. The battery supplies the remaining current. The load voltage is determined by the battery during the sudden demand. The recommended float charge voltage applied to the battery during normal demand is about 2.2 to 2.25 volts per cell for Pb cells and about 1.4 and 1.45 volts per cell for NiCd cells. This will ensure full capacity is maintained in the battery without manual supervision.

Typical battery-plus-charger units can be rated up to 250 volts and 400 amps. Some oil companies prefer to restrict the DC voltage to 120 volts for safety reasons.

17.2.1.3 Boost charge

As the name implies boost charging is used to quickly restore the capacity of the battery, usually following a heavy demand. The boost current may be much larger than the rated float charging current. When boost charging is required the charger operates in the constant voltage mode but with a raised voltage. The raised voltage causes the boost current. As the battery becomes charged the boost current falls. When the current falls to a predetermined value the control circuit automatically switches the charger back into the float charge mode. An auto-manual switch is often provided to enable boost charging to be applied as required.

The elevated DC voltage may not be tolerated by the load and so care needs to be taken at the specification stage to ensure that boost charging is permissible.

17.2.1.4 Trickle charge

Trickle charging is used only for Pb cells. The current used in trickle charging is very much less than the rated battery current. The method is used for storage batteries which supply little or no current as a normal condition. They therefore remain charged for long periods and a small trickle of current is sufficient to maintain the charge.

However, batteries are best kept 'working' otherwise chemical degrading occurs internally and the battery loses performance. Batteries in these conditions should be heavily discharged periodically and immediately charged up quickly with a boost charge, if permissible, followed by a float type charge. When fully charged the mode is changed back to trickle charging.

NiCd cells should not be trickle charged, and they should be given a heavy discharge-charge cycle occasionally to ensure that their internal condition remains in good order.

NiCd cells tend to require less attention and maintenance than Pb cells.

17.2.2 Batteries

Batteries are used to store DC energy which is later used to supply a block of energy to a load, often in the form of a high current for a short time e.g. rewinding mechanism springs in switchgear, emergency lighting, emergency instrumentation power for control panels and control devices, starter motors on engines and gas turbines.

Batteries used for heavy current industrial applications are invariable of two kinds:-

- Lead-acid (Pb).
- Nickel-cadmium (NiCd).

A battery consists of a number of cells connected in series. The series connection is necessary to create sufficient load voltage. Each cell has a low voltage which is peculiar to the type of cell and independent of the current and rating of the cell. The cell voltages are shown in Table 17.1.

The maximum cell voltages during charging should not exceed 2.7 volts per cell for Pb cells and 1.85 volts per cell for NiCd cells.

Suppose a nominal voltage of 110 DC is required then at least 54 Pb cells or 89 NiCd cells would be required.

The size of a battery is defined as its ampere-hour capacity, since capacity is related to charge (Q) which equals current $(I) \times$ time (T). Hence a battery can supply a large current for a short time, or a small current for a large time.

Therefore the engineer needs to determine the nature of the load current as a function of time over a typical operating period. For example a switchgear battery may be needed to supply instrument lamps on a continuous basis and spring charging current on an occasional basis.

Table 17.1. Cell voltages

Cell type	Open circuit voltage fully charged (volts)	Load voltage during discharge (volts)	Minimum recommended discharged voltage (volts)
Pb	2.05	2.0	1.85
NiCd	1.28	1.2	1.0

If there is a total failure from the main supply then it will usually be necessary to maintain the continuous current for 4 hours so that the state of the plant will be known during the failure. During this time it would be expected that the main supply would be restored. Hence the 4 hours can be used as the 'operating cycle' of the battery in the event that the charger is unable to supply current.

Batteries may be installed in several ways, e.g. integral with the charger, in a separate cubicle or on open racks. The choice usually depends upon the physical size of the complete battery. Large batteries are more suited to an open rack installation.

17.2.2.1 Worked example

Consider the following situation as an example.

A switchboard consists of 20 circuit breakers. Each circuit breaker has, two indicator lamps each taking 1 amp continuously, a tripping solenoid taking 5 amps for one second, and a spring charging motor for reclosing which takes 3 amps for 30 seconds. The battery needs to supply current for 4 hours when a mains failure occurs. The ampere-hour (AH) duty is:-

- Lamps $20 \times 2 \times 1 \times 4 = 160$ AH
- Tripping $\dfrac{20 \times 5 \times 1}{3600} = 0.03$ AH
- Spring charging $\dfrac{20 \times 3 \times 30}{3600} = 0.5$ AH
- Contingency typically 15% $= 24.08$ AH
- Total capacity $= 184.61$ AH rounded up to 185 AH

The contingency allows for the battery being in a partial state of charge before the loss of supply. The rated AH capacity and voltage are now known. Reference 3 gives other examples plus a general description of battery charging principles.

In recent years there has been a tendency to prefer Pb cells instead of NiCd cells. This has been due to the development of what has become known as 'maintenance free' or 'sealed type' lead-acid batteries. The basic concept is one of retaining the gases evolved during the charging process and to allow the oxygen to recombine as float charging takes place, see Reference 4. If the operating and ambient conditions are not subject to excessive variation then the concept is satisfactory in practice and the life expectancy of the battery can be as much as 10 years.

If too much gas is evolved and is released through a special safety valve than the life expectancy will be reduced. The amount of gas evolved is a function of the float charging current level and the ambient temperature. The temperature of the electrolyte will be a function of the ambient temperature of the air surrounding the battery. Therefore a high float charging current and a high ambient temperature will cause the life expectancy to fall. If the ambient temperature has an average value of 30°C then the life expectancy will be halved, and at 40°C reduced to a quarter, i.e. 2 to 3 years instead of 10.

In practice it is therefore essential to ensure that the temperature within the battery room or cabinet remains reasonably constant and as close to 25°C as possible, the lower the temperature the better will be the result. At the same time the float charging current should be controlled in an accurate manner, and boost charging should not be available to the battery.

The international standards IEC60623, 60896 and 60993 are useful references for vented lead-acid and nickel-cadmium cells.

17.3 REDUNDANCY CONFIGURATIONS

It is common practice to have two inverters available to supply a common distribution board or switchboard. How they are configured and controlled depends upon the performance required when one unit fails. If a short duration interruption can be tolerated then a simple electromagnetic changeover switch can be used to switch the load over to a live standby unit. This is called a 'standby redundant' UPS system.

A better method, also called standby redundant, is to incorporate a static switch in each of the inverter output circuits. Static switches can function rapidly, with an almost imperceptible disturbance at the load terminals. One static switch is kept 'open' whilst the other is 'closed'.

A more reliable method is called a 'parallel redundant' UPS system, but it requires a more sophisticated control system. Both UPS units are energised to share the common load equally. When one unit fails it is switched out of service and the second unit takes over the full load. Figure 17.3 shows the system which also has an off-load bypass supply switched in service by a static switch. This method can be expanded to incorporate three or more units in parallel, although this is seldom found in oil industry practice. It is a practice used in the computer-based industries such as banking and financial investment. It is a method that lends itself to piecemeal expansion.

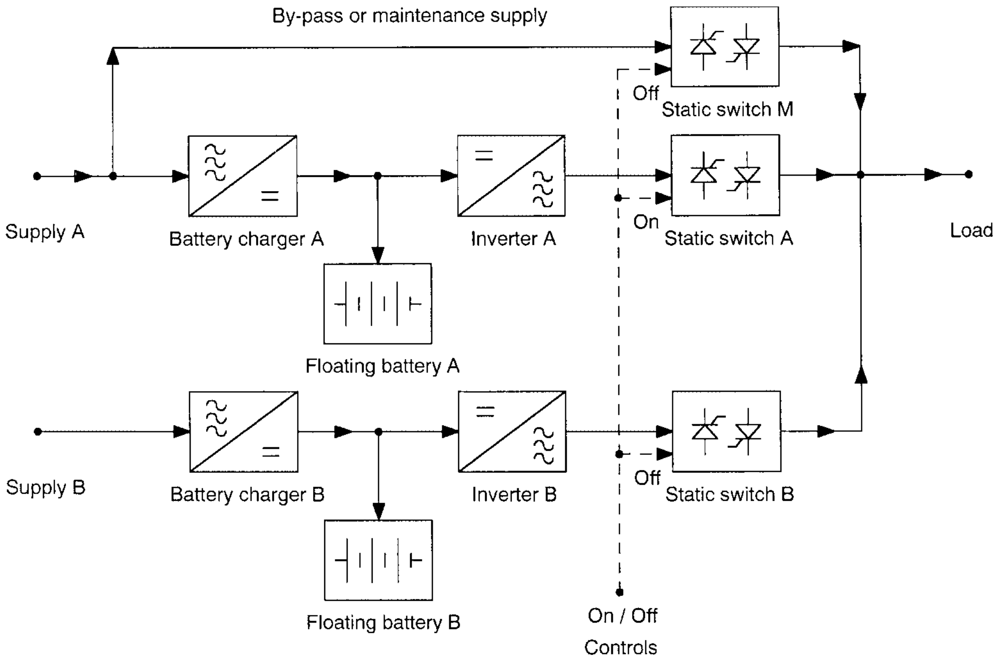

Figure 17.3 Dual redundant UPS with a bypass supply and static switches.

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18

Miscellaneous Subjects

18.1 LIGHTING SYSTEMS

Normal lighting should provide approximately 75% of the total illumination an area of a plant that is densely filled with processing equipment and buildings. Sparsely filled areas such as road ways and perimeter fences can be fully illuminated with normal lighting, unless emergency escape routes exist in these areas.

Emergency lighting should therefore provide between 25% and 30% of the illumination in processing areas. These criteria generally apply to both outdoor and indoor locations, and to onshore and offshore installations. Emergency lighting should be supplied by power from emergency diesel generators, except for lighting that illuminates escape routes. Escape route lighting requires a source of battery power that should last for at least one hour from a loss of all other power sources. The battery may be integral with the lighting fitting or a common battery and local distribution panel for a room or group of rooms, access ways, corridors and the like. The lighting level for escape lighting does not need to be high, a typical value is 20 lux for indoor areas is adequate. Individual oil companies have their own recommendations on these subjects.

Offshore and marine installations are by nature very compact and therefore some additional requirements are generally required, especially with regard to escape routes. Escape lighting should be provided for exit doorways, sleeping cabins in the living quarters, stairways, walkways, corridors, lounges, recreation rooms, dining rooms and gallies. It is essential to illuminate embarkation stairways, helideck, helideck offices, survival craft stations, waiting room, and areas that are associated with personnel having to leave the facility in an organised manner. If in doubt provide more than is a minimum requirement.

Emergency lighting has some separate requirements to escape lighting. For example the personnel operating the plant need to be able to see and operate control panels, visual display units, start-up emergency generators and systems, carry out switching operations, test for hazardous gas, test certain equipment and generally manage an emergency situation. They require a minimum amount of emergency lighting. Consequently the following areas and functions need to be properly illuminated.

- Plant main control room and radio room.
- Emergency generator room or module.
- Main switchroom.
- Main generator room or module.

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- All areas in the living quarters.
- All workshops, stores, cranes and utility areas.
- Offshore installation manager (OIM) offices.
- Obstructed areas within the plant.
- Vent stacks and flare booms.
- Perimeter areas.

During an emergency the personnel should be able to access portable lamps and torches. These should be located adjacent to exit doors, in operational rooms, plant rooms, emergency accommodation areas, OIM's offices, central control room and muster areas. They should be provided with charger units and be suitable for zone 1 hazardous areas, and be capable of operating for at least five hours.

Where possible the control of lighting fittings should be from a non-hazardous area, i.e. one adjacent to the hazardous area, using double pole switches. The supply neutral should be switchable. In rare situations this may not be practical in which case a switchboard or distribution board suitable for the hazardous area and the environmental conditions will need to be installed e.g. Zone 1, IP55 or 56, with a suitable gas group and temperature class, see Chapter 10.

It is often a good practical consideration to use only lighting fittings in a plant that are suitable for Zone 1 areas that are also exposed to wet weather conditions e.g. IP66 enclosures of at least Ex (e) hazardous area types, unless of course they are installed indoors in areas where water sprays are not needed. Indoor process areas such as gas compressor modules require water-based fire-fighting deluge systems. Such locations require waterproof electrical fittings of all types, e.g. lighting, junction boxes, local control stations, local control panel. Locations such as control rooms, computer rooms, electronic equipment rooms, accommodation areas and offices do not require such hazardous area fittings, and good quality domestic or light industrial fittings are usually suitable and aesthetically acceptable.

Some areas are suitable for floodlighting and high-pressure sodium fittings can be used.

The incoming three-phase supply to the lighting distribution panels should be provided with four pole switches or circuit breakers, to ensure that the neutral is opened when the panel is de-energised for maintaining sub-circuits in hazardous areas. The sub-circuit loading should be arranged to give a balanced load on the incoming supply. Each sub-circuit will be a single-phase consumer, for which the single-phase two-wire supply can be taken between one phase and neutral of a four-wire system, or a single-phase two-winding step down transformer can be used. The use of a small transformer will ensure that the voltage required for the light fittings is well matched. Occasionally a 440 V three-phase supply is used throughout a plant, for which the line-to-neutral voltage is 254 V. A single- phase nominal voltage of 254 V is out of range for the products of some manufacturers of lighting fittings. A choice of 415 V/240 V, 400 V/230 V or 380 V/220 V would enable a wider choice of standard equipment to be used.

Fluorescent lamps should be chosen and located carefully where they illuminate rotating shafts, so as to avoid a stroboscopic effect that shows the shaft to appear stationary even though it is in fact rotating at a high speed.

Lighting schemes within modules and compact plant areas should be divided into at least two groups so that a supply failure does not put the whole area into darkness. This consideration applies to both normal and emergency schemes.

When designing a lighting circuit it is customary practice to size the cables so that the farthest lamp from the supply receives no less than 95% of its nominal voltage. In addition it is assumed that all the lighting fittings are energised when this design calculation is made.

18.1.1 Types of Lighting Fittings

As a general guide to the appropriate types of fittings that can be used, the following are suitable:

- Industrial weatherproof fluorescent usually double 40 watt tubes for non-hazardous general areas.
- Ex (e) certified and weatherproof fluorescent, also double 40 watt tubes, for hazardous areas.
- Ex (e) or Ex (d) certified and weatherproof floodlights of the SON-T type, for areas such as well-head, platform legs and sea surface lighting.
- Ex (e) or Ex (d) certified and weatherproof bulkhead fittings with a single 60 watt incandescent lamp.
- Ex (n) certified and weatherproof fluorescent with single or double tubes for Zone 2 and non-hazardous areas, and areas where corrosion and determination will be minimal.

Note that low-pressure sodium lamps are not generally permitted in hazardous areas because they are considered to be a risk with regard to igniting hazardous gases. Fittings made from aluminium and its alloys should be avoided because the oxide that invariably forms after a time is considered as a potential source of sparks caused by mechanical impact.

18.1.2 Levels of Illumination

The levels of illumination needed at different locations and within rooms are given as a general guide in Table 18.1.

Table 18.1. Illumination levels of onshore and offshore plants

Location and equipment	Illumination level in lux, see Note 1
Laboratory	500
Computer room	500
Radio room	500
Gymnasium	500
Medical treatment room	500
Pharmacy	500
Helicopter reception offices	500
Helicopter operations office	500
Administration offices	400 to 500
Drawing office	400
Library and reading room	400
Kitchen and galley	300 to 500
Manned process modules	300
Central control room	300 Note 2

(*continued overleaf*)

Table 18.1. (*continued*)

Location and equipment	Illumination level in lux, see Note 1
Local control room	300
Laundry	300
Medical consulting room	300
Lecture room or theatre	300
Medical consulting room	300
Drillers console	300
Workshop	300
Print and reprographic room	300
Major rotating equipment areas and module	200
Major switchroom	200
Rear of control panels	200
Battery and UPS room	200
HVAC	200
Bulk storage room	200
Well-head area	150
Drill floor	150
Radio equipment room	150
Electronic equipment	150
Local equipment room	150
Food store	150
Dining and mess area	150
General recreation room	150
Projector presentation room	150
General storage room	150
Rest room	150
Visitors room	150
Wash room and showers	150
Toilets	150
General process areas	100
Mud pump area	100
Shale shaker area	100
Drilling sack store	100
Medical storage room	100
Locker rooms	100
Minor materials storage room	100
Corridors, stairs and ladders	100
Gauge glasses	100
Cinema	100
Elevators	100
Roof areas	100
Drilling derrick access points	50
Seawater level and below platform	50
Accommodation cabins	50
Outdoor walkways and access ways	50
Lifeboat and muster stations	50

Table 18.1. (*continued*)

Location and equipment	Illumination level in lux, see Note 1
Material storage and handling yards	50
Road tanker loading areas	25
Drill pipe laydown area	10
General car parking area	1 to 5

Note 1: Some oil companies specify the level of illumination to be floor level, whilst others prefer it at a working desk height, e.g. 0.7 to 0.85 m.

Note 2: The lighting level in the central control room can be arranged to be wholly or partly adjustable so as to minimise glare and eyestrain whilst operating visual display units (VDU) or man–machine interfaces (MMI).

Helideck lighting is a specialised subject that is covered by national and international regulations.

It is recommended to supply the helideck landing circle light fittings from a DC service e.g. 110 VDC uninterruptible supply, that should have a 110 VAC back-up supply so that the DC system can be maintained without switching off the circle lighting.

A comprehensive source of general information on lighting is Reference 1. It also describes in detail how to calculate lighting levels.

18.2 NAVIGATION AIDS

This sub-section mainly applies to offshore and marine installations, and is given as general guidance. For more detail appropriate references should be sought and carefully studied, and their latest revisions verified.

Navigation aids consist of the following equipment:

- Flashing marker lights.
- Fog horns.
- Platform nameplates.
- Aircraft hazard lights.
- Helideck landing facilities.
- Radio communications and beacons.
- Radar.
- Echo-sounding and sonar.

18.2.1 Flashing Marker Lights

A typical requirement is that recommended by the British Department of Trade document 'Standard Making Schedule for Offshore Installations',

1. White and red lights flashing the Morse letters ‘U’ every 15 seconds as follows:

Eclipse	1.00	s
Flash	1.00	s
Eclipse	1.00	s
Flash	3.00	s
Eclipse	8.00	s
Total Period	15.00	s

2. Fog signals sounding the ‘U’ every 30 seconds as follows:

Blast	0.75	s
Silent	1.00	s
Blast	0.75	s
Silent	1.00	s
Blast	2.50	s
Silent	24.00	s
Total Period	30.00	s

3. Illuminated identification panels.
4. Navigation buoys.

18.2.2 White and Red Flashing Lights

The ‘normal’ range and ‘apparent intensity’ of these flashing lights should be in accordance with the local requirements, e.g. for UK waters, IALA publication ‘Recommendations for the Notation of Luminous Intensity and Range of Lights’. Appendix II (16th November 1996) and BS 942 (1949) clauses 10 and 11 respectively.

18.2.2.1 Main lights

The main white lights should have a ‘nominal’ range of 15 miles and be visible in every direction of approach, there should normally be a minimum of two and a maximum of four main white lights.

18.2.2.2 Subsidiary lights

Subsidiary red lights of 3 miles ‘nominal’ range should be positioned to mark the horizontal extremities of the structure, in positions not occupied by white lights, to indicate any irregular projections of the complex.

18.2.2.3 Secondary lights

Secondary white lights of 10 miles ‘nominal’ range and visible in every direction of approach should automatically come into operation in the event of failure of the 15 mile main white lights; these are normally mounted in similar location to the main white lights.

18.2.2.4 Operation and control of lighting systems

Navigation lighting systems can be fitted with a device to automatically switch on 15 minutes before sunset until sunrise or whenever the visibility is less than 2 sea miles. There can also be a manual override device to enable the navigation aids to be switched on during unusual conditions or for maintenance and testing etc.

Failure of any of the navigation lights can be indicated in the central control room and in the radio room.

In the event of failure of the main white lights control equipment, control should automatically be transferred to the secondary system, which would cause the secondary and the main lights to flash in synchronism, and generate an alarm in the central control room and the radio room.

All subsidiary lights should operate in synchronism.

The secondary and subsidiary lights can be equipped with an automatic lamp changer or multiple filament bulb. This provides a minimum of one standby lamp or filament which will be automatically activated in the event of a filament failure. Filament failure should produce an alarm in the central control room and the radio room until a defective bulb is replaced.

On long narrow structures or structures linked by bridges where lights may otherwise be several hundred metres apart, intermediary 3 mile red lights should be mounted in positions to deter vessel from colliding with the central sections of the structure of bridges.

The secondary and subsidiary lights should be capable of operating for 96 hours from a battery power source which is independent of the main supply. The equipment would normally operate on the main AC supply, with automatic switching to an alternative AC supply in the event of main supply failure, and automatic switching to battery supplies when no AC supply is available.

18.2.3 Navigation Buoys

Navigation marker buoys can be wave or solar powered or alternatively fitted with batteries. They would be retained in a position to facilitate quick manual launching, and provision should be made for ready inspection and maintenance of batteries.

18.2.4 Identification Panels

The structure identification panels usually consist of black letter and figures one metre high on a yellow background with illumination or be on a retro-reflective background.

18.2.5 Aircraft Hazard Lighting

Hazard lighting should be provided on all projections from the structure which could present a danger to helicopters approaching the platform. Positions where it would be impractical to fit red lights due to the possibility of damage or difficulty of maintenance caused by high temperature, such as flare towers and exhaust stacks, would be flood lit from convenient locations.

In the event of main supply failure the hazard lighting would be supplied from an emergency generator or battery supply.

No form of lighting on the structure should be capable of creating a hazard to helicopters by night-blinding the pilot due to dazzle or glare.

18.2.6 Helicopter Landing Facilities

Helideck markings and illumination should be in accordance with appropriate standards, e.g. BSIDD55/1978 and GODAC Part II, Section 5.3.6.

A high frequency radio beacon with a minimum range of 30 miles can be provided for the guidance of approaching helicopters, and VHF/AM radio would be provided for communication with pilots to comply with the appropriate standards, for the location.

The structure would also be equipped with suitable devices for ascertaining the wind speed and direction, air temperature, barometric pressure, visibility and cloud cover.

18.2.7 Radar

Radar is not used on all offshore platforms. Its use is determined by the nature of the platform and the frequency and type of local sea traffic. When surveillance radar is installed precautions should be adopted to ensure the minimum of danger to personnel from high energy radiation and dangers associated with rotating aerial scanners, interference with electronic instruments and communication, and the elimination of ignition in hazardous atmosphere in accordance with the standards e.g. BS3192 and 4992.

All of the equipment and interconnecting cables should be located in a safe area. The transmitters and aerials should not be located near telecommunication equipment, electronic instruments and similar equipment which could suffer interference or damage due to high energy radio frequency radiation. The aerials must be positioned to prevent the creation of high energy radio frequency fields in hazardous areas where they could cause ignition.

The aerials should be installed in such a manner and location as to allow reasonable safe access for at least two people for servicing and maintenance, whilst preventing access to unauthorised personnel.

Emergency stop switches could be provided in a safe position, adjacent to the aerials, to switch off the scanners and transmitters.

18.2.8 Radio Direction-Finder

Platforms that are permanently manned would require equipment for obtained bearings on radio navigation beacons and survival craft transmitting on international distress frequencies. If the equipment is of a type approved by the British Department of Trade (or similar national standard) in accordance with SOLAS (1974) Regulation 12, then the SOLAS requirements could also be supplemented as follows:

- The equipment should be located in the radio room.
- The aerials and feeder cables should be located in a safe area as close as possible to the radio room.

- An emergency power supply should provide a minimum of 6 hours duration, and minimum of 3 hours of this supply should be from batteries. The batteries, charger and supply cables should be in a safe area as close as possible to the radio room.

18.2.9 Sonar Devices

If echo-sounding equipment is required then it should be of a type approved by the Department of Trade, or similar national authority appropriate to the location, in accordance with SOLAS (1974). The installation of sonar devices should be in accordance with appropriate standards, e.g. BS5345 Part I (1976), BS5490 (1977), Reference 2, and particular regard should be directed towards the dangers that high-powered underwater sonar transmissions may present during diving operations.

18.3 CATHODIC PROTECTION

Cathodic protection is the responsibility of the corrosion engineer or metallurgist. The subject is fundamentally reasonably simple to understand but can be extremely mathematical in its application.

Direct current is arranged to flow out from the impressed anodes into the surrounding electrolyte, which is the sea water for offshore structures or the damp ground for onshore structures. The current returns through the structure itself and then back to the negative terminal of the impressed current source. The direction of current as described prevents the loss of metal from the structure into the electrolyte. This is opposite in direction to the natural current present due to corrosion action.

The electrical engineer is not usually involved in the chemistry of the system, his work is mainly associated with sizing the AC and DC cables, accounting for the power requirements and ensuring that the equipment satisfies any hazardous area requirements that may exist.

Impressed current systems require low-voltage high-current DC power. The voltages are typically 12, 25 and 50 volts. The currents are typically 100 to 800 amperes from one unit. The power is supplied by transformer rectifier units in which the transformer coils and the power rectifier are usually immersed in insulating oil to improve heat removal. The AC supply is usually three phase at LV voltage, e.g. 380 to 440 volts, and the supply power factor is about 0.75 lagging.

The output voltage is adjustable between +33% and −25% to take care of local site variations. The correct setting is determined at site during commissioning. Adjustments are often made periodically as the site conditions vary or if the installation is modified.

The anodes are made of various materials and the choice is determined by the physical conditions, the electric field pattern, current densities, cost and anode corrosion. Anode current densities vary between 10 amperes per metre squared for silicon iron to more than 1000 amperes per metre squared for platinised and lead alloys.

The electrical engineer needs to size AC and DC cables and to choose them to suit the physical environment.

Reference 3 although rather dated gives an excellent treatment of the theory of practice of cathodic protection although the subject has no doubt been given a more up-to-date treatment by other authors. Another reference of a more practical nature is Reference 4.

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19

Preparing Equipment Specifications

19.1 THE PURPOSE OF SPECIFICATIONS

The main purpose of preparing a specification for an item of equipment is to ensure that the purchaser, who may also become the owner, obtains the equipment required, rather than what the supplier or manufacturer thinks the purchaser should have. In many situations the difference in perception of the requirements may be small and insignificant. However, for complicated equipment such as high-voltage switchgear and generation systems the differences may be very significant.

In order to satisfy both the requirements of the owner and the available options from the supplier, it is necessary to describe the requirements in various degrees of detail. The degree of detail will be a function of the type of equipment. Complex equipment such as large motors, generators, high-voltage switchgear and variable speed drive systems will need a more detailed description than the more standardised equipment such as power cables, low-voltage motors and, to some extent, low-voltage motor control centres.

Manufacturers of complex equipment regularly meet the needs of different owners, whose requirements vary in content and emphasis. A particular owner may have different requirements for the same type of equipment when it is used in offshore, as opposed to onshore, installations. These environments may be radically different, e.g. Northern North Sea, desert conditions in the Middle East, hot and humid climates of tropical locations. For example, the methods of cooling the equipment and the ability to withstand corrosive conditions will be very different in these extremes of environment.

On the other hand, simple equipment is less sensitive to extremes of location and environment. The main aspect that affects simple equipment is its full-load rating for low and high ambient temperatures. The details of the construction will be almost unaffected. Simple equipment used in high ambient temperatures will tend to be physically larger and heavier. A motor of a given shaft output rating may have a larger standard frame size when used in a desert than one used on a North Sea production platform.

A standard specification of the owner should take account of what is generally available in the market, and what can reasonably be called for as options. It is uneconomical and impractical to overspecify aspects which a manufacturer cannot fulfil at a reasonable cost and with a sensible production duration. Where possible the aim should be to match what the manufacturer can offer from his standard range of equipment. An efficient approach by the purchaser is to call for equipment that is a standard but most suitable product of the manufacturer plus the options offered, if these are

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needed, and then design the power system around the equipment to be purchased. In general this will also reduce the amount of time needed to design the power system.

For some types of projects there has become an emphasis on ‘functionality’ when specifications are being prepared. Care needs to be exercised in describing functional aspects of a specification. Most people understand the function of basic equipment such as generators, motors and switchgear and yet, in order to obtain what is ultimately required, it is necessary to pay attention to design and performance details. Functionality implies a more interrelated type of existence, as is the case with systems of equipment rather than individual items of equipment. A few good examples of applying a functional approach in the specification of process control systems are SCADA systems, modern protective relaying systems, variable speed drive systems and power management control systems. These equipments comprise a system of computers, measuring devices, controller set points, switchgear and rotating machines. Here the whole system must be functionally defined, and all the individual elements must be fully compatible from the conceptual stage of the specification.

With most specifications there are some key aspects that should be clearly stated or defined, the omission of which can cause embarrassment, delay and extra costs at a later date e.g. at the factory inspection, during installation and commissioning. A well-designed data sheet to accompany the specification will do much to avoid ambiguity or the omission of requirements. The data sheet should comprise two parts, a part completed by the purchaser to define the requirements and a corresponding part for the manufacturer to state what is offered.

The content of the specification should bear a relationship to the importance of the equipment in the power system and to its capital cost. If the content is too brief or too general then it may not satisfy the intended purpose of the specification and inferior equipment may be chosen.

In summary the requirements of the owner can be arranged in the following groups:-

- Essential requirements.
- Desirable requirements. Those which may be easily available in the market as options.
- Incidental requirements. Those which would be useful but not critical to the performance of the equipment. These may not be easily available, could be described as ‘nice to have’ and should therefore be avoided.

19.2 A TYPICAL FORMAT FOR A SPECIFICATION

The following format is reasonably typical of an equipment specification. Owners and purchasers, of course, have their particular style and preferences as to the order in which the paragraphs and clauses are placed in the specification document.

- Introduction.
- Scope of supply.
- Service and environmental conditions.
- Compliant international standards.
- Definition of technical and non-technical terms.
- Performance (or functional) requirements.
- Design and construction details.
- Inspection and testing.

- Spare parts.
- Documentation.
- Packing and transportation.
- Appendices, if necessary.

19.2.1 Introduction

In this introductory section there should be a brief description of where the equipment is to be located, what type of installations will use the equipment and whether the environment is hazardous or non-hazardous (or both).

19.2.2 Scope of Supply

A summary listing should indicate all the main components that constitute the equipment, e.g. AC generator, coupling, exciters, AVR, terminal boxes, lubrication system, stator cooling system, heat exchangers.

Where appropriate it is prudent to describe or list what is not included in the scope of supply. This will minimise misunderstandings at a later stage when quotations are being compared, e.g. for the above example, gearbox, prime mover, base frame or skid assembly.

19.2.3 Service and Environmental Conditions

Here should be explained the range of environmental (ambient) temperatures, humidity, winds, and available cooling water conditions. The design ambient temperature should be stated. The type of weather throughout the year may have an influence on the design of the equipment, e.g. dust-laden wind, heavy storms, corrosive rain, air contaminated with chemicals. Outdoor and indoor conditions should be described if appropriate.

19.2.4 Compliant International Standards

A list of only the most appropriate international standards should be included. The title, identification number and latest revision number should be given. If too many standards for the type of equipment are listed, then much confusion can arise at a later date when the quality assurance checks are made. Some standards have similar titles but have subtle differences and applications. (Mixing European and US standards can give rise to misinterpretations of their definitions and suitability as they are not necessarily identically equivalent to each other, such as in the case with some BSI and IEC standards that meet the CENELEC harmonisation norms.)

19.2.5 Definition of Technical and Non-technical Terms

When it is proposed to issue an enquiry for the purchase of equipment on an international basis, it should be borne in mind that the interpretation of words and phrases, which may not be in regular use by the recipient, can suffer through translation. Some of the international standards, e.g. IEC60034, 60050, 60079, include sub-sections or clauses for defining words, phrases and terms. Sometimes these definitions are not easy to grasp.

It is recommended that particularly important words, phrases, terms and abbreviations are defined in the specification itself, especially if they differ in use from say those given in an IEC specification. (An example that regularly appears is the difference in meaning between 'shall' and 'should'.)

Some of the material in this section could equally well be placed at the end of the document as an appendix.

19.2.6 Performance or Functional Requirements

Somewhere in the specification, or the data sheet, should be stated the expected life duration of the equipment, e.g. 25 years, and a reasonable duration of continuous service between major maintenance operations, e.g. 3, 4 or 5 years. These durations will depend upon the type of equipment, but for major items such as large generators, large high-voltage motors, switchboards, motor control centres, power transformers, these durations can be regarded as typical for the oil industry.

If equipment is to be specified for use in hazardous areas, e.g. Zone 1, Zone 2, then the equipment as purchased should not have been modified in any manner that could invalidate its hazardous area certification. Components that can be vulnerable to modification are terminal boxes, gland plates and threaded entries.

The basic requirements for performance can be categorised as follows:-

- Starting up.
- Normal continuous operation.
- Permissible but limited overloading.
- Short-circuit withstand.
- Shutting down.

It will be useful to the recipient to have an understanding of the power system or network into which the equipment will belong. This is especially important when specifying the high-voltage generation and distribution equipment, and some of the main low-voltage equipment such as switchgear. The modes of operation of the power system may have some bearing upon the design of the equipment being specified, e.g. method of earthing neutrals, minimum and maximum fault currents, dips in system voltage and frequency, normal and abnormal switching configuration.

The owner may have some restriction on how to start up and shut down equipment, e.g. limits on starting currents of motors, voltage dip limits at switchgear, duration of start up or shut down, purging with safe air or inert gas, interlocking schemes, manual or automatic sequences.

For some equipment, especially generators and their prime-movers, the normal or rated duty may need to be emphasised so that the correct rating for the prime-mover is chosen, and an adequate margin for short-term permissible overloading exists. Emergency generators used offshore may need to be allowed to run in overloaded conditions until they run out of fuel or actually fail. International specifications should be referred to for the description of full-load duty for particular types of equipment, for example IEC60034 for generators and motors and for switchgear see sub-section 7.1.

If equipment needs to function continuously in high ambient temperatures, e.g. 40°C or higher, then the derating of the manufacturer's standard equipment should be quoted and explained by the manufacturer. This is especially important with switchgear busbars and circuit breakers. Some manufacturers may not wish to quote for high ambient conditions, and many of the international standards use 40°C as their upper limit.

The short-circuit withstand performance may be important with certain types of equipment, e.g. generators, high-voltage motors, switchgear, power transformers. This should be described or stated in the data sheet. The rms and peak values of short-circuit currents may need to be described.

Some equipment may be sensitive to unbalanced loading, unbalanced supply voltages or the harmonic content of the supply.

19.2.7 Design and Construction Requirements

Oil industry equipment tends to be more robust than normal industrial equipment due to the often harsh and hostile environments in which it is expected to function without trouble for long periods of time. The indirect cost of equipment failures and outages is high and reliability is of paramount importance.

An essential requirement is the definition of the degree of protection of the enclosure for the environment, which may be either outdoor or indoor, and hazardous or non-hazardous. The international standards most often used are IEC60529 and NEMA-ICS1-110 for the degree of protection against liquids and particles. These references are applied for the hazardous area protection. See also Chapter 10.

Wound components such as motor and transformer windings need to have their insulation specified to withstand the surface temperature of the copper conductors. IEC60085 and ANSI/NEMA describe the different classes of insulation that are normally available. Where IEC60085 or ANSI/NEMA is the reference, the two most common are Class B and Class F. These state the maximum temperature rise in degrees Celsius above the conductor temperature when the temperature of the cooling medium for the equipment is no greater than 40°C.

For most equipment ratings used in the oil industry the temperature rise limits are 80°C for Class B and 100°C for Class F (Class H allows 125°C). It is common practice to specify Class F insulating materials but to restrict the actual temperature rise to that of Class B. These stem from the recommendation in IEC60085 that for ratings equal and above 5000 kVA or if the iron core length is equal and above one metre, that this combination of classes should be used.

Various IEC standards for switchgear refer to IEC60694 sub-section 4.4.1 for the requirements of rated current and sub-section 4.4.2 for temperature rise of enclosed components such as bare terminals, busbars and risers, panel surfaces, and built-in apparatus. It also refers to IEC60085 for the classes of insulation. Busbars and risers can be bare or insulated and so it is not practical to state a requirement for their temperature rise in the project specification.

The owner may have particular requirements for the materials to be used for insulation and their impregnation. This may be due to their experience with marine and highly humid environments.

Other aspects that should be included are protective devices, measurement detectors, terminal blocks, segregation of circuits and terminals, voltage surge suppression, skid construction, floor frames, lifting eyes, jacking points, earthing bosses, indicating devices, control switches, automatic voltage regulators, exciters, detachable panels and doors, forced cooling, shaft bearings and seals, lubrication systems, anti-condensation heaters, noise levels, labelling and nameplates, painting etc. Some of these may be efficiently included in the data sheet.

19.2.8 Inspection and Testing

Inspection and testing of the purchased equipment is one of the most important tasks in the engineering of a project. Its importance is sometimes underestimated. The first serious tests that the purchaser will witness are those in the factory where the equipment is assembled. These tests will also include a physical inspection of the equipment.

It is therefore important to state clearly in the specification what inspection and testing will be required and, where appropriate, what are the acceptable limits of the results. Most tests required in the oil industry are covered in international specifications and these can be used as references. However, not all those in the reference documents need to be carried out in all cases. It is therefore prudent to state the requirements in the project specification in one or more of the following methods:

- Write a detailed description of exactly what is required, including the limits that are acceptable and the form in which the results should be reported. This method ensures a ‘self-contained’ approach that is very beneficial during the actual testing operation. Often time is limited to perform tests and to have all the requirements to hand without having to search through related documents enables the work to be completed very efficiently.
- Quote the exact clause numbers and sub-section headings in the reference documents for the particular tests to be performed. This may be less efficient when the time of the tests becomes due, especially if the reference documents are not easily to hand. If a statement is made such as ‘the switchgear shall be tested in accordance with the XYZ-123 international standard’ and no other clarification is included, then many debates can arise at the time of testing.

Whichever method is used it should be carefully checked by a quality assurance department before the specification is approved for purchasing the equipment.

Some types of equipment require ‘production tests’, ‘type tests’, ‘performance tests’, ‘routine tests’, ‘abbreviated tests’ or ‘special tests’, or a combination of these tests. The subtitles are sometimes used with different meanings. Production tests are required for complex equipment such as high-voltage generators and motors, and these tests are performed in the factory before the complete unit is assembled. For example the rotors are balanced without the stator, air-to-water heat exchanges can be tested to withstand hydraulic pressure, winding insulation and individual coil insulation can be tested.

Type tests are performed on one from a group of identical units. These tests are comprehensive and some of which are usually only performed once in the life span of the equipment.

If the equipment is a standard product of the manufacturer for which existing certificates can show that a type test has previously been carried out, then the purchaser may wish to accept the certificate without repeating the test. This is largely a matter of choice than necessity.

Routine and abbreviated tests are generally the same form of tests. These are applied to those units in a group that have not been type tested. If only one unit is to be purchased and a type test has been waived then a routine test is usually performed and the results compared to those of a previous type test. The number of different tests included in the routine tests is less than that of the type tests.

Some of the tests may be identical in each category. Routine tests are usually witnessed by the owner or purchaser.

Performance tests are those tests that need to be carried out on combined equipment such as a gas-turbine driven generator or a pump driven by a high-voltage motor. In such cases the dynamic relationship between the various equipments is of interest. For example, rotor vibration, critical speeds, run-up time to full speed, starting up and shutting down sequences, full-load and over-load performances, heat dissipation and cooling medium performance.

Occasionally 'special tests' may be required. These may be due to the need to operate the unit in an unusual mode or to test special control systems that may involve associated equipment such as a power management system or a control panel. Special tests may be needed to verify the operation of protective devices in the equipment rather than the equipment itself, but which require the device to be in its fully functional position on its host equipment. The owner or the purchaser usually witnesses performance and special tests.

Routine tests usually include a thorough inspection of the equipment both before and after the testing is complete. Routine testing should not be confused with sample testing. For example a switchboard may consist of many panels of essentially the same type, e.g. motor starters, transformer feeders. The testing schedule should state whether samples of similar types could be tested in lieu of testing all the units. In either case a full routine test is generally required. Functional testing of mechanical operation should be applied to all the units, e.g. open and close contactors, rack in and out circuit breakers, operate switches and controls.

19.2.9 Spare Parts

At the inquiry stage it is common practice to ask the manufacturer to list or describe what spare parts are needed for commissioning purposes and for normal use of the equipment.

19.2.10 Documentation

For equipment such as generators and switchgear the documentation can be extensive. Some of it is needed by the project design engineers as soon as possible after the purchase order is placed. The delivery of documentation can be made at the following basic stages:-

- Tender documentation.
- Purchase order documentation.
- At the time of delivery of the equipment.

Documentation can be divided into drawings and documents, some of which are listed in Appendix E.

19.2.10.1 Tender documentation

The following dimensional drawings would normally be required at the tendering stage of a project, so that comparison can be made between the various tendering manufacturers,

- Plans and elevations of the main structure.
- Base frame or skid dimensions.
- Attached equipment such as heat exchangers and ducting.
- Location of fitting eyes and jacking points.
- Cable box positions.
- Cable gland plate positions.
- Nameplate details.
- One-line diagrams.
- Typical schematic diagrams.
- Control and logic diagrams.

In addition, the following written documents would normally be required,

- Completed data sheets.
- Quality assurance plan and procedures.
- Inspection and testing plan and procedures.
- Detailed list of performance, type, routine and special tests.
- Hazardous area certificates and certificates of conformity, see Chapter 10.
- Spare parts list.
- List of attached equipment, e.g. anti-condensation heaters, temperature detectors.
- Heat dissipation of units.
- Weight of each major component, e.g. heat exchangers, rotors, stators.
- Copies of existing type tests certificates.
- Reliability data, e.g. mean time before failure.

19.2.10.2 Purchase order documentation

After the tendering process has been completed and an order is about to be placed the following documents would be required as soon as possible,

- Revised versions of the documents submitted at the tender stage.
- Completed data sheets.
- Foundation loading details.
- Lubrication system details.
- Rotor removal and replacement procedure.
- Full details of all cable termination, gland plates and boxes.
- Lay-down area adjacent to the equipment.

- Detailed list of spare parts.
- One-line diagrams, schematic diagrams, block diagrams etc., for the specific equipment being purchased.
- Functional narrative descriptions of start up, normal operation and shut down.
- Interconnection diagrams.
- Schedule of controls, alarms and event messages.

19.2.10.3 At the time of delivery

Before the equipment is delivered to the site it will normally undergo the type and routine tests in the factory. These tests are often referred to as the factory acceptance tests (FAT). Some documents are required before the FAT and others afterwards. Those required before are usually the inspection reports as part of the quality assurance plan, instruction manuals for transportation, storage, installation and commissioning routine maintenance.

After the FAT is complete the purchaser would normally require the testing report and a set of revised drawings.

19.2.11 Appendices

Appendices may be needed to give particular details, e.g. hazardous area applications, testing data, special tests, bearings and lubrication requirements, noise information, protective relay data, interlocking requirements, switchgear cubicle contents, control panel requirements, and copies of partially completed data sheets.

20

Summary of the Generalised Theory of Electrical Machines as Applied to Synchronous Generators and Induction Motors

20.1 INTRODUCTION

A summarised description of the ‘generalised theory’ of electrical machines is given, with an emphasis on synchronous generators and induction motors. Many texts are available that provide detailed mathematical treatments of the subject, for example References 1 to 6. Some texts develop the theory from a more practical perspective such as References 7 to 12.

The mathematical treatments are very similar, but there are some subtle differences in the matrix transformations that are needed. Examples of these differences are, constants in the matrix inversions, directions of rotation of stator applied voltages, directions of rotation of the rotor shaft, invariance of power in transformation, base quantities for per-unit systems. In most cases the derived quantities e.g. synchronous reactances, transient reactances, sub-transient reactances, time contents are either the same or very nearly the same, after the inherent simplifications have been made. Usually the data used in power system studies are subject to reasonably large tolerances e.g. ±15%, ±25%. For some machinery and transformers the maximum ranges of these tolerances are given in the international standards e.g. IEC60034 Part 1, BS4999 Part 1. The results of the studies will therefore be subject to similar tolerances and so the benefit of applying a highly detailed set of equations in the study is questionable. Hence, a set of equations that has been simplified by reasonable assumptions will provide adequate results in most cases e.g. Reference 5, Chapters 12 and 13.

The theory described herein is primarily applicable to balanced three-phase circuits and to balanced disturbances such as the three-phase short circuit, changes of loading, switching lines or cables in or out of circuit. The theory as presented is not directly suitable for unbalanced conditions such as line-to-ground faults, line-to-line faults, single-phase loading and unbalanced loading. For unbalanced analysis the references given in this chapter should be studied in depth. When a power system is being designed for an oil industry plant the most important studies are those for balanced faults and disturbances. Usually the unbalanced situations are less severe and are of lesser importance. For unbalanced situations it is necessary to be sure that a proprietary computer

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program does contain the appropriate mathematical equations, and that they are based on the properly applied theory.

20.2 SYNCHRONOUS GENERATOR

The theory described will assume that the synchronous generator (and motor) can be adequately presented by three balanced stator windings for connection to the supply, one field winding on the rotor and two damper windings on the rotor. The d-axis has the field winding (f) and one of the damper windings (*kd*) ascribed to it, whilst the q-axis has only one damper winding (*kq*). The theory presented starts from the well-established definitions of the most frequently encountered resistances, inductances and reactances that are used in proprietary computer programs and for which numerical data can usually be obtained from manufacturers. Numerical data can often be the design data before the machine is built, unless the machine is the standard product of the manufacturer in which case the data may have been derived from actual factory tests. Otherwise some of these data are verified during the testing of the machine before it is delivered to the customer. Testing is usually limited to obtaining the resistances and reactances in the d-axis and the stator windings. Special tests are required for obtaining the q-axis data (IEEE112, IEC60034), but these tests are not normally required by the customer. This means that the q-axis data are subject to a wider tolerance than the d-axis data by the time the machine is delivered to the customer.

The established definitions are:-

a) Resistances

R_a	Resistance of a stator or armature winding.
R_{kd}	Resistance of the d-axis rotor damping winding.
R_{kq}	Resistance of the q-axis rotor damping winding.
R_{fd}	Resistance of the d-axis rotor field winding.
R_{ext}	Resistance of a component connected in series with the stator winding, one in each phase.

Note: A lower case R is often used in the literature.

b) Inductances

M_{md}	Mutual inductance between windings in the d-axis.
M_{mq}	Mutual inductance between windings in the q-axis.
L_{la}	Leakage inductance of a stator winding.
L_{lkd}	Leakage inductance of the d-axis rotor damping winding.
L_{lkq}	Leakage inductance of the q-axis rotor damping winding.
L_{lfd}	Leakage inductance of the d-axis rotor field winding.
L_{ext}	Inductance of a component connected in series with the stator winding, one in each phase.

c) Reactances at the nominal system frequency ω_n

X_{md}	Mutual reactance between windings in the d-axis.
X_{mq}	Mutual reactance between windings in the q-axis.
X_{la}	Leakage reactance of a stator winding.

X_{lkd}	Leakage reactance of the d-axis rotor damping winding.
X_{lkq}	Leakage reactance of the q-axis rotor damping winding.
X_{lfd}	Leakage reactance of the d-axis rotor field winding.
X_{ext}	Reactance of a component connected in series with the stator winding, one in each phase.

d) Frequencies

f_n	nominal cyclic frequency of the power system in cycles per second or hertz.
ω_n	nominal angular frequency of the power system in radians per second $= 2\pi f_n$.
f	any cyclic frequency of the power system within its normal operating range in cycles per second.
ω	any angular frequency of the power system within its normal operating range in radius per second $= 2\pi f$.

Note: ω and f could be the frequency of the system when speed governor action is present, or the fundamental frequency of a variable frequency e.g. as used in the speed control of synchronous or induction motors.

e) Leakage inductances are due to flux which only links with its own winding and is caused by its own current.

f) Mutual inductances are due to flux which links two windings that share the same magnetic circuit. The same flux is created by either of the currents in the two windings. Mutual inductances are defined between two windings, not three or more, even though there may be several windings sharing the same magnetic circuit e.g. the d-axis of a synchronous machine, a three-winding three-phase transformer. The mutual inductance between the three pairs of windings in a magnetic circuit of three windings can often be assumed to be equal e.g. $M_{12} = M_{13} = M_{23} = M$.

g) Self or total inductances are the addition of the leakage inductance of a particular winding and the mutual inductance between it and another winding. See Figure 20.1.

h) Reactances at frequencies other than the nominal frequency.

Each of the reactances X_{md} through X_{ext} and others yet to be defined or that exist in the power system could be modified as the frequency of the system changes, e.g. during a long disturbance such as starting a large motor with a high inertia load. The necessary modification is simply to apply the ratio of the disturbance frequency (ω) to the nominal frequency (ω_n) as a multiplying factor e.g., X_{md} changes to $X_{md}\omega/\omega_n$. This modification applies especially to machines supplied from variable frequency power sources. In systems where the frequency deviations are small during a disturbance the modification is usually ignored. The difference in computed results will be small compared with the tolerances on the data used in the program.

i) Flux linkages

A coil or winding carrying a current I will produce a proportional amount of flux $\emptyset$, provided the permeability of the magnetic circuit remains constant for all values of the current. The winding will usually consist of N closed loops of conductor connected in series, with each loop being one turn. Hence the winding has N turns. The total amount of flux linking the N turns of the winding

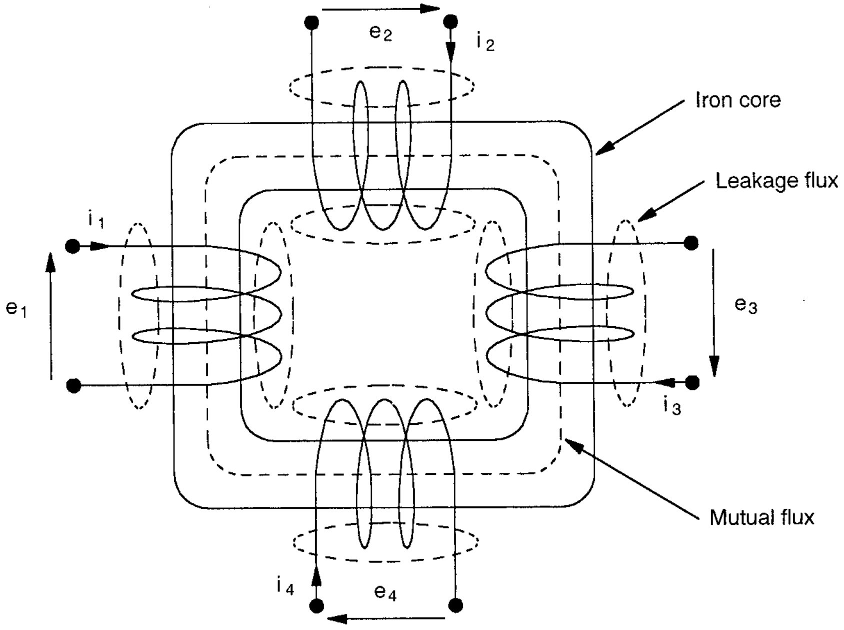

Figure 20.1 Mutually coupling and leakage fluxes in coils that share a common magnetic iron core.

is called the flux linkage ψ. An emf is induced in the winding when the current is changed and therefore when the flux linkage is changed in sympathy with the current. The emf e induced is:-

$$\begin{aligned} e &= \frac{\mathrm{d}\psi}{\mathrm{d}t} \\ &= \frac{\mathrm{d}\psi}{\mathrm{d}I}\cdot\frac{\mathrm{d}I}{\mathrm{d}t} = L\frac{\mathrm{d}I}{\mathrm{d}t} \end{aligned} \tag{20.1}$$

which opposes the applied voltage at the terminals of the winding.

Where L is the inductance of the winding in henrys (or flux linkages per ampere). If I varies sinusoidally then the emf is induced in a co-sinusoidal manner,

$$\begin{aligned} e &= L\frac{\mathrm{d}(\hat{I}\sin\omega t)}{\mathrm{d}t} = \omega L\hat{I}\cos\omega t \quad \text{volts} \\ &= X\hat{I}\cos\omega t \end{aligned}$$

where $X = \omega L$ is the inductive reactance at the frequency ω.

When the emf is induced in one winding by the current changing in a second winding the process is called 'induction by transformer action' or 'transformer induced emf'.

The rate of change of flux linkages can be brought about by rotating one winding with respect to a second winding, as is the fundamental situation in a motor or generator. If the current that produces the flux linkages is kept constant but its winding is rotated at an angular velocity ω_r then the emf induced is,

$$e = \omega_r \psi \quad \text{volts}$$

This process is called 'induction by rotating action' or 'rotationally induced emf'.

These two processes are fundamental to the induction of emfs in all the windings of a motor or generator.

20.2.1 Basic Mathematical Transformations

The generalised theory when applied in a suitable manner has the very convenient effect of removing the sinusoidal variations that are at the frequency of the power system. The frequency variations are those which are associated with the instantaneous currents, voltages and emfs. Their removal occurs, when these variables are transformed to the d and q axes. In effect the d and q-axes stator currents and voltages become envelope values of their corresponding stator three-phase sinusoidal quantities. This is very advantageous when digital computers are used to solve single machine and especially multi-machine transient problems. This is similar to using rms quantities in circuit analysis instead of instantaneous quantities. The labour and calculation times are greatly reduced. Two commonly used matrix transformations for currents, voltages and emfs are:-

a) Transform a, b, c variables to d, q, o variables

$$\begin{pmatrix} v_d \\ v_q \\ v_o \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} k \begin{pmatrix} \cos\theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ \sin\theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \tag{20.2}$$

b) Transform d, q, o variables to a, b, c variables

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \begin{matrix} = \\ = \\ = \end{matrix} k_i \begin{pmatrix} \cos\theta & \sin\theta & 1.0 \\ \cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) & 1.0 \\ \cos(\theta + 120^\circ) & \sin(\theta + 120^\circ) & 1.0 \end{pmatrix} \begin{pmatrix} v_d \\ v_q \\ v_c \end{pmatrix} \tag{20.3}$$

Where (20.3) is the inverse transformation of (20.2) and the lower-case letter 'v' represent the instantaneous variation of the corresponding peak value of voltage 'v'. The same transformations apply to the instantaneous currents i_a through i_o. The suffices 'o' are attached to the zero sequence instantaneous quantities, which are essentially added to the matrices to make them invertable. Under balanced circuit conditions and balanced disturbances the zero sequence components have no effect on the computed results. Their use in the 'generalised theory' to study line-to-ground faults and single-phase unbalanced loading should be approached with some caution. The combining of the symmetrical component theory with the 'general theory' should be undertaken with care, the additional mathematics becomes formidable, see Reference 5, Chapters 9 and 10, Reference 13, and Reference 3, Chapter X.

The two constants k and k_i have different values in the literature and occur as interrelated pairs e.g. where $k = 2/3$, $k_i = 1.0$ see References 5, 7, 8 and 13, when $k = \sqrt{2/3}$, $k_i = \sqrt{2/3}$ and the 0.5 and 1.0 constant become $\sqrt{1/2}$ see References 10, 13 and 14. The most commonly used constants are $k = 2/3$ and $k_i = 1.0$. Harris *et al*, Reference 13, Chapter 3, discuss this subject at length, in relation to power invariance and the choice of base parameters for per-unit systems. Bimbhra, Reference 10, also discusses transformations in considerable detail.

From (20.1) the emf induced in a winding is,

$$e = \frac{\mathrm{d}\psi}{\mathrm{d}t}$$

The voltage (v) applied to the winding must always balance this emf (e) and the resistive volt-drop (IR) of the winding conductor carrying the current, hence:-

$$v = RI + \frac{\mathrm{d}\psi}{\mathrm{d}t}$$

Where $\mathrm{d}\psi/\mathrm{d}t$ will in some windings be a combination of transformer induced and rotationally induced emfs. The flux linkages ψ will be the sum of its own linkages due to its own currents and all the linkages from windings sharing the same magnetic circuit. For the synchronous generator which has three stator windings and three rotor windings, as described in sub-section 20.2 a) to g), the set of voltage equations are:-

$$\begin{pmatrix} v_a \\ v_b \\ v_c \\ v_f \\ v_{kd} \\ v_{kq} \end{pmatrix} = \begin{pmatrix} R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{fd} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix}$$

$$+ p \begin{pmatrix} L_{aa} & M_{ab} & M_{ac} & M_{af} & M_{akd} & M_{akq} \\ M_{ba} & L_{bb} & M_{bc} & M_{bf} & M_{bkd} & M_{bkq} \\ M_{ca} & M_{cb} & L_{cc} & M_{cf} & M_{ckd} & M_{ckq} \\ M_{fa} & M_{fb} & M_{fc} & L_{fdfd} & M_{fkd} & M_{fkq} \\ M_{kda} & M_{kdb} & M_{kdc} & M_{kdf} & L_{kdkd} & M_{kdkq} \\ M_{kqa} & M_{kqb} & M_{kqc} & M_{kqf} & M_{kqkd} & L_{kqkq} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix} \qquad (20.4)$$

Where, p is the differential operator $\frac{\mathrm{d}}{\mathrm{d}t}$.

Equation (20.4) has the matrix form, $[v] = [R][i] + p[L]\,[i]$.

The mutual inductances M_{ij} in the triangle above the leading diagonal are equal to those M_{ji} in the lower triangle and represent the mutual inductance between winding i and winding j. Where i and j take the suffices a, b, c through to k_q. For a salient pole synchronous generator or motor some of the mutual and self-inductances are sinusoidal functions of the rotor position θ.

For a squirrel cage induction motor none of the mutual and self-inductances are functions of the rotor position.

Equation (20.2) can be applied to v_a, v_b and v_c and again to i_a, i_b and i_c. The zero sequence terms can be neglected.

The substitution exercise is very tedious, but eventually yields the following expression:-

$$\begin{pmatrix} v_d \\ v_q \\ v_f \\ v_{kd} \\ v_{kq} \end{pmatrix} = \begin{pmatrix} R \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix} + \begin{pmatrix} p & +\omega & 0 & 0 & 0 \\ -\omega & p & 0 & 0 & 0 \\ 0 & 0 & p & 0 & 0 \\ 0 & 0 & 0 & p & 0 \\ 0 & 0 & 0 & 0 & p \end{pmatrix} \begin{pmatrix} \psi_d \\ \psi_q \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{pmatrix} \tag{20.5}$$

Where, $[R] = [R_a, R_a, R_f, R_{kd}, R_{kq}]^T$ and superscript T means transpose.

Note: Since the damper circuits have no external connections and are short circuited by end rings, the terminal voltages v_{kd} and v_{kq} are zero, as shown in Figure 20.2.

c) Mutual inductances

Most authors identity the various mutual inductances in each axis of (20.4) e.g. M_{ab}, M_{af}, M_{akd}, and then assume them to be equal as, M_d for the d-axis and M_q for the q-axis. Some analyses have been published in which these mutual inductances have been assumed to be unequal, particularly when two or more damper windings have been included in each axis, see References 6, 15 and 16.

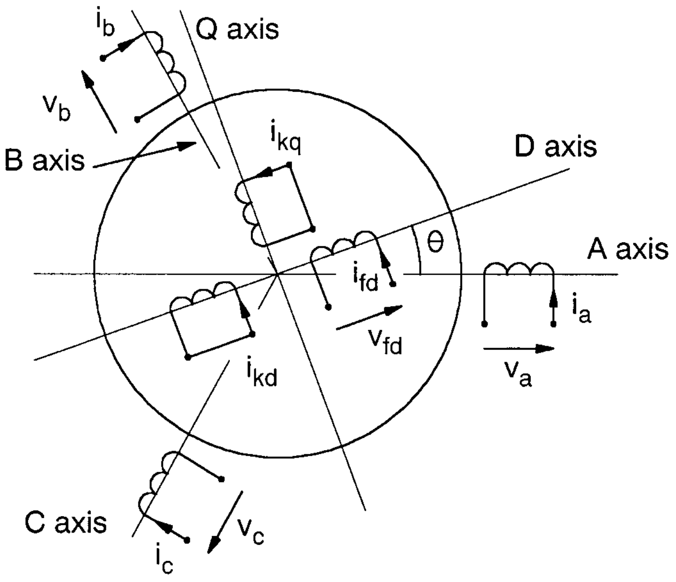

Figure 20.2 Mutually coupled circuits in the A-B-C phase and d-q axis reference frames.

d) Flux linkage equations

The flux linkage variables in (20.5) can now be established in terms of equal mutual inductances.

$$\begin{pmatrix} \psi_d \\ \psi_q \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{pmatrix} = \begin{pmatrix} (M_d + L_{la}) & 0 & M_d & M_d & 0 \\ 0 & (M_q + L_{la}) & 0 & 0 & M_q \\ M_d & 0 & (M_d + L_{lfd}) & M_d & 0 \\ M_d & 0 & M_d & (M_d + L_{lkd}) & 0 \\ 0 & M_q & 0 & 0 & (M_q + L_{lkq}) \end{pmatrix}$$

$$\times \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix} \qquad \begin{matrix} (20.6) \\ (20.7) \\ (20.8) \\ (20.9) \\ (20.10) \end{matrix}$$

A set of first-order differential equations can be obtained by rearranging the leading diagonal terms in the square matrix on the right-hand side of (20.5). Hence:-

$$\begin{pmatrix} p\psi_d \\ p\psi_q \\ p\psi_f \\ p\psi_{kd} \\ p\psi_{kq} \end{pmatrix} = \begin{pmatrix} v_d \\ v_q \\ v_f \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} \\ \\ R \\ \\ \\ \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix} - \begin{pmatrix} 0 & +\omega & 0 & 0 & 0 \\ -\omega & 0 & 0 & 0 & 0 \\ - & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \psi_d \\ \psi_q \\ \psi_f \\ \psi_{kd} \\ \psi_{kq} \end{pmatrix} \tag{20.11}$$

Equation (20.11) in conjunction with equations (20.6) to (20.10), the external stator network and field excitation equations can be used to compute the flux linkages. These equations represent the machine in its full form. Later some simplifications will be made, which make very little loss of accuracy in the solution and will substantially speed up the digital integration of the differential equations.

e) Shaft torque and shaft power

The per-unit torque T_e developed in the shaft is given by:-

$$T_e = \psi_d i_q - \psi_q i_d$$

The power P_e developed can be calculated from the mechanical expression, power = torque × speed. Hence the per-unit power developed in the machine is:-

$$P_e = \frac{\omega}{\omega_n} T_e$$

f) Operational impedances and derived reactances

In order to derive the familiar reactances e.g. X''_d the sub-transient reactance, it is first necessary to obtain the ‘operational impedances’. (In control theory terminology these would be called ‘transfer functions’.)

Since the inductances in (20.6) to (20.10) are constant it is a simple exercise to differentiate both sides of the equation. Equations (20.6) to (20.10) and its differentiated form can now be substituted into (20.11) to obtain voltage equations that are functions of the currents, and thereby eliminate the flux linkages. The resulting equations are,

$$\begin{pmatrix} v_d \\ v_q \\ v_f \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_a + L_{ad}p & \omega L_q & M_d p & M_d p & \omega M_q \\ -\omega L_d & R_a + L_{aq}p & -\omega M_d & -\omega M_d & M_q p \\ M_d p & 0 & R_f + L_{ff}p & M_d p & 0 \\ M_d p & 0 & M_d p & R_{kd} + L_{kd}p & 0 \\ 0 & M_q p & 0 & 0 & R_{kq} + L_{kq}p \end{pmatrix}$$

$$\times \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_{kd} \\ i_{kq} \end{pmatrix} \qquad \begin{matrix} (20.12) \\ (20.13) \\ (20.14) \\ (20.15) \\ (20.16) \end{matrix}$$

In the steady state the transformation of the three-phase currents and voltages into their d and q axis equivalents, when the rotor is rotating at the synchronous speed, causes them to become constant values. The magnitude of these constant values is equal to the peak value of their corresponding rms values in the phase windings. This is because the transformations have been made with a synchronous reference frame.

In addition the differential terms in (20.12) to (20.16) become zero and so do the currents in the damper windings. Hence by using suffix 'ss' the steady state version of (20.12) to (20.16) become:

$$\begin{pmatrix} v_{dss} \\ v_{qss} \\ v_{fss} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} R_a & \omega L_q & 0 & 0 & \omega M_q \\ -\omega L_d & R_a & -\omega M & -\omega M & 0 \\ 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & R_{kd} & 0 \\ 0 & 0 & 0 & 0 & R_{kq} \end{pmatrix} \begin{pmatrix} i_{dss} \\ i_{qss} \\ i_{fss} \\ 0 \\ 0 \end{pmatrix} \tag{20.17}$$

The steady state flux linkages become from (20.6) to (20.10),

$$\begin{pmatrix} \psi_{dss} \\ \psi_{qss} \\ \psi_{fss} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} (M_d + L_{la}) & 0 & M_d & M_d & 0 \\ 0 & (M_q + L_{la}) & 0 & 0 & M_q \\ M_d & 0 & (M_d + L_{lfd}) & M_d & 0 \\ M_d & 0 & M_d & (M_d + L_{lkd}) & 0 \\ 0 & M_q & 0 & 0 & (M_q + L_{lkq}) \end{pmatrix} \begin{pmatrix} i_{dss} \\ i_{qss} \\ i_{fss} \\ 0 \\ 0 \end{pmatrix} \tag{20.18}$$

These equations can be used to determine the initial conditions of the synchronous machine in a computer program.

If i_f and i_{kd} are eliminated in (20.12) and (20.14) and (20.6) and after much manipulation the following reactances and time constants can be determined. References 3, 5 and 17 describe the elimination process and the necessary assumptions required to obtain the time constants.

By referring to Chapter VI of Reference 3 sub-section 25, in particular, the algebraic substitutions and a sequence of approximations can be studied, from which the following results are most frequently used. In sub-section 20.2c herein the symbols for the leakage reactances are usually quoted slightly differently, X_{la}, X_{lkd}, X_{klq} and X_{lfd} become X_a, X_{kd}, X_{kq} and X_f respectively. It should be remembered that these are leakage reactances, wherein the suffix '1' emphasises the fact.

g) Derived reactances

D-axis synchronous reactance $X_d = X_a + X_{md}$

D-axis transient reactance $X'_d = X_a + \dfrac{X_{md}X_f}{X_{md} + X_f}$

D-axis sub-transient reactance $X''_d = X_a + \dfrac{X_{md}X_f X_{kd}}{X_{md}X_f + X_{md}X_{kd} + X_f X_{kd}}$

Q-axis synchronous reactance $X_q = X_a + X_{mq}$

Q-axis sub-transient reactance $X''_q = X_a + \dfrac{X_{mq}X_{kq}}{X_{mq} + X_{kq}}$

Q-axis transient reactance X'_q does not exist when only one winding is present in the rotor. If a second winding is placed on the q-axis, such as used to represent the deep-bar effect in an induction motor then X'_q does exist. In most synchronous generator and synchronous motor studies the use of X'_q does not arise, but in some situations it is given a value equal to X_q, for example a computer program may be written to accept a value of X'_q to suit the form in which the equations have been presented in the program. If a value of zero or 'infinity' were to be inserted into the program than a strange result may be given.

h) Time constants

D-axis transient open-circuit time constant $T'_{do} = \dfrac{1}{\omega R_f}(X_f + X_{md})$

D-axis transient short-circuit time constant $T'_d = \dfrac{1}{\omega R_{kd}}\left(X_f + \dfrac{X_{md}X_a}{X_{md} + X_a}\right)$

D-axis sub-transient open-circuit time constant $T''_{do} = \dfrac{1}{\omega R_{kd}}\left(X_{kd} + \dfrac{X_{md}X_f}{X_{md} + X_f}\right)$

D-axis sub-transient short-circuit time constant

$$T''_d = \frac{1}{\omega R_{kd}}\left(X_{kd} + \frac{X_{md}X_a X_f}{X_{md}X_a + X_{md}X_f + X_a X_f}\right)$$

D-axis damper leakage time constant $T_{kd} = \dfrac{1}{\omega R_{kd}}X_{kd}$

Armature time constant $T_a \simeq \dfrac{X_2}{\omega R_a}$

Q-axis sub-transient open-circuit time constant $T''_{qo} = \dfrac{1}{\omega R_{kq}}(X_{kq} + X_{mq})$

Q-axis sub-transient short-circuit time constant $T''_q = \dfrac{1}{\omega R_{kq}}\left(X_{kq} + \dfrac{X_{mq}X_a}{X_{mq} + X_a}\right)$

Q-axis damper leakage time constant $T_{kq} = \dfrac{1}{\omega R_{kq}}X_{kq}$

Negative phase sequence reactance

$$X_2 = \sqrt{X''_d \cdot X''_q} \quad \text{or} \quad \frac{X''_d + X''_q}{2} \quad \text{or} \quad \frac{2X''_d X''_q}{X''_d + X''_q}$$

Zero phase sequence reactance X_o has a value lower than X''_d and is a complex function of the slot pitching of the stator windings and the leakage reactance present in their end windings, see Reference 7, Chapter XII.

i) Operational impedances in the d-axis.

The equation for the operational impedance that relates the d-axis flux linkages to the stator current i_d and the rotor excitation v_f is,

$$\Psi_d = \frac{X_d(p)}{\omega}i_d + \frac{G(p)}{\omega}\,v_f \tag{20.19}$$

where,

$$X_d(p) = \frac{(1 + T''_d p)(1 + T''_d p)}{(1 + T''_{do} p)(1 + T''_{do} p)}\,X_d$$

and,

$$G(p) = \frac{(1 + T_{kd} p)}{(1 + T''_{do} p)(1 + T''_{do} p)}\,\frac{X_{md}}{R_f}$$

j) Operational impedance in the q-axis.

The equation that relates the q-axis flux linkages to the stator current i_q is,

$$\Psi_q = \frac{X_q(p)}{\omega}\,i_q \tag{20.20}$$

Where,

$$X_q(p) = \frac{(1 + T''_q p)}{(1 + T''_{qo} p)}\,X_q$$

The process of obtaining expressions for the derived reactances, operational impedances and time constants was based on the notion that only one damper winding exists on each axis. Krause in Reference 5 applied the process to a synchronous machine that has two damper windings on the q-axis. This would be advantageous when studies are being performed with large solid pole machines such as steam power plant generators, which are nowadays rated between 100 and 660 MW. Very similar functions are formed for the q-axis as are formed for the d-axis. To represent three windings on the d-axis would require a formidable amount of algebraic manipulation, from which the benefits may only be small and there will then be the problem of obtaining the extra parameters from either design data or factory tests.

Hence the machine with one damper winding on each axis is adequate for most practical situations, certainly for those in the oil industry.

20.3 SOME NOTES ON INDUCTION MOTORS

At this stage it can be noted that equations (20.5) to (20.11) can be applied to induction motors, but with the following modifications:-

a) Omit the line and row pertaining to the field winding.

b) There is no saliency and so corresponding d-axis and q-axis parameters are equal. The mutual inductances are all equal, which can be denoted as M_{dq} or M.

c) The damper windings *kd* and *kq* have identical structures and parameters.

d) The d, q notation for the rotor axes will be retained for comparison purposes. Some authors, e.g. Reference 11, use the notation r, s to denote the stator and the rotor circuits where as many others use a combination of both notations i.e. *dr*, *qr*, *ds*, *qs*: *rd*, *rq*, *sd*, *sq*, e.g. References 5, 15, 18, 19, 20 and 21, Also used is the notation *ld*, *lq*, 2*d*, and 2*q* e.g. in Reference 12, where l and 2 are used in equivalent circuits of induction motors to represent the stator (primary −1) and rotor (secondary −2) windings.

e) Additional three phase to two axis transformations are required for the following reasons:-

    i) The rotor has a uniform construction. The conductors consist of solid copper bars fixed in slots axially along and near the surface of the rotor. Usually one conductor fills a slot. The ends of the conductors at the drive end of the shaft are short circuited with a copper ring. The ends at the non-drive end are also short circuited by a similar ring. The conductors form what is called a 'single cage' or 'squirrel cage' design. There are no external connections by way of slip rings or commutators.

    ii) A cage design has no wound or physical poles, as with a synchronous machine. The cage creates its own poles as it rotates. A three-phase winding with the same number of poles as the stator is automatically formed by the induction of rotor currents.

    iii) The three-phase rotor windings need to be replaced by equivalent two-axis windings fixed to the rotor. A second transformation is required to convert these windings to a set that rotates at the frequency of the phase voltages applied to the stator. Although the induction machine is simpler in construction and operation than the synchronous machine, the transformation mathematics are more complicated. A basic explanation of the above is given by Cotton in Reference 12 and a more sophisticated mathematical treatment is given by Krause in Reference 5 for machines with a greater number of windings, i.e. additional rotor windings. Cotton in Chapter 31 presents equations of stator-applied voltages in terms of the stator resistive volt-drops and the $d{-}q$ axis flux linkages. He shows that these are of identical form to those of the synchronous machine. (It can be implied from this conclusion that a computer program could be written using the same form of equations for both type of machines. This observation has been commented upon in the literature e.g. References 22 and 23. Reference 23 considers double-cage induction motors in which the 'deep bar' effect is included, and results were obtain for motors having ratings in the range of 2500 hp to 22,000 hp.) The form of these stator equations are:-

$$v_d = R_a i_d + p\psi_d - \omega\psi_q$$

$$v_q = R_a i_q + p\psi_q + \omega\psi_d$$

f) The rotor equations involving the flux linkages are:-

For the synchronous machine rotor

$$
\begin{aligned}
v_f &= R_f i_f + p\psi_f \\
0 &= R_{kd} \cdot i_{kd} + p\psi_{kd} \\
0 &= R_{kq} \cdot i_{kq} + p\psi_{kq} \\
v_f &= R_f i_f + pL_{fd} i_f + pM_d i_d + pM_d i_{kd} \\
0 &= R_{kd} \cdot i_{kd} + pL_{kd} i_{kd} + pM_d i_d + pM_d i_f \\
0 &= R_{kq} \cdot i_{kq} + pL_{kq} \cdot i_{kq} + pM_q i_q
\end{aligned}
$$

a) Induction machine rotor

$$
\begin{aligned}
0 &= R_{kd} \cdot i_{kd} + p\psi_{kd} \\
0 &= R_{kq} \cdot i_{kq} + p\psi_{kq} \\
0 &= R_{kd} \cdot i_{kd} + pL_{kd} \cdot i_{kd} + pM_d i_d \\
0 &= R_{kq} \cdot i_{kq} + pL_{kq} \cdot i_{kq} + pM_q i_q
\end{aligned}
$$

At this stage operational impedances and time constants have been derived for synchronous machines, and for induction machines, if appropriate substitutions are made as shown in Reference 23.

20.3.1 Derived Reactances

The derived reactances are those most frequently used to specify synchronous generators and motors. They are the synchronous, transient and sub-transient reactances in the d and q-axes. The most convenient method of deriving these is from the application of a three-phase short circuit at the terminals of the unloaded machine, whether it be a generator or a motor. For a motor the testing procedure is more complicated as described in sub-section 5 of Reference 23. The d-axis reactances are easily obtained from normal factory tests. The q-axis are usually taken as their design values because the necessary factory tests are more difficult to perform. The tests are described in for example IEEE standard 112 and BS4296.

20.3.2 Application of Three-phase Short Circuit

The following derivations are made for a synchronous generator, after which the derivations applicable to induction motors are given by a heuristic comparison.

Generators and motors are often connected to their associated switchboards or networks by an impedance. This impedance can be a cable, an overhead line, a unit transformer or a combination of these components. The intermediate circuit introduced in the stator circuit will contain resistance and inductive reactance, the effect of which is to modify the time constants in the generator and motor equations, and the performance of these machines under most transiently disturbed conditions. This aspect has been mentioned in the literature e.g. References 24, 25 and 26 but is easily overlooked when developing computer programs.

In a multi-machine network the generators and motors should be considered in relation to the ‘source impedance’ to which they are connected. This impedance will also be dependent upon the location and type of disturbance e.g. near to a generator, remote from a generator, three-phase fault, line-to-ground fault, change in the state of the load such as starting a large motor direct-on-line.

The following discussion applies to a synchronous machine that has one field and two damper windings.

There are various methods of solving the equations for a three-phase short circuit on the basic that the set of equations are linear and where the use of Laplace transforms, or the Heaviside calculus, is appropriate. See References 3, 5, 6 and 8 for examples. These methods are complicated and appropriate assumptions concerning the relative magnitudes of resistances, inductances and time constants need to be made in order to obtain practical solution. The relative magnitudes of the parameters are derived from typical machinery data. Adkins in Reference 3 gives a solution of the following form,

$$\begin{aligned}
i_a &= \sqrt{2}\ V_{o/c}\left[\frac{1}{X_d} + \left(\frac{1}{X''_d} - \frac{1}{X_d}\right)e^{\frac{-t}{T''d}} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{\frac{-t}{T''d}}\right]\cos(\omega t + \theta)\\
&\quad - \left(\frac{X''_d + X''_q}{2X''_d X''_q}e^{\frac{-t}{Ta}}\right)\cos\theta - \left(\frac{(X''_q - X''_d)}{2X''_d X''_q}e^{\frac{-t}{Ta}}\right)\cos(2\omega t + \theta)\\
&= \sqrt{2}\ V_{o/c}\ (A + B + C + D + E)
\end{aligned}$$

Where A, B and C are the fundamental frequency synchronous, transient and sub-transient AC components,

E is due to the sub-transient saliency and contributes a small double frequency component, usually small enough to be neglected.

D is the DC offset caused by the switching angle θ and the values of the sub-transient reactances.

θ is the angle of the open-circuit sinusoidal terminal voltage when the short circuit is applied.

All the reactances and time constants are the same as those defined in sub-section 20.2.1g) and h)

In a situation where the disturbance is remote from the machine the short circuit time constants and the derived reactances X_d, X'_d, X''_d, X_q, (X'_q), X''_q and X_2 are all functions of the external reactance X_e since it should be added to X_a. Likewise R_e should be added to R_a. R_a does not appear in the time constants except for T_a.

An example of the decrement in the short-circuit current for a synchronous generator is given in sub-section 7.2.10 where its relevance to switchgear is described.

The worst-case situation for calculating the fault current in phase A is when the switching angle θ is zero, the DC offset is then at its maximum value.

The above expression is adequate for data that are typically available for the industry. The armature resistance R_a is only present in the time constant T_a. (Krause offers a more complete solution in which the omission of R_a is minimised. The effect is then to modify the time constant T_a

in the terms for the DC offset and the sub-transient saliency.) The inclusion of an external impedance such as a unit transformer that has both reactance and resistance will only have the modifying effect as mentioned above because the external reactance will be much greater than the external resistance. The ratios of reactance to resistance in high voltage circuits is usually at least 10:1. The external reactance added to X_d, X'_d, X''_q will also reduce the magnitude of the instantaneous short-circuit current for all values of time.

The time constant T_a is important because it influences the lower envelope of the short-circuit current wave form to such an extent that the current can fail to cross the time axis until several cycles have been completed. This is demonstrated in 7.2.10 and Figure 7.1 shows the result. The behaviour of the instantaneous current imparts a heavy duty on the stator circuit breakers. Should this be anticipated in practice, from preliminary design studies, then the equipment involved should be specified accordingly.

20.3.3 Derived Reactances and Time Constants for an Induction Motor

The absence of the field winding can be used to convert the mathematical model of the synchronous machine into one for an induction machine. In addition the mutual inductance in the q-axis is made equal to mutual inductance in the d-axis, i.e. the machine becomes symmetrical in both axes. The matrix equations (20.6) to (20.16) are modified as shown below. In these equations the mutual inductances M_d and M_q become M, L_{lkd} and L_{lkq} become L_{lk}, R_{kd} and R_{kq} become R_k. All the derived reactances and time constants for an induction machine are equivalent to those applicable to the q-axis of the synchronous machine.

Some of the literature use ‘transient’ notation, e.g. References 3, 22 and 28. Others use ‘sub-transient’ notation particularly in relation to fault current contribution in power systems, e.g. Reference 24.

Most literature use transient notation, Adkins, Ramsden IEE68 Fitzgerald and Kingsley. Others use sub-transient notation particularly in relation to fault current contribution in power systems.

Equations (20.6) to (20.10) become:-

$$\begin{pmatrix} \psi_d \\ \psi_q \\ \psi_{kd} \\ \psi_{kq} \end{pmatrix} = \begin{pmatrix} M + L_{la} & 0 & M & 0 \\ 0 & M + L_{la} & 0 & M \\ M & 0 & M + L_{kd} & 0 \\ 0 & M & 0 & M + L_{kq} \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ i_{kd} \\ i_{kq} \end{pmatrix} \tag{20.21}$$

It is reasonable to regard the rotor windings as damper windings and use the notation of sub-transient reactances. Hence the following derived reactances and time constants are appropriate to induction machines.

Equation (20.11) becomes:-

$$\begin{pmatrix} p\psi_d \\ p\psi_q \\ p\psi_{kd} \\ p\psi_{kq} \end{pmatrix} = \begin{pmatrix} v_d \\ v_q \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} \\ R \\ \\ \end{pmatrix} \begin{pmatrix} i_d \\ i_q \\ i_{kd} \\ i_{kq} \end{pmatrix} - \begin{pmatrix} 0 & +\omega & 0 & 0 \\ -\omega & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \psi_d \\ \psi_q \\ \psi_{kd} \\ \psi_{kq} \end{pmatrix} \tag{20.22}$$

Equations (20.12) to (20.16) become:-

$$\begin{bmatrix} v_d \\ v_q \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_a + L_a p & \omega L_{dq} & Mp & \omega M \\ -\omega L_{dq} & R_a + L_a p & -\omega M & Mp \\ Mp & 0 & R_k + L_k p & 0 \\ 0 & Mp & 0 & R_k + L_k p \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{20.23}$$

where ω is the rotor speed,

$$L_{dq} = M + L_{la}$$

and

$$L_k = M + L_{kd} = M + L_{kq}$$

The operational impedances become:-

$$X_d(p) = X_q(p) = \frac{(1 + T_d'' p)}{1 + T_{do}'' p} X_d \qquad \text{where} \quad T_q'' = T_d'' \qquad \text{and} \quad T_{qo}'' = T_{do}''$$

And $G(p)$ does not exist.

$$T_{do}'' = T_{qo}'' = \frac{1}{\omega R_k}(X_k + X_m)$$

$$T_d'' = T_q'' = \frac{1}{\omega R_k}\left[X_k + \frac{X_m X_a}{X_m + X_a}\right]$$

$$T_k = \frac{X_k}{\omega R_k}$$

T_{do}' and T_d' do not exist.

The flux linkage equations can be rewritten using the symmetrical parameters and the rotor speed as ω_r:-

$$v_d = R_a i_d + p\psi_d - \omega_r \psi_q$$

$$v_q = R_a i_q + p\psi_q + \omega_r \psi_d$$

$$0 = R_k i_{kd} + p\psi_{kd}$$

$$0 = R_k i_{kq} + p\psi_{kq}$$

Application of a three-phase short circuit to the terminals of an unloaded induction motor is not a practical factory test, especially for a large high-voltage motor, because the motor can only be excited at its stator windings from the power supply. A three-phase short circuit at or near the stator terminals can occur in practice e.g. damaged supply cable, damage in the cable terminal box. The parameters of the stator and rotor windings can be obtained from other factory tests. However, the derived reactance can be defined in the same manner as those for the synchronous machine, but with the assumptions regarding symmetry and the deletion of the field winding taken into account. The derived reactances become:-

$$X_d = X_q = X_a + X_m$$

$$X'_d = X'_q = X''_d = X''_q = X_a + \frac{X_m X_k}{X_m + X_k}$$

$$X_2 = X''_d \qquad \text{(negative sequence reactance)}$$

$$T_a = \frac{X'_d}{\omega R_a}$$

20.3.4 Derivation of an Equivalent Circuit

Equation (20.23) can be rewritten with the rotationally induced emfs correctly represented by the rotor speed ω_r instead of ω as in the case of the synchronous machine:-

$$\begin{bmatrix} v_d \\ v_q \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_a + L_a p & \omega_r L_{dq} & Mp & \omega_r M \\ -\omega_r L_{dq} & R_a + L_a p & -\omega_r M & Mp \\ Mp & 0 & R_k + L_k p & 0 \\ 0 & Mp & 0 & R_k + L_k p \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_{kd} \\ i_{kq} \end{bmatrix} \tag{20.24}$$

Where $\omega_r = (1 - s)\omega$, ω is the frequency of the power supply, and s is the slip of the rotor speed.

The familiar equivalent circuit for the induction motor will be developed from (20.24). The oil industry occasionally uses variable frequency power supplies to start and run variable speed pumps and compressors. The nominal frequency applied to the motor is ω_n. The inductances in (20.24) can be changed to their nominal reactances by using the nominal frequency ω_n. The steady state variables replace the instantaneous variables and the differential operator p is replaced by the steady state frequency in conjunction with the j operator.

$$\begin{bmatrix} V_d \\ V_q \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_a + \dfrac{X_d}{\omega_n} j\omega & (1 - s)\dfrac{\omega}{\omega_n} X_{dq} & \dfrac{X_{md}}{\omega_n} j\omega & (1 - s)\dfrac{\omega}{\omega_n} X_{md} \\ -(1 - s)\dfrac{\omega}{\omega_n} X_{dq} & R_a + \dfrac{X_d}{\omega_n} j\omega & -(1 - s)\dfrac{\omega}{\omega_n} X_{md} & \dfrac{X_{md}}{\omega_n} j\omega \\ \dfrac{X_{md}}{\omega_n} j\omega & 0 & R_k + \dfrac{X_k}{\omega_n} j\omega & 0 \\ 0 & \dfrac{X_{md}}{\omega_n} j\omega & 0 & R_k + \dfrac{X_k}{\omega_n} j\omega \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_{kd} \\ I_{kq} \end{bmatrix} \tag{20.25}$$

Where V_d, V_q, I_d, I_q, I_{kd} and I_{kq} are the phasor equivalents of their instantaneous variables.

For the balanced three-phase operation of the motor the following discussion applies. In the above equation the magnitude of the q-axis variables are equal to their corresponding d-axis variables. The operator j is required in the q-axis variables to identify its 90° phase advance from the d-axis.

It can now be seen that the two q-axis equations are identical in form to the d-axis equations. Hence the solution of one pair gives the same form of solution for the second pair. Consider the d-axis pair:-

$$\begin{bmatrix} V_d \\ 0 \end{bmatrix} = \begin{bmatrix} R_a + \dfrac{X_d}{\omega_n} j\omega & (1-s)\dfrac{\omega}{\omega_n} X_{dq} & \dfrac{X_{md}}{\omega_n} j\omega & (1-s)\dfrac{\omega}{\omega_n} X_{md} \\ \dfrac{X_{md}}{\omega_n} p & 0 & R_k + \dfrac{X_k}{\omega_n} j\omega & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_{kd} \end{bmatrix}$$

Equation (20.25) has the same form as (20.12) to (20.16) and (20.21) the same for as (20.6) to (20.10). When the machine runs at a speed that is different from the synchronous speed, and is only changing slowly, the d and q axis variables are sinusoids not constants. The frequency of the d and q variables is the slip frequency, see Reference 3, Chapter VII, and Reference 27 Art 6-6.

Consider a synchronous generator supplying a load consisting of a static element and an induction motor. Let the motor be small in rating compared with the generator. The motor is to be started direct-on-line to drive a pump. Before closing the circuit breaker to the motor the d and q axis currents and voltages in the generator and static load will be constant values. After the circuit breaker is closed the motor will carry its starting currents, which will be sinusoidal. These sinusoidal currents and their associated voltages will be superimposed on the currents and voltages of the static load. The generator will have similar superimposed variables in its stator circuits. The actual phase variables can be found by a suitable inverse transformation in the synchronous reference frame. The root-mean-square values of the phase variables can then be found on a cycle-by-cycle basis.

20.3.5 ‘Re-iteration or Recapitulation’

The two-axis ‘generalised theory’ has been applied to the synchronous and induction machines in a similar manner thus far. It has been assumed that an idealised ‘mathematical’ machine adequately represents them under most practical operating conditions. The idealised machine has a few subtle differences from the practical machines normally encountered. The differences are carefully made to simplify the mathematical analysis. The practical machines have their primary windings fixed in the stator. These are fed from the three-phase supply at the synchronous frequency. The secondary windings are fixed in the rotor. The d and q-axes are fixed on the rotor. In the generalised machine theory the relative motion is obtained by transposing the windings. The field and damper windings are placed in the reference (d–q axes) frame. The reference frame can be taken to be stationary, to rotate at the synchronous velocity or to rotate at the rotor velocity. Adkins in Reference 3 calls these pseudo-stationary windings or coils. Krause in Reference 5 explains in detail the various choices that appear in the literature, and which choice is appropriate to a particular analysis. Some of the graphical results given in Reference 5, sub-section 4.11 for example, may appear strange at first sight but are peculiar to the particular frame of reference used.

The synchronous generator has been considered as a set of coupled windings in which the primary windings are in the rotor and the secondary windings are in the stator. A practical motor has the primary-secondary notation reversed. The primary windings are in the stator and the secondary windings in the rotor, i.e. similar to a static transformer. The main difference in the winding configuration is that of the primary in the machines. The synchronous machine has a two-phase winding and the induction machine a three-phase winding. Therefore the three-phase winding needs to be converted into an equivalent two-phase primary winding. The three-phase currents and voltages in the primary are transformed to their equivalent two-phase variables. These transformations are detailed in References 3, 5 and 6 for example. The result is a transposition of the rows in the voltage-current equation (20.24) and the insertion of suffices 1 and 2, 1 for the primary and 2 for the secondary (as with static transformers). Equation (20.24) becomes:-

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Mp & 0 & R_2 + L_2 p & 0 \\ 0 & Mp & 0 & R_2 + L_2 p \\ R_1 + L_1 p & \omega_r L_{dq} & Mp & \omega_r M \\ -\omega_r L_{dq} & R_1 + L_1 p & -\omega_r M & Mp \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \tag{20.26}$$

Where: $R_1 = R_a$, $R_2 = R_k$, $L_1 = L_a$, $L_2 = L_k$ and $L_{dq} = M + L_{la}$.

Replace suffix 'a' with '1', and suffices 'kd' and 'kq' with '2'.

The corresponding flux linkage equation, derived from (20.21), becomes:-

$$\begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d2} \\ \psi_{q2} \end{bmatrix} = \begin{bmatrix} M + L_{l1} & 0 & M & 0 \\ 0 & M + L_{l1} & 0 & M \\ M & 0 & M + L_{l2} & 0 \\ 0 & M & 0 & M + L_{l2} \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \tag{20.27}$$

And similarly from (20.21) and differentiating:-

$$\begin{bmatrix} p\psi_{d1} \\ p\psi_{q1} \\ p\psi_{d2} \\ p\psi_{q2} \end{bmatrix} = \begin{bmatrix} (M + L_{l1})p & 0 & Mp & 0 \\ 0 & (M + L_{l1})p & 0 & Mp \\ Mp & 0 & (M + L_{l2})p & 0 \\ 0 & Mp & 0 & (M + L_{l2})p \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \tag{20.28}$$

And the voltage equation (20.5) becomes:-

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ v_{d2} \\ v_{q2} \end{bmatrix} = \begin{bmatrix} R \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} p & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & \omega \\ 0 & 0 & -\omega & p \end{bmatrix} \begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d2} \\ \psi_{q2} \end{bmatrix} \tag{20.29}$$

Substituting (20.28) into (20.29) are rearranging the terms gives,

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + (M + L_{l1})p & 0 & Mp & 0 \\ 0 & R_1 + (M + L_{l1})p & 0 & Mp \\ Mp & \omega M & R_2 + (M + L_{l2})p & \omega(M + L_{l2}) \\ -\omega M & Mp & -\omega(M + L_{l2}) & R_2 + (M + L_{l2})p \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \tag{20.30}$$

The two upper rows represent the stator and the two lower rows the rotor.

Similarly (20.25) becomes:

$$\begin{bmatrix} V_{d1} \\ V_{q1} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\dfrac{\omega}{\omega_n}X_{L1} & 0 & j\dfrac{\omega}{\omega_n}X_m & 0 \\ 0 & R_1 + j\dfrac{\omega}{\omega_n}X_{L1} & 0 & j\dfrac{\omega}{\omega_n}X_m \\ j\dfrac{\omega}{\omega_n}X_m & \dfrac{\omega_r}{\omega_n}X_m & R_2 + j\dfrac{\omega}{\omega_n}X_{L2} & \dfrac{\omega_r}{\omega_n}X_m \\ -\dfrac{\omega_r}{\omega_n}X_m & j\dfrac{\omega}{\omega_n}X_m & -\dfrac{\omega_r}{\omega_n}X_m & R_2 + j\dfrac{\omega}{\omega_n}X_{L2} \end{bmatrix} \begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d2} \\ I_{q2} \end{bmatrix} \tag{20.31}$$

Where V_{d1}, V_{q1}, I_{d1}, I_{q1}, I_{d2} and I_{q2} are the phasor equivalents of their instantaneous values, X_{L1} is the total reactance of the primary and X_{L2} that of the secondary. For the balanced three-phase operation of the induction motor the following discussion applies.

$$\begin{bmatrix} V_{d1} \\ -jV_{d1} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\dfrac{\omega}{\omega_n}X_{L1} & 0 & j\dfrac{\omega}{\omega_n}X_m & 0 \\ 0 & R_1 + j\dfrac{\omega}{\omega_n}X_{L1} & 0 & j\dfrac{\omega}{\omega_n}X_m \\ j\dfrac{\omega}{\omega_n}X_m & \dfrac{\omega_r}{\omega_n}X_m & R_2 + j\dfrac{\omega}{\omega_n}X_{L2} & \dfrac{\omega_r}{\omega_n}X_m \\ -\dfrac{\omega_r}{\omega_n}X_m & j\dfrac{\omega}{\omega_n}X_m & -\dfrac{\omega_r}{\omega_n}X_m & R_2 + j\dfrac{\omega}{\omega_n}X_{L2} \end{bmatrix} \begin{bmatrix} I_{d1} \\ -jI_{d1} \\ I_{d2} \\ -jI_{d2} \end{bmatrix} \tag{20.32}$$

Consider the first and third rows in (20.32), and define the rotor slip speed as $s\omega = \omega - \omega_r$. The comments following (20.25) regarding pairs of equations also apply here.

These two rows become:-

$$V_{d1} = \left[R_1 + j\frac{\omega}{\omega_n}X_{L1}\right]I_{d1} + j\frac{\omega}{\omega_n}X_m I_{d2} \tag{20.33}$$

$$0 = \frac{s\omega}{\omega_n}X_m I_{d1} + \left[R_2 + j\frac{s\omega}{\omega_n}X_{L2}\right]I_{d2} \tag{20.34}$$

Divide the secondary equation by the slip s:-

$$0 = j\frac{\omega}{\omega_n}X_m I_{d1} + \left[\frac{R_2}{s} + j\frac{\omega}{\omega_n}X_{L2}\right]I_{d2} \tag{20.35}$$

The equations (20.33) and (20.35) represent the familiar stationary coupled circuit shown in Figure 20.3.

The magnitude of the axes variables is equal due to the symmetry of the winding construction, as shown in (20.32). Hence $|V_{q1}| = |V_{d1}|$, $|I_{q1}| = |I_{d1}|$ and $|I_{q2}| = |I_{d2}|$. The relationship between

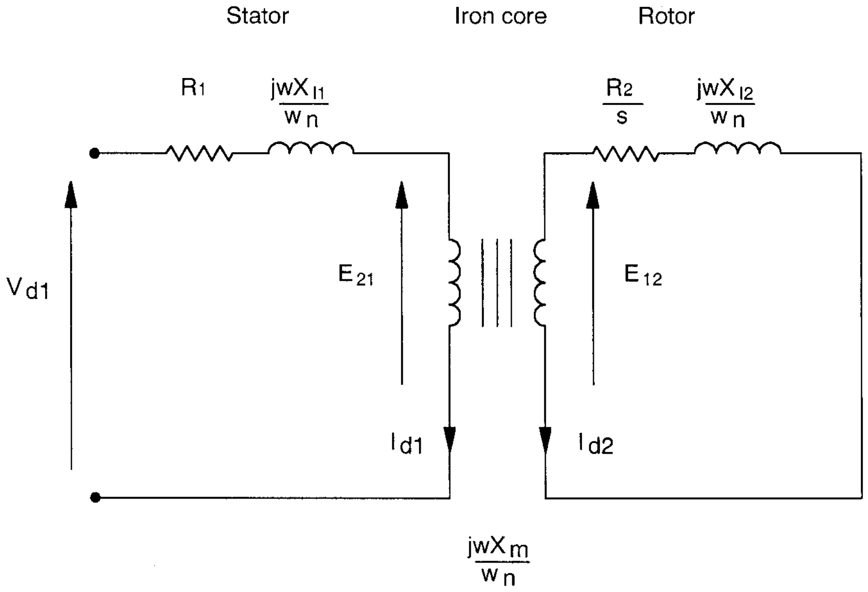

Figure 20.3 Equivalent circuit of an induction motor using mutual coupling.

these variables and the magnitude of the phase-to-neutral stator supply variables is simply:-

$$V_1 = V_{dl} + jV_{ql} = \frac{1}{\sqrt{2}}(v_{dl} - jv_{ql})$$

$$|V_1| = \sqrt{V_{dl}{}^2 + V_{ql}{}^2} = \frac{1}{\sqrt{2}}\sqrt{v_{dl}{}^2 + v_{ql}{}^2}$$

$$\therefore \quad |V_1| = \sqrt{V_{dl}{}^2 + V_{dl}{}^2} = \sqrt{2}V_{dl}$$

An equivalent Tee circuit can be formed by assuming the inductive shunt impedance carries the sum of the stator and rotor currents.

In (20.33) delete the suffix '*d*', subtract $j\frac{\omega}{\omega_n}X_m I_1$ from the first term on the right-hand side and add it to the second term:-

$$V_d = [R_1 + j\omega(X_{L1} - X_m)]I_1 + j\frac{\omega}{\omega_n}X_m(I_2 + I_1)$$

In (20.35) subtract $j\frac{\omega}{\omega_n}X_m I_2$ from the second term on the right-hand side and add it to the first term:-

$$0 = j\frac{\omega}{\omega_n}X_m(I_1 + I_2) + \left[\frac{R_2}{s} + j\frac{\omega}{\omega_n}(X_{L2} - X_m)\right]I_2$$

The following resistances and reactances can be defined when referred to the stator at the nominal power system frequency:-

$X_1 = X_{L1} - X_m$ is the stator leakage reactance.
$X_2 = X_{L2} - X_m$ is the rotor leakage reactance, not to be confused with the negative sequence reactance.
X_m is the magnetising reactance.
R_1 is the stator winding resistance.
R_2 is the rotor winding resistance.
s is the rotor slip with respect to frequency ω.

The resistance R_2/s represents the total power dissipated in one phase winding of the rotor. This consists of a resistive loss in the winding itself and the shaft power transmitted to the mechanical load. The resistance can be divided into two parts:-

$$\frac{R_2}{s} = R_2 + \frac{(1-s)}{s} R_2$$

Where R_2 is the rotor winding resistance and $(1-s)R_2/s$ is the equivalent rotor resistance of the mechanical load.

A practical motor has two additional losses that are significant. One is a resistive loss in the iron core due to eddy currents. The other is a mechanical loss due to the cooling fans and bearings on the shaft, plus the frictional losses due to the presence of the air in the air gap and which surrounds the moving parts of the rotor. The total amount of these losses can be presented approximately by a constant shunt resistance R_c placed in parallel with the magnetising shunt reactance $\omega \mathrm{X}_m/\omega_n$. The equivalent circuit for a motor fed from a fixed frequency supply is shown in Figure 5.1 and from a variable frequency supply in Figure 15.11.

Note: The direction of I_2 can be reversed and its sign changed in the shunt circuit R_c and X_m.

The sub-transient reactance of the motor at the nominal frequency can be defined in terms of the familiar reactances in the equivalent circuit.

$$X''_d = X''_q = X_1 + \frac{X_m X_2}{X_m + X_2}$$

and

$$X_d = X_q = X_1 + X_m$$

Many practical motors are designed to give efficient performance near to their rated speed, high starting torque and a reasonably low starting current. These are somewhat conflicting requirements for the design of a single squirrel-cage motor that has fixed resistances and reactances. The motor designer is able to make the rotor resistance and rotor reactance functions of the slip. The resistance is caused to increase with an increase in slip and the reactance to decrease with slip. The change in the performance of the motor at different values of slip becomes comparable with a double squirrel-cage motor. The variable characteristic is obtained by placing part of the rotor winding bars in the bottom of a deep and narrow slot. Some slots have specially shaped cross-sectional areas to obtain a pronounced effect in the bottom of the slot. The variable characteristic is also described as the ‘deep-bar effect’ or ‘skin effect’, see Reference 8, Chapter XIII and Reference 27, Chapter 10. The effect of variable resistance is more significant than the change in reactance. The designer is able to achieve a typical resistance change ratio of 4:1 and an accompanying reactance ratio of 0.5:1, when the slip changes from unity at standstill to approximately 0.01 at full-load. See Figures 5.2 and 5.3. Approximate formulae for these changes are:-

$$\text{Rotor resistance } R_2 = (R_{21} - R_{20})s + R_{20}$$

$$\text{Rotor reactance } X_2 = (X_{21} - X_{20})s + X_{20}$$

Where suffix ‘0’ represents the full-load value and suffix ‘1’ represents the standstill value.

Some motor designers apply the reactive change to the sum of the stator and rotor leakage reactances:-

$$X_{12} = X_1 + X_2 = (X_{121} - X_{120})s + X_{120}$$

Most designers consider the stator resistance as a constant value.

The equivalent circuit may be used for transient performance studies such as determining the starting, or run-up, time of the motor when coupled to its load. Its currents and voltages are usually their rms values at the supply frequency. It is known that large and rapid oscillations in electrical torque occur when an induction motor is started direct-on-line.

These oscillatory torques are approximately symmetrical about the torque calculated form the simple equivalent circuit and decay to zero as the rotor accelerates.

The equivalent circuits such as those in Figures 5.1 and 15.11 cannot be used for this type of study, and the more precise d–q axes equations involving the stator flux linkages must be used, see Reference 5. These equations would be more useful to the motor designer than the power system designer, where he is concerned with the stresses, strains and materials used in the construction of the motor windings, shafts, couplings and their keys.

When the equivalent circuit is suitable it can be treated as a passive circuit in that no differential equations need to be solved for the currents or voltages in the circuit. The only differential equation associated with the circuit is the torque necessary to accelerate the rotor and its coupled load. For this purpose the standard form of equations for the electrical torque are appropriate, in which the air-gap voltage V_m should be used.

20.3.6 Contribution of Three-phase Short-circuit Current from Induction Motor

20.3.6.1 Fault at the motor

When a running induction motor has a short-circuit applied to its terminals the air-gap flux creates an emf that drives a current into the fault. The motor is then driven by the inertia of its load. The speed may be assumed to be unchanged for the duration of the fault current, which in practice for small motors is only a few cycles at the supply frequency i.e. less than 60 milliseconds. For large motors the duration may as long as 250 milliseconds, see Reference 23. This is due to the higher X-to-R ratio in the short circuit than is the case with small motors. The impedance to the fault current consists of the transient reactance (equal to the sub-transient reactance) and the stator resistance. This will be shown below.

The authors of References 6 and 27 give analyses of the short-circuit current of an induction motor that has only one winding in each axis of the rotor. These analyses result in a simple equation of the form,

$$I_1'' = \left(\frac{E_1''}{X''} e^{\frac{-t}{T''}} \right)$$

where E'' is the air-gap phase-to neutral voltage before the fault was applied,

$$T'' = \frac{X''}{R_1}$$

and

$$X'' = X_1 + X_m - \frac{X^2{}_m}{X_2 + X_m}$$

Which approaches X_1 when X_m is large compared with X_1 and X_2.

The DC off-set has been ignored in the above equation, which is a reasonable assumption for small motors.

A more comprehensive treatment of the subject is given in Reference 23 in which comparisons were made with actual test results taken from large motors. The treatment also takes account of the DC off-set and the 'deep-bar' effect of the rotor conductors and slots. These are important factors to consider, especially with large high-voltage motors. The problem of delayed zero crossing is discussed in sub-section 7.2.11 in relation to the breaking current duty of circuit breakers. The problem arose with generators from the possibility that a poor combination of the armature time constant T_a and the sub-transient reactance X_d'' could occur. A very similar effect can occur with large motors. Kalsi *et al* in Reference 23 showed that the peak value of the current in the first half-cycle could be as high as 12 times the rated peak current, largely due to the full DC off-set that can occur, see Figure 20.4.

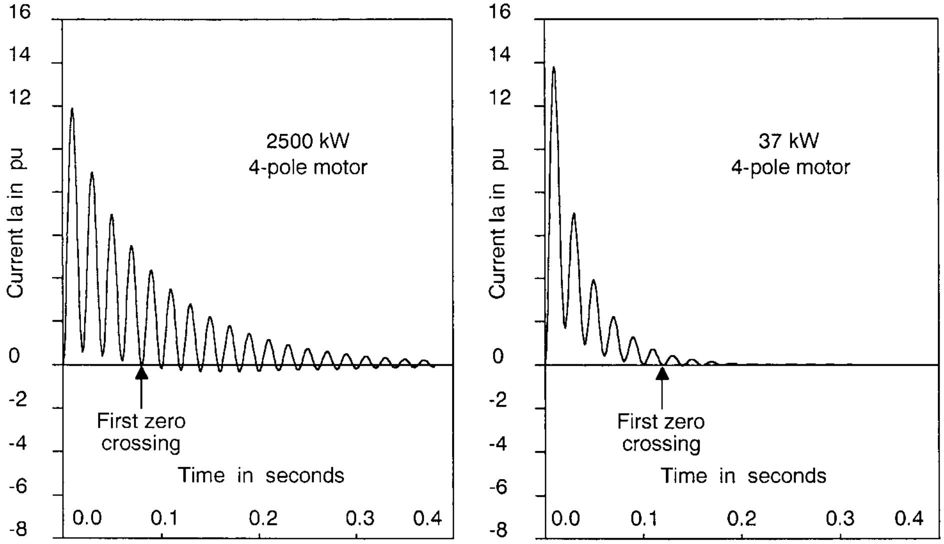

Figure 20.4 Short-circuit current decrement for a 2500 kW and a 37 kW induction motor. These motors have a relatively high armature time constant Ta that causes the initial offset of the waveform. The 'deep bar' effect in the rotor has been taken into account.

Note that Figure 20.4 shows the short circuit current for a fault inside the terminal box of the motor when its internal emf is acting alone, i.e. the stator is isolated from its supply. In practice there will be the transient and the steady state in-feeds of fault current from the upstream switchgear, which will act in addition to that created within the motor. When a motor feeds current back into its faulted upstream system, e.g. short circuit at the busbars of the motor control center, then the motor feeder cables will attenuate the motor current to some extent. A low voltage motor feeder cable usually has a low X-to-R ratio and, for long route lengths, reasonably significant impedance when it is compared with the one per-unit impedance of the motor. Hence the attenuation effect will be more pronounced than with high voltage motors. In addition the reduction in the X-to-R ratio in the stator circuit will usually cause the initial decay of the motor contribution to be faster than for a high voltage motor. The absence of current zero-crossings in the initial period may also be much reduced or even eliminated altogether.

Oil industry power systems often have generators and large motors connected to the same high-voltage switchboards. Hence there is the possibility of, more than may be expected, contributions of sub-transient current from the generators and motors. This will unduly stress the switchgear.

It can be noted that equation 8 in Reference 23 has a very similar form to the equation for the phase current i_a of a generator in sub-section 7.2.7. With appropriate assumptions and approximations the phase current i_a of an induction motor can be presented in the same manner.

The motor parameters normally given by a manufacturer are those given in sub-section 5.2.1, i.e. R_1, X_1, R_{20}, R_{21}, X_{20}, X_{21}, X_m and R_c. The parameters take account of the ‘deep-bar’ effect in the rotor. The following reactances and time constants can be defined in the same manner as for a generator.

Synchronous reactance

$$X = X_1 + X_m$$

Transient reactance

$$X' = X_1 + \frac{X_m X_{20}}{X_m + X_{20}}$$

Sub-transient reactance

$$X'' = X_1 + \frac{X_m X_{20} X_{21}}{X_m X_{20} + X_{20} X_{21} + X_m X_{21}}$$

Armature time constant

$$T_a = \frac{X''}{\omega R_1}$$

Transient short-circuit time constant

$$T' = \frac{X_{20} + \dfrac{X_m X_1}{X_m + X_1}}{\omega R_{20}}$$

Sub-transient short-circuit time constant

$$T'' = \frac{X_{21} + \dfrac{X_m X_1 X_{20}}{X_m X_1 + X_1 X_{20} + X_m X_{20}}}{\omega R_{21}}$$

These reactance and time constants can now be used to replace their corresponding ones in the equation for the short-circuit current in phase A of the motor, i_a, as previously used for a generator.

As with the generator short circuit, the worst-case condition of the equation for the motor is when the switching angle ϕ_o is zero. The equation becomes:-

$$I_a = V_{pk}\left[\left[\frac{1}{X''}-\frac{1}{X'}\right]\exp\frac{-t}{T''}+\frac{1}{X'}\exp\frac{-t}{T''}\right]\cos(\omega t)+V_{pk}\frac{1}{X''}\exp\frac{-t}{T_a} \qquad (20.36)$$

Figure 20.4 was drawn from equation (20.36).

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Appendix A

Abbreviations Commonly used in Electrical Documents

A

A	Amperes, amps.
A.C. or AC or a.c.	Alternating current or voltage.
ACB	Air circuit breaker.
ACSR	Aluminium conductor steel reinforced.
AGME	American Gear Manufacturer's Association
AH	Ampere-hour capacity of batteries.
ANSI	American National Standards Institute.
API	American Petroleum Institute.
ASTA	Association of Short-circuit Testing Authorities.
ASME	American Society for Testing and Materials.
AVR	Automatic voltage regulator.
AWA	Aluminium wire armour.

B

B or b	Electrical susceptance.
Bar or bar	Pressure in atmospheres.
BASEEFA	British Approvals Service for Electrical Equipment in Flammable Atmospheres.
BIL	Breakdown insulation level.
BSI, BS or CP	British Standards Institution, or its publications.
Btu	British thermal unit.

C

C	Electrical capacitance.
CACA	Totally enclosed air circuit, air cooled.
CACW	Totally enclosed air circuit, water cooled.
CAD	Computer aided design.
CB	Circuit breaker.

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CBCU	Circuit breaker control unit.
CCR	Central control room.
cct.	Circuit.
CCU	Central control unit.
CEGB	Central Electricity Generating Board (UK).
CENELEC	European Committee for Electrotechnical Standardisation.
cont.	Continuous quantity.
COR CU	Corrugated copper.
Cos ϕ	Power factor.
CPU	Central processing unit.
CSA or csa	Cross-sectional area.
CSI	Current source inverter.
CSP	Chloro-sulphonated polyethylene.
CSS	Computerised synchronising system.
C.T. or CT	Current transformer.
CU	Un-tinned copper.
CUWB	Copper wire braid.

D

d	Day.
db(A)	Measurement unit of sound, Decibels, absolute.
D.C. or DC or d.c.	Direct current or voltage.
DCS	Distributed control system.
DE	Drive end of a shaft.
deg C or °C	Thermal temperature in degrees Celsius or Centigrade.
deg F or °F	Thermal temperature in degrees Fahrenheit.
deg K or °K	Thermal temperature in degrees Kelvin.
DIN	Verein Deutscher Ingenieure.
DMS	Data management system.
DMT	Definite minimum time.
DnV	Det Norsk Veritas (Norway).
DOL or D.O.L.	Direct-on-line starting of induction motors.
DWR	Divided winding rotor synchronous generator.

E

E	Earth or ground.
ECHA	Equipment certified for hazardous areas.
EEC	European Economic Community.
EEMVA	The Engineering Equipment and Materials Users Association.
EHV	Extra high voltage.
EIEMA	The Electrical Installation Equipment Manufacturer's Association (UK).
ELCB	Earth Leakage Circuit Breaker.
ELV	Extra low voltage, less than 51 volts.
EMA	Ethylene methyl acrylate.
EMC	Electromagnetic compatibility.

EMI	Electromagnetic interference.
EMF or e.m.f.	Electromotive force.
EPDM	Ethylene propylene diene monomer.
EPR	Ethylene propylene rubber.
ERA	Electrical Research Association (UK).
ERM	Electronic restart module.
ESD	Emergency shut down.
ESP	Electric submersible pump.
Ex () or Ex ‘ ’	Certification symbol for hazardous area equipment.
EEx () or EEx ‘ ’	Certification symbol for hazardous area equipment, with European harmonisation of standards.
EWS	Engineering work station.

F

F, f or Hz	Frequency.
FBA	Factory built assemblies.
FCU	Feeder control unit.
F and G	Fire and Gas.
FEED	Front-end engineering and design of a project.
Freq.	Frequency.
FAT	Factory acceptance testing.
Fig.	Figure.
Flex	Flexible, used for cables.

G

G or g	Electrical conductance, or ground.
GCB	Gas circuit breaker.
GCP	Generator control panel.
GIS	Gas insulated switchgear.
GOR	Gas to oil ratio of oil well fluids.
GRP	Glass reinforced plastic.
GSWA	Galvanised steel wire armour.
GSWB	Galvanised steel wire braid.
GTG or GT	Gas-turbine generator.
GTO	Gate turn off thyristor.

H

h or hr	Hour.
HCL	Hydrogen chloride, gas or acid.
HF	High frequency.
HOFR	Heat and oil resisting, flame retardant.
HRC	High rupturing capacity.
HV	High voltage, above 600 volts.
HVAC	Heating ventilation and air conditioning.
Hz	Frequency in cycles per second, or hertz.

I

I	Current in amperes.
IAC or Iac	Alternating current.
IALA	International Association of Lighthouse Authorities.
ICI	Imperial Chemical Industries plc (UK).
IDC or Idc	Direct current.
IDMT	Inverse definite minimum time.
IEC	International Electrotechnical Commission.
IEE	The Institution of Electrical Engineers of UK.
IEEE	The Institute of Electronic and Electrical Engineers of USA.
I/O	Input or output signals or quantity.
IMO	International Maritime Organisation.
IMCS	Integrated motor control system.
IMS	Information management system.
inst.	Instantaneous quantity.
int.	Intermittent quantity.
IP	Institute of Petroleum (UK) and its publications.
IP	Ingress protection code, see IEC60529.
IR	Insulation resistance.
IS	Intrinsically safe signal, circuit or equipment.
Is/In or IS/IN	Ratio of starting current to running current.
ISO	International Standards Organisation.

J

J	Energy in joules or newton-metres.
J	Current density, amps/mm^2.

K

kA	Kilo-amperes.
KEMA	Short circuit testing authority in The Netherlands.
kg	Kilogram.
km	Length in kilometres.
kpm	Kilometres per hour.
kV or Ku	Kilo-volts.
kVA	Kilo-volt-amperes.
kVAr	Reactive kilo-volt-amperes.
kW	Kilowatts.

L

L	Electrical inductance in henries.
L	Line or local control operation.
LAN	Local area network.
lbs	Weight of a substance in pounds.
LDS	Low density foam.

LED	Light emitting diode.
LEL	Lower explosive limit.
LF	Low frequency.
LHS	Left-hand side.
Lloyds	Lloyds Register of Shipping (UK).
LMS	Load management system.
LNG	Liquefied natural gas.
loc or (L)	Local operation.
LPG	Liquefied petroleum gas.
LSDS or LSS	Load shedding system.
LSF	Low smoke and fumes, applied to cables and wires.
LSLH	Low smoke low halogen.
LSRS or LSR	Load sharing system.
LV	Low voltage, 51 to 599 volts.
L1, L2, L3, N	Notation for line and neutral voltages and currents.
LUX	Level of illumination.

M

m	Length or dimension in metres, or month.
mA	Current in milli-amperes.
man or (M)	Manual operation.
mbar	Milli-bar.
MB	High-pressure mercury, without phosphor coating.
MBF	High-pressure mercury, with phosphor coating.
MBFR	High-pressure mercury, with phosphor coating and internal reflector.
MBI	High-pressure discharge with metallic halides.
MBIF	High-pressure discharge with metallic halides, with phosphor coating.
MBR	Double-ended linear arc tube.
MBTF	Combination of MBF lamp and a filament lamp.
MCB	Miniature circuit breaker.
MCC	Motor control centre.
MCCB	Moulded case circuit breaker.
MCF	Switch-start lamp, also used for tubular fluorescent lamps in general.
MCFE	Starterless lamp, coated with silicone.
MCFA	Starterless lamp, with earth strip, mainly used in cold environments.
MCR	Maximum continuous rating.
MCU	Motor control unit.
MESG	Maximum experimental safe gap.
Mho	Unit of electrical admittance.
MIC	Minimum ignition current.
MICC	Mineral insulated calander cable.
MIMIC	Mimic display panel.
mm	Length or dimension in millimetres.
MMF or mmf	Magneto-motive force.
MMI	Man–machine interface.
MMSCF	Million standard cubic feet of a gas.

Mole %	Molecular weight in %.
MSW	Module steelwork.
MT	Mica glass tape.
MTBF	Mean time between failures.
MTTR	Mean time to repair.
MV	Medium voltage.
mV	Voltage in millivolts.
MVA	Mega-volt-amperes.
MVAr	Reactive mega-volt-amperes.
MW	Megawatts.

N

N or n	Number of items e.g. generators installed.
N or n	Number of turns in a winding.
N or n	Neutral terminal or line.
NACE	National Association of Corrosion Engineers (USA).
NBR	Nitrile butadiene rubber.
NC or N/C	Normally closed switching device.
NDE	Non-drive end of a shaft.
NEMA	The National Electrical Manufacturer's Association (USA).
NEC	National Electric Code (USA).
NER	Neutral earth resistor.
NFPA	National Fire Protection Association (USA).
Ni	Nickel metal.
NO or N/O	Normally open switching device.
NOx	Nitrogen based gas emissions.
NPT	National pipe threads (USA).
NS	Used to describe a type of variable speed AC motor
NTS	Not to scale.

O

O	Open, off or stop.
OC or O/C	Overcurrent or open circuit.
OCB	Oil circuit breaker.
OF or O/F	Overfrequency.
OFAF	Forced circulation of internal liquid, forced heat exchanging to external air.
OFAN	Forced circulation of internal liquid, natural heat exchanging to external air.
OHL or OHLine	Overhead line.
Ohms	Unit of electrical resistance or impedance.
OIM	Offshore installation manager.
OL or O/L	Overload.
ONAF	Naturally circulated internal liquid, forced heat exchanging to external air.
ONAN	Naturally circulated internal liquid, natural heat exchanging to external air.

OSHA	Occupational Health and Safety Administration (USA).
OV or O/V	Overvoltage.

P

P or W	Active power, watts.
PA	Public address system.
p or s	Laplace operator in mathematics, for transfer functions.
PC	Programmable controller or personal computer.
PAM	Pulse or pole amplitude modulation.
PCC	Point of common connection.
PB or Pb	Lead metal.
PBWB	Phosphor bronze wire braid.
PBCU or TCU	Tinned copper.
PELV	An extra-low voltage system similar to SELV but connected to earth at some point.
P & ID	Piping and instrument diagram.
PF or pf	Power factor.
Ph or ph	Phases of an electrical circuit.
pk or peak	Peak value of an instantaneous quantity.
PLC	Programmable logic controller.
PMS	Power management system.
POL	Polyethylene.
PTB	Physilalish Technische Bundesanstalt.
PTP	Polyethylene terephthalate.
PTFE	Polytetra fluoro ethylene.
pu or p.u.	Per unit.
PVC	Polyvinyl chloride.
PVDF	Polyvinylidene fluoride.
PWM	Pulse width modulation.

Q

Q	Reactive power, volt-amperes-reactive.
QA	Quality assurance.
QC	Quality control.

R

R or r	Electrical resistance.
Rad or rad	Angular displacement in radians.
RAM	Random access memory.
RCU	Remote control unit.
Ref. or REF.	Reference.
rem or (R)	Remote operation.
RHS	Right-hand side.
RMS, rms	Root mean square.

RMU	Ring main unit.
ROM	Read only memory.
RTD	Resistance temperature detector.
RTU	Remote transmitter unit.
Rx	Receiver.

S

S	Apparent power in volt-amperes.
s or p	Laplace operator in mathematics, for transfer functions.
S	Slip of a rotating machine with respect to 1.0 pu.
SBM	Single buoy mooring.
SC or S/C	Short circuit.
SCADA	Supervisory control and data acquisition system.
SCF	Standard cubic feet of a gas.
SDR	Single discipline review.
SECT	Skin effect current trace heating.
SELV	Safety extra-low voltage.
SF6	Sulphur hexafluoride.
SI	Système Internationale d'Unités
SLI	Double-ended, linear arc tube.
SOLAS	Safety of life at sea, a document relating to marine practice.
SON	Diffused ellipsoidal outer bulb, single-ended lamp.
SON-T	Clear tubular outer bulb, single-ended lamp.
SON-TD or − L	Clear tubular outer bulb, double-ended lamp.
SON-R	SON lamp, with internal reflector.
SOL CU	Solid copper.
SOX	U-shaped arc tube, single-ended lamp.
Sox	Sulphur based gas emissions.
SP	Single phase.
sq	Square, e.g. sq mm is square millimetres.
sq2	Square root of 2.0 = 1.414214
sq3	Square root of 3.0 = 1.732051
SSR	Synchronisation check protection relay.
STG	Steam turbine generator.
STR CU	Stranded copper.
SWA	Steel wire armour.
SWBD	Switchboard.
SWGR	Switchgear.
SYNC or Sync	Synchronising.

T

T or t	Time, usually in seconds.
Td	Time constant in seconds for the quantity 'd'.
TDRM	Time delayed restart relay.

TEFC	Totally enclosed fan cooled.
temp.	Temperature.
TESFC	Totally enclosed separate fan cooled, fan attached to an auxiliary motor shaft.
TG	Turbo-generator, gas or steam.
THF	Telephone harmonic factor.
TOP	Gas-turbine operating temperature (hot-end blade temperature).
TM	Technical measurement system of units.
TCP	Gas-turbine control panel.
TLX	Cold starting tubular fluorescent lamp, with single-pin caps.
TPN	Three-phase and neutral power supply.
TPPL	Total plant peak load.
TPRL	Total plant running load.
Tran. or Tx	Transformer.
Tx	Transmitter.

U

U	Voltage, also used for energy.
UC or U/C	Undercurrent.
UCP	Unit control panel.
UEL	Upper explosive limit.
UF or U/F	Underfrequency.
UHF	Ultra high frequency.
UI or U/I	Undercurrent.
UL or U/L	Underload.
UL	Underwriters Laboratory (USA).
UNO	Unless noted otherwise.
UPS	Uninterruptible power supply unit.
UV or U/V	Undervoltage.

V

V or U	Voltage or volts.
VA	Volt-amperes.
VAC or Vac	Alternating voltage.
VAr or Var	Reactive volt-amperes.
VDC or Vdc	Direct voltage.
VDE	Verband Deutscher Electrechniker (Germany).
VDI	Verein Deutscher Ingenieure (Germany).
VDU	Visual display unit.
VHF	Very high frequency.
VSI	Voltage source inverter.
VSD or VSDS	Variable speed drive systems.
V.T. or VT	Voltage transformer.
v/v	Comparison by volume, per-unit.

W

W or P	Active power, watts.
w or ω	Frequency in radians per second.
wdg.	Winding of a machine or transformer.
WHRU	Waste heat recovery unit.

X

X or x	Electrical reactance.
XLPA	Cross-linked polyalkene.
XLPE	Cross-linked polyethylene.

Y

Y or y	Electrical admittance.
y	Year.

Z

Z or z	Electrical impedance.
ZH	Zero halogen, as used for cables.

Numerical

1P or SP	Single phase.
3P	Three-phase supply.
3P-N	Three-phase and neutral supply.
3P-N-E	Three-phase neutral and earth supply.
2W	Two-wire supply.
3W	Three-wire supply.
4W	Four-wire supply.

Appendix B

A List of Standards Often Used for Designing Electrical Systems and for Specifying Equipment

Note .... Reference in {} brackets supersede the original references.

B.1 INTERNATIONAL ELECTRO-TECHNICAL COMMISSION (EUROPE)

Ref	Description	
IEC60027	Part 1:	Letter symbols to be used in electrical engineering.
IEC60034	Rotating electrical machines.	
	Parts 1, 2, 4, 5, 6, 8 and 14 in particular	
	Part 1:	Rating and performance.
	Part 2:	Methods of determining losses and efficiency.
	Part 4:	Methods of determining synchronous machines quantities
	Part 5:	Classification of degrees of protection provided by enclosures for rotating machines
	Part 6:	Methods of cooling rotating machinery.
	Part 7:	Symbols for types of construction and mounting arrangement.
	Part 8:	Terminal markings and direction of rotation.
	Part 12:	Starting performance of single-speed three-phase cage induction motors for voltages up to and including 660 V.
	Part 14:	Mechanical vibration of certain machines with shaft heights 56 mm and higher.
IEC60038	IEC standard voltages.	
IEC60043 {IEC600521}	Recommendations for alternating current watt-hour meters.	
IEC60050	International electro-technical vocabulary {65 sections}	

(*continued overleaf*)

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake
ISBN: 0-471-49631-6

Ref	Description
IEC60051	Recommendation for direct acting indicating electrical measuring instruments and their accessories.
	Part 2: Special requirements for ampere-meters and voltmeters.
IEC60056	High-voltage alternating-current circuit breakers.
IEC60059	Standard current ratings.
IEC60060	High voltage test techniques.
	Part 1: General definitions and test requirements.
	Part 2: Measuring systems.
	Part 3: Measuring devices.
	Part 4: Application guide for measuring devices.
IEC60071	Insulation coordination.
	Part 1: Definitions, principles and rules.
	Part 2: Application guide.
	Part 3: Phase-to-phase insulation coordination. Principles, rules and application guide. (Superseded by Part 1, 7th edition).
IEC60072-1	Dimensions and output ratings – frame numbers 56 to 400.
IEC60072-2	Dimensions and output ratings – frame numbers 355 to 1000.
IEC60073	Indicating lamps.
IEC60076	Power transformers.
	Part 5: Ability to withstand short circuit.
IEC60079	Electrical apparatus for explosive gas atmospheres.
	Part 0: General requirements.
	Part 1: Construction and verification test of flameproof enclosures of electrical apparatus.
	Part 2: Electrical apparatus with type of protection '*p*'.
	Part 5: Sand-filled apparatus.
	Part 6: Oil-immersed apparatus.
	Part 7: Increased safety '*e*'.
	Part 10: Classification of hazardous areas.
	Part 11: Construction and test of intrinsically safe and associated apparatus.
	Part 13: Construction and use of rooms of buildings protected by pressurisation.
	Part 14: Electrical installations in explosive gas atmospheres (other than mines).
	Part 15: Electrical apparatus with type of protection '*n*'.
	Part 16: Artificial ventilation for the protection of analyser(s) houses.
	Part 17: Recommendations for inspection and maintenance of electrical installation in hazardous areas (other than mines).
	Part 18: Encapsulation '*m*'.
IEC60083	Plugs and socket-outlets for domestic and similar general use.
IEC60085	Recommendations for the classifications of insulating materials in relation to their thermal stability in service.
IEC60088	Standard related current (2 to 63 A) of fuse links for LV
IEC60092	Electrical installation in ships.

Ref	Description
IEC60092-3	Part 1: Cables (construction, testing and installations).
IEC60092-101	Part 101: Definitions and general requirements.
IEC60092-352	Part 352: Choice and installation of cables for low-voltage power systems.
IEC60092-353	Part 353: Single and multicore cables with extruded solid insulation for rated voltages 0.6/1 kV.
IEC60092-354	Part 354: Single- and three-core power cables with extruded insulation for rated voltages 6 kV, 10 kV and 15 kV.
IEC60092-359	Part 359: Sheathing materials for shipboard power and telecommunication cables.
IEC60092-375	Part 375: Shipboard telecommunication cables and radio-frequency cables. General instrumentation, control and communication cables.
IEC60092-376	Part 376: Shipboard multicore cables for control circuits.
IEC60092-505	Part 505: Special features-mobile offshore drilling units.
IEC60112	Methods for determining the comparative and the proof-tracking indices of solid insulating material under moist conditions.
IEC60113	Diagrams, charts and tables.
IEC60120	Dimensions of ball and socket coupling of string insulator units.
IEC60129	Isolators and earth switches above 1000 volts.
IEC60146	Semiconductor converters.
	Part 1: Specifications of basic requirements.
	Part 2: Semiconductor self-commutated converters.
IEC60156	Insulating liquids – determination of the breakdown voltage at power frequency
IEC60157	LV switchgear and controlgear.
{IEC60947}	Part 1: Contactors
IEC60158	LV control gear for industrial use.
{IEC60947}	Part 1: Contactors.
IEC60182	Basic dimensions of winding wires.
IEC60183	Guide to the selection of high-voltage cables.
IEC60185	Current transformers.
IEC60186	Voltage transformers.
IEC60189	Low-frequency cables and wires with PVC insulation and PVC sheath
	Part 1: General test and measuring methods
IEC60214	On load tap changes.
IEC60227	Polyvinyl chloride insulated cables of rated voltages up to and including 450/750 V.
	Part 1: General requirements
	Part 2: Test methods.
IEC60228	Conductors for insulated cables.
IEC60245	Rubber insulated cables of rated voltages up to and including 450/750 V. Six parts.
IEC60247	Measurements of relative permittivity, dielectric dissipation. Factor and DC resistivity of insulating liquids.

(*continued overleaf*)

Ref	Description
IEC60251	Methods of test for winding wires. Part 1: Enamelled round wires
IEC60255 and BS142	Electrical protection relays. Part 3: Single input energising quantity measuring relays with dependent or independent time. Part 5: Insulation tests for electrical relays. Part 6: Measuring relays and protection equipment. Part 8: Thermal electrical relays. Part 12: Directional relays and power relays with two input energising quantities. Part 13: Biased (percentage) differential relays. Part 16: Impedance measuring relays. Part 20: Protection (protective) systems. Part 23: Contact performance.
IEC60265	High-voltage switches Part 1: High-voltage switches for rates voltages above 1 kV and less than 52 kV.
IEC60269	Low-voltage fuses Part 1: General requirements.
IEC60270	Partial discharge measurements.
IEC60277 (withdrawn)	Definitions for switchgear and control gear.
IEC60282	High-voltage fuses. Part 1: Current-limiting fuses. Part 2: Expulsion and similar fuses.
IEC60287	Calculation of the continuous current rating of cables (100% load factor)
IEC60292	LV motor starters
IEC60298	High-voltage metal enclosed switchgear and controlgear.
IEC60309	Plugs, socket-outlets and couplers for industrial purposes. Part 1: General requirements. Part 2: Dimensional interchangeability requirements for pin and contact-tube accessories. Part 3: Particular requirements for plugs, socket-outlets, connectors and appliance inlets for use in explosive gas atmospheres.
IEC60331	Fire resisting characteristics of electric cables.
IEC60332	Tests on electric cables under fire conditions. Part 1: Test on a single vertical insulated wire or cable. Part 2: Test on a single small vertical insulated copper wire or cable. Part 3: Tests on bunched wires or cables.
IEC60337	Control auxiliary switches, relays and pushbuttons.
IEC60354	Loading guide for oil immersed transformers.

Ref	Description
IEC60363	Short-circuit current evaluation with special regard to rated short-circuit capacity of circuit-breakers in installations in ships.
IEC60364	Requirements for electrical installations 7 parts, 6 appendices also called the IEE wiring regulations 16th edition.
IEC60376	Specification and acceptance of new sulphur hexafloride.
IEC60383	Insulators for overhead lines with a nominal voltage above 1000 V.
	Part 1: Ceramic or glass insulators units for AC systems-definitions, test methods and acceptance criteria.
	Part 2: Insulator strings and insulator sets for AC systems-definitions, test methods and acceptance criteria.
IEC60408 {IEC60947} {Part 3}	Low-voltage air-break switches, air-break disconnectors and fuse combination units.
IEC60409	Guide for the inclusion of reliability clauses into Specifications for components (or parts) for electronic equipment.
IEC60414	Safety requirements for indicating and recording measuring instruments and accessories.
IEC60417	Graphical symbols for use on equipment. Index, survey and compilation of the single sheets. Note, there are 12 supplements.
IEC60420	High-voltage alternating current switch-fuse combinations.
IEC60433	Characteristics of string insulator units of the long rod type.
IEC60439	Low-voltage switchgear and control gear assemblies.
	Part 1: Type-tested and partially type-tested assemblies.
	Part 2: Particular requirements for busbar trunking systems.
	Part 3: Particular requirements for low-voltage switchgear and controlgear assemblies intended to be installed in places where unskilled persons have access for their use–distribution boards.
	Part 4: Particular requirements for assemblies for construction sites (ACS).
	Part 5: Particular requirements for assemblies intended to be installed outdoors in public places (CDC).
IEC60445	Identification of apparatus terminals and general rules for a uniform systems of terminal making, using an alphanumeric notation.
IEC60446	Identification of insulated and bare conductors by colours.
IEC60470	High-voltage alternating current contactors, Amendment No. 1.
IEC60473	Dimensions for panel-mounted indicating and recording electrical measuring instruments.
IEC60478	Stabilised power supplies, DC output.
	Part 1: Terms and definitions.
	Part 2: Rating and performance.
IEC60479	Effects of current on human beings and livestock.
	Part 1: General aspects.
IEC60502	Extruded solid dielectric insulated power cables from 1 kV up to 30 kV.

(*continued overleaf*)

Ref	Description
IEC60529	Classification of degrees of protection provided by enclosures (IP Code).
IEC60536	Part 1: Classification of electrical and electronic equipment with regard to protection against electric shock.
	Part 2: Guideline to requirements for protection against electric shock.
IEC60549	High-voltage fuses for the external protection of shunt Power capacitors.
IEC60551	Measurement of transformer and reactor sound levels.
IEC60555	Disturbances in supply systems caused by household appliances and similar electrical equipment.
	Part 1: Definitions
	Part 2: Harmonics
	Part 3: Voltage fluctuations.
IEC60593	Internal fuses and internal over-pressure disconnections for shunt capacitors.
IEC60606	Application guide for power transformers
IEC60614	Specifications for conduits for electrical installations.
	Part 1: General requirements.
	Part 2: Particular specifications for conduits. Section one Metal conduits.
IEC60616	Terminal and tapping markings for power transformers.
IEC60617	Graphic symbols for diagrams.
	Part 1: General information, general index.
	Cross-reference tables.
IEC60623	Vented nickel-cadmium prismatic rechargeable single cells.
IEC60632	High-voltage motor starters.
	Part 1: Direct-on-line full voltage starters.
IEC60644	Specifications for high-voltage fuse links for motor circuit applications.
IEC60662	High pressure sodium vapour lamps.
IEC60664	Insulation coordination within low-votage systems including clearness and creepage distances for equipment.
	Part 1: Principles, requirements and tests.
	Part 3: Use of coatings to achieve insulation coordination of printed board assemblies.
IEC60686	Stabilised power supplies AC output.
IEC60688	Electrical measuring transducers for converting AC electrical quantities into DC electrical quantities.
	Part 1: General purpose transducers.
IEC60694	Common clauses for high-voltage switchgear and controlgear standards. Amendment No. 1.
IEC60722	Guide to lightning impulse and switching impulse testing of power transformers and reactors.
IEC60726	Dry type power transformers.
IEC60742	Isolating transformers and safety isolating transformers.
IEC60745	Safety of handheld motor operated electric tools.
	Part 1: General requirements.
	Part 2: 17 sections covering drills, hammers, grinders etc.

Ref	Description
IEC60751	Platinum resistance thermometer sensors.
IEC60754	Test on gases evolved during combustion of electric cables.
	Part 1: Determination of the amount of halogen acid gas evolved during the combustion of polymeric materials taken from cables.
	Part 2: Determination of degree of acidity amount of gases evolved during the combustion of polymeric materials taken from cables by measuring pH and conductivity.
IEC60781	Application guide for calculation of short-circuit currents in low-voltage radial systems.
IEC60800	Heating cables with a rated voltage of 300/500 V for comfort heating and prevention of ice formation.
IEC60801	Electromagnetic compatibility for industrial process measurement and control equipment:
	Part 1: General introduction.
	Part 2: Electrostatic discharge requirements-test severity level 4.
	Part 3: Radiated electromagnetic field requirements-test severity level 3.
	Part 4: Noise immunity against fast transient disturbances-test severity level 3.
	Part 5: Surge immunity requirements-test severity level 4.
	Part 6: Immunity to conducted radio frequency disturbances above 9 kHz-test severity level 2.
IEC60812	Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA).
IEC60815	Guide for the selection of insulators in respect of polluted conditions.
IEC60826	Loading strength of electrical overhead lines.
IEC60831	Shunt power capacitors of the self-healing type for AC systems having a rated voltage up to and including 1000 V.
	Part 1: General-performance, testing and rating-safety requirements – Guide for installation and operation.
	Part 2: Ageing test, self-healing and destruction test.
IEC60836	Specification for silicone liquids for electrical purposes.
IEC60840	Tests for power cables with extruded insulation for rated voltage above 30 kV.
IEC60851	Methods of test for winding wire.
	Part 1: General
IEC60865	Short-circuit currents – Calculation of effects.
	Part 1: Definitions and calculation methods.
	Part 2: Examples of calculation.
IEC60871	Shunt capacitors for AC power systems having a rated voltage above 660 V.
	Part 1: General-performance, testing and rating-safety requirements – Guide for installation and operation
	Part 2: Endurance testing.

(*continued overleaf*)

Ref	Description
IEC60885	Electric test methods for electric cables.
	Part 1: Electrical tests for cables, cords and wires for voltages up to and including 450/750 V.
	Part 2: Partial discharge tests.
	Part 3: Test methods for partial discharge measurement on lengths of extruded power cable.
IEC60896	Stationary lead-acid batteries. General requirements and methods of test.
IEC60898	Circuit breakers for overcurrent protection for household and similar installations.
IEC60905	Loading guide for dry type power transformers.
IEC60906	IEC systems of plugs and socket-outlets for household and similar purposes.
	Part 1: Plugs and socket-outlets 16 A 250 V AC
	Part 2: Plugs and socket-outlets 15 A 125 V AC
IEC60909	Short-circuit current calculation in three-phase AC systems. Third impression 1991.
	Part 1: Factors for the calculation of short-circuit currents in three-phase AC systems according to IEC60909.
	Part 2: Electrical equipment – Data for short-circuit current calculation in accordance with IEC60909 (1988).
IEC60944	Guide for the maintenance of silicone transformer liquids.
IEC60947	Low-voltage switchgear and control gear.
	Part 1: General rules.
	Part 2: Circuit breakers.
	Part 3: Switches, disconnectors, switch disconnectors, and fuse-combination units.
	Part 4: Contractors and motor starters. Section one: electromechanical contactors and motor starters.
IEC60993	Electrolyte for vented nickel cadmium cells.
IEC61000	Electromagnetic compatibility (EMC)
IEC61000-1-1	Part 1: General – Section 1: Application and interpretation of fundamental definitions and terms.
IEC61000-2-1	Part 2: Environmental – Section 1: Description of the environment: electromagnetic environment for low-frequency conducted disturbances and signaling in public power supply systems.
IEC61000-2-2	Part 2: Environment – Section 2: Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems.
IEC61000-2-4	Part 2: Environment – Section 4: Compatibility levels in industrial plans for low-frequency conducted disturbances.
IEC61000-3-2	Electromagnetic compatibility (EMC) limits for harmonic current emissions (equipment current <16 A per phase)

Ref	Description
IEC61000-4-11	Part 4: Testing and measuring techniques – section 11: Voltage dips, short interruptions and voltage variations immunity tests: Basic EMC publication.
IEC61000-5-2	Electromagnetic compatibility (EMC). Part 5: Installation and mitigation guidelines – section 2: Earthing and cabling.
IEC61010	Safety requirements of electrical equipment for measurement, control and laboratory use. Part 1: General requirements.
IEC61029	Safety of motor-operated transportable tools. Part 1: General requirements.
IEC61034	Part 1: Measurement of smoke density of cables burning under defined conditions. Test apparatus. Part 2: Measurement of smoke density of cables burning under defined conditions. Test procedure and requirements.
IEC61039	General classification of insulating liquids.
IEC61067	Glass and glass polyester fibrewoven tapes. Definitions, classifications and general requirements.
IEC61084	Cable trunking and ducting systems for electrical installation. Part 1: General requirements.
IEC61089	Round wire concentric lay overhead electrical standard conductors.
IEC61203	Synthetic organic esters for electrical purpose – guide for maintenance of transformer esters in equipment.
IEC61294	Insulating liquids – determination of the partial discharge inception voltage (PDIV): Test procedure.
EN50006	The limitations of disturbances in electrical supply networks caused by domestic and similar appliances equipped with electronic devices.
EN50085	Cable trunking systems and cable ducting systems for electrical installations. Part 1: General requirements ratified European text.
EN55014	Specification for radio interference limits and measures for equipment embodying small motors, contacts, control and other devices causing similar interference.
EN55015	Limits and methods of measurement of radio interference characteristics of fluorescent lamps and luminaires.
EN55022	Limits and methods of measurement of radio interference characteristics of information technology equipment.

B.2 INSTITUTE OF PETROLEUM (UK)

Ref	Description
IP	Model code for safe practices, Parts 1, 8 and 15.

B.3 INTERNATIONAL STANDARDS ORGANISATION (WORLDWIDE)

Ref	Description
ISO3	Preferred numbers (voltages, currents, kVA etc.).
ISO281	Rolling bearings – dynamic load ratings and rating life.
ISO1000	Specification for SI units and recommendations for the use of their multiples and of certain other units.
ISO1680	Acoustics: Test code for the measurement of airborne noise emitted by rotating electrical machinery.
ISO1813	Antistatic endless V-belts – electrical conductivity-characteristics and methods of test.
ISO2372	Mechanical vibration of machines with operating speeds from 10 to 200 rev /sec. Basis for specifying evaluation standards.
ISO3046/IV	Reciprocating internal combustion engines: Performance. Part 1: Specifications for standard reference conditions and declarations of power, fuel consumption and lubricating oil consumption. Part 2: Test methods Part 3: Specification of test measurements. Part 4: Speed governing. Part 5: Torsional vibrations. Part 6: Specifications for overspeed protection. Part 7: Specifications for codes for engine power.
ISO5292	Industrial V-belt drives. Calculation of power ratings.
ISO9000	Quality management and quality assurance standards – guidelines for selection and use.
ISO9001	Quality systems. Model for quality assurance in design, development, production, installation and servicing.
ISO9002	Quality systems. Model for quality assurance in production, installation and servicing.
ISO9003	Quality systems. Model for quality assurance in final inspection and test.
ISO9004	Quality management and quality system elements.

B.4 BRITISH STANDARDS INSTITUTION (UK)

Ref	Description
BS116	Oil circuit breakers (for alternating current systems above 1 kV)
{BS5311: 1 to 7}	{High-voltage alternating current circuit breakers.}
BS162	Electric power switchgear and associated apparatus.
{BS7354}	{Code of practice for the design of high voltage open terminal stations.}
BS170	
{BS5000: 2}	{Rotating electrical machines of particular types or for particular applications. Part 2: Specific requirements or turbine type synchronous machines.}

Ref	Description
BS229	Flameproof enclosure of electrical apparatus.
BS350	Part 1: Conversion factors and tables. Basis of tables.
BS801	Cable sheaths, lead and lead alloy.
BS921	Rubber mats for electrical purposes.
BS1259	Intrinsically safe electrical apparatus and circuits for use in explosive atmospheres.
BS2045	Preferred numbers (for voltages, currents kVA etc.).
BS2613	
{BS5000: 99}	{Rotating electrical machines of particular types or for particular applications. Part 99: Machines for miscellaneous applications.}
BS2627	Wrought aluminium for electrical purposes: wire.
BS2757	Method for determining the thermal classification of electrical insulation.
BS2782	Methods of testing plastics.
BS2783	Specification for copper and copper alloys. Wire.
BS3192	Safety requirements for radio transmitting equipment status.
{BSEN60215}	
BS3535	Isolating transformers and safety isolating transformers.
BS3763	The international system of units (SI). Withdrawn.
{BS 5555}	
See ISO 1000	
BS3988	Wrought aluminium for electrical purposes: solid conductors.
BS4066	Electrical cables, tests under fire conditions.
BS4109	Copper for electrical purposes.
BS4142	Method for rating industrial noise affecting mixed residential and industrial areas.
BS4296	Methods of test for determining synchronous machine quantities.
BS4683: 3	Electrical apparatus for explosive atmospheres.
{BSEN60922}	{Electrical apparatus for explosive atmosphere with type of protection *N*.}
BS4782	Ballasts for discharge lamps.
{BSEN60922}	{Auxiliaries for lamps – Ballasts for discharge lamps. (excluding tubular fluorescent lamps) General and safety requirements.}
{BSEN60923}	{Performance requirements for ballasts for discharge lamps (excluding tubular fluorescent lamps).}
BS4800	Specification for paint colours for building purposes.
BS4992	Guide to protection against ignition and detonation
(withdrawn)	initiated by radio frequency radiation. Replaced by BS6656 and BS6657.
BS4999	General requirements for rotating electrical machines. Part 140: Specification for voltage regulation and parallel operation of AC synchronous generators.
BS5000	Rotating electrical machines of particular types or for Particular applications. All parts.

(*continued overleaf*)

Ref	Description
BS5099	Specification for safety of machinery.
BS5266	Code of practice for emergency lighting.
BS5304	Code of practice for safety of machinery.
BS5308	Instrument cables.
BS5311	High-voltage alternating current circuit breakers.
BS5345	Code of practice for the selection, installation and maintenance of electrical apparatus for use in potentially explosive atmospheres (other than mining applications or explosives manufactures).
BS5467	Specification for 600/1000 V and 1900/3300 V armoured electric cables having thermosetting insulation.
BS5468	Cross-linked polyethylene insulation of electric cables.
BS5486	Low-voltage switchgear and controlgear assemblies. Parts: 1, 2, 11, 12 and 13. Mostly withdrawn.
BS5490	Check (sonar devices).
BS5501	Electrical apparatus for potentially explosive atmospheres.
BS5555 See ISO 1000	Specification for SI units and recommendations for the use of their multiples and of certain other units.
BS6007	Rubber insulated cables for electric power and lighting.
BS6121	Cable glands. Part 1.
{BSEN50014, 50018 and 50019}	(were the hazardous area parts of BS5345).
BS6195	Insulated flexible cables and cords for electric power and lighting.
BS6231	Specification for PVC insulated cables for switchgear and control gear wiring.
BS6234	Insulated cables, polyethylene.
BS6290	Lead-acid stationary cells and batteries.
BS6346	PVC insulated cables for electricity supply.
BS6351	Electric surface heating.
BS6360	Electric conductors, insulated cables.
BS6387	Performance requirement for cables required to maintain circuit integrity under fire conditions.
BS6467	Electrical apparatus with protection by enclosure with use in the presence of combustible dusts.
BS6469	Insulated cables, insulation and sheaths, test methods.
BS6480	Power cables, impregnated paper – insulated, lead or lead alloy sheathed.
BS6500	Insulated flexible cords.
BS6622	Specification for cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 3.8/6.6 kV up to 19/33 kV.
BS6651 (Was CP326)	The protection of structures against lightning.
BS6656	Guide to prevention of inadvertent ignition of flammable atmospheres by radio-frequency radiation.

Ref	Description
BS6657	Guide to prevention of inadvertent initiation of electro-explosive devices by radio-frequency radiation.
BS6724	Armoured cables for electricity supply having thermosetting insulation with low emissions of smoke and corrosive gases when affected by fire.
BS6746	Specification for PVC insulation and sheath of electric cables.
BS6883	Specification for elastomer insulated cables for fixed wiring in ships and on mobile and fixed offshore units.
BS6899	Specification for rubber insulation and sheath of electric cables.
BS6941	Electrical apparatus for explosive atmospheres with type of protection *N*.
BS7211	Thermosetting insulated cables (non-armoured) for electric power and lighting with low emissions of smoke and corrosive gases when affected by fire.
BS7244	Flame arresters for general use.
BS7354	Design of HV stations for earthing.
BS7430	Code of practice for earthing.
BS7622 {BSEN50268 pt 1}	Measurement of smoke density of electric cables burning under defined conditions. Test apparatus.
BS7629	Part 1: Specification for 300/500 V fire resistance electric cables having low emission of smoke and corrosive gases when affected by fire. Multicore cables (renamed in 1997). Part 2: Specification for 300/500 V fire resistant electric cables having low emission of smoke and corrosive gases when affected by fire. Multipair cables (renamed in 1997).
BS7655	Insulation and sheaths, electric cables.
BS7671	See IEC60364
BS7835	Specification for armoured cables with extruded cross-linked polyethylene or ethylene propylene rubber insulation for rated voltages from 3.8/6.6 kV up to 19/33 kV having low emission of smoke and corrosive gases when affected by fire.
BS7846	Electric cables. 600/1000 V armoured fire-resistant cables having thermosetting insulation and low emission of smoke and corrosive gases when affected by fire.
BS7889	Specification for 600/1000 V single-core un-armoured electric cables having thermosetting insulation.
BS7917	Elastomer insulated fire resistant (limited circuit integrity) cables for fixed wiring in ships and on mobile and fixed off-shore units. Requirements and test methods.
BS9000	General requirements for a system for electronic components for assured quality.
BSEN10257	Part 1: Zinc and zinc alloy coated non-alloy steel wire for armouring either power cables or telecommunication cables. Land cables.

(*continued overleaf*)

Ref	Description
	Part 2: Zinc and zinc alloy coated non-alloy steel wire for armouring either power cables or telecommunication cables. Submarine cables.
BSEN12166	Copper and copper alloys. Wire for general purposes.

B.5 AMERICAN PETROLEUM INSTITUTE (USA)

Ref	Description
API500	Recommended practice for classification of locations for electrical installations at petroleum facilities classified as Class 1, Division 1 or Division 2. Part A is for refining facilities. Part B is for process facilities. Part C is for transportation facilities.
API610	Centrifugal pumps for general refinery services.
API617	Centrifugal compressors for general refinery services.
API670	Non-contacting vibration and axial position monitoring systems.

B.6 COUNSEIL INTERNATIONAL DES GRANDS RESEAUX ELECTRIQUES (FRANCE)

Ref	Description
CIGRE	Working Group 36.05: Equipment producing harmonics and conditions governing their connection to the mains power supply. ELECTRA 123, March 1989, pp 20–37.

B.7 ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION (UK)

Ref	Description
EEMUA107	Recommendations for the protection of diesel engines for use in Zone 2 hazardous areas.
EEMUA122	Guide to user needs for technical documentation (engineering).
EEMUA132	Three-phase induction motors.
EEMUA133	Underground armoured cable protection against solvent penetration and corrosive attack.
EEMUA140	Noise: Procedure specification.

Ref	Description
EEMUA141	Guide to the use of noise procedure specification.
EEMUA148	Reliability specification.

B.8 ELECTRICITY COUNCIL (UK)

Ref	Description
G5/3	Limits for harmonics in the United Kingdom electricity supply systems (Electricity Council, London).

B.9 VERBAND DEUTSCHER ELECTRECHNIKER (GERMANY)

Ref	Description
VDE0875	Specification for radio interference suppression of electrical appliances and systems.
VDE0295	
VDE0875	Specification for radio interference suppression of electrical appliances and systems.

B.10 INSTITUTE OF ELECTRONIC AND ELECTRICAL ENGINEERS INC. (USA)

Ref	Description
IEEE32	Standard requirements, terminology and test procedures for neutral grounding devices.
IEEE80	IEEE guide for safety in AC substation grounding.
IEEE81	IEEE guide for measuring earth resistivity, ground impedance and earth surface potentials of a ground system.
	IEEE112 IEEE standard test procedure for polyphase induction motors and generators.
IEEE344	IEEE recommended practice for seismic qualification of class 1E equipment for nuclear power generating stations.
IEEE519	Recommended practices and requirements for harmonic control in electrical power systems.
IEEE979	IEEE guide for substation fire protection.
IEEE1100	Recommended practice for powering and grounding sensitive electronic equipment.
IEEEC37.2	IEEE standard electrical power system device function numbers.

B.11 MISCELLANEOUS REFERENCES FROM THE UK

Ref	Description
DINV19250	Control technology. Fundamental safety aspects to be considered for measurement and control equipment.
ERA69-30	Current rating standards for distribution cables.
ERA74-29	A method for calculating ratings for cables in multilayer groups on trays.
IALA	Recommendation for the notation of luminous intensity and range of lights. Appendix II. Dated 16th November 1966.
IALA	The definition and method of calculation of the nominal range and usual range of a fog signal. Dated 1st May 1984.
Dept of	Survey of aids to navigation on offshore structures.
Trade UK	Instructions for the guidance of surveyors (HMSO).
IEE	Regulations for the electrical and electronic equipment of ships with recommended practice for their implementation. 6th edition, 1990. ISBN 0 86 3-41 217-3.
IEE	Requirements for electrical installations. IEE wiring regulations. 16th edition, 1997 (also BS7671: 1992). ISBN 0 852-98927-9.
OSHA1910.25	Occupational noise exposure.

Appendix C

Numbering System for Protective Devices, Control and Indication Devices for Power Systems

C.1 APPLICATION OF PROTECTIVE RELAYS, CONTROL AND ALARM DEVICES FOR POWER SYSTEM CIRCUITS

The requirements for the different types of HV and LV circuits in a typical oil industry power system are summarised below. The IEEE device numbers commonly used in the oil industry are listed in sub-section C.2.

1. **Utility intake above 11 kV.**
   25, 27, 51V, 51N, 86, 87.
2. **Unit transformer-generator intake above 11 kV.**
   Primary circuit, see note 1.
   Secondary circuit 25, 26, 27, 32, 40, 46, 51V, 51G, 59, 64, 81, 86, 87.
3. **Switchgear busbar zone protection above 11 kV.**
   86, 87 see note 2.
4. **Switchgear bus-section and bus-couplers above 11 kV.**
   25, 27 see note 3, 86.
5. **Transformer feeders above 11 kV.**
   Primary circuit, 23 see note 4, 49, 50, 51, 51N, 86, 87.
   Secondary circuit, 23 see note 4, 51G see note 5, 64 see note 6, 86.
6. **Unit transformer-motor feeders above 11 kV.**
   Primary circuit, 23 see note 4, 26, 27, 59, 86, 87.
   Secondary circuit, 23 see note 4, 51G, 64, 87 see note 1.
   Motor, 25 see note 4, 26, 46, 49, 50, 51N, 87.
7. **Overhead line feeder above 11 kV.**
   51, 51N, 86.

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8. **HV generator intake-turbine driven.** See Figure 12.2.
   26, 27, 32, 40, 46, 51V, 51G, 58, 59, 64, 81, 86 see note 7, 87.
9. **HV overhead line intake.**
   25, 27, 51V, 51N, 86, 87 see note 8.
10. **HV/HV/tertiary transformer feeder.** See Figure 12.11.
    Primary circuit, 23 see note 4, 49, 50, 51, 51N, 86, 87.
    Loaded secondary circuit, 23 see note 4, 51, 51G, 64, 81, 86, 87.
    Loaded tertiary circuit, 23 see note 4, 51, 51G see note 5, 64 see note 6, 86, 87.
11. **HV/LV transformer feeder, rated 5 MVA and above.** See Figure 12.9.
    Primary circuit, 23 see note 4, 49, 50, 51, 51N, 86, 87.
    Secondary circuit, 23 see note 4, 51G, 58 see note 5, 81 see note 6, 86.
12. **HV/LV transformer feeder, rated below 5 MVA.** See Figure 12.10.
    Primary circuit, 23 see note 4, 49, 50, 51, 51N.
    Secondary circuit, 23 see note 4, 51G see note 5, 64 see note 6, 86.
13. **HV switchgear bus-section and bus-coupler circuit breakers.**
    25 see note 2, 27, 86.
14. **HV DOL induction motors, 2.5 MW and above, see note 9.** See Figure 12.15.
    26, 46, 49, 50, 51N, 86, 87.
15. **HV DOL induction motors, below 2.5 MW, see note 9.** See Figure 12.15.
    26, 46, 49, 50, 51N, 86.
16. **HV variable speed drive induction motors.**
    At the switchboard, see note 10. 50N, 51, 86, 87 see note 12.
    At the unit control panel, see note 11. 27, 46, 49, 50, 50N, 58, 59.
17. **HV static loads, see note 10.**
    50, 50N, 51, 86.
18. **HV interconnectors, single and parallel cables, protection at both ends.** See Figure 12.14.
    51, 51N, 86 see note 13.
19. **HV single and parallel submarine cables, protection at both ends.** See Figure 12.14.
    51, 51N, 86 see note 13.
20. **HV busbar earthing transformer for busbars in switchboards.**
    49, 50, 51, 51G, 86.
21. **HV overhead line feeders, see note 14.**
    51, 51N, 86.
22. **HV plain cable feeders.** See Figure 12.14.
    51, 51N, 86.
23. **LV main generator intake-engine driven.**
    26, 27, 32, 40, 51V, 51G, 58, 59, 64, 81, 86.
24. **LV emergency generator intake-engine driven.**
    26, 27, 32, 40, 51V, 51G, 58, 59, 81, 86.

25. **LV switchgear bus-section and bus-coupler circuit breakers.**
    86.
26. **LV interconnectors, single and parallel cables, protection at both ends.**
    51, 51N, 86.
27. **LV DOL induction motors, 37 kW to 250 kW.** See Figure 12.19.
    46, 49, 50, 50N see note 15, 86.
28. **LV DOL induction motors, below 37 kW.** See Figure 12.19.
    49 see note 16, 50 see note 16.
29. **LV static loads and feeders to distribution boards.**
    51, 51N see note 17, 86 see note 18.

C.1.1 Notes to sub-section C.1

1. In the situation where a generator has a unit transformer it is recommended that two forms for differential protection are provided. One will be for the generator by itself, and denoted 87G. The second will be an overall scheme for the generator and the unit transformer, and denoted 87T.
2. Bus-zone protection is recommended to be of the high-speed balanced voltage type. Each section of busbars should be protected as one zone. There are other options available that are technically more complex and hence more expensive. It is normal practice to overlap adjacent zones at bus-section and bus-coupler circuit breakers. The bus-zone protection scheme can also be provided with a test facility that can be used while the switchboard is in its normally energized state.
3. The undervoltage relay is usually provided with time delay settings, and used to trip the consumers fed from the particular bus-section.
4. A device required for starting and stopping forced air-cooling fans.
5. An unrestricted earth fault relay that is connected in the star-point earth circuit of the equipment being protected. The characteristic is time dependent so that time coordination is achieved with the 50 N devices downstream.
6. A restricted earth fault relay is used with generators and transformers to detect internal faults. The relay will usually be of the voltage operated instantaneous type.
7. The generator switchgear is recommended to have two separate lockout relays. One will receive all the electrical protection relay trip signals, and denoted as 86–1. The other will receive a master trip signal (or several trip signals) from the turbine unit control panel, and denoted as 86–2.
8. Normally only required on critical circuits.
9. Modern relays combine the 46, 49, 50, 51 N and 86 functions; together with others such as motor stalling, number of starts, thermal state at the time of starting, undercurrent, overloading, high-set current limit.
10. The manufacturers of the static loads and variable speed drives may require special protection devices for their equipment.
11. The manufacturer of the variable speed drive may provide some protection devices in the unit control panel. These devices may be inter-tripped with the main circuit breaker.
12. The manufacturer of the variable speed drive may recommend the 87 relay. It may be part of the UCP as mentioned in Note 11. It should not be necessary for motors below 2.5 MW.

13. A relay common to the parallel circuits would normally be adequate.
14. The relays would be fitted into the main switchboard, not at intermediate locations along the overhead line route.
15. The use of a 50 N relay is recommended in relation to the maximum earth-loop impedance allowed for the particular consumer. This will be a function of the motor rated power, the route length and the type of armouring used for the motor power cable.
16. The use of the 49 and 50 relay(s) may be replaced by thermal and magnetic elements within the circuit breaker or starter unit for the particular motor. This is normally only required for small motors.
17. The use of a 51 N should be considered when time coordination is required with distribution board consumers e.g. lighting, small power socket outlets and welding socket outlets. Static loads which do not feed downstream consumers should be fitted with a 50 N relay.
18. The hand-reset feature of a moulded case or miniature circuit breaker may replace the 86 relay. There may be a project requirement to use fuses. For low power circuits an auto-reset device (29) may be acceptable, provided that it does not reclose the circuit breaker or contactor.
19. The need for trip circuit supervision depends to a large extent on the importance of the circuit connected by the power circuit breaker, e.g. utility company incomers, main generators, HV circuits. One of the IEEE code numbers in the range 95 to 99 can be used to identify the trip circuit supervision relay.

C.2 ELECTRICAL POWER SYSTEM DEVICE NUMBERS AND FUNCTIONS

The devices in switching equipment are referred to by numbers, with appropriate suffix letters when necessary, according to the functions they perform.

These numbers are based on a system adopted as standard for automatic switchgear by the IEEE, and incorporated in American Standard C37.2–1970. (updated 1991). The suffix letters are also shown in the IEEE standard. The following are the most frequently encountered in the oil industry.

Device Number	Definition and Function
21	**Distance relay** is a device that functions when the circuit admittance or impedance or reactance increases or decreases beyond predetermined limits.
23	**Temperature control device** functions to raise or lower the temperature of a machine or other apparatus, or of any medium, when its temperature falls below, or rises above, a predetermined value.
25	**Synchronising or synchronism-check device** operates when two AC circuits are within the desired limits of frequency, phase angle or voltage, to permit or to cause the paralleling of these two circuits.
26	**Apparatus thermal device** functions when the temperature of the shunt field or the damper winding of a machine, or that of a load limiting or load shifting resistor or of a liquid or other medium exceeds a predetermined value. It also functions if the temperature of the protected apparatus, such as a power rectifier, or of any medium decreases below a predetermined value.

Device Number	Definition and Function
27	**Undervoltage relay** is a device that functions on a given value of undervoltage.
32	**Directional power relay** is one which functions on a desired value of power flow in a given direction, or upon reverse power resulting from arc back in the anode or cathodic circuits of a power rectifier.
37	**Undercurrent or under-power relay** functions when the current or power flow decreases below a predetermined value.
38	**Bearing protective device** functions on excessive bearing temperature, or on other abnormal mechanical conditions, such as undue wear, which may eventually result in excessive bearing temperature.
40	**Field relay** functions on a given or abnormally low value or failure of machine field current, or on an excessive value of the reactive component of armature current in an AC machine indicating abnormally low field excitation.
46	**Reverse-phase, or phase-balance, current relay is a relay** which functions when the poly-phase currents are of reverse-phase sequence, or when the poly-phase currents are unbalanced or contain negative phase-sequence components above a given amount.
49	**Machine, or transformer, thermal relay** is a relay that functions when the temperature of a machine armature, or other load carrying winding or element of a machine, or the temperature of a power rectifier or power transformer (including a power rectifier transformer) exceeds a predetermined value.
50	**Instantaneous overcurrent, or rate-of-rise relay** is a relay that functions instantaneously on an excessive value of current, or on an excessive rate of current rise, thus indicating a fault in the apparatus or circuit being protected.
51	**AC time overcurrent relay** is a relay with either a definite or inverse time characteristic that functions when the current in an AC circuit exceeds a predetermined value.
52	**AC circuit breaker is a device** that is used to close and interrupt an AC power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.
58	**Rectification failure relay** is a device that functions if one or more anodes of a power rectifier fail to fire, or to detect an arc-back or on failure of a diode to conduct or block properly.
59	**Overvoltage relay** is a relay that operates on a given difference in voltage, or current input or output of two circuits.
60	**Voltage or current relay** is a relay that operates by comparing these variables in two circuits, in the form of a difference relay, e.g. star-point comparator for capacitor banks.
64	**Ground protective relay** is a relay that functions on failure of the insulation of a machine, transformer or of other apparatus to ground, or on flashover of a DC machine to ground.

(*continued overleaf*)

Device Number	Definition and Function
	It should be noted that this function is assigned only to a relay which detects the flow of current from the frame of a machine or enclosing case or structure of a piece of apparatus to ground, or detects a ground on a normally ungrounded winding or circuit. It is not applied to a device connected in the secondary circuit or secondary neutral of a current transformer, or in the secondary neutral of current transformer, connected in the power circuit of a normally grounded system.
65	**Governor** is the assembly of fluid, electrical or mechanical control equipment used for regulating the flow of water, steam, or other medium to the prime mover for such purposes as starting, holding speed or load, or stopping.
67	**AC directional overcurrent relay** is a relay that functions on a desired value of AC overcurrent flowing in a predetermined direction.
74	**Alarm relay** is a device other than an annunciator, which is used to operate, or to operate in connection with, a visual or audible alarm.
81	**Frequency relay** is a relay that functions on a predetermined value of frequency – either under or over or on normal system frequency – or rate of change of frequency.
86	**Locking-out relay** is an electrically operated, hand or electrically reset, relay that functions to shut down and hold an equipment out of service on the occurrence of abnormal conditions.
87	**Differential protective relay** is a protective relay that functions on a percentage or phase angle or other quantitative difference of two currents or of some other electrical quantities.

Appendix D

Under-Frequency and Over-Temperature Protection of Gas-Turbine Driven Generators

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When a large increase in active power is applied to a gas-turbine driven generator two important transient responses occur. Firstly the shaft speed and hence the system frequency decreases, which happens at a rate mainly determined by the total moment of inertia of the rotating masses in the gas turbine and the generator, and the magnitude of the change in power. Initially the fuel valve does not change its state because the feedback of the speed change takes time to be detected and amplified. The gas turbine initially responds in its open-loop control mode. After a short delay the fuel valve responds and allows more fuel to be burned in the combustion chamber. Hence the combustion or 'operating' temperature increases and more power is delivered to the shaft. Closed-loop control action is applied to the fuel valve, whilst the valve stem is within its limiting positions.

If the increase in active power is small then the change in the valve stem position will also be small and will remain within its limits. In this situation the response of the frequency and temperature will be an initial overshoot followed by a convergence to a new steady state. The response may exhibit some oscillatory behaviour, depending upon the amount of forward gain and feedback damping used in the control system.

If the increase in active power is large then the change in the valve stem position will also be large, and may be large enough for it to reach its upper hard limit. When the valve is fully open it will pass a finite amount of fuel. The operating temperature will reach its maximum possible value, which will be above its preset shutdown or tripping value. No closed-loop control action can take place unless the power generated by the limited fuel is enough to recover the shaft speed. If the speed recovers sufficiently to be within the limits of the control system, then the fuel valve will be corrected by the necessary feedback control action.

Figures D.1 through D.6 show the responses described above. Figures D.1–D.3 apply to a single-shaft gas-turbine generator rated in the order of 5 MW. Figures D.4–D.6 apply to a two-shaft gas-turbine generator that has a similar rating. The results shown are derived from the control system diagrams in Figures 2.16 and 2.17. In general the single-shaft machine is more responsive, and is more tolerant of the larger changes in power. However, the excursions of operating temperature are greater. The excursions of temperature in the two-shaft machine are smaller due to the intervention of the 'least signal selector' safety control system. In all of the 11 cases considered the single-shaft

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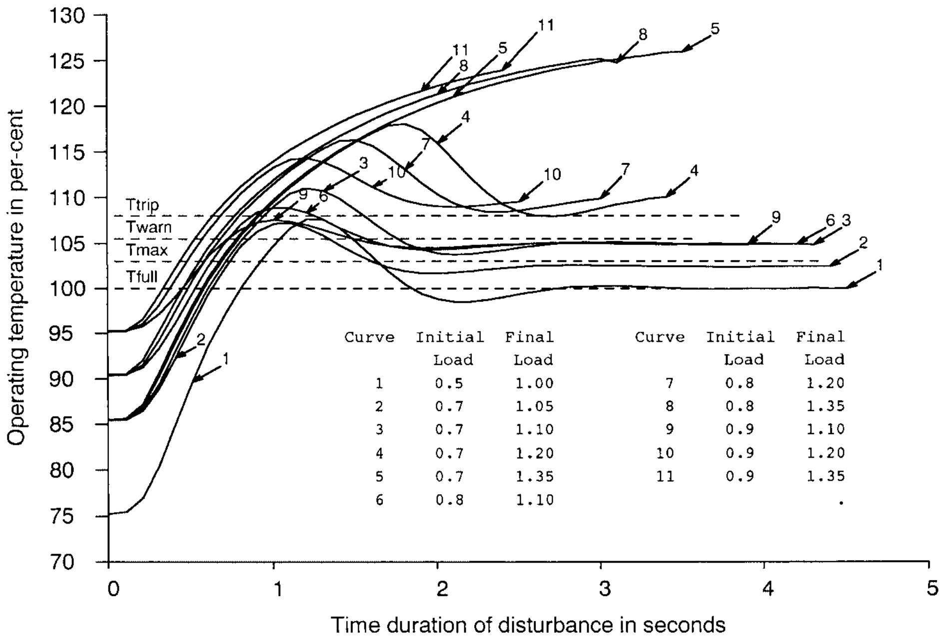
machine recovers its shaft speed and system frequency. Note that some of the larger disturbances would not normally occur in a practical power system, but are included to illustrate and compare the operation of the control systems involved. The two-shaft machine exhibits a wider deviation in shaft speed and system frequency than the single-shaft machine, and generally takes longer to recover. This illustrates the customarily held view that a single-shaft machine has a more superior performance than a two-shaft machine for electrical power applications.

Typical alarm and tripping limits are also shown in Figures D.1 and D.4. The single-shaft machine reaches these limits generally faster than the two-shaft machine, again due to the effect of the 'least signal selector' safety control system. The trip setting for the over-temperature limit for the two-shaft machine is seen to be rather sensitive due to the 'flat' shape that follows the initial response. The warning alarm for the two-shaft machine is reached in about twice the time taken for the single-shaft machine.

Figures D.3 and D.6 show the responses of frequency in the first one second. Both machines respond in much the same way in the first half second. This is due to the fact that this part of the response is 'open loop' and is mainly determined by the mechanical inertia and the size of the disturbance, as discussed in Chapter 21 of Reference 1; see also sub-section 2.5 herein. Also shown in these two figures are typical setting levels for underfrequency (81) multi-stage relays. In addition to the setting levels the relays should also have time delay settings, so that coordination with other power system equipment can be achieved, e.g. automatic voltage regulators of generators, automatic re-acceleration of induction motors, see also sub-section 7.6 herein. For the settings shown the relays would respond in the range of about 70 to 150 milliseconds, which is typically about half the response



Curve	Initial Load	Final Load	Curve	Initial Load	Final Load
1	0.5	1.00	7	0.8	1.20
2	0.7	1.05	8	0.8	1.35
3	0.7	1.10	9	0.9	1.10
4	0.7	1.20	10	0.9	1.20
5	0.7	1.35	11	0.9	1.35
6	0.8	1.10			

Figure D.1 Over-loading a single-shaft gas-turbine generator. Operating temperature versus time.

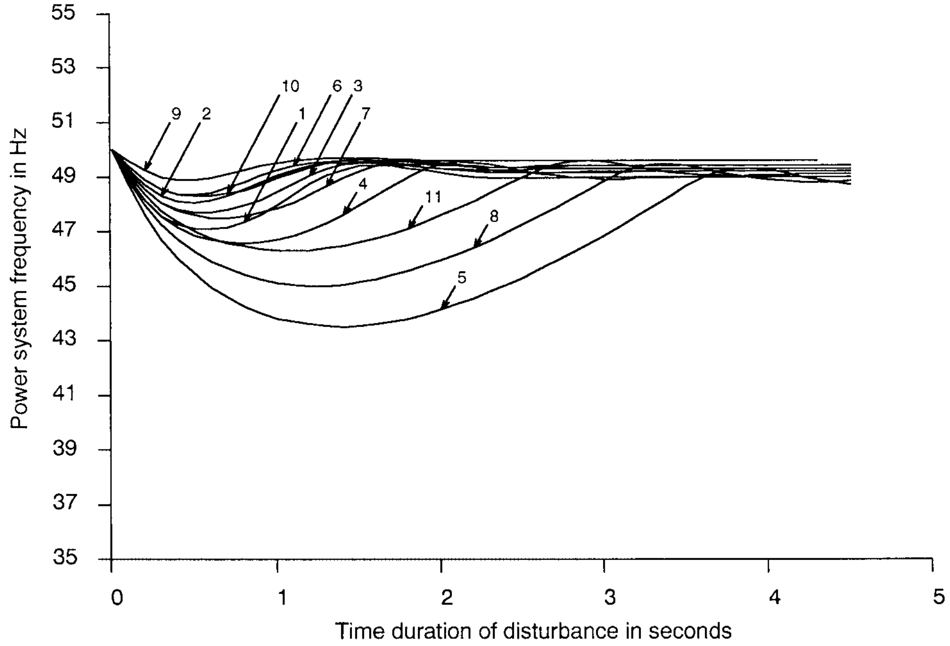


Figure D.2 Over-loading a single-shaft gas-turbine generator. Power system frequency versus time.

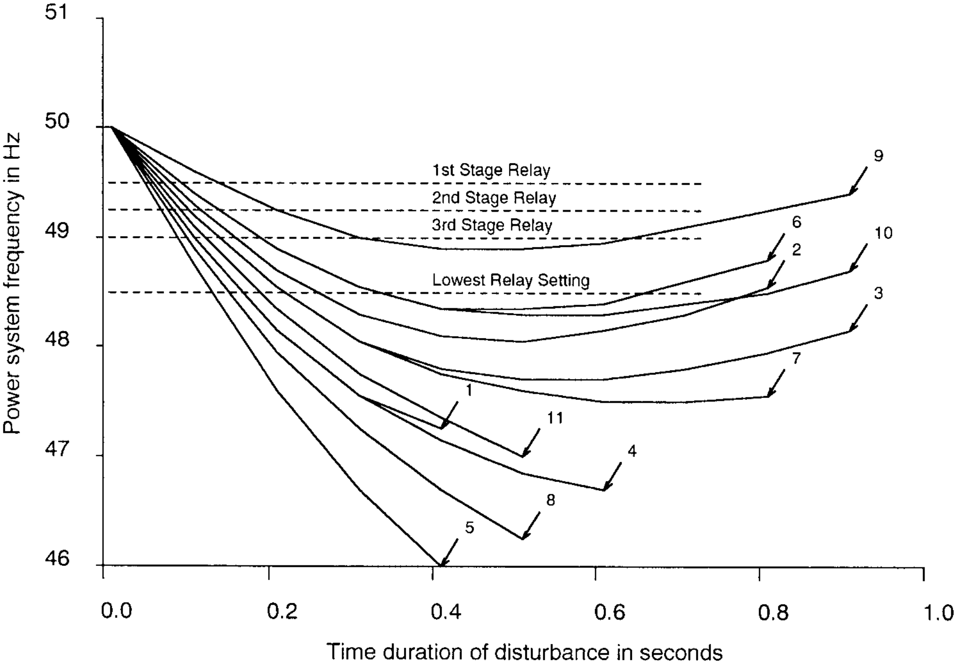
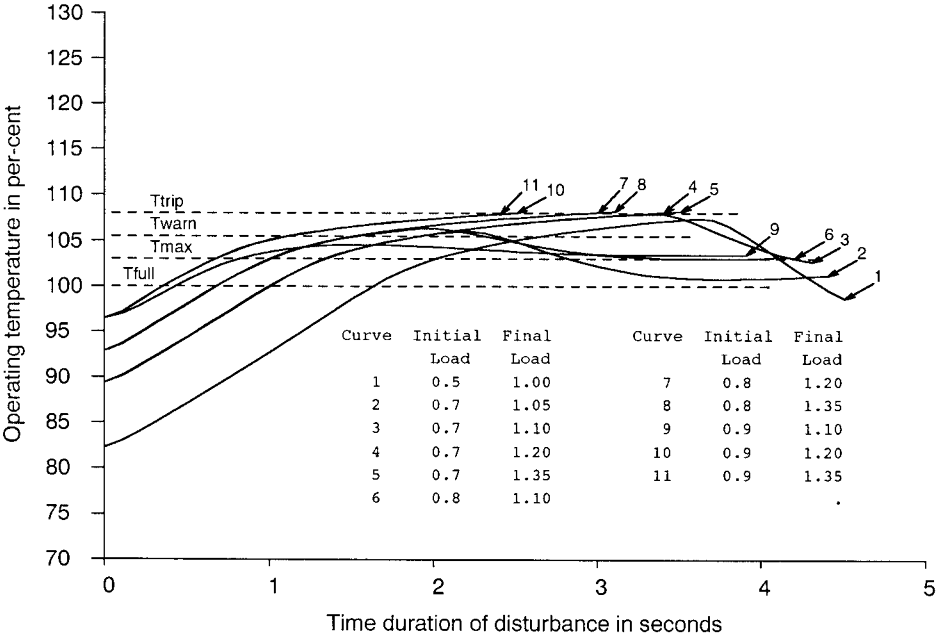


Figure D.3 Over-loading a single-shaft gas-turbine generator. Power system underfrequency relay settings.



Curve	Initial Load	Final Load
1	0.5	1.00
2	0.7	1.05
3	0.7	1.10
4	0.7	1.20
5	0.7	1.35
6	0.8	1.10
7	0.8	1.20
8	0.8	1.35
9	0.9	1.10
10	0.9	1.20
11	0.9	1.35

Figure D.4 Over-loading a two-shaft gas-turbine generator. Operating temperature versus time.

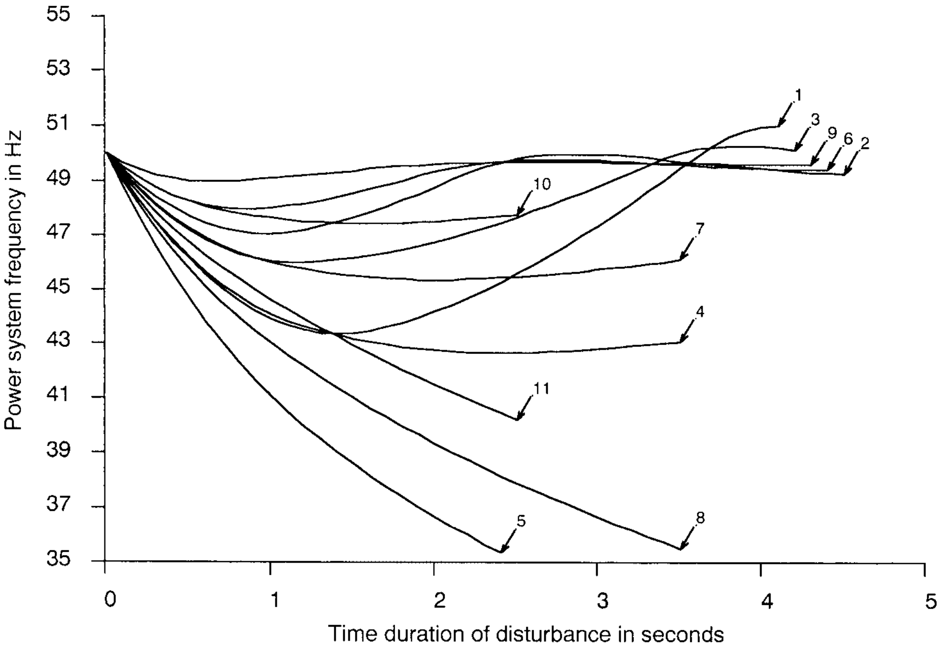


Figure D.5 Over-loading a two-shaft gas-turbine generator. Power system frequency versus time.

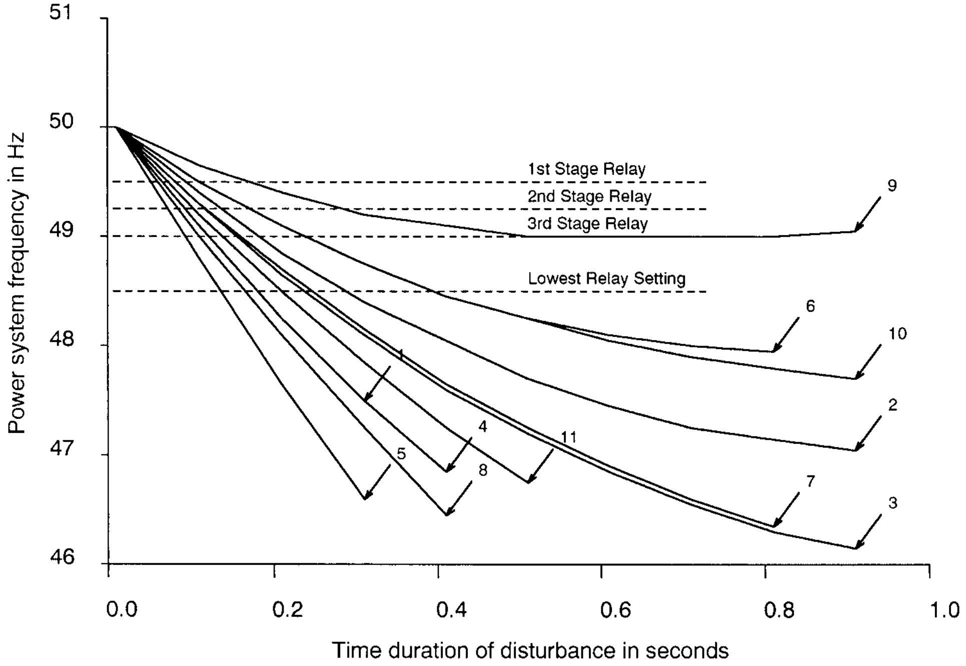


Figure D.6 Over-loading a two-shaft gas-turbine generator. Power system underfrequency relay settings.

time of the over-temperature alarms. Hence there is an implied relationship between underfrequency and over-temperature protection of the power system. When the power system is being designed, and the protection systems established, these two functions should be treated in a coordinated manner, so that the best overall performance is obtained.

REFERENCE

1. Applied protective relaying. Westinghouse Electric Corporation, 1976 Relay-Instrument Division, Newark, NJ 07101. Library of Congress Card No. 76-8080.

Appendix E

List of Document Types to be Produced During a Project

During the course of a project there will be a large number of documents produced for structures, systems and equipment. Apart from contractual and commercial documents there will be those for engineering, design, specification and testing of the systems and equipment in particular. These will be produced from two main sources. Firstly those from the design contractor, who is sometimes called the consultant, and secondly those from the many manufacturers who are involved in the project. Let the first set of documents be called ‘Contractors Documents’, and the second set the ‘Manufacturers Documents’. Listed below are the various types of documents that are produced for the different phases of a project for the electrical and allied structures, systems and equipment. The sequence of the list is in approximately the time and logical order of a typical project plan. Some activities run in series whilst others run in parallel. The list is not exhaustive, but is typical for an oil industry plant, and can be used as a starting point or as a checklist when estimating what has to be done in the project. The description or title of each type of document is very typical of those used throughout the industry.

Feasibility studies are often carried out at the beginning of a project to screen out different options that may be possible to develop further. These studies are relatively short in duration and only deal with the essential aspects of the design that will eventually emerge. Effort is usually concentrated in exploring the technical viability of the options available, to assess the amount and size of the main items of equipment, buildings and structures, thereby enabling an estimate of the plot area and its maximum height to be established. A rough estimate of the total weight and cost of equipment and the cost of site construction is usually made. For all the disciplines involved the total man-hours of work done is typically up to 5000.

Conceptual design or front-end engineering and design take the feasibility study work a stage further by expanding the chosen or best option in greater detail, including estimating costs more precisely. The main process systems are divided into more detail and consequently the work to be undertaken by all the other disciplines is increased in order to further delineate their contributions. Typically the total number of man-hours involved can be up to 25,000. For some projects the separation of feasibility studies from the conceptual design work may not take place, they may well be combined in a common scope of work.

Detail design takes the conceptual design or front-end engineering work as its starting reference and develops it in fine detail to the point where each piece of equipment and its location on site

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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are clearly identified. Much of the work involves producing drawings, diagrams, specifications, and detailed instructions for construction practices, plus all the purchasing and testing documentation. For a large project the total number of man-hours may be several hundreds of thousands, and represents the largest part of the cost of engineering the project.

E.1 CONTRACTORS DOCUMENTS

E.1.1 Feasibility Studies

The contractors documents may include the following:-

- Document list and index.
- Project execution statement.
- Project engineering philosophy divided into major subjects.
- Operating philosophy for the power system.
- Report for the power management system operation and design.
- Key single-line diagram.
- Single-line diagram of each main switchboard.
- Load schedule of each switchboard.
- Report for load flow calculations.
- Short circuit calculations and a report.
- Report for harmonic penetration studies.
- Report of protective relaying studies.
- Report for the study of sizing of major equipment.
- Narrative for describing the interfacing of control and indication with other disciplines.
- Plot plans showing the locations of electrical equipment.
- Plot plans showing hazardous areas.
- Plot plans showing main cable and overhead line routes.
- Plans, elevations and sections of buildings and main rooms.
- Equipment lists, including their unique tag numbers.
- Report of earthing system studies.
- Report for the sizing of the main cables and overhead lines.
- Project specifications for major items of equipment, optional.
- Project data sheets for major items of equipment, optional.

E.1.2 Conceptual Design

Some of the documents developed in this phase of the project may be revised versions of those prepared in E.1.1. The contractors documents may include the following:-

- Document list and index.
- Project execution statement.

- Project engineering philosophy divided into major subjects.
- Operating philosophy for the power system.
- Report for the power management system operation and design.
- Key single-line diagram.
- Single-line diagram of each switchboard.
- Load schedule of each switchboard.
- Report for load flow calculations.
- Short circuit calculations and a report.
- Report for harmonic penetration studies.
- Report of protective relaying studies.
- Report for the study of sizing of major equipment.
- Plot plans showing the locations of electrical equipment.
- Plot plans showing hazardous areas.
- Plot plans showing main cable and overhead line routes.
- Plans, elevations and sections of buildings and main rooms.
- Plans, elevations and sections of large electrical equipment, e.g. switchgear, motor control centers, transformers, generators, HV motors.
- Equipment lists, including their unique tag numbers.
- Schedule of protective relaying settings.
- Report of earthing system studies.
- Report for the sizing of the main cables and overhead lines.
- Report for the selection of lighting equipment types and illumination levels, including sample calculations, optional.
- Block cable schematic diagrams.
- Schedules of cables.
- Project equipment specifications.
- Project equipment data sheets.
- Schedules of switchboard control and indication requirements, optional.
- Block diagrams for control, indication, measurements, interlocking, synchronising, and interfacing with intelligent networks.
- Narrative for describing the interfacing of control and indication with other disciplines.

E.1.3 Detail Design

Some of the documents developed in this phase of the project may be revised versions of those prepared in E.1.2. The contractors documents may include the following:-

- Document list and index.
- Project execution statement.
- Project engineering philosophy divided into major subjects.
- Operating philosophy for the power system.

- Report for the power management system operation and design.
- Key single-line diagram.
- Single-line diagram of each switchboard.
- Load schedule of each switchboard.
- Report for load flow calculations.
- Short circuit calculations and a report.
- Report for harmonic penetration studies.
- Report of protective relaying studies.
- Report for the study of sizing of major equipment.
- Plot plans showing the locations of electrical equipment.
- Plot plans showing hazardous areas.
- Plot plans showing main cable and overhead line routes.
- Plans, elevations and sections of buildings and main rooms.
- Plans, elevations and sections of large electrical equipment, e.g. switchgear, motor control centers, transformers, generators, HV motors.
- Plans and elevations for cable trenching, racking and routing.
- Details of cable trench cross-sections and contents.
- Equipment lists, including their unique tag numbers.
- Schedule of protective relaying settings.
- Report of earthing system studies.
- Report for the sizing of the main cables and overhead lines.
- Report for the selection of lighting equipment types and illumination levels, including sample calculations.
- Block cable schematic diagrams.
- Schedules of cables.
- Schedules of cable drums.
- Project specifications for all items of equipment.
- Project data sheets for all items of equipment.
- Schedules of switchboard control and indication requirements.
- Wiring diagrams for switchboards and motor control centers.
- Wiring diagrams for control and annunciator panels.
- Wiring and terminal connection diagrams for generators, large motors, pumps, compressors and heavy machinery.
- Wiring and terminal connection diagrams for marshalling and junction boxes.
- Wiring and terminal connection diagrams for heat-tracing systems.
- Block diagrams for control, indication, measurements, interlocking, synchronising, and interfacing with intelligent networks.
- Narrative and detailed diagrams for interfacing details with other disciplines.
- Detail design diagrams and drawings for equipment fixings and installation for both large and small equipment.

- Detail design diagrams and drawings for the earthing of equipment and systems, for both large and small equipment including non-electrical items such as vessels and fences.

E.2 MANUFACTURERS DOCUMENTS

E.2.1 Feasibility Studies

The manufacturers documents may include quotations for particular items of equipment such as generators, large motors and main switchboards. These quotations would include technical information and budget cost estimates, and possibly references to other customers and projects.

E.2.2 Conceptual Design

The manufacturers documents may include the following:-

- Document list and index.
- Report for the functional design of the power management system.
- Plans and elevations for the power management system equipment.
- Single-line diagrams for the switchboards.
- Single-line diagrams for the motor control centers.
- Schedules of switchboard protective devices.
- Brochures for the protective relaying equipment.
- Setting up and commissioning manuals for the protective relaying equipment.
- Plans, elevations and sections of switchboards and motor control centers.
- Plans, elevations and sections of generators and their prime movers.
- Plans, elevations and sections of large motors and their driven machines.
- Plans, elevations and sections of power transformers and reactors.
- Termination details in major equipment terminal boxes, e.g. generators, HV motors, optional.

E.2.3 Detail Design

The manufacturers documents may include the following:-

- Document list and index.
- Report for the functional design of the power management system.
- Plans and elevations for the power management system equipment.
- Single-line diagrams for the switchboards.
- Single-line diagrams for the motor control centers.
- Schedules of switchboard protective devices.
- Brochures for the protective relaying equipment.
- Setting up and commissioning manuals for the protective relaying equipment.

- Plans, elevations and sections of switchboards and motor control centers.
- Plans, elevations and sections of generators and their prime movers.
- Plans, elevations and sections of large motors and their driven machines.
- Plans, elevations and sections of power transformers and reactors.
- Plans, elevations and sections of skid-mounted equipment.
- Plans, elevations and sections of UPS and battery banks.
- Plans, elevations and sections of control and large marshalling panels.
- Manuals for commissioning and testing main items of equipment, e.g. switchboards and motor control centers, generators, transformers.
- Block diagrams for control, indication, measurements, interlocking, synchronising, interfacing with intelligent network systems.
- Interfacing details with other equipment and disciplines.
- Wiring diagrams for control and annunciator panels.
- Wiring and terminal block diagrams for equipment.
- Termination details in major equipment terminal boxes, e.g. generators, HV motors.

Appendix F

Worked Example for Calculating the Performance of a Gas Turbine

F.1 THE REQUIREMENTS AND DATA GIVEN

A 12 MW gas turbine generator is required to operate at sea level with an ambient temperature T_1 of 20°C and a combustion temperature T_3 of 950°C. The following data apply.

Compressor	
Pressure ratio of the compressor r_{pc}	11.0
Compressor efficiency η_c	0.85
Ratio of specific heats for compression γ_c	1.4
Specific heat at constant pressure C_{pc}	1.005 kJ/kg°K
Ambient pressure	1.0 bar
Turbine	
Pressure ratio of the turbine r_{pt}, nominal	11.0
Turbine efficiency η_t	0.87
Combustion pressure drop $\Delta P_{23}/P_{23}$	0.04
Ratio of specific heats for expansion γ_t	1.33
Specific heat at constant pressure C_{pt}	1.147 kJ/kg°K
Heat rate	15.750 MJ/kWh
Losses	
Inlet ducting and silencer pressure drop ΔP_1	125 mm of water
Exhaust ducting pressure drop ΔP_4	50 mm of water
Gear box efficiency η_{gb} at full load	0.985 per unit
Generator energy conversion efficiency η_{gen}	0.985 per unit
Fuel	
LHV for hydrocarbon natural gas	37.50 MJ/kg
Fuel air ratio by mass	0.01 per unit

F.2 BASIC REQUIREMENTS

Assume constant specific heat $C_p = C_{pc}$, and $\gamma = \gamma_c$. Ignore the losses in the ducting, gear box and generator.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake
ISBN: 0-471-49631-6

Find the following:-

1. Ideal compressor outlet temperature T_2 in °K and °C.
2. Ideal turbine outlet temperature T_4 in °K and °C.
3. Ideal cycle efficiency η_i in per unit.
4. Compressor outlet temperature T_{2e} in °K and °C.
5. Turbine outlet temperature T_{4e} in °K and °C due to expansion efficiency η_t.
6. Practical cycle efficiency η_p per unit, with η_c and η_t included.
7. Find the pressure ratio $r_{p\,\max}$ that causes the maximum power to be delivered to the generator.

F.3 DETAILED REQUIREMENTS

Assume the specific heats are functions of temperature and take account of the pressure drops ΔP_1, ΔP_{23} and ΔP_4.

Find the following:-

8. Compressor outlet temperature T_{2ea} in °K and °C, due to compression efficiency η_c and the inlet pressure drop ΔP_1.
9. Turbine outlet temperature T_{4ea} in °K and °C, due to expansion efficiency η_t, the combustion pressure drop ΔP_{23}, and the outlet pressure drop ΔP_4.
10. The work done on the mass flow to produce the desired output power of 12 MW.
11. Theoretical thermal efficiency η_{pa} per unit, with all the losses included.
12. Overall thermal efficiency η_{pao} with all losses included.

F.4 BASIC SOLUTIONS

Step 1. From (2.14),

$$\delta = (1.0 - 1.4)/1.4 = -0.2857$$

$$(P_2/P_1)^{\delta} = 11.0^{-0.2857} = 0.50403$$

Therefore,

$$T_2 = T_1/0.50403 = (273.0 + 20.0)/0.50403 = 581.31^{\circ}\text{K or } 308.31^{\circ}\text{C}.$$

Step 2. From (2.15),

$$(P_3/P_4)^{\delta} = 11.0^{-0.2857} = 0.50403$$

Therefore,

$$T_4 = T_3 \times 0.50403 = (273.0 + 950.0) \times 0.50403 = 616.43^{\circ}\text{K or } 343.43^{\circ}\text{C}.$$

Step 3.

$$r_p^{\delta} = 11.0^{-0.2857} = 0.50403$$

and

$$r_p^{\beta} = 11.0^{+0.2857} = 1.984$$

Therefore, from (2.17),

$$\begin{aligned}\eta_i &= 1.0 - \frac{(273.0 + 950.0) \times 0.50403 - (273.0 + 20.0)}{(273.0 + 950.0) - ((273.0 + 20.0) \times 1.984)} \\ &= 1.0 - \frac{323.43}{641.69} = 0.496 \text{ per unit}\end{aligned}$$

Step 4. From (2.18),

$$\begin{aligned}T_{2e} &= \frac{581.31}{0.85} + \left(1.0 - \frac{1.0}{0.85}\right) \times 293.0 \\ &= 632.18^\circ\text{K or } 359.18^\circ\text{C.}\end{aligned}$$

Step 5. Also from (2.18),

$$\begin{aligned}T_{4e} &= 616.43 \times 0.87 + (1.0 - 0.87) \times 1223.0 \\ &= 695.28^\circ\text{K or } 422.28^\circ\text{C.}\end{aligned}$$

Step 6. From (2.20),

$$\begin{aligned}\eta_p &= \frac{1223.0(1.0 - 0.50403) \times 0.85 \times 0.87 - 293.0(1.984 - 1.0)}{1223.0 \times 0.85 - 293.0(1.984 - 1.0 + 0.85)} \\ &= \frac{160.25}{502.188} = 0.319 \text{ per unit}\end{aligned}$$

Step 7. From (2.27),

Let

$$\begin{aligned}d &= \frac{1.4}{2(1.0 - 1.4)} = -1.75 \\ r_{\text{p max}} &= (293.0/(1223.0 \times 0.85 \times 0.87))^d \\ &= 7.187 \text{ per unit}\end{aligned}$$

F.5 DETAILED SOLUTIONS

Step 8. Initially convert the pressure drops into the SI system of measurement units of 'bar'.

$$\Delta P_1 = 125.0/10200.0 = 0.01226 \text{ bar}$$

And

$$\Delta P_4 = 50.0/10200.0 = 0.0049 \text{ bar}$$

The combustion pressure drop in 'bar' is,

$$\Delta P_4 = r_{pt} \times P_4 \times 0.04 = 11.0 \times 1.0 \times 0.04 = 0.44 \text{ bar}$$

Step 9. The relationship between 'γ' over the range of 1.33 to 1.4 and 'C_p' over the range of 1.005 and 1.147 respectively, is approximately a straight-line law of the form '$y = a + bx$'. Hence by using these pairs of points, $a = 1.895425$ and $b = -0.49296$.

Therefore,

$$\gamma = 1.895425 - 0.49296\ C_p$$

Step 10. The pressure ratio is not affected by the change in inlet pressure to the compressor. The outlet temperature will remain constant at $T_2 = T_{2e} = 632.18^\circ\mathrm{K}$ or 359.18°C.

Step 11. The outlet pressure of the compressor will be,

$$\begin{aligned} P_2 + \Delta P_2 &= r_p(P_1 + \Delta P_1) = 11.0 \times (1.0 - 0.01226) \\ &= 10.8651 \text{ bar} \end{aligned}$$

The inlet pressure to the turbine will be,

$$P_3{}' = P_2 + \Delta P_2 - \Delta P_{23} = 10.8651 - 0.44 = 10.4251 \text{ bar}$$

The outlet pressure of the turbine will be,

$$P_4{}' = P_4 + \Delta P_4 = 1.0 + 0.0049 = 1.0049 \text{ bar}$$

Hence the pressure ratio of the turbine is,

$$r_{pt} = \frac{P_3{}'}{P_4{}'} = \frac{10.4251}{1.0049} = 10.3743$$

The specific heats C_{pc} and C_{pt} are functions of the temperature within the compressor and turbine respectively. A reasonable approximation is to use the average of T_1 and T_{2e} for the compressor, call this T_{12e}, and the average of T_3 and T_{4e} for the turbine, call this T_{34e}. The variation of C_p with temperature is given in Table 2.1 as a cubic equation for three fuel-to-air ratios, zero, 0.01 and 0.02 per unit by mass. The value of 0.01 is appropriate for this example. At the same time the ratio of specific heats γ_c and γ_t are functions of the specific heat at constant pressure. Simple linear functions can be used to estimate the appropriate value of γ for a given C_p, as follows,

$$\gamma_c = a_c + b_c C_{pc} \quad \text{and} \quad \gamma_t = a_t + b_t C_{pt},$$

where

$$a_c = a_t = 1.895425 \quad \text{and} \quad b_c = b_t = -0.49296$$

An iterative procedure is necessary in order to stabilise the values of C_{pc}, γ_c and T_{2e} for the compressor and C_{pt}, γ_t and T_{4e} for the turbine. The conditions for the compressor need to be calculated before those of the turbine.

Step 12. Find the compressor conditions

The starting conditions for iterating the compressor variables are,

$$\begin{aligned} C_{pc} &= 1.005 \\ \gamma_c &= 1.895425 - 0.49296 \times 1.005 = 1.4 \\ T_1 &= 293.0^\circ\text{K} \\ T_{2e} &= 632.18^\circ\text{K},\ \text{found from Step 4} \qquad \text{[step 12.1]} \end{aligned}$$

The average value of T_1 and T_{2e} is 462.59°K. From the cubic expression in Table 2.1 for a fuel-to-air ratio of zero, the revised value of C_{pc} is,

$$\begin{aligned} C_{pcn} &= 0.99653 - 1.6117 \times 10^{-4} \times 462.59 \\ &\quad + 5.4984 \times 10^{-7} \times 462.59^2 - 2.4164 \times 10^{-10} \times 462.59^3 \\ &= 0.99653 - 0.074557 + 0.117662 - 0.023921 = 1.015718 \end{aligned}$$

The new value of γ_c is $1.895425 - 0.49296 \times 1.015718 = 1.3947$. Now recalculate T_{2e},

$$T_{2e} = \frac{293.0 \times (11.0 - 1.0 + 0.85)}{0.85} = 627.78^\circ\text{K}$$

The new average value of T_1 and T_{2e} is 460.39°K.

Step 13. Recycle.

Repeat this iterative process from [step 12.1] until the variables settle at their stable values. These eventually become,

$$\begin{aligned} C_{pc} &= C_{pcn} = 1.01531 \\ \gamma_c &= \gamma_{cn} = 1.394917 \\ T_{2e} &= 627.934^\circ\text{K or } 354.934^\circ\text{C} \end{aligned}$$

Step 14. Find the turbine conditions.

The starting conditions for iterating the turbine variables are,

$$\begin{aligned} C_{pt} &= 1.005 \\ \gamma_t &= 1.895425 - 0.49296 \times 1.147 = 1.33 \\ T_1 &= 293.0^\circ\text{K} \\ T_4 &= {r_{pt}}^{0.2481} = 10.3743^{0.2481} = 684.46^\circ\text{K} \qquad \text{[step 14.1]} \\ T_{4e} &= 684.46 \times \eta_t + (1 - \eta_t) \times 1223.0 = 754.47^\circ\text{K} \end{aligned}$$

The average value of T_3 and T_{4e} is 988.734°K. From the cubic expression in Table 2.1 for a fuel-to-air ratio of 0.01, the revised value of C_{pt} is,

$$\begin{aligned}C_{ptn} &= 1.0011 - 1.4117 \times 10^{-4} \times 988.734 \\ &\quad + 5.4973 \times 10^{-7} \times 988.734^2 - 2.4691 \times 10^{-10} \times 988.734^3 \\ &= 1.160278\end{aligned}$$

The new value of γ_t is $1.895425 - 0.49296 \times 1.160278 = 1.32345$, and $T_4 = 690.436$°K. Now recalculate T_{4e},

$$T_{4e} = 690.436 \times 0.87 + (1.0 - 0.87) \times 1223.0 = 759.67^\circ\text{K}$$

The new average value of T_3 and T_{4e} is 991.334°K.

Step 15. Recycle.

Repeat this iterative process from [step 14.1] until the variables settle at their stable values. These eventually become,

$$\begin{aligned}C_{pt} &= C_{ptn} = 1.16088 \\ \gamma_t &= \gamma_{tn} = 1.323156 \\ T_{4e} &= 991.455^\circ\text{K or } 718.455^\circ\text{C}\end{aligned}$$

Step 16. The work done on the gearbox input shaft, from (2.32) is found as follows,

$$\begin{aligned}\delta_t &= \frac{1 - \gamma_t}{\gamma_t} = \frac{1.0 - 1.323156}{1.323156} = -0.24423 \\ U_{\text{outea}} &= 1.16088 \times 1223.0 \times (1.0 - 10.3743^{-0.24423}) \times 0.87 \\ &= 537.592 - 340.062 = 197.53 \text{ kJ/kg}\end{aligned}$$

Step 17. Include the gearbox and generator losses.

The losses between the gearbox input shaft and the electrical terminals of the generator U_{losses} are,

$$U_{\text{losses}} = (0.015 + (1.0 - 0.985)) \times 12.0 = 0.36 \text{ MW}$$

Hence the input to the gearbox is $12.0 + 0.36 = 12.36$ MW. From sub-section 2.3 the mass flow of the air–fuel mixture 'm' is,

$$\begin{aligned}m &= \frac{W_{\text{out}}}{U_{\text{outea}}} = \frac{12.36 \times 1000.0}{197.53} \\ &= 62.573 \text{ kg/sec} = 225263 \text{ kg/hour}\end{aligned}$$

Step 18. Find the theoretical efficiency η_{pa}.

From (2.20) the theoretical efficiency η_{pa} can be found by using the appropriate pressure ratios and ratios of the specific heats.

Let

$$T_{4a} = T_3(1 - {r_{pt}}^{\delta t})\eta_c\ \eta_t$$

$$T_{1a} = T_1({r_{pt}}^{\beta t} - 1)$$

$$T_{3a} = T_3\ \eta_c$$

and

$$T_{2a} = T_1({r_{pc}}^{\beta t} - 1 + \eta_c)$$

then

$$\eta_{pa} = \frac{T_{4a} - T_{1a}}{T_{3a} - T_{2a}}$$

therefore,

$$\begin{aligned}
T_{4a} &= 1223.0 \times (1.0 - 10.3743^{-0.24423}) \times 0.85 \times 0.87 = 393.627^\circ\text{K} \\
\beta_c &= \frac{\gamma_c - 1}{\gamma_c} = \frac{1.394917 - 1.0}{1.394917} = +0.28311 \\
T_{1a} &= 293.0 \times (11.0^{+0.28311} - 1.0) = 284.694^\circ\text{K} \\
T_{3a} &= 1223.0 \times 0.85 = 1039.55^\circ\text{K} \\
T_{1a} &= 293.0 \times (1.971652 - 1.0 + 0.85) = 533.744^\circ\text{K} \\
\eta_{pa} &= \frac{393.627 - 284.694}{1039.55 - 533.744} = 0.2154 \text{ per unit}
\end{aligned}$$

Step 19. Find the overall thermal efficiency η_{pao}.

From (2.33) and allowing for the losses in the gearbox and generator, the overall thermal efficiency η_{pao} can be found as follows.

$$\eta_{pao} = \frac{U_{\text{oute}}}{U_{\text{fea}}}\ \eta_{gb}\ \eta_{\text{gen}}$$

The value of C_{pf} can be taken as the average value of T_3 and T_{2e}, call this T_{23},

$$T_{23} = \frac{1223.0 + 627.934}{2} = 925.467^\circ\text{K}$$

Substitute T_{23} in the cubic expression for a fuel–air ratio of 0.01 in Table 2.1 to find the appropriate value of C_{pf},

$$\begin{aligned}
C_{pf} &= 1.0011 - 1.4117 \times 10^{-4} \times 925.467 \\
&\quad + 5.4973 \times 10^{-7} \times 925.467^2 - 2.4691 \times 10^{-10} \times 925.467^3 = 1.14558 \\
U_{\text{fea}} &= 1.14558 \times (1223.0 - 627.934) = 681.695 \text{ kJ/kg} \\
\eta_{pa} &= \frac{U_{\text{outea}}}{U_{\text{fea}}} = \frac{197.530}{681.695} = 0.28976 \text{ per unit} \\
\eta_{pao} &= 0.28976\ \eta_{gb}\ \eta_{\text{gen}} \\
&= 0.28976 \times 0.985 \times 0.985 = 0.28114 \text{ per unit}
\end{aligned}$$

Appendix G

Worked Example for the Calculation of Volt-drop in a Circuit Containing an Induction Motor

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G.1 INTRODUCTION

The following example explains how volt-drop calculations can be carried out. Initially the subject is approached from a rigorous standpoint. Subsequently various simplifications are introduced, their results compared and their appropriateness discussed. The calculation sequence is:-

- Rigorous solution, see a) to p).
- Simplified solution, see q) to t).
- Formulae method based on kVA ratings, see u).
- Graphical estimation, see v).

Figure G.1 is a simplified one-line diagram of a power generation and distribution system that would be suitable for most oil industry power systems that have their own power generating plants, e.g. an off-shore production platform. Figure G.2 is the equivalent diagram showing the basic symbols and configuration needed for the volt-drop calculation process. The example data are given below:-

i) Generator data.
3 generators, each rated at 3.125 MVA at 0.8 PF lagging.
Rated voltage = 13.8 kV, $X'_d = 25\%$, $R_a = 2\%$.

ii) Switchboard data.
Rated voltage = 13.8 kV
Standing load = 900 kW at 0.9 PF lagging ($\cos\phi_{og}$).

iii) Transformer data.
Rated at 3.15 MVA.
Rated voltage ratio = 13.2 : 4 kV. $X_{tpu} = 6\%$, $R_{tpu} = 0.7\%$.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake
ISBN: 0-471-49631-6

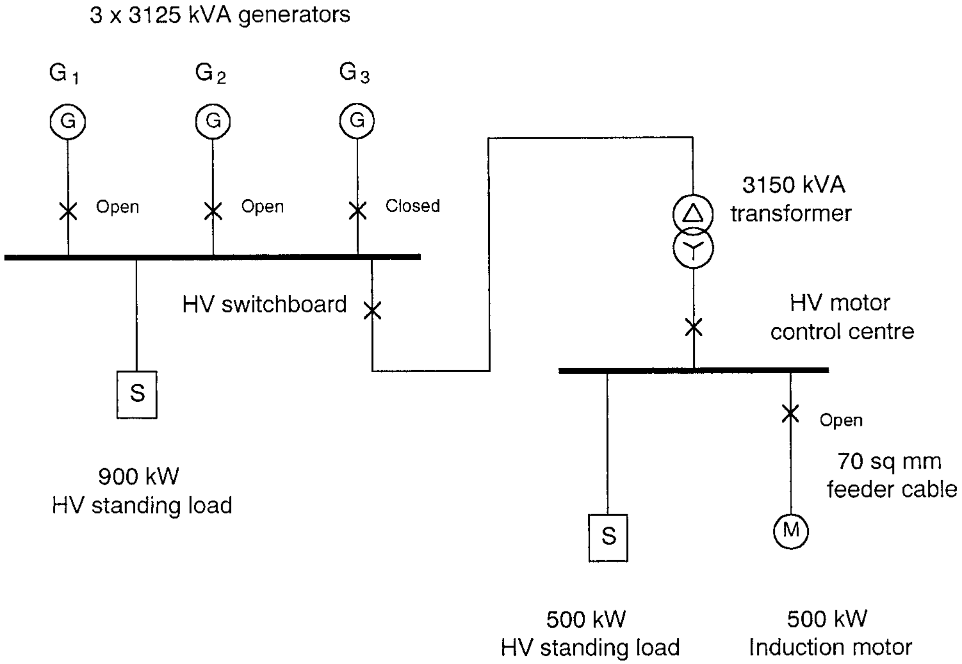

Figure G.1 Simplified one-line diagram for calculating the volt-drop of a 500 kW HV motor.

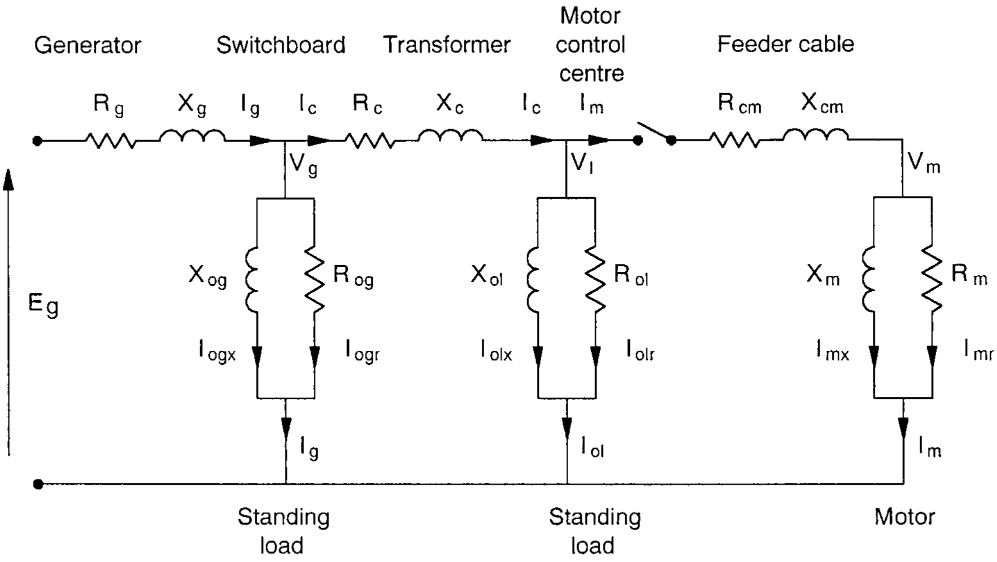

Figure G.2 Basic equivalent circuit for calculating the volt-drop of a 500 kW HV motor.

iv) Motor control centre data.
Rated voltage = 4.16 kV
Standing load = 500 kW at 0.85 PF lagging ($\cos\phi_{\text{ol}}$).

v) Motor feeder cable

Conductor size	=	70 mm^2
Conductor temperature	=	75°C
Specific resistance R_{km}	=	0.343 ohms per km
Specific reactance X_{km}	=	0.129 ohms per km
Rated voltage	=	5 kV
Rated frequency	=	60 Hz
Route length	=	1500 m

vi) Motor

Rated voltage	=	4 kV
Rated efficiency	=	95%
Rated power factor	=	0.88 lagging
Starting current	=	5 times the full-load current
Starting power factor	=	0.25 lagging

Convert the data to the system base values.

a) For convenience choose the system base kVA and voltages to be:-

$$\text{System base kVA} = \text{Generator kVA} = 3125$$

$$\text{System base voltage at the switchboard} = 13,800 \text{ volts}$$

$$\begin{aligned}\text{System base voltage at the MCC} &= 13,800 \times \text{transformer ratio}\\ &= 13,800 \times \frac{4000}{13,200} = 4181.8 \text{ volts,}\end{aligned}$$

b) The system base value of the generator impedance $R_g + jX_g$ is the same as that for the generator kVA base.

$$R_g + jX_g = R_a + jX'_d = 0.02 + j0.25 \text{ pu}$$

c) Convert the transformer impedance to the system base values.

$$\begin{aligned}R_c + jX_c &= (R_{\text{pu}} + jX_{\text{pu}})\frac{(\text{base kVA})\ (\text{trans pri voltage})^2}{(\text{trans kVA})\ (\text{base pri voltage})^2}\\ &= (0.7 + j6.0)\frac{(3125)(13,200)^2}{(3150)(13,800)^2} = 0.00635 + j0.05446 \text{ pu}\end{aligned}$$

d) Switchboard (SWBD) parallel circuit components.

Convert to system base values.

$$\begin{aligned}
\text{SWBD load kVA} &= S_{\text{og}} = \frac{\text{SWBD load power}}{\text{SWBD load power factor}}\\
&= \frac{P_{\text{og}}}{\cos\phi_{\text{og}}} = \frac{900 \times 1000}{0.9} = 1000 \times 10^3 \text{ VA}\\
\text{SWBD load kVA/phase} &= S_{\text{ogp}} = \frac{1000 \times 1000}{3} = 333 \times 10^3 \text{ VA}\\
\text{SWBD load power/phase} &= P_{\text{ogp}} = \frac{900 \times 1000}{3} = 300 \times 10^3 \text{ VA}\\
\text{SWBD load reactive power/phase} &= Q_{\text{ogp}} = \sqrt{}(S_{\text{ogp}}{}^2 - S_{\text{ogp}}{}^2)\\
&= 145.29 \times 10^3 \text{ VAr}\\
\text{Ohmic resistance per phase} &= R_{\text{ogp}} = \left(\frac{\text{Phase voltage}}{\text{Phase active power}}\right)^2\\
&= \left(\frac{V_{\text{og}}}{P_{\text{ogp}}}\right)^2 = \frac{13,800 \times 13,800}{3 \times 300 \times 10^3} \times 10^6\\
&= 211.6 \text{ ohms per phase}\\
\text{Ohmic reactance per phase} &= X_{\text{ogp}} = \left(\frac{\text{Phase voltage}}{\text{Phase reactive power}}\right)^2\\
&= \left(\frac{V_{\text{og}}}{Q_{\text{ogp}}}\right)^2 = \frac{13,800 \times 13,800}{3 \times 145.29 \times 10^3} \times 10^6\\
&= 436.92 \text{ ohms per phase}
\end{aligned}$$

Convert to the system base impedance values.

$$\text{System impedance in per-unit} = \text{Ohmic impedance} = \frac{(\text{load base kVA})\ (\text{system base kVA})}{(\text{system base voltage})^2(\text{load base kVA})}$$

Hence

$$R_{\text{og}} = \frac{(211.6 \times 1000 \times 1000)(3125 \times 1000)}{(13,800)^2(1000 \times 1000)} = 3.4722 \text{ pu}$$

And

$$X_{\text{og}} = \frac{(436.92 \times 1000 \times 1000)(3125 \times 1000)}{(13,800)^2(1000 \times 1000)} = 7.1696 \text{ pu}$$

These are the parallel elements of the load in per-unit at the system base.

e) Motor control centre (MCC) parallel circuit components.

Convert to system base values.

$$\text{MCC load kVA} = S_{ol} = \frac{\text{MCC load power}}{\text{MCC load power factor}}$$

$$= \frac{P_{ol}}{\cos\phi_{ol}} = \frac{500 \times 1000}{0.85} = 588.235 \times 10^3 \text{ VA}$$

$$\text{MCC load kVA/phase} = S_{olp} = \frac{588.235 \times 1000}{3} = 196.078 \times 10^3 \text{ VA}$$

$$\text{MCC load power/phase} = P_{olp} = \frac{500 \times 1000}{3} = 166.667 \times 10^3 \text{ VA}$$

$$\text{MCC load reactive power/phase} = Q_{olp} = \surd({S_{olp}}^2 - {S_{olp}}^2)$$

$$= 103.29 \times 10^3 \text{ VAr}$$

$$\text{Ohmic resistance per phase} = R_{olp} = \left(\frac{\text{Phase voltage}}{\text{Phase active power}}\right)^2 =$$

$$= \left(\frac{V_{ol}}{P_{olp}}\right)^2 = \frac{4160 \times 4160}{3 \times 166.67 \times 10^3} \times 10^6$$

$$= 34.61 \text{ ohms per phase}$$

$$\text{Ohmic reactance per phase} = X_{olp} = \left(\frac{\text{Phase voltage}}{\text{Phase reactive power}}\right)^2$$

$$= \left(\frac{V_{ol}}{Q_{olp}}\right)^2 = \frac{41,600 \times 4160}{3 \times 103.29 \times 10^3} \times 10^6$$

$$= 55.848 \text{ ohms per phase}$$

Convert to the system base impedance values.

$$\text{System impedance in per-unit} = \text{Ohmic impedance} = \frac{\text{(load base kVA) (system base kVA)}}{\text{(system base voltage)}^2\text{(load base kVA)}}$$

Hence

$$R_{ol} = \frac{(34.61 \times 588.235 \times 1000)(3125 \times 1000)}{(4160)^2(588.235 \times 1000)} = 6.2498 \text{ pu}$$

and

$$X_{ol} = \frac{(55.848 \times 588.235 \times 1000)(3125 \times 1000)}{(4160)^2(588.235 \times 1000)} = 10.085 \text{ pu}$$

These are the parallel elements of the load in per-unit at the system base.

f) Motor feeder cable. Convert to system base.

A 70 mm^2 three-core 5 kV cable has an ohmic impedance of $0.343 + j0.129$ ohms per kilometre per phase and a current rating of 250 A. Hence the total ohmic impedance is $0.5145 + j0.1935$ ohms per phase.

$$\begin{aligned}\text{The total VA rating for the cable} &= \sqrt{3} \times \text{Rated line voltage} \times \text{Rated phase current}\\ &= \sqrt{3} \times 5000 \times 250 = 2.165 \times 10^6 \text{ VA}\\ \text{The VA rating for the cable per phase} &= 0.3333 \times 2.165 \times 10^6 = 721.67 \times 10^3\\ \text{The 1.0 pu impedance of the cable per phase} &= V_{\text{olp}} = \frac{5000}{\sqrt{3} \times 250}\\ &= 11.547 \text{ ohms per phase.}\end{aligned}$$

Hence the per-unit impedance of this particular cable at its own base is:-

$$R_{\text{pu}} + jX_{\text{pu}} = \frac{0.5145 + j0.1935}{11.547} = 0.04456 + j0.01676 \text{ pu}$$

Convert this impedance to the system base:-

$$\begin{aligned}R_{\text{cm}} + jX_{\text{cm}} &= (R_{\text{pu}} + jX_{\text{pu}})\frac{(\text{base kVA})\ (\text{cable rated voltage})^2}{(\text{cable kVA})\ (\text{system base voltage})^2}\\ &= \frac{(0.04456 + j0.01676)(3125)(5000)^2}{(2.165 \times 10^6)(13,800)^2}\\ &= 0.00844 + j0.003175 \text{ pu}\end{aligned}$$

g) Motor running conditions (suffix ‘*r*’)

$$\begin{aligned}\text{Motor rated voltage} &= 4000.0 \text{ volts}\\ \text{Motor system base voltage} &= 4181.8 \text{ volts}\\ \text{Motor terminal voltage} &= 4160.0 \text{ volts}\\ \text{Input power to each phase} &= \frac{\text{Rated power output}}{3 \times \text{efficiency}}\\ P_{\text{mrp}} &= \frac{500}{3 \times 0.95} \times 10^3 = 175.44 \text{ kW}\\ \text{Input VA to each phase} &= \frac{\text{Rated power input}}{\text{Power factor}}\\ S_{\text{mrp}} &= \frac{175.44}{0.88} \times 10^3 = 199.36 \text{ kVA}\\ \text{Input VAr to each phase} &= \sqrt{(S_{\text{mrp}}{}^2 - S_{\text{mrp}}{}^2)}\\ Q_{\text{mrp}} &= 1000.0 \times \sqrt{(199.36^2 - 175.44^2)} = 94.68 \text{ kVAr}\end{aligned}$$

At the motor rating base the phase ohmic resistance R_{mrp} is:-

$$\begin{aligned}R_{\text{olp}} &= \left(\frac{\text{Phase voltage}}{\text{Phase active power}}\right)^2\\ &= \frac{4000 \times 4000}{3 \times 175.44 \times 10^3} = 30.4 \text{ ohms per phase}\end{aligned}$$

Similarly the phase ohmic reactance X_{mrp} is:-

$$X_{\text{olp}} = \left(\frac{\text{Phase voltage}}{\text{Phase reactive power}}\right)^2$$
$$= \frac{4000 \times 4000}{3 \times 94.68 \times 10^3} = 56.32 \text{ ohms per phase}$$

Convert this impedance to the motor per-unit base.

The 1.0 pu motor kVA per phase $= S_{\text{mrp}} = 199.36$

The 1.0 pu motor impedance per phase $= Z_{\text{mrp}}$

$$Z_{\text{mrp}} = \left(\frac{\text{Phase voltage}}{\text{Phase VA}}\right)^2$$
$$= \frac{4000 \times 4000}{3 \times 199.36 \times 10^3} = 26.75 \text{ ohms per phase}$$

Hence the per-unit motor running resistance is R_{olppu}:-

$$R_{\text{olppu}} = \frac{R_{\text{mrp}}}{Z_{\text{mrp}}} = \frac{30.4}{26.75} = 1.136 \text{ pu per phase}$$

And the per-unit motor running reactance is X_{olppu}:-

$$X_{\text{olppu}} = \frac{X_{\text{mrp}}}{Z_{\text{mrp}}} = \frac{56.32}{26.75} = 2.105 \text{ pu per phase}$$

Where R_{olppu} and X_{olppu} are parallel components representing the motor during the full-load running condition. Convert this impedance to the system base at the motor system voltage of 4181.8 volts.

$$R_{\text{mr}} + jX_{\text{mr}} = (R_{\text{mrppu}} + jX_{\text{mrppu}})\frac{(\text{base kVA})\ (\text{motor rated voltage})^2}{(\text{motor kVA})\ (\text{system base voltage})^2}$$
$$= \frac{(1.136 + j2.105)(3125)(4000)^2}{(3 \times 199.36 \times 10^3)(4181.8)^2}$$
$$= 5.4324 + j10.065 \text{ pu}$$

h) Motor running conditions (suffix 's')

$$\text{Rated current to each phase} = \frac{\text{Rated input VA}}{\sqrt{3} \times \text{Rated motor voltage}}$$
$$P_{\text{mrp}} = \frac{598.08}{\sqrt{3} \times 4000} \times 10^3 = 86.33 \text{ amps}$$

Starting current = 5 × Rated current = 431.63 amps

The starting impedance Z_{msp} is:-

$$Z_{\mathrm{msp}} = \frac{\text{Phase voltage}}{\text{Starting current}}$$

$$= \frac{4000}{\sqrt{3} \times 431.64} = 5.35 \text{ ohms per phase}$$

The starting resistance R_{msp} (parallel branch) is:-

$$Z_{\mathrm{msp}} = \frac{Z_{\mathrm{msp}}}{\cos\phi_{\mathrm{s}}} = \frac{5.35}{0.25} = 21.4 \text{ ohms per phase}$$

The starting reactance X_{msp} (parallel branch) is:-

$$X_{\mathrm{msp}} = \frac{Z_{\mathrm{msp}}}{\sin\phi_{\mathrm{s}}} = \frac{5.35}{0.9682} = 5.526 \text{ ohms per phase}$$

Hence the per-unit motor starting resistance is R_{msppu}:-

$$R_{\mathrm{msppu}} = \frac{R_{\mathrm{msp}}}{Z_{\mathrm{msp}}} = \frac{21.4}{26.75} = 0.80 \text{ pu per phase}$$

And the per-unit motor starting reactance is X_{msppu}:-

$$X_{\mathrm{msppu}} = \frac{X_{\mathrm{msp}}}{Z_{\mathrm{msp}}} = \frac{5.526}{26.75} = 0.2066 \text{ pu per phase}$$

Where, R_{msppu} and X_{msppu} are parallel components representing the motor during the starting condition. Convert this impedance to the system base at the motor system voltage of 4181.8 volts.

$$R_{\mathrm{ms}} + jX_{\mathrm{ms}} = (R_{\mathrm{msppu}} + jX_{\mathrm{msppu}})\frac{(\text{base kVA})\ (\text{motor rated voltage})^2}{(\text{motor kVA})\ (\text{system base voltage})^2}$$

$$= \frac{(0.8 + j0.2066)(3125)(4000)^2}{(598.08 \times 10^3)(4181.8)^2}$$

$$= 0.38244 + j0.9875 \text{ pu}$$

i) Summary of the results thus far.

The data to be used in the per-unit circuit diagram in Figure G.2 are:-

Generator $R_{\mathrm{g}} = 0.2$ pu
$X_{\mathrm{g}} = 0.25$ pu
SWBD parallel load $R_{\mathrm{og}} = 3.4722$ pu
$X_{\mathrm{og}} = 7.1676$ pu
Transformer $R_{\mathrm{c}} = 0.00635$ pu
$X_{\mathrm{c}} = 0.05446$ pu
MCC parallel load $R_{\mathrm{ol}} = 6.2498$ pu
$X_{\mathrm{ol}} = 10.085$ pu

Motor feeder cable $R_{\mathrm{cm}} = 0.00844$ pu
$X_{\mathrm{cm}} = 0.003175$ pu
Motor running $R_{\mathrm{mr}} = 5.43024$ pu
$X_{\mathrm{mr}} = 10.065$ pu
Motor starting $R_{\mathrm{ms}} = 3.8244$ pu
$X_{\mathrm{ms}} = 0.9875$ pu

j) Rigorous solution

The sequence of calculations is as follows:-

- Initial conditions, using suffix ‘*o*’.
- Running conditions, using suffix ‘*n*’.
- Starting conditions, using suffix ‘*s*’.
- Compare the calculated voltages and find the volt-drops.
- Design comments.

k) Initial conditions

The motor starter is open and the generator terminal voltage is 1.0 per-unit.

Hence,

$$V_{\mathrm{go}} = 1.0 + j0.0 \text{ pu.}$$

Find the initial values of I_{c} and V_{l}, i.e. I_{co} and V_{lo}, noting that $I_{\mathrm{m}} = 0.0$

At the MCC the parallel load is R_{ol} in parallel with X_{ol}.

Convert the parallel load into a series load of $R_{\mathrm{ol1}} + jX_{\mathrm{ol1}}$.

The formulae for this conversion are:-

$$R_{\mathrm{oll}} = \frac{R_{\mathrm{ol}} {X_{\mathrm{ol}}}^2}{{R_{\mathrm{ol}}}^2 + {X_{\mathrm{ol}}}^2} \quad \text{pu per phase}$$

$$X_{\mathrm{oll}} = \frac{X_{\mathrm{ol}} {R_{\mathrm{ol}}}^2}{{R_{\mathrm{ol}}}^2 + {X_{\mathrm{ol}}}^2} \quad \text{pu per phase}$$

Where

$$R_{\mathrm{ol}} = 6.2498 \text{ and } X_{\mathrm{ol}} = j10.085$$

Hence,

$$Z_{\mathrm{oll}} = R_{\mathrm{oll}} + jX_{\mathrm{oll}} = 4.5156 + j2.7985 \text{ pu}$$

The impedance seen at the SWBD is

$$\begin{aligned} Z_{\mathrm{ol1}} + Z_{\mathrm{c}} &= 0.00635 + 4.5156 + j(0.05446 + 2.7985) \\ &= 4.5220 + j2.8530 \text{ pu} \end{aligned}$$

$$\begin{aligned} Z_{\mathrm{oll}} &= \frac{V_{\mathrm{go}}}{Z_{\mathrm{oll}} + Z_{\mathrm{c}}} = \frac{1.0 + j0.0}{4.5220 + j2.8530} \\ &= 0.1582 - j0.0998 \text{ pu} \end{aligned}$$

$$V_{\mathrm{lo}} = \frac{V_{\mathrm{go}} Z_{\mathrm{oll}}}{Z_{\mathrm{oll}} + Z_{\mathrm{c}}} = 0.9936 - j0.0080 \text{ pu,}$$

which has a magnitude of 0.9936 pu.

Find the initial emf, E_o, of the generator.

At the SWBD the parallel load is R_{og} in parallel with X_{og}.

Convert the parallel load into a series load of $R_{ogl} + jX_{ogl}$.

$$R_{og} = 3.4722 \text{ pu and } X_{og} = j7.1696 \text{ pu},$$

hence Z_{ogl} is:-

$$Z_{ogl} = R_{ogl} + jX_{ogl} = 2.8125 + j1.3622 \text{ pu}.$$

The initial load current I_{ogo} is:-

$$I_{ogo} = \frac{V_{go}}{Z_{ogl}} = \frac{(1.0 + j0.0)(2.8125 - j1.3621)}{2.8125^2 + 1.3621^2}$$
$$= 0.288 - j0.1395 \text{ pu}.$$

The total initial generator current I_{go} is:-

$$I_{go} = I_{ogo} + I_{co} = 0.1582 - j0.0998 + 0.288 - j0.1395$$
$$= 0.4462 - j0.2393 \text{ pu}.$$

Hence,

$$E_o = V_{go} + I_{go}Z_g = 1.0 + j0 + (0.4461 - j0.2393)(0.02 + j0.25) \text{ pu}$$
$$= 1.0687 + j0.1068 \text{ pu, which has a magnitude of } 1.0741 \text{ pu}.$$

l) Running conditions

The motor starter is closed and the generator emf is 1.0741 per-unit.

Assume the rated impedance for the motor since this will give a worst-case running impedance for it. (The 500 kW motor will be over-sized in any case with respect to the driven machine by about 10% and so the actual impedance will be about 10% higher than the rated impedance.)

The parallel impedance of the running motor is Z_{mn}:-

$$R_{mn} = 5.4324 \text{ and } X_{mn} = j10.065 \text{ pu}$$

The series impedance of the running motor is Z_{mnl}:-

$$Z_{mnl} = R_{mnl} + jX_{mnl} = 4.2069 + j2.2706 \text{ pu}$$

Now add the feeder cable impedance in series to obtain the total series impedance between the MCC and the motor. Call this total impedance Z_{mnlc}.

$$\begin{aligned} Z_{\text{mnlc}} &= R_{\text{mnlc}} + jX_{\text{mnlc}} = R_{\text{mnlc}} + R_{\text{cm}} + j(X_{\text{mnlc}} + X_{\text{cm}}) \\ &= 0.00844 + 4.2069 + j(0.003175 + 2.2706) \\ &= 4.2153 + j2.2738 \text{ pu} \end{aligned}$$

The total load on the MCC consists of the static load Z_{ol1} (series components) in parallel with the cable and motor Z_{mnlc} (series components). The total impedance Z_{oln} is therefore:-

$$Z_{\text{oln}} = R_{\text{oln}} + jX_{\text{oln}} = \frac{Z_{\text{oll}} \times Z_{\text{mnlc}}}{Z_{\text{oll}} + Z_{\text{mnlc}}} = 2.1828 + j1.2590 \text{ pu}$$

The impedance seen at the SWBD for the cable, motor and MCC load is Z_{cn}:-

$$\begin{aligned} Z_{\text{cn}} = Z_{\text{oln}} + Z_c &= 2.1828 + j1.2590 + 0.00635 + j0.05446 \\ &= 2.1891 + j1.3135 \text{ pu} \end{aligned}$$

This impedance is in parallel with that of the local load Z_{og} on the SWBD. The total equivalent load on SWBD is Z_{ogn} where:-

$$Z_{\text{ogn}} = R_{\text{ogn}} + jX_{\text{ogn}} = \frac{Z_{\text{ogl}} \times Z_{\text{cn}}}{Z_{\text{ogl}} + Z_{\text{cn}}} = 1.2341 + j0.6746 \text{ pu}$$

Hence the total impedance seen by the generator emf E_{o} is Z_{gn}:-

$$\begin{aligned} Z_{\text{ogn}} &= R_{\text{g}} + R_{\text{ogn}} + j(X_{\text{g}} + X_{\text{ogn}}) \\ &= 0.02 + 1.2341 + j(0.25 + 0.6746) \\ &= 1.2541 + j0.9246 \text{ pu} \end{aligned}$$

The current in the generator I_{gn} is:-

$$I_{\text{gn}} = \frac{E_{\text{o}}}{Z_{\text{gn}}} = \frac{1.0687 - j0.1068}{1.2541 + j0.9246} = 0.5928 - j0.3519 \text{ pu}$$

Hence the terminal voltage of the generator V_{gn} is:-

$$\begin{aligned} V_{\text{gn}} &= \frac{E_{\text{o}} Z_{\text{ogn}}}{Z_{\text{gn}}} = \frac{(1.0687 + j0.1068)(1.2341 + j0.6746)}{1.2541 + j0.9246} \\ &= 0.9689 - j0.0344 \text{ pu, which has a magnitude of 0.9695 pu.} \end{aligned}$$

Similarly the voltage of the MCC V_{ln} is:-

$$\begin{aligned} V_{\text{ln}} &= \frac{V_{\text{gn}} Z_{\text{oln}}}{Z_{\text{cn}}} = \frac{(0.9689 - j0.0344)(2.1828 + j1.259)}{2.1891 + j1.3135} \\ &= 0.9556 - j0.0504 \text{ pu, which has a magnitude of 0.9570 pu.} \end{aligned}$$

m) Starting conditions

The motor starter is closed. Repeat the procedure as for l) the running conditions, but with the starting impedance using the suffix '*s*' for starting.

The parallel impedance of the running motor is Z_{mn}:-

$$R_{\mathrm{ms}} = 3.8244 \text{ and } X_{\mathrm{ms}} = j0.9875 \text{ pu}$$

The series impedance of the running motor is Z_{msl}:-

$$Z_{\mathrm{msl}} = R_{\mathrm{msl}} + jX_{\mathrm{msl}} = 0.2390 + j0.9257 \text{ pu}$$

Now add the feeder cable impedance in series to obtain the total series impedance between the MCC and the motor. Call this total impedance Z_{mlc}.

$$\begin{aligned} Z_{\mathrm{mslc}} &= R_{\mathrm{mslc}} + jX_{\mathrm{mslc}} = R_{\mathrm{mslc}} + R_{\mathrm{cm}} + j(X_{\mathrm{mslc}} + X_{\mathrm{cm}}) \\ &= 0.00844 + 0.2390 + j(0.003175 + 0.9257) \\ &= 0.2475 + j0.9289 \text{ pu} \end{aligned}$$

The total load on the MCC consists of the static load Z_{oll} (series components) in parallel with the cable and motor Z_{mnsc} (series components). The total impedance Z_{ols} is therefore:-

$$Z_{\mathrm{ols}} = R_{\mathrm{ols}} + jX_{\mathrm{ols}} = \frac{Z_{\mathrm{oll}} \times Z_{\mathrm{mslc}}}{Z_{\mathrm{oll}} + Z_{\mathrm{mnsc}}} = 0.3050 + j0.7874 \text{ pu}$$

The impedance seen at the SWBD for the cable, motor and MCC load is Z_{cs}:-

$$\begin{aligned} Z_{\mathrm{cs}} = Z_{\mathrm{ols}} + Z_{\mathrm{c}} &= 0.3050 + j0.7874 + 0.00635 + j0.05446 \\ &= 0.3114 + j0.8418 \text{ pu} \end{aligned}$$

This impedance is in parallel with that of the local load Z_{og} on the SWBD. The total equivalent load on SWBD is Z_{ogs} where:-

$$Z_{\mathrm{ogs}} = R_{\mathrm{ogs}} + jX_{\mathrm{ogs}} = \frac{Z_{\mathrm{ogl}} \times Z_{\mathrm{cs}}}{Z_{\mathrm{ogl}} + Z_{\mathrm{cs}}} = 0.3631 + j0.6375 \text{ pu}$$

Hence the total impedance seen by the generator emf E_{o} is Z_{gs}:-

$$\begin{aligned} Z_{\mathrm{ogs}} &= R_{\mathrm{g}} + R_{\mathrm{ogs}} + j(X_{\mathrm{g}} + X_{\mathrm{ogs}}) \\ &= 0.02 + 0.3631 + j(0.25 + 0.6375) \\ &= 0.3831 + j0.8875 \text{ pu} \end{aligned}$$

The current in the generator I_{gs} is:-

$$I_{\mathrm{gns}} = \frac{E_{\mathrm{o}}}{Z_{\mathrm{gs}}} = \frac{1.0687 - j0.1068}{0.5395 + j0.9713} = 0.5395 - j0.9713 \text{ pu}$$

Hence the terminal voltage of the generator V_{gs} is:-

$$V_{gs} = \frac{E_o Z_{ogs}}{Z_{gn}S} = \frac{(1.0687 + j0.1068)(0.3631 + j0.6375)}{0.3838 + j0.8892}$$

$$= 0.8151 - j0.0087 \text{ pu, which has a magnitude of } 0.8152 \text{ pu.}$$

Similarly the voltage of the MCC V_{ls} is:-

$$V_{ls} = \frac{V_{gs} Z_{ols}}{Z_{cn}S} = \frac{(0.8151 - j0.0087)(0.3050 + j0.7874)}{0.3114 + j0.8418}$$

$$= 0.7660 - j0.0199 \text{ pu, which has a magnitude of } 0.7669 \text{ pu.}$$

Similarly the motor voltage V_{ms} is:-

$$V_{ms} = \frac{V_{ls} Z_{msl}}{Z_{msl} + Z_{cm}} = \frac{(0.7660 - j0.0199)(0.2390 + j0.9257)}{0.2390 + j0.9257 + 0.00844 + j0.003175}$$

$$= 0.7626 - j0.0140 \text{ pu, which has a magnitude of } 0.7627 \text{ pu.}$$

n) Calculate the percentage volt-drops

The customary method of defining volt-drop is in percentage terms as follows:-

$$\text{Volt-drop in percent} = \frac{\text{No-load voltage} - \text{Loaded voltage}}{\text{No-load voltage}} \times 100\%$$

Where the no-load voltage is the service voltage that exists before the change in load is applied and the loaded voltage is the service voltage during the application of the change in load. For example, when a motor is being started there are two aspects to consider. Firstly, the situation at the motor terminals since this determines the ability of the motor to create enough torque during the starting period and, secondly, at the MCC since this influences the performance of existing loads and their contactor coils. Other parts in the power system could be examined in a similar manner, e.g. at the generator terminals and its switchboard. The motor example above may be used to illustrate these comments:-

- Motor terminal volt-drop in percent.

  No-load voltage = pre-disturbance voltage at the MCC.

  Loaded voltage = voltage at the motor terminals at starting or running of the motor.

$$\text{Volt-drop at starting\%} = \frac{V_{lo} - V_{ms}}{V_{lo}} \times 100\%$$

$$= \frac{0.9936 - 0.7627}{0.9936} \times 100\% = 23.24\%$$

$$\text{Volt-drop at running\%} = \frac{V_{slo} - V_{mn}}{V_{lo}} \times 100\%$$

$$= \frac{0.9936 - 0.9552}{0.9936} \times 100\% = 3.86\%$$

- MCC terminal voltage in percent.

  No-load voltage = pre-disturbance voltage at the MCC.

  Loaded voltage = voltage at the MCC at starting or running of the motor.

$$\begin{aligned}\text{Volt-drop at starting\%} &= \frac{V_{lo} - V_{ls}}{V_{lo}} \times 100\% \\ &= \frac{0.9936 - 0.7669}{0.9936} \times 100\% = 22.82\% \\ \text{Volt-drop at running\%} &= \frac{V_{lo} - V_{ln}}{V_{lo}} \times 100\% \\ &= \frac{0.9936 - 0.9570}{0.9936} \times 100\% = 3.68\%\end{aligned}$$

- Generator and SWBD terminal voltage in percent.

  No-load voltage = pre-disturbance voltage at the SWBD.

  Loaded voltage = voltage at the SWBD at starting or running of the motor.

$$\begin{aligned}\text{Volt-drop at starting\%} &= \frac{V_{go} - V_{gs}}{V_{go}} \times 100\% \\ &= \frac{1.0 - 0.8152}{1.0} \times 100\% = 18.48\% \\ \text{Volt-drop at running\%} &= \frac{V_{go} - V_{gn}}{V_{go}} \times 100\% \\ &= \frac{1.0 - 0.9695}{1.0} \times 100\% = 3.05\%\end{aligned}$$

o) Examine the actual volt-drops

Although the percentage volt-drops are now known, and they give an indication of the seriousness of the volt-drop by simple inspection, what is important as far as each piece of equipment is concerned is the actual voltage on its terminals in volts. This is especially important when the rated voltage of the equipment is different from the nominal operating value as in the above example. Consider each component.

- The motor.

  Rated voltage = 4000.0 volts
  Nominal operating system voltage = 4181.8 volts
  Starting voltage received = 4181.8 × 0.7627 volts
  = 3189.5 volts = 79.74% of the rated value
  Running voltage received = 4181.8 × 0.9552 volts
  = 3994.4 volts = 99.86% of the rated value

- The motor control centre.

  Rated voltage = 4160.0 volts
  Nominal operating system voltage = 4181.8 volts

Starting voltage at the busbars = 4181.8×0.7669 volts
= 3207.0 volts = 77.09% of the rated value
Running voltage at the busbars = 4181.8×0.9570 volts
= 4002.0 volts = 96.20% of the rated value

- The generator switchboard.

Rated voltage = 13800.0 volts
Nominal operating system voltage = 13800.0 volts
Starting voltage at the busbars = 13800.0×0.8152 volts
= 11249 volts = 81.52% of the rated value
Running voltage at the busbars = 13800.0×0.9695 volts
= 13379 volts = 96.95% of the rated value

The motor may have been specified for a starting voltage drop of 15% and a running voltage drop of 2.5%. In the example the voltage received by the motor during starting would be 79.74% and so the voltage drop of 20.26% would have been excessive. However, the running voltage drop would be 0.14% which is well within the specified value. The MCC could experience problems with its contactor coils during motor starting due to the voltage drop being too large. The contactors on existing energised circuits could fail to hold in once the busbar voltage drops below 75%. The actual voltage during starting of 77.09% would be just sufficient for reliable operation. The running voltage would be well within specification for a motor control centre, i.e. only 3.8% volt-drop. If the feeder transformer was fitted with a tap-changing device then the actual running voltage could be maintained at a value nearer to its nominal value. The generator switchboard volt-drop of 18.48% at starting is just about acceptable, but well within limits during the running situation.

p) Design comments

From the results it can be seen that direct-on-line starting of the motor is only just possible when only one generator is available. High volt-drops occur during the starting period. However, several corrective measures can be taken:-

- Recalculate the volt-drops for the cases where two and three generators are running before the motor is started direct-on-line. If the results are satisfactory then an operating restriction can be imposed that at least two generators should be running initially.
- Recalculate using a ‘reduced voltage’ starting method, e.g. a Korndorfer starter, and one running generator. In this case also add the impedance of the starting device to the impedance of the motor feeder cable, and account for any transformer voltage ratio that may be present.
- Reduce the transient reactance of the generators to say 0.15 per-unit and recalculate the results.
- Reduce the starting current to running current ratio of the motor to say four times and recalculate the results.
- Consider a combination of the above measures.

The calculation process is lengthy if attempted by manual methods and is best programmed in a small desktop computer that can handle complex numbers. Such a programming exercise is simple to achieve. In order to screen various alternative cases it is possible to make some valid simplifications in the proposed system and to use a simpler calculation method.

q) Simplified solution

In the proposed system, used as the example above, it is acceptable to ignore the cable impedance $R_{cm} + jX_{cm}$ and the transformer impedance $R_c + jX_c$ for approximate calculation purposes. This is only allowable for the following reasons:-

- The power system distribution cables or overhead lines are well rated for their current duty and are short in length.
- The series impedances for cables are usually small in comparison with the transient reactances and load impedances, but this is not always the case with low voltage situations where for example the route lengths of cables can be relatively long.

Figure G.3 shows a simplified form of Figure G.2, where Z_o is the equivalent impedance of Z_{ol} in parallel with Z_{og} and is calculated as follows:-

$$R_o = \frac{1}{\dfrac{1}{R_{ol}} + \dfrac{1}{R_{og}}} = 2.2321 \text{ pu}$$

$$X_o = \frac{1}{\dfrac{1}{X_{ol}} + \dfrac{1}{X_{og}}} = 4.1903 \text{ pu}$$

r) Initial conditions

The motor starter is open. The motor terminal V_{mo} equals the generator terminal V_{go} voltage, which is 1.0 per-unit.

Hence,

$$V_{mo} = V_{go} = 1.0 + j0.0 \text{ pu.}$$

Find the initial values of I_c and V_l, i.e. I_{co} and V_{lo}, noting that $I_m = 0.0$

At the MCC the parallel load is R_o in parallel with X_o.

Convert the parallel load into a series load of $R_{ol} + \text{j}\ X_{ol}$.

The conversions are:-

$$R_{ol} = \frac{R_o X_o^2}{R_o^2 + X_o^2} \text{ pu per phase}$$

$$X_{ol} = \frac{X_o R_o^2}{R_o^2 + X_o^2} \text{ pu per phase}$$

Where R_o and X_o were found above.

Hence

$$Z_{ol} = R_{ol} + jX_{ol} = 1.7388 + j0.9262 \text{ pu}$$

$$I_{oo} = I_{go} = \frac{V_{mo}}{Z_{ol}} = \frac{1.0 + j0.0}{1.7388 + j0.9262} = 0.448 - j0.2386 \text{ pu}$$

This compares well with I_{go} found in the rigorous case.

$$\begin{aligned} E_o &= V_{go} + I_{oo}Z_g = 1.0 + j0 + (0.448 - j0.2386)(0.02 + j0.25) \text{ pu} \\ &= 1.0686 + j0.1072 \text{ pu, which has a magnitude of } 1.0740 \text{ pu.} \end{aligned}$$

Which is within 0.01% of the rigorous case.

s) Running conditions

The motor starter is closed and the generator emf is 1.0740 per-unit.

The parallel impedance of the running motor is Z_{mn}:-

$$R_{mn} = 5.4324 \text{ and } X_{mn} = j10.065 \text{ pu}$$

The series impedance of the running motor is Z_{mnl}:-

$$Z_{mnl} = R_{mnl} + jX_{mnl} = 4.2069 + j2.2706 \text{ pu}$$

The total load resistance on the SWBD is R_{ln} where:-

$$R_{ln} = \frac{R_o \times R_{mn}}{R_o + R_{mn}} = 1.5821 \text{ pu}$$

The total load reactance on the SWBD is X_{ln} where:-

$$X_{ln} = \frac{X_o \times X_{mn}}{X_o + X_{mn}} = 2.9586 \text{ pu}$$

The series equivalent resistance is R_{ogn}:-

$$R_{ogn} = \frac{2.9586 \times 2.9586 \times 1.5821}{2.9586^2 + 1.5821^2} = 1.2303 \text{ pu}$$

The series equivalent reactance is X_{ogn}:-

$$X_{ogn} = \frac{2.9586 \times 1.5821 \times 1.5821}{2.9586^2 + 1.5821^2} = 0.6579 \text{ pu}$$

The total impedance seen by the generator emf E_o is Z_{gn}:-

$$\begin{aligned} Z_{gn} &= R_g + R_{ogn} + j(X_g + X_{ogn}) \\ &= 0.02 + 1.2303 + j(0.25 + 0.6579) \\ &= 1.2503 + j0.9079 \text{ pu} \end{aligned}$$

The current in the generator I_{gn} is:-

$$\begin{aligned} I_{gn} = E_o &= \frac{(1.0686 - j0.1072)(1.2503 - j0.9079)}{2.3875} \\ &= 0.6004 - j0.3502 \text{ pu} \end{aligned}$$

Hence the terminal voltage of the generator V_{gn} is:-

$$V_{gn} = \frac{E_o Z_{ogn}}{Z_{gn}}$$
$$= 0.9691 - j0.0359 \text{ pu, which has a magnitude of } 0.9697 \text{ pu.}$$

t) Starting conditions

The motor starter is closed. Repeat the procedure as for s) but use the motor starting impedance, and using the suffix '*s*' for starting.

The parallel impedance of the running motor is Z_{mn}:-

$$R_{ms} = 3.8244 \text{ and } X_{ms} = j0.9875 \text{ pu}$$

The total load resistance on the SWBD is R_{ls} where:-

$$R_{ls} = \frac{R_o \times R_{ms}}{R_o + R_{ms}} = 1.4095 \text{ pu}$$

The total load reactance on the SWBD is X_{ls} where:-

$$X_{ls} = \frac{X_o \times X_{ms}}{X_o + X_{ms}} = 0.7991 \text{ pu}$$

The series equivalent resistance is R_{ogs}:-

$$R_{ogs} = \frac{0.7991 \times 0.7991 \times 1.4095}{0.7991^2 + 1.4095^2} = 0.3429 \text{ pu}$$

The series equivalent reactance is X_{ogs}:-

$$X_{ogs} = \frac{0.7991 \times 1.4095 \times 1.4095}{0.7991^2 + 1.4095^2} = 0.6047 \text{ pu}$$

The total impedance seen by the generator emf E_o is Z_{gs}:-

$$\begin{aligned} Z_{gs} &= R_g + R_{ogs} + j(X_g + X_{ogs}) \\ &= 0.02 + 0.3429 + j(0.25 + 0.6047) \\ &= 0.3629 + j0.8547 \text{ pu} \end{aligned}$$

The current in the generator I_{gs} is:-

$$\begin{aligned} I_{gns} = E_o &= \frac{(1.0686 - j0.1072)(0.3629 - j0.8547)}{0.8622} \\ &= 0.5560 - j1.0142 \text{ pu} \end{aligned}$$

Hence the terminal voltage of the generator V_{gs} is:-

$$\begin{aligned} V_{gs} &= I_{gs} Z_{ogs} \\ &= 0.8040 - j0.0115 \text{ pu, which has a magnitude of } 0.8040 \text{ pu.} \end{aligned}$$

This is nearly equal to V_{ms}.

The voltage V_{gs} is within 1.5% of the rigorous case but too optimistic for the motor voltage. However, most of the volt-drop is due to the generator impedance in either case and so once some cases have been screened in this way then the more accurate method may be applied to the serious cases. Since the result is optimistic it therefore requires a safety margin of 2% to 5% to be added when this method is used. The percentage volt-drops can be calculated as follows:-

- Generator and motor terminal volt-drop in percent.

$$\begin{aligned} \text{Volt-drop at starting\%} &= \frac{V_{mo} - V_{ms}}{V_{mo}} \times 100\% \\ &= \frac{1.0 - 0.8040}{1.0} \times 100\% = 19.6\% \end{aligned}$$

which is about 4% better than the rigorous case.

u) Formular method based on kVA rating

The simplification of the power system can be generalised by using a formular method. The simplified system can be represented by Figure G.3, where:-

Z_g is the source impedance, e.g. generator transient reactance.
Z_m is the motor impedance (Z_{mr} for running and Z_{ms} for starting).
Z_l is the standing load impedance, Z_o in Figure G.3.

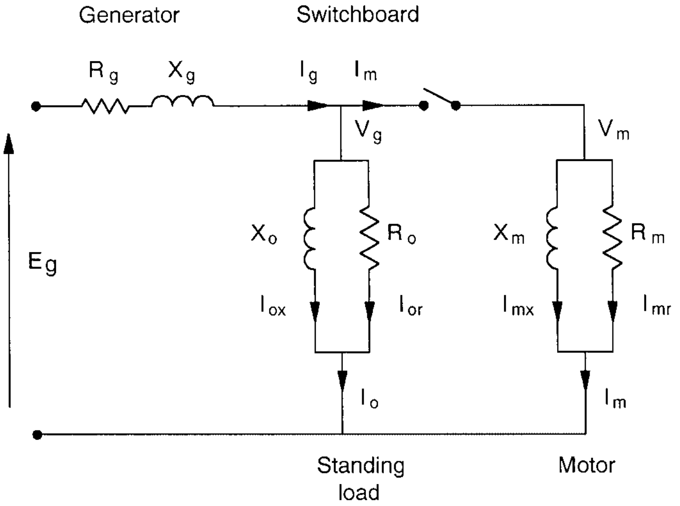

Figure G.3 Reduced equivalent circuit for calculating the volt-drop in a 500 kW HV motor.

All the impedances are in their complex form $R + jX$.

The simplifications made in t) have been applied viz:-

- Cable impedances have been ignored.
- Transformer impedances have been ignored.
- All the standing loads are grouped at the generator terminals.

The initial conditions are easily calculated. The terminal voltage V_o is known and assumed to be $1.0 + j0.0$ per unit. The motor starter is open. The initial circuit consists of Z_l in series with Z_g and is fed by E_o. The initial load current I_l is I_{lo}.

$$I_{lo} = \frac{V_o}{Z_l} \text{ and } E_o = V_o + I_{lo}$$

Therefore it consists of Z_l in series with Z_g and is fed by E_o. The initial load current I_l is I_{lo}.

$$E_o = V_o\left(1 + \frac{V_o}{Z_l}\right)$$

The general case for the running conditions are also easily calculated. The motor starter is closed. The motor and load impedance are then connected in parallel. The total of these impedances is Z_{lm} in series with Z_g and is fed by E_o. The initial load current I_l where:-

$$Z_{lm} = \frac{Z_l Z_m}{Z_l + Z_m}$$

and

$$\begin{aligned} V &= \frac{E_o Z_{lm}}{Z_{lm} + Z_g} \\ &= \frac{V_o(1 + Z_g)Z_{lm}}{Z_l(Z_{lm} + Z_g)} \end{aligned}$$

Let

$$a = (Z_l + Z_g)Z_{lm}$$

and

$$b = (Z_{lm} + Z_g)Z_l$$

Therefore

$$V = \frac{aV_o}{b}$$

$$\text{The Percentage volt-drop} \Delta V = \left(\frac{V_o - V}{V}\right) \times 100\%$$

$$\Delta V = \left(V_o - \frac{aV_o}{b}\right) \times 100\%$$

Note that

$$\frac{a}{b}V_o = \frac{Z_g(Z_l - Z_{lm})}{(Z_l + Z_g)Z_{lm}}$$

Substitute for

$$Z_{lm} = \frac{Z_l Z_m}{Z_l + Z_m}$$

Hence,

$$\frac{Z_l - Z_{lm}}{Z_l + Z_m} = \frac{Z_l}{Z_m}$$

The percentage volt-drop

$$\Delta V = \left(\frac{Z_g Z_l}{(Z_l + Z_g)Z_m}\right) \times 100\%$$

The volt-drop ΔV is only of interest in its magnitude.

Therefore

$$|\Delta V| = \frac{|Z_g||Z_l|}{|Z_l + Z_g||Z_m|} \times 100\%$$

Which makes the calculation of volt-drop much easier. However, all these impedances must be correctly reduced to the common system base as follows. It can be shown that the actual parameters may be easily converted to their per-unit system base parameters. The motor, load and generator impedances can be represented in terms of their kVA, or MVA, and voltage bases.

$$Z_g = \frac{Z_{gen} S_{base} V_{gen} V_{gen}}{S_{gen} V_{gbase}{}^2} \quad \text{pu}$$

$$Z_m = \frac{S_{base} V_{motor} V_{motor}}{S_{motor} V_{mbase}{}^2} \quad \text{pu}$$

$$Z_l = \frac{S_{base}}{S_{load}} \quad \text{pu}$$

Where V_{gbase} is the system base voltage at the generator, e.g. 13 800 volts in the example.

V_{mbase} is the system base voltage at the motor or MCC, e.g. 4181.8 volts in the example.

V_{gbase}, V_{mbase}, S_{base}, V_{gen} and V_{motor} are real or scalar numbers.

Z_{gen}, S_{gen}, S_{motor} and S_{load} are complex numbers and S_{motor} has to be chosen for the starting or running case.

Example. Consider the data used for the rigorous case for starting the motor.

$$Z_g = 0.02 + j0.25 \text{ and so } |Z_g| = 0.2508 \text{ pu}$$

$$Z_l = Z_{ol} = 1.7388 + j0.9262 \text{ and so } |Z_g| = 1.9701 \text{ pu}$$

$$Z_{lm} = Z_{ml} = 0.2391 + j0.9259 \text{ and so } |Z_g| = 0.9563 \text{ pu}$$

$$Z_l + Z_g = 1.7588 + j1.1762 \text{ and so } |Z_l + Z_g| = 2.1158 \text{ pu}$$

Therefore

$$|\Delta V| = \frac{0.2508 \times 1.9701}{2.1158 \times 0.9563} \times 100 = 24.42\%$$

Which compares pessimistically with the simple case (19.6%) but closely with the rigorous case (23.24 %).

v) Graphical estimation

This sub-section develops a simple graphical method for quickly estimating volt-drops for direct-on-line starting situations. The following data forms the basis of the graphical results:

- The generator data.

$$Z_g = 0.1, 0.15, 0.2, 0.25 \text{ and } 0.3 \text{ pu}$$

$$R_g = 0.0 \text{ pu}$$

$$S_{base} = S_{gen} = 10,000 \text{ kVA}$$

$$\text{Rated power factor} = 0.8 \text{ lagging}$$

- The standing load data.

$$\text{Rated power factor} = 0.9 \text{ lagging}$$

$$\text{Load} = 0.0, 50.0 \text{ and } 80.0\% \text{ of } S_{gen}$$

$$|Z_l| = 1.25, 2.0 \text{ and infinity (no-load) pu}$$

Where

$$\begin{aligned} Z_l &= 1.25(0.9 + j0.436) \text{ for } 80\% \text{ load} \\ &= 2.00(0.9 + j0.436) \text{ for } 50\% \text{ load} \\ &= \infty(0.9 + j0.436) \text{ for } 0\% \text{ load} \end{aligned}$$

- Motor data.

Table G.1 shows the appropriate data for a range of four-pole high voltage motors.

Example. Consider a 630 kW motor and a 80% standing load.

$$|Z_g| = 0.25 \text{ pu}$$

$$|Z_m| = 0.1713 \times \frac{0.2508}{747.81} = 2.2907 \text{ pu}$$

$$Z_l = 1.25(0.9 + j0.436) = |1.25| \text{ pu}$$

$$|Z_l + Z_g| = |j0.25 + 1.25(0.9 + j0.436)| = |1.457| \text{ pu}$$

Therefore

$$|\Delta V| = \frac{0.25 \times 1.25}{1.457 \times 2.2907} \times 100 = 9.363\%$$

Table G.1. Motor data for graphical estimation of volt-drop

Motor rating (kW)	Efficiency (per-unit)	Power factor at full load	kVA rating at full load	I_s/I_n ratio	Power factor at starting	kVA at starting	Z_{ms} at starting per-unit
315	0.9455	0.8603	387.2	6.787	0.217	2628.3	0.1473
430	0.9537	0.8715	517.4	6.445	0.219	3334.3	0.1552
630	0.9595	0.8780	747.8	5.838	0.208	4365.6	0.1713
720	0.9608	0.8788	852.6	5.619	0.202	4790.9	0.1780
800	0.9617	0.8791	946.3	5.453	0.196	5158.6	0.1834
1,100	0.9638	0.8780	1299.8	5.000	0.179	6498.5	0.2000
1,500	0.9654	0.8756	1774.4	4.661	0.162	8270.0	0.2145
2,500	0.9680	0.8722	2961.0	4.347	0.137	12,872	0.2300
5,000	0.9717	0.8742	5886.6	4.397	0.111	25,883	0.2274
6,300	0.9726	0.8763	7392.3	4.527	0.104	33,461	0.2209
8,000	0.9730	0.8786	9358.1	4.712	0.096	44,093	0.2122
11,000	0.9727	0.8806	12,843	5.017	0.086	64,440	0.1993

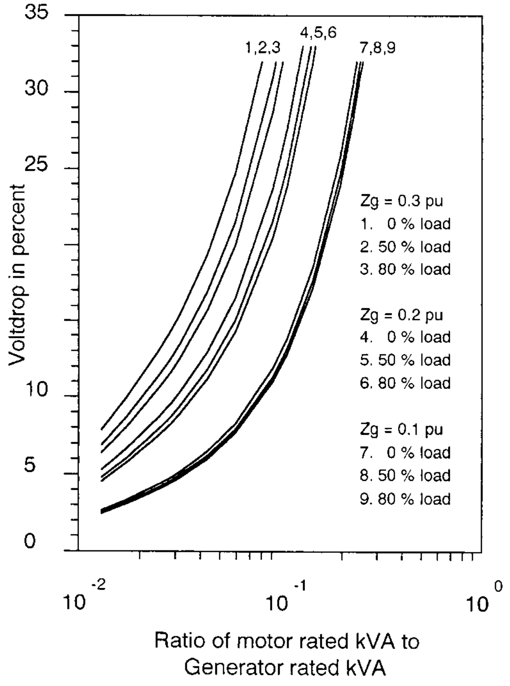

Figure G.4 Volt-drop when starting an induction motor. Volt-drop in per-unit versus the ratio of the motor kVA rating to the generation kVA capacity, for different values of generator per transient impedance Z_g and standing load.

Figure G.4 shows the results of all the cases given in Table G.1. The volt-drop $|\Delta V|$ is plotted against the ratio $S_{\text{motor}}/S_{\text{gen}}$ so that a generalised presentation may be used. Note that these graphs can be used for most cases where generators up to about 30 MVA are present. Extrapolations can be used with confidence for generators above 30 MVA which have transient

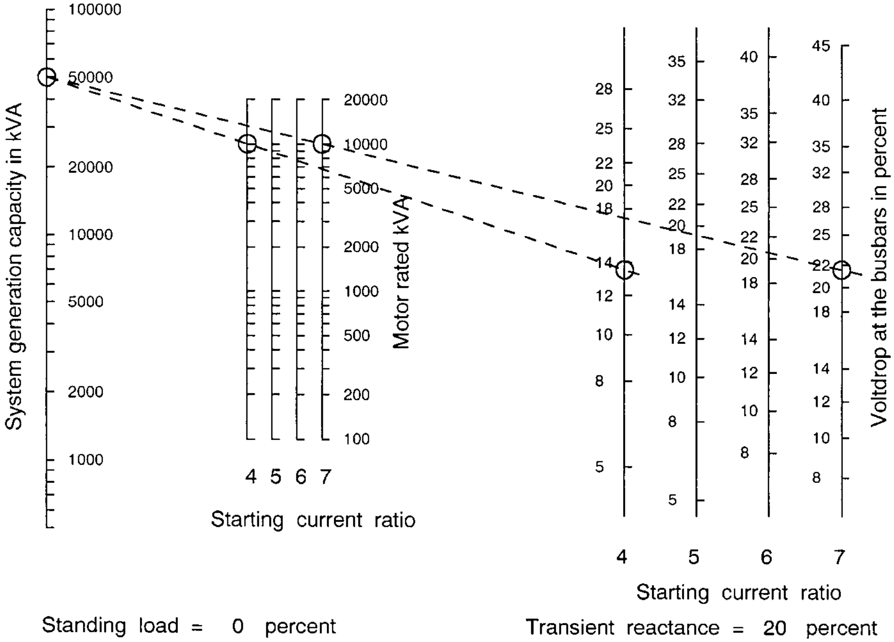

Figure G.5 Volt-drop when starting an induction motor. Nomograph for the volt-drop in per-unit versus the ratio of the motor kVA rating to the generation kVA capacity, for a generator transient impedance Z_g of 0.2 pu and zero standing load. The motor can have different ratios of starting current to running current.

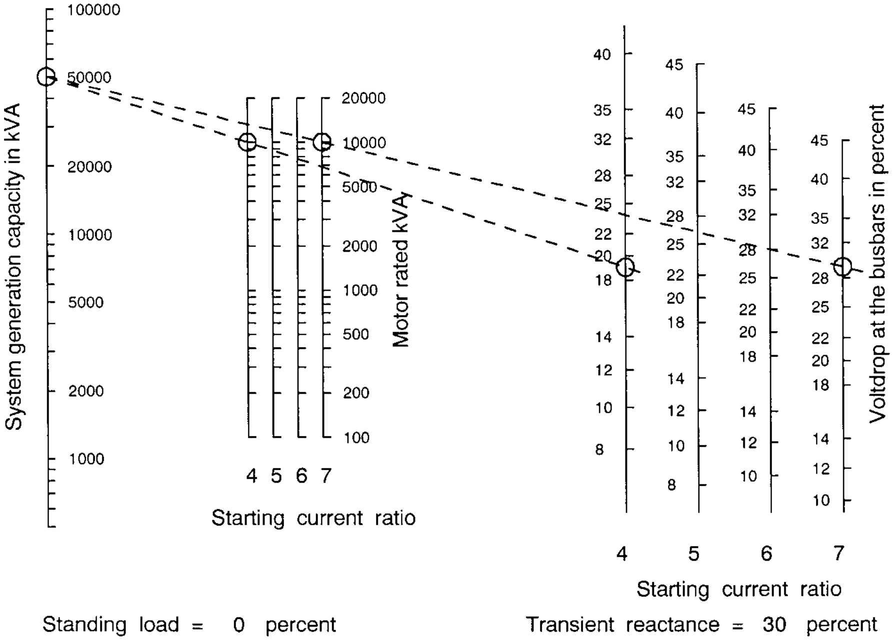

Figure G.6 Volt-drop when starting an induction motor. Nomograph for the volt-drop in per-unit versus the ratio of the motor kVA rating to the generation kVA capacity, for a generator transient impedance Z_g of 0.3 pu and zero standing load. The motor can have different ratios of starting current to running current.

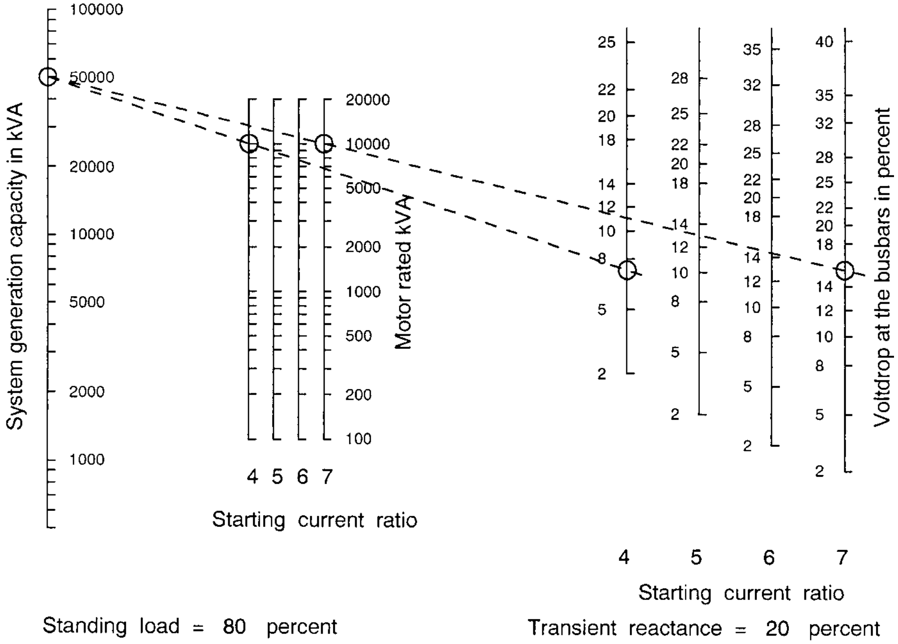

Figure G.7 Volt-drop when starting an induction motor. Nomograph for the volt-drop in per-unit versus the ratio of the motor kVA rating to the generation kVA capacity, for a generator transient impedance Z_g of 0.2 pu and 0.8 pu standing load. The motor can have different ratios of starting current to running current.

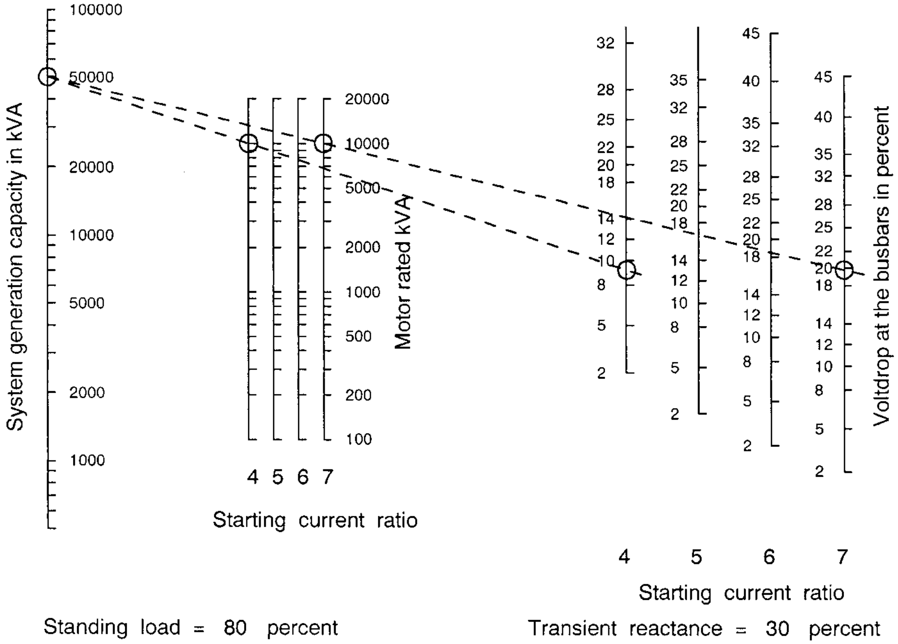

Figure G.8 Volt-drop when starting an induction. Nomograph for the volt-drop in per-unit versus the ratio of the motor kVA rating to the generation kVA capacity, for a generator transient impedance Z_g of 0.3 pu and 0.8 pu standing load. The motor can have different ratios of starting current to running current.

reactances between 15% and 25%, and for motors up to about 15 MW. The main parameter of the motor is the starting-to-running current ratio, which should not fall below 4 for the extrapolation to be valid.

The results can be represented in a more comprehensive manner by using a nomograph, as shown in Figures G.5, 6, 7 and 8. Each nomograph caters for four different starting-to running current ratios, i.e. 4, 5, 6 and 7. References 1 and 2 describe how to draw a nomograph.

REFERENCES

1. Alexander S. Levens, Nomographs. John Wiley & Sons (1948 and 1959). Library of Congress Card No. 59-11819.
2. S. Brodetsky, A first course in nomography. G. Bell and Sons Ltd (reprinted 1938).

Appendix H

Worked Example for the Calculation of Earthing Current and Electric Shock Hazard Potential Difference in a Rod and Grid Earthing System

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H.1 WORKED EXAMPLE

A 33 kV overhead line terminates at a pole in a small switching station. The distance to the pole from the source is 15 km, but of course there are many other poles along the route. The subject pole is earthed at its footings.

The overhead line ohmic data are:-

$$\text{Positive sequence impedance } Z_{1\text{pkm}} = 0.35 + j0.4 \text{ ohms/km.}$$

$$\text{Negative sequence impedance } Z_{2\text{pkm}} = 0.35 + j0.4 \text{ ohms/km.}$$

$$\text{Zero sequence impedance } Z_{0\text{pkm}} = 0.7 + j1.5 \text{ ohms/km.}$$

The sending end of the line has a 100 MVA transformer that has the following ohmic data:-

$$\text{Positive sequence impedance } Z_{1t} = 0.1084 + j1.084 \text{ ohms/phase.}$$

$$\text{Negative sequence impedance } Z_{2t} = Z_{1t} \text{ ohms/phase.}$$

$$\text{Zero sequence impedance } Z_{0t} = Z_{1t} \text{ ohms/phase.}$$

It will be assumed that the source impedance Z_s feeding the transformers is small enough to be neglected. To illustrate the difficulty in finding a suitably low resistance to earth it will be assumed that the secondary winding of the transformer is solidly earthed and hence the NER resistance R_n is zero, a non-zero value will be recommended at the conclusion of the calculations. However, it will be assumed that the resistance to earth R_{en} at the source transformer is 1.5 ohms. The resistance to earth at the far end pole is R_{ep}, which needs to be determined. This requires a suitable grid and rod system to be chosen. The calculation process will be carried out in a series of steps.

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

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Step 1. Find the total positive, negative and zero sequence impedances in the circuit.

The total positive sequence impedance Z_1 is:-

$$\begin{aligned} Z_1 &= 15.0(0.35 + j0.4) + 0.1084 + j1.084 \\ &= 5.3584 + j7.084 \text{ ohms} \end{aligned}$$

The total negative sequence impedance Z_2 is:-

$$Z_2 = Z_1 = 5.3584 + j7.084 \text{ ohms}$$

The total zero sequence impedance Z_0 is:-

$$\begin{aligned} Z_0 &= \frac{15.0 Z_{0\text{pkm}}(R_{\text{en}} + R_{\text{ep}})}{(15.0 \times Z_{0\text{pkm}}) + R_{\text{en}} + R_{\text{ep}}} + Z_{0p} + Z_{0t} \\ &= \frac{(10.5 + j22.5)(1.5 + R_{\text{ep}})}{12.0 + R_{\text{ep}} + j22.5} + 10.6084 + j23.584 \end{aligned} \tag{H.1.1}$$

Hence Z_0 is a function of R_{ep}.

In this worked example the zero sequence impedance includes the impedance of the over-head earthing conductor as a simple conductor spanning the 15 km route length. In practice the intermediate poles will be earthed at their own footings and also bonded to the over-head earthing conductor. These bonding connections will form a type of ‘ladder’ network that involves the resistance to earth at each pole. The effect of this may be to reduce the amount of current entering the ground at the far end pole, i.e. the subject of these calculations. Table H.1a would then contain different values of currents.

Step 2. Find the total root-mean-square fault current.

The total root-mean-square fault current I_f is:-

$$I_f = 3I_0 = \frac{3V_p}{3R_f + Z_1 + Z_2 + Z_0} \tag{H.1.2}$$

Where I_0 = the symmetrical rms zero sequence current.
V_p = the phase-to-neutral driving voltage at the source.
R_f = the resistance of the fault itself, assumed to be zero.
Z_1 = the total positive sequence impedance.
Z_2 = the total negative sequence impedance.
Z_0 = the total zero sequence impedance.

Therefore inserting the numerical data gives,

$R_1 = 5.3584$ ohms, $X_1 = 7.084$ ohms,

$R_2 = 5.3584$ ohms, $X_2 = 7.084$ ohms,

R_0 = real part of Z_0, X_0 = imaginary part of Z_0.

$V_p = 33{,}000/\sqrt{3} = 19{,}053$ volts/phase.

Table H.1a. Earth fault current as a function of earth resistance

Earth resistance (ohms)	Earth fault current (amps)	Proportion of current diverted to the		X-to-R ratio (pu)
		O/H line (pu)	Pole (pu)	
0.25	1314.73	0.0683	0.9692	1.6023
0.50	1310.23	0.0777	0.9647	1.5876
0.75	1305.70	0.0870	0.9601	1.5736
1.00	1301.13	0.0962	0.9555	1.5602
1.25	1296.54	0.1053	0.9509	1.5474
1.50	1201.92	0.1143	0.9463	1.5351
1.75	1287.30	0.1233	0.9416	1.5233
2.00	1282.66	0.1321	0.9370	1.5121
4.00	1245.83	0.1992	0.8993	1.4383
6.00	1210.65	0.2603	0.8617	1.3874
8.00	1178.15	0.3156	0.8248	1.3532
10.0	1148.73	0.3654	0.7890	1.3311
15.0	1088.41	0.4695	0.7065	1.3094
20.0	1043.88	0.5496	0.6347	1.3141
25.0	1010.86	0.6120	0.5734	1.3307
30.0	985.98	0.6611	0.5211	1.3523
35.0	966.84	0.7005	0.4754	1.3754
40.0	951.83	0.7325	0.4382	1.3985
50.0	930.11	0.7808	0.3765	1.4417
60.0	915.38	0.8153	0.3292	1.4794
70.0	904.88	0.8409	0.2920	1.5120
80.0	897.07	0.8605	0.2622	1.5399
90.0	891.08	0.8760	0.2377	1.5640
100.0	886.36	0.8885	0.2173	1.5850

Note 1. These are in relation to the magnitude of the total current, since both currents are complex quantities having different phase angles.

Table H.1a shows the value of I_f for different values of R_{ep}. It also shows the division of current between the overhead line earthing conductor and the footings of the pole.

Table H.1b shows the 'doubling factor', the peak factor and the power factor of currents that flow in an inductive circuit that has different X-to-R or R-to-X factors.

A small site may be constrained by a number of factors. Assume the site is located in a region of high resistivity with a low water table. The constraints on the design are:-

- The surface resistivity is higher than that of the lower soil.
- A grid with earthing rods attached will be needed.
- Use a rod diameter no less than 0.01 m.
- Allow the rods to be driven deep into the ground.
- Use the least site area as possible, i.e. 30 to 256 m^2.
- Let the overhead earthing conductor divert some of the fault current.

Table H.1b. Properties of the fault current for different X-to-R ratios

X-to-R ratio (pu)	R-to-X ratio (pu)	Doubling factor (pu)	Peak factor (pu)	Power factor (pu)
0.1	10.0000	1.0000	1.4142	0.9950
0.2	5.0000	1.0000	1.4142	0.9806
0.3	3.3333	1.0000	1.4143	0.9578
0.4	2.5000	1.0004	1.4148	0.9285
0.5	2.0000	1.0019	1.4169	0.8944
0.6	1.6667	1.0053	1.4217	0.8575
0.7	1.4286	1.0112	1.4301	0.8192
0.8	1.2500	1.0197	1.4421	0.7809
0.9	1.1111	1.0305	1.4573	0.7433
1.0	1.0000	1.0432	1.4753	0.7071
1.1	0.9091	1.0575	1.4955	0.6727
1.2	0.8333	1.0729	1.5174	0.6402
1.3	0.7692	1.0892	1.5404	0.6097
1.4	0.7143	1.1060	1.5642	0.5812
1.5	0.6667	1.1231	1.5884	0.5547
1.6	0.6250	1.1404	1.6127	0.5300
1.7	0.5882	1.1576	1.6370	0.5070
1.8	0.5556	1.1746	1.6611	0.4856
1.9	0.5263	1.1914	1.6859	0.4657
2.0	0.5000	1.2079	1.7082	0.4472
3.0	0.3333	1.3509	1.9105	0.3162
4.0	0.2500	1.4559	2.0590	0.2425
5.0	0.2000	1.5335	2.1687	0.1961
6.0	0.1667	1.5924	2.2520	0.1644
7.0	0.1429	1.6384	2.3170	0.1414
8.0	0.1250	1.6752	2.3691	0.1240
9.0	0.1111	1.7053	2.4117	0.1104
10.0	0.1000	1.7304	2.4472	0.0995
15.0	0.0667	1.8110	2.5612	0.0665
20.0	0.0500	1.8546	2.6229	0.0499
25.0	0.0400	1.8819	2.6614	0.0400
30.0	0.0333	1.9006	2.6878	0.0333
35.0	0.0286	1.9142	2.7070	0.0286
40.0	0.0250	1.9245	2.7216	0.0250
45.0	0.0222	1.9326	2.7331	0.0222
50.0	0.0200	1.9391	2.7423	0.0200
100.0	0.0100	1.9691	2.7847	0.0100
200.0	0.0050	1.9844	2.8064	0.0050
300.0	0.0033	1.9896	2.8137	0.0033
400.0	0.0025	1.9922	2.8174	0.0025
500.0	0.0020	1.9937	2.8196	0.0020

- Use the method described in IEEE80 sub-section 14.4 even though it is more applicable to much larger sites, but include the earthing rods.
- If possible limit the maximum resistance to earth at the site to 5 ohms.

Step 3. Find the resistance R_{ep} at the pole.

The following calculations are based on the methods given in IEEE80 Appendix C. The same symbols and notation are generally used to avoid confusion with the reference. The design data and constraints are:-

- Fault duration $t_s = 0.5$ sec
- Resistivity of lower layer $\rho = 100$ to 1000 ohm-m
- Resistivity of upper layer $\rho_s = 1000$ to 5000 ohm-m
- Thickness of upper layer $h_s = 0.2$ and 1.0 m
- Depth of burial of grid $h = 0.5$ and 1.0 m
- Site area $A = 36$ to 256 m^2
- Diameter of rods $d_r = 0.02$ and 0.2 m
- Depth of each rod $l_r = 10$ and 50 m
- Number of meshes in each side of the grid $N_{\text{mesh}} = 3$ to 8
- Spacing between the mesh nodes $d_{\text{sp}} = 2.0$ m

The results of the calculations are shown in Table H.1c; Case C.3 is used for the worked example. In this case the following additional information was used:-

- Number of outer peripheral rods $N_{\text{rod1}} = 4$
- Number of inner rods $N_{\text{rod2}} = 0$
- Number of rods on each side of grid $N = 2$
- Diameter of grid conductors $d_m = 0.01$ m

Calculate the resistivity derating factor $C_s\{h_s, K\}$ from (13.3), in which $u_s = \surd(1 + (2\ \mathrm{mh}_s/0.08)^2)$. The number of terms m is taken to be 25 in order to obtain good convergence of the factor. The reflection factor K is found from ρ and ρ_s to be -0.6667 per-unit. $C_s\{h_s, K\}$ is found to be 0.8338 for this example.

The approximate grid resistance R_{epo} without the earthing rods can be found from Figure H.1a, which was derived from Figure B.1 of IEEE80 but applicable to small sizes of the mesh R_{epo}, is approximately:-

$$R_{\text{epo}} = \frac{\rho 51.94}{1000} = 51.94 \text{ ohms},$$

which is too high and indicates the need for rods.

At this stage the 50 kg step and touch voltages can be calculated from $C_s\{h_s, K\}$, since ρ_s and t_s are constants. The step voltage E_{step50} is: -

$$E_{\text{step50}} = \frac{(1000 + 6C_s\rho_s)\ 0.116}{\surd t_s} = 4267 \text{ volts}.$$

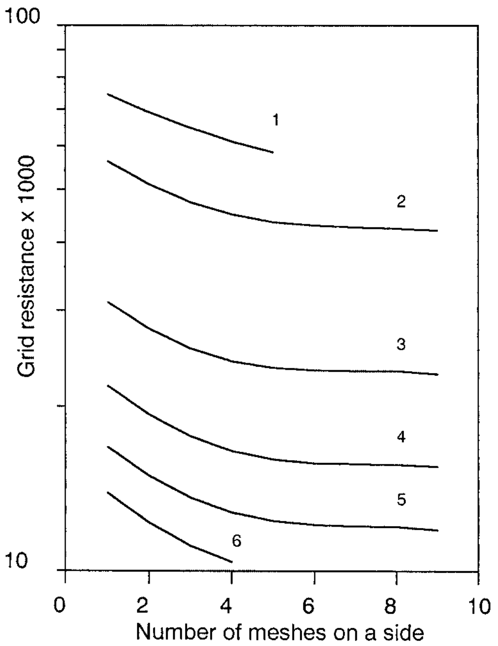

Figure H.1a Grid resistance versus the number of meshes on a side of a grid.

Similarly the touch voltage E_{touch50} is:-

$$E_{\text{touch50}} = \frac{(1000 + 1.5C_s\rho_s)\ 0.116}{\sqrt{t_s}} = 1190 \text{ volts.}$$

These two equations apply as criteria whether or not earthing rods are used. At this stage the magnitude of the portion of the fault current I_f entering the ground has not been used in the equations for voltages. It is necessary to calculate the corner mesh voltage E_m, which is given by equation 71 in IEEE80,

$$E_m = \frac{\rho_s I_g K_s K_i}{L} = 1854 \text{ volts.}$$

after solving equations 68 and 69 for K_m and K_i. However, K_m is also dependent on the current flowing into the ground, I_{fe}, and so the resistance to earth for the grid and rods must first be calculated. The corner mesh potential can also be found Figure H.1b, which was again derived from Figure B.2 of IEEE80.

Calculate the constants K_1 and K_2 that relate to the geometries of the grid and rods. They can be found from Figures 18(a) and 18(b) in IEEE 80. However, for the cases considered their approximate values are $K_1 = 1.15$ and $K_2 = 4.75$. The apparent resistivity ρ_a found from equation 46 in IEEE80 for the cases considered:-

$$\rho_a = \frac{l_r \rho \rho_s}{\rho(h_s - h) + \rho_s(l_r + h - h_r)} = 995.22 \text{ ohm-m.}$$

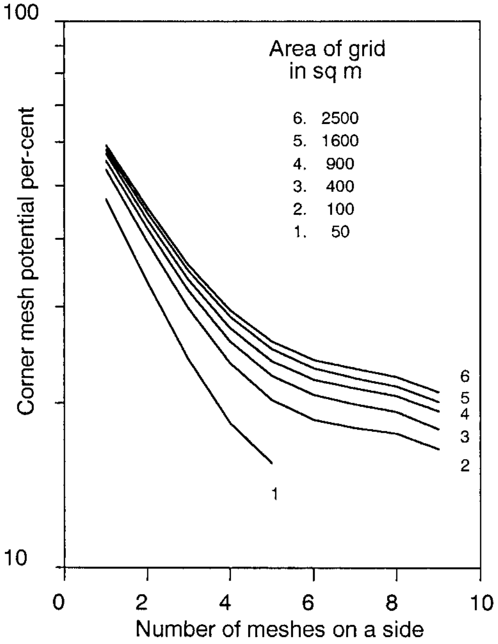

Figure H.1b Corner mesh potential versus the number of meshes.

If ρ_a is calculated to be close to ρ then take ρ_a to equal ρ as a conservative estimate, therefore $\rho_a = 1000$ for this example.

Now find the total amount of material to be used in the grid and rods.

The total length L_r of the ground rods is:-

$$L_r = (N_{\text{rod1}} + N_{\text{rod2}})l_r = 200 \text{ m}$$

Note, let the total number of rods be N_{rod} which equals $N_{\text{rod1}} + N_{\text{rod2}}$.

The total length L_g of the grid conductors is:-

$$L_g = 2nl_{\text{grid}} = 120 \text{ m}$$

Where $l_{\text{grid}} = (n - 1)d_{\text{sp}}$ is the buried length of one side of the grid, which is 10 m. The integer 'n' is the number of nodes on one side of the grid, or the number of meshes in one side plus 1.

The total length of buried rods and grid conductors including bonding connections is the weighted total L_c:-

$$L_c = L_g + 1.15L_r = 350 \text{ m}$$

Having now obtained the lengths of rods and grid conductors it is now possible to calculate the ground resistance R_{ep} using equations 41, 42, 43, 44 and 46 from sub-section 12.3 of IEEE80.

The following auxiliary equations are introduced to simplify the work involved:-

$$
\begin{aligned}
U_{11} &= \frac{\rho_s}{\pi L_g} &&= 13.263 \\
h_d &= \sqrt{(d_m h)} &&= 0.0707 \\
U_{12} &= \log_e(2L_g/h_d) &&= 8.13 \\
U_{13} &= \frac{K_1 L_g}{A^{0.5}} &&= 13.8 \\
U_{21} &= \frac{\rho_a}{2\pi n l_r} &&= 0.531 \\
U_{22} &= \log_e(8l_r/d_r) &&= 9.903 \\
U_{23} &= \frac{2K_1 l_r}{A^{0.5}} &&= 11.5 \\
U_{24} &= (n^{0.5} - 1)^2 &&= 2.101 \\
U_{31} &= \frac{\rho_a}{\pi L_g} &&= 2.653 \\
U_{32} &= \log_e(2L_g/l_r) &&= 1.569
\end{aligned}
$$

Where L_g = total length of the grid conductors
l_r = average length of a buried rod, but in this example all the rods are the same length
h_d = weighted depth of the grid

Let

R_{11} = resistance of the grid conductors
R_{22} = resistance of all the ground rods
R_{12} = mutual resistance between the whole grid and all the rods

From equations 42, 43 and 44 from IEEE80, these resistances are: -

$$
\begin{aligned}
R_{11} &= U_{11}(U_{12} + U_{13} - K_2) &&= 227.86 \text{ ohms} \\
R_{22} &= U_{21}(U_{22} - 1 + (U_{23}U_{24})) &&= 17.541 \text{ ohms} \\
R_{12} &= U_{31}(U_{32} + U_{13} - K_2 + 1) &&= 30.82 \text{ ohms}
\end{aligned}
$$

From equation 41, for both the grid and the rods R_{ep} becomes:-

$$
R_{\mathrm{ep}} = \frac{R_1 R_2 - {R_{12}}^2}{R_1 + R_2 - 2R_{12}} = 16.582 \text{ ohms}
$$

Find the corner mesh voltage data.

Calculate the constants K_h, K_{ii} and K_m for use in equation 68 from IEEE80.

$$K_h = (1 + h)^{0.5} = 1.2247$$

Use the following auxiliary equations to simplify the work:-

$$U_1 = \frac{{d_{\text{sp}}}^2}{16hd_m} = 50.0$$

$$U_2 = \frac{(d_{\text{sp}} + 2h)^2}{8d_{\text{sp}}d_m} = 56.25$$

$$U_3 = \frac{h}{4d_m} = 12.5$$

$$U_4 = \frac{8}{\pi(2n - 1)} = 0.2315$$

$$U_5 = \frac{K_{ii}}{K_h} = 0.8165$$

Where K_{ii} in this example is 1.

$$K_m = \frac{\log_e(U_1 + U_2 - U_3) + U_5 \log_e(U_4)}{2\pi} = 0.5325$$

Also from the explanation in sub-section 14.5.1 in IEEE80 the correction factor K_i is required, which is:-

$$K_i = 0.656 + 0.172N_n = 1.688$$

Where, N_n = 6 – number of parallel conductors in each direction of the grid, which equals the number of nodes on each side of the grid.
K_h = 1.2247 – correction factor for the depth of the grid.
K_{ii} = 1.0 – correction factor if the rods are placed inside the grid area.
K_m = 0.5325 – spacing factor for the mesh voltage.
K_i = 1.688 – correction factor for the grid geometry as a function of the number of nodes on each side of the grid.

Having found R_{ep}, K_m and K_i it is now possible to find the mesh voltage E_m as follows. The resistance R_{ep} is substituted into the fault current equations (H.1.1) and (H.1.2), to give the total fault current I_f. The earth return circuit between the pole at point A in Figure 13.12 and the earthing connection at point B at the source is a parallel circuit of the resistances to earth R_{en} and R_{ep} and the overhead earth return line impedance Z_{eoh}. The parallel combination is:-

$$Z_e = \frac{Z_{\text{eoh}}(R_{\text{en}} + R_{\text{ep}})}{Z_{\text{eoh}} + R_{\text{en}} + R_{\text{ep}}} = 11.019 + j5.5597 \text{ ohms}$$

Where

$$Z_{\text{eoh}} = \text{route length} \times Z_{0\text{pkm}} = 10.5 + j22.5 \text{ ohms.}$$

The proportion of current entering the ground I_{fe} is therefore:-

$$\begin{aligned}|I_{\mathrm{fe}}| &= |Z_e I_f/(R_{\mathrm{en}} + R_{\mathrm{ep}})|\\ &= 0.6826 \times 1057.4 = 721.74 \text{ amps.}\end{aligned}$$

See Case C.3 in Tables H.1c and H.1d.

The corner mesh voltage E_m in the centre of the mesh at any corner of the grid is: -

$$E_m = \frac{\rho I_{\mathrm{fe}} K_m K_i}{L_g + 1.15 L_r} = 1853.6 \text{ volts}$$

Table H.1c. Data for earth resistance, touch voltage, ground potential rise and corner mesh voltage for different grid and rod designs

Case	Resistivities		Area A	dr	hs	h	Nrod	l_r	N_{mesh}
	ρ	ρ_s							
A.1	100	1000	36	0.02	0.2	0.5	2	10	3
A.2	100	1000	64	0.02	0.2	0.5	2	10	4
A.3	100	1000	100	0.02	0.2	0.5	4	10	5
A.4	100	1000	144	0.02	0.2	0.5	4	10	6
A.5	100	1000	196	0.02	0.2	0.5	5	10	7
A.6	100	1000	256	0.02	0.2	0.5	5	10	8
B.1	1000	5000	36	0.02	0.2	0.5	2	10	3
B.2	1000	5000	64	0.02	0.2	0.5	2	10	4
B.3	1000	5000	100	0.02	0.2	0.5	4	10	5
B.4	1000	5000	144	0.02	0.2	0.5	4	10	6
B.5	1000	5000	196	0.02	0.2	0.5	5	10	7
B.6	1000	5000	256	0.02	0.2	0.5	5	10	8
C.1	1000	5000	36	0.02	0.2	0.5	2	50	3
C.2	1000	5000	64	0.02	0.2	0.5	2	50	4
C.3	1000	5000	100	0.02	0.2	0.5	4	50	5
C.4	1000	5000	144	0.02	0.2	0.5	4	50	6
C.5	1000	5000	196	0.02	0.2	0.5	5	50	7
C.6	1000	5000	256	0.02	0.2	0.5	5	50	8
D.1	1000	5000	36	0.2	0.2	0.5	2	50	3
D.2	1000	5000	64	0.2	0.2	0.5	2	50	4
D.3	1000	5000	100	0.2	0.2	0.5	4	50	5
D.4	1000	5000	144	0.2	0.2	0.5	4	50	6
D.5	1000	5000	196	0.2	0.2	0.5	5	50	7
D.6	1000	5000	256	0.2	0.2	0.5	5	50	8
E.1	1000	5000	36	0.2	0.2	2.0	2	50	3
E.2	1000	5000	64	0.2	0.2	2.0	2	50	4
E.3	1000	5000	100	0.2	0.2	2.0	4	50	5
E.4	1000	5000	144	0.2	0.2	2.0	4	50	6
E.5	1000	5000	196	0.2	0.2	2.0	5	50	7
E.6	1000	5000	256	0.2	0.2	2.0	5	50	8

Table H.1d. Results for earth resistance, touch voltage, ground potential rise and corner mesh voltage for different grid and rod designs

Case	R_{ep}	E_{touch50}	GPR	E_m	I_{fe}	I_f
A.1	4.421	361	4796	1214	1085	1217
A.2	3.716	361	4133	914	1112	1229
A.3	3.215	361	3638	613	1132	1238
A.4	2.838	361	5254	509	1147	1245
A.5	2.544	361	2947	412	1158	1250
A.6	2.307	361	2694	343	1168	1254
B.1	44.13	1190	16,842	4271	382	929
B.2	37.11	1190	16,161	3580	435	947
B.3	32.12	1190	15,523	2618	483	964
B.4	28.37	1190	14,936	2338	526	980
B.5	25.43	1190	14,382	2009	565	995
B.6	23.07	1190	13,862	1766	601	1008
C.1	21.33	1190	13,431	3069	630	1020
C.2	18.59	1190	12,644	2953	680	1040
C.3	16.58	1190	11,968	1854	722	1057
C.4	15.02	1190	11,373	1808	757	1072
C.5	13.76	1190	10,841	1541	788	1085
C.6	12.71	1190	10,360	1351	815	1097
D.1	19.28	1190	12,856	3250	667	1035
D.2	16.92	1190	12,087	3103	715	1054
D.3	15.17	1190	11,433	1936	754	1071
D.4	13.80	1190	10,861	1879	787	1085
D.5	12.69	1190	10,351	1595	816	1097
D.6	11.76	1190	10,043	1394	841	1108
E.1	19.24	1190	12,947	3408	678	1035
E.2	16.88	1190	12,073	3286	715	1054
E.3	15.14	1190	11,421	2068	754	1071
E.4	13.78	1190	10,851	2022	787	1085
E.5	12.67	1190	10,343	1729	816	1098
E.6	11.75	1190	9884	1521	841	1109

It is also necessary to relate the corner mesh voltage E_m to the ground potential rise GPR of the grid and rod system.

$$\mathrm{GPR} = I_{\mathrm{fe}} R_{\mathrm{ep}} = 11967.9 \text{ volts}$$

Hence expressing E_m as a percentage (E_{mpc}) of the GPR gives:-

$$E_{\mathrm{mpc}} = \frac{E_m \times 100}{\mathrm{GPR}} = 15.49\%$$

Comments on the results

Case A. The resistivity of the lower soil was chosen to be a moderate value of 100 ohm-m. Low values of resistance to earth at the pole, R_{ep}, were easily obtained. The main criterion is that the corner mesh voltage E_m must be less than the 50 kg touch voltage E_{touch50}. Only one case A.6 satisfies this criteria, 343 volts is less than 361 volts. This case requires a relatively large site area of 256 m^2 for a pole and its associated equipment.

Case B. The resistivities were raised to values typical of dry and arid locations. In all cases the resistance to earth could not be reduced to 5 ohms. Again the 'mesh-touch' criteria could not be achieved. A satisfactory design could not be found.

Case C. The rods were driven deeper into the ground, to a depth of 50 m. The increase in depth by a factor of 5 only reduced the resistances to about 50% of their values in Case B. Some reduction in the corner mesh voltage was obtained.

Case D and E. Increasing the rod diameter by a factor of 10 and burying the grid deeper by a factor of 4 made very little difference to the results in Case C.

Necessary improvements.

In view of the difficulties found in providing a satisfactory solution, it would be advisable to include the 'ladder' network referred to in H.1 and re-calculate the results. If this does not improve the situation significantly then two main improvements should be considered. Firstly use a neutral earth resistor at the source to restrict the earth return current to between 50 and 100 amps. This will directly reduce E_m to values below E_{touch50}. Secondly reduce the fault clearing time t_s from 0.5 to 0.2 seconds. This may not be easily achieved. A sensitive earth current protective relay may need to be installed, e.g. core balance 51 N or 50 N relay. Reducing t_s to 0.2 seconds will raise the E_{touch50} by a factor of 1.581, which in Cases B to E causes E_{touch50} to become 1881 volts. This allows several of the cases to become feasible, e.g. B6, C3, C4, C5 and C6. The whole exercise should be repeated for other poles along the route so as to check whether or not a poorer situation could exist.

It may be noted that the simple treatment of the zero sequence impedances in the example would tend to be more appropriate to a remote switching station fed by an underground cable.

Appendix I

Conversion Factors for the SI System of Units

(Note, the abbreviation SI means Système International d'Unitès, ref: 11th General Conference of Weight and Measures, date 1960). The conversion factors shown below can be found in many documents, for example in References 1 to 7 are a few sources.

I.1 FUNDAMENTAL SI UNITS

Seven basic units

Quantity	Name of SI unit	Symbol
Amount of a substance	mole	mol
Current	ampere	A
Length	metre	m
Luminous intensity	candela	cd
Mass	kilogram	kg
Temperature	Kelvin	K
Time	seconds	s

Two additional SI units

Quantity	Name of SI unit	Symbol
Plain angle	radian	rad
Solid angle	steradian	sr

I.2 DERIVED NON-ELECTRICAL UNITS

Non-electrical units	Name of SI unit	Symbol
Energy, work done and heat	joule	J
Force	newton	N

(*continued overleaf*)

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake

ISBN: 0-471-49631-6

Non-electrical units	Name of SI unit	Symbol
Illumination	lux	lx
Luminous flux	lumen	lm
Mechanical stress	pascal	Pa
Power	watt	W
Pressure	pascal	Pa

I.3 DERIVED ELECTRICAL UNITS

Electrical units	Name of SI unit	Symbol
Capacitance	farad	F
Charge	coulomb	C
Conductance	siemens	S
Inductance	henry	H
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T
Potential, potential difference, electromotive force, (voltage, volt-drop)	volt	V
Resistance	ohm	Ω

I.4 CONVERSIONS

I.4.1 Length

Convert	to	Multiply by
fathom	m	1.8288
ft, feet	m	0.3048
in, inch	mm	25.4
km	miles	0.62137
m	inch	39.3701
m	ft	3.2808
mil = 0.001 inch	mm	0.0254
mile	km	1.60934
Mm	inch	0.0393701
UK nautical mile	km	1.85318
US nautical mile	km	1.85200
yd, yard	m	0.9144

I.4.2 Area

Convert	to	Multiply by
acre	m^2	4046.86
acre	km^2	0.00404686
acre	ha	0.404686
circular mil	mm^2	0.0005067
ft^2	m^2	0.0929030
in^2	mm^2	645.16
in^2	m^2	0.00064516
m^2	ft^2	10.7636
$mile^2$	km^2	2.58999
$mile^2$	ha	258.999
mm^2	$inch^2$	0.001550
yd^2	m^2	0.836127

I.4.3 Volume

Convert	to	Multiply by
dm^3	l	1.0
ft^3	UKgal	6.2288
ft^3	USgal	7.4805
ft^3	dm^3	28.3168
in^3	mm^3	16387.1
litre	UK pints	1.7597
litre	US pints	2.1127
litre	Usgal	0.2641779
litre	Ukgal	0.2199756
m^3	litre	1000.0
m^3	UKgal	219.97
m^3	Usgal	264.172
oz (fluid ounce)	cm^3	28.4131
pint	dm^3	0.568261
pint	l	0.568261
quart	dm^3	1.13652
UK gallon	dm^3	4.54609
UK gallon	l	4.54609
UK gallon	UK pint	8.00
UK gallon	ft^3	0.1605
UK gallon	US gallon	1.20095
US gallon	dm^3	3.78541
US gallon	l	3.78541
US gallon	US pint	10.0

(*continued overleaf*)

Convert	to	Multiply by
US pint	UK pint	1.20095
US gallon	ft^3	0.1337
US gallon	in^3	231.03
US gallon	UK gallon	0.832674
US barrel	US gallons	42.0
US barrel	UK gallons	34.97
yd^3	m^3	0.764555

I.4.4 Mass and Density

Convert	to	Multiply by
lb	kg	0.45359237
lb/ft^3	kg/m^3	16.0185
lb/in^3	Mg/m^3	27.6799
kg/m^3	lt/ft^3	0.03243
lb/UK gal	kg/m^3	0.099776
lb/US gal	kg/m^3	0.119826
oz (ounce)	g	28.3495
oz (troy)	g	31.1035
slug	kg	14.5939
UK ton (long ton)	kg	1016.05
UK ton (long ton)	tonne	1.01605
US ton (short ton)	kg	907.185
kg	lb	2.2046

I.4.5 Velocity and Acceleration

Convert	to	Multiply by
ft/min	m/s	0.00508
ft/s	m/s	0.3048
ft/s^2	m/s^2	0.3048
km/h	m/s	0.277778
miles/hour	m/s	0.44704
miles/hour	km/h	1.609344
UK knot	km/h	1.85318
US knot	km/h	1.85200

I.4.6 FORCE

Convert	to	Multiply by
dyne	N	10^{-8}
kgf	N	9.80665
lbf	N	4.44822
ozf	N	0.278014
poundal	N	0.138255
tonf (UK)	kN	9.96402

I.4.7 Torque

Convert	to	Multiply by
dyne-cm	N-m	10^{-7}
kmf-m	N-m	9.80665
lbf-ft	N-m	1.35582
lbf-in	N-m	0.112985

I.4.8 Power

Convert	to	Multiply by
ch (metric HP)	W	735.499
ft-lbf/s	W	1.35582
hp or HP	W	745.700
hp or HP	ft-lbf/s	550.0
hp or HP	kgf-m/s	76.04
hp or HP	W	745.70
kgf-m/s	W	9.80665
kW	ft-lbf/s	737.6
kW	hp	1.3410

I.4.9 Energy and Work

Convert	to	Multiply by
BTU or btu	kJ	1.05506
btu	international cal	251.996
btu	15°C cal	252.074
btu	thermochem cal	252.164
btu	ft-lbf	778.6(778.17)
btu	kcal	0.252
btu	kgf-m	107.6
btu	W-s	1055.0

(*continued overleaf*)

Convert	to	Multiply by
btu	kW-h	0.00002931
btu/ft^3	kcal/m^3	8.899
btu/lb	kcal/kg	0.5556
erg	J	10^{-7}
ft-lbf	J	1.35582
ft-pdl	J	0.0421401
hp-h, HP-h	MJ	2.68452
international-cal	J	4.18680
kgf-m	J	9.80665
kJ	btu	0.9478
kJ	kW-h	0.000278
kJ	Btu	0.9478
kJ	ft-lbf	737.6
kW-h	MJ	3.6
litre-atmosphere	J	101.328
therm	btu	100000.0
therm	MJ	105.506
thermo chemical-cal	J	4.18400
15°C-cal	J	4.18550

I.4.10 Pressure

Convert	to	Multiply by
atm, atmosphere	kN/m^2	101.325
atm, atmosphere	Pa	101325.0
atm, atmosphere	bar	1.01325
atm (international)	lbf/in^2	14.6959
atm (international)	lbf/ft^2	2116.22
atm (international)	kgf/m^2	10332.27
atm (international)	in of water 60°F	407.17
atm (international)	in of mercury 32°F	29.921
atm (international)	mm of mercury 32°F	760.00
at (metric technical)	kgf/cm^2	1.0
at (metric technical)	bar	0.98066
at (metric technical)	lbf/in^2	14.2233
bar	lbf/in^2	14.5
bar	ft of water	33.455
bar	m of water	10.2
bar	mm of mercury	750.1
bar	in of mercury	29.53
b, bar	N/m^2	100000.0
b, bar	kPa	100.0
inches of water	mb	2.49089

Convert	to	Multiply by
inches of mercury	mb	33.8639
inches of mercury	N/m^2	3386.39
kgf/cm^2	kN/m^2	98.0665
kgf/m^2	N/m^2	9.80665
lbf/in^2	mb	68.9476
lbf/in^2	kgf/cm^2	0.0703
lbf/in^2	N/m^2	6894.76
mm of mercury	mb	1.33322
N/m^2	lbf/in^2	0.000145
N/m^2	ft of water	0.0003345
N/m^2	mm of mercury	0.0075
N/m^2	m of water	0.000102
N/m^2	in of mercury	0.0002953
Pa, pascal	N/m^2	1.0
pdl/ft^2	N/m^2	1.48816
pressure in inches of water	lbf/in^2	0.036127
torr (mm of Hg)	N/m^2	133.322
UK ton/ft^2	kN/m^2	107.252

I.4.11 Moment of Inertia and Momentum

Convert	to	Multiply by
lb-in^2	kg-m^2	2.92640×10^{-4}
lb-ft^2	kg-m^2	0.042140
lb-ft/s (linear)	kg-m/s	0.138255
lb-ft/s (rotational)	kg-m/s	0.042140
oz-in^2	kg-m^2	1.82900×10^{-6}

I.4.12 Illumination

Convert	to	Multiply by
angular degrees	rad	3.1415926536/180.0
cd/ft^2	cd/m^2	10.7639
cd/in^2	cd/m^2	1550.0
footcandle, lm/ft^2	lx	10.7639
phot, lm/ft^2	lx	10000.0
radians	degrees	180.0/3.1415926536 =57.2957795131

I.4.13 Electricity and Magnetism

Convert	to	Multiply by
gauss	tesla, T	10^{-4}
gilbert	A	$10/4\pi$
kWh	J	3.5×10^6
kV/in	kV/m	39.3701
maxwell	weber, Wb	10^{-8}
oersted	A/m	$1000/4\pi$
V/mil	kV/m	39.3701

I.4.14 Miscellaneous Quantities

Convert	to	Multiply by
°C	°K	$C + 273.15$
°C	°F	$F = 32 + C9/5$
°F	°C	$C = (F - 32)5/9$
°F	°K	$K = (F + 459.67)5/9$
°R	°F	$F = R - 459.67$
°R	°K	5/9
ft^3/ min	USbarrels/day	256.475
imperial ton	lb	2240.0
US short ton	lb	2000.0
imperial slug	lb	32.1740
in^3 of water (60°F)	in^3 of mercury (32°F)	0.073551
in^3 of mercury (32°F)	in^3 of water (60°F)	13.596
in^3 of mercury (32°F)	lb	0.4905
kg	lb	2.20462
kN	kgf	101.97
kN	lbf	224.81
kg/s	lb/h	7936.64
kg/s	UKton/h	3.5431
lbf	kgf	0.4536
lb/ft^3	kg/m^3	16.0185
lb/in^3	g/cm^3	27.68
m/s	ft/s	3.28084
m^3/h	ft^3/ min	0.5886
m^3/h	UKgal/min	3.666
m^3/h	USgal/min	4.403
m^3/h	USbarrels/day	150.955
m^3/ kg	ft^3/lb	16.02
Metric tonne	kg	1000.0
miles/UKgal	km/litre	0.354005
UKgal/mile	litre/km	2.82481
UKgal/min	USbarrels/day	41.175
Usgal/min	USbarrels/day	34.286

Convert	to	Multiply by
USbarrels/day	USgal/min	0.029
USbarrels/day	ft^3/h	0.2339
calorific value, btu/ft^3	kJ/m^3	37.2589
specific heat capacity (btu/lb-°F)	J/kg-°CorK	4186.8
specific heat capacity (btu-s/ft^3-°F)	kJ/m^3-°CorK	67.0661
specific entropy (btu/lb-°F)	J/kg-°CorK	4186.8
thermal resistivity (ft^2-h-°F/btu-in)	m^2-s-°C/J-m	6.93347
specific energy (btu/lb)	J/kg	2327.0
heat flow rate (btu/hour)	W or J/s	0.293071
heat flow rate (kcal/hour)	W	1.163
thermal conductivity (kW/m-°K)	btu/ft-h-°R	0.2388

I.5 INTERNATIONAL STANDARDS ORGANISATION (ISO) CONDITIONS

Standard altitude	0.0m, sea level
Standard pressure	29.9212 inches of mercury 1.013250 bar or 14.6959 lbf/in^2
Standard relative humidity	0.0
Standard temperature	15.0°C or 59.0°F

I.6 STANDARD TEMPERATURE AND PRESSURE (STP) CONDITIONS

Standard pressure	29.9212 inches of mercury 1.013250 bar or 14.6959 lbf/in^2
Standard temperature	0.0°C or 32.0°F

I.7 REGULARLY USED CONSTANTS

Constants	Numerical value	Symbol
Absolute zero temperature	−273.16°C	
Absolute zero temperature	−459.69°F	
Absolute zero temperature	0.0°K	

(*continued overleaf*)

Constants	Numerical value	Symbol
Acceleration	9.80665 m/s^2	g
due to gravity	32.174 ft/s^2	g
Base of natural logarithms	2.7182818285	e
Density of water	1.0 kg/m^3 = 0.062428 lb/ft^3	
Pi	3.1415926536	π
Specific volume of water	1.0 m^3/ kg = 16.01850 ft^3/lb	

I.8 REGULARLY USED PREFIXES

Pico	10^{-12}
Nano	10^{-9}
Micro	10^{-6}
Milli	10^{-3}
Centi	10^{-2}
Deci	10^{-1}
Kilo	10^{+3}
Mega	10^6
Giga	10^9
Tera	10^{12}

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Index

Accelerating power 304, 441
Acidic environment 395
Active power 4, 5
Admittance relay 320
Air gap
  Flux 62
  Voltage 62, 103
Alarms and indication
  for variable speed drive system 433
Aluminium, in cables as conductors 184, 192
Ambient temperature, see temperature
Ampere-turns 67, 324
Arcing time 174
Armature reaction, and time constant 62, 65, 489, 493
Asymptotic current, of mold case circuit breakers 450
Asymptotic current, of overcurrent relays 318
Asymptotic value, of a fuse operating current 177, 450
Atmospheric
  Pressure 24
  Temperature 24, 27
Automatic voltage regulation and regulators
Automatic voltage regulators 83, 89, 97, 275, 324, 332, 335, 444, 540
  Effect on over current protection 315
  Effect on short circuit current 150
  Type 1 and type 2 89
Auto-synchronising main generators 447

Back pressure 26
Balanced loads 145
Balanced three-phase circuits 479
Barrier glands for cable 259
Batteries
  Ambient temperature 456
  Ampere-hour capacity 455
  Boost charging 454
  Charging 453
  Constant current charging 453
  Constant voltage charging 453
  Float charging 454
  Lead acid 455
  Maintenance free 456
  Nickel cadmium 455
  Sealed type 456
Battery charger 451
Base MVA 279
Base MVA rating 271
Bi-polar power transistors 402
Black starting 3
Block diagram 89
Bonding conductors 354, 356, 371
Bridges
  Diode 402
  Smoothing in 413
  6-pulse rectifier 413, 417
  12-pulse rectifier 417
Bridge-connected thyristor inverter 392
Buried conductors, shapes of 369
Busbars
  Clean earth 372
  Copper and aluminium 144
  Earthing 146
  Neutral 146
  Noise pick-up from earthing 382
  Voltage 444

Cables 183
  Acid gas 245
  Aluminium wire armour 198
  Charging current 357
  Copolymer 188
  Cross-linking 189
  Cross-sectional area of conductors 198
  Derating factors for ambient temperature 202

Handbook of Electrical Engineering: For Practitioners in the Oil, Gas and Petrochemical Industry. Alan L. Sheldrake
ISBN: 0-471-49631-6

Cables (*Continued*)
  Derating factors for ground temperature 204
  Directly buried 124, 199
  Ducts, trenches and direct burial 206
  Elastomer 187
  Emission of toxic gases and smoke 244, 245, 246
  Fire resistance 245
  Galvanised steel wire 198
  Halogen gas 245
  Heavy-duty polymeric sheathing 198
  Hydrochloric and hydrofluoric acid 245
  Insulating compounds 196, Appendix A
  Laid in trefoil 206
  Laid in underground ducts 199
  Low smoke zero halogen 246
  Metallic materials used in 183
  Motor feeder 123
  Multi-core 372
  Phosphor bronze wire braid 198
  Plain feeder 12, 332, 346
  Racks 124
  Reduced flame propagation 244
  Resin and resin polymers 188
  Sizing tables 222
  Stranding of wires in conductors 193
  Thermoplastic 187
  Thermosets 187
  Tinned copper wire braid 198
  Trenches 124
Cable construction
  Armouring 192, 198
  Conductor 192
  Extruded polymer sheathing 197
  Inner sheathing 192
  Insulation 192
  Outer sheathing 192
  Semiconductor screens 192, 196, 197
Cascaded devices 451
Capacitance charging current of cables 72, 340
Cathodic protection 467
  Anodes 467
  Hazardous areas 460, 467
  Impressed current 467
  Off-shore structures 467
  On-shore structures 467
Ceiling voltage of the exciter 88, 318
Certification of hazardous area equipment 265
Circuit breakers 154
  Four-pole for hazardous area supplies 365, 460
  Air-break 146
  Comparison with fuses 162
  Miniature 233
  Molded case 154
  Sulphur hexafluoride 146, 147
  Vacuum 146, 147
Clearance time 178
  For circuit breakers 277
  Of fault current 532
  Total, for switchgear 225
Closed-loop,
  Control of the rectifier 389, 391, 392, 399, 539
Closed-loop,
  Transfer function 43
Coefficients
  Even 415
  Even harmonics 431
  Odd 413
  Odd harmonics 431
  Triplen 413
Combustion temperature 11
Commutation 385, 388, 402
  Angle 402, 409, 414, 421, 423
  Reactance 407
  Notches 406
  Mode1 operation 403, 405
  Mode 2 operation 404, 405
  Mode 3 operation 405
Commutator 490
Components, two-axis 68
Compression ratio 29
Compressors 108, 385, 386, 391, 402
  Variable speed drives for 433, 495
Concrete buildings 356
Condition monitoring of gas turbines 435
Conductivity of soil and ground materials 355
Contactors, coordination of 154, 155, 159, 167, 343, 344
Contingency, typical for future load growth 199
Control and indication for switchgear 158
Control gear 143
Cooling
  CACA and CACW 80
  Fans 80
  Forced air for transformers 145
  Heat exchangers 80
  ONAF 12

  ONAN 12
  TEFC 80
  Water 121, 139
Coordination, of contactors and fuses 155
Coordination, see also contactors
  Complete for molded case circuit breakers 167, 450
  Of cascaded devices 451
  Of fuses and molded case circuit breakers 450
  Poor 451
  Underfrequency relays 540, 543
Copper
  Annealed 184
  Hard-drawn 184
  In cables as conductors 192, 193
Copper and copper alloy 63
Copper, bonding conductors for earthing 354
Corner mesh voltage 369
Corner step voltage 369
Coupling, loose and tight 303, 306
Crushed rock used in earthing systems 367
Cubicle
  Type of switchgear 147, 371
  Earthing of 382
Current
  Asymmetrical 174
  Charging of capacitance in long feeder cables 72, 340, 357
  Constant, in inverters 423
  Decrement of short circuit 277, 492
  Derated for cables 243
  Doubling 274, 283
  Full-load 230
  Fundamental 142
  Fundamental instantaneous 409
  Harmonic and stray, in generator neutral circuit 324
  High-set 329
  High starting 336
  Instantaneous 142
  Inrush, of motors 340
  Inrush, of transformers 141
  Negative phase sequence 322, 339
  Noise pick-up 373
  Noise pick-up in earthing busbars 382
  Nominal, of relays 348
  Overloading 242
  Peak short-circuit 145
  Plug setting 348
  Positive sequence 339
  Rated, of cables 199
  Root mean square 409
  Short circuit withstand 473
  Stalling, of induction motors 341
  Stray 372
  Sub-transient fault 151
  Symmetrical 174
  Threshold, for molded case circuit breakers 164
  Through-fault 329
  Transformer 311
  Transformer, core-balance 333, 340, 343, 345
  Transformers, star/delta interposing 322
  Transient fault 151
  Unbalanced 142
  Zeros and crossing points 79, 274, 502
Current contribution
  Sub-transient fault 151
  Transient fault 151
Current rating
  Busbar normal 8
  Fault 8
Cylindrical rotor construction 61

Damper bars 63, 68
Damper windings 480, 490
Damping 84
Damping characteristics 304
Damping feedback 88, 539
DC off-set current 151, 293, 492, 502
DC off-set of fault current 149
DC link capacitor 398, 422
DC link inductor 398, 422
DC motors 385, 394, 401, 407
Deceleration factor 118
Decrement of fault currents 300, 315
Deep-bar effect, and factor 101, 102, 400, 480, 500, 502, 503
Definite time delay 318
Delay angle 404, 408
Delta connected motors 392
Derating, see Factors
Diesel
  Engine 19
  Generators 3
Diesel engines, emergency 449
Diesel generators, emergency 459
Dimensions, influence on reactances 67
Direct-on-line starting 107, 124, 176, 312, 318, 336, 441, 500, 573, 580

Dirty engine, gas turbine 38
Diversity factor 4
Diversity factor applied to loads 199
Double frequency 492
Double insulation 235
Double wound transformers 364
Doubling factor for fault current 164, 285, 287, 292
Down-hole pumping 385
Downstream
  Circuit 332
  Circuit breaker 293, 450
  Coordination and back-up of protective devices 333
  Devices 333, 348
  Feeders 312
  Fuses 330, 450
  Molded case circuit breakers 450
  Motors 318
  Protective devices 333
  Switchboard 329
  Switchgear 157, 163, 318
  Transformer 318
D-Q axis or two-axis theory 64, 308
Drive end 80, 120
Drilling
  Equipment 407
  Oil wells, DC motors systems 410
  Rigs 323, 328, 386, 394, 432
  Wells 385
  Vessels 354
Droop 84
  Gain of speed governors 325
  Governing of generators 433
  Of DC output voltage 408
Droop characteristic, of a gas turbine 43
Duty
  Continuous 3
  Current limiting short-time, of fuses 177
  Fault breaking 149
  Fault breaking rms, of switchgear 152
  Fault making for switchgear 291
  Fault current withstand, of switchgear 154
  Intermittent 3
  Non-current limiting long-time, of fuses 177
  Standby 3
  Symmetrical breaking, of switchgear 274
  Worst case situation for maximum fault making 277
Earth and ground notation 355
Earth fault, in relation to earth loop impedance 233
Earth leakage circuit breaker 241
Earth loop impedance 200, 224, 240
Earthing
  Apparent resistivity of soil 590
  Disconnection time 235, 242
  Double insulation 235
  Fixed equipment 235
  Grid and rod system 585
  Hand-held equipment 235
  Portable equipment 235
  TN and TT systems 242
  TN, TT and IT systems 235
Earthing
  And grounding, defined 353
  High impedance 323
  Grid resistance 589
  In cubicles and panels 382
  Inductor or transformer 328
  Low impedance 323
  Mutual resistance between the grid and rods 592
  Resistance of all the rods 592
  Resistance of the grid conductors 592
  Solid at the star-point 333
  TN, TT and IT systems 364
  TNC, TNS, TNCS, TT and IT systems 360
Earthing busbars
  Clean 382
  Clean and instrument connections 382
  General 382
  Single point earths 382
Earth loop impedance 343, 345
Eddy current induction 304
Eddy currents, in cable screens 381
Efficiency
  Electro-mechanical conversion 37
  Ideal cycle 26
  Of an induction motor 101, 106, 107
  Of compression 29
  Of turbine 29
  Practical cycle 29
Electrical power in the two-axis form 54
Electric shock 147, 233, 343, 351, 354, 355, 356, 364, 367
  At the far end of a cable 366, 367
  Corner mesh voltage 590, 595
  High risk 369
  Ground potential rise 595
  In a neutral circuit 365

  Step voltage 589
  Touch voltage 589
Electrolytic tank, for slip ring motors 391
Electromagnetic interference 399
Electromagnetic damping 304
Electromotive force, EMF 85, 99
  Emf behind an impedance 274
  Induced in a transformer 134, 137
  Sub-transient emf 275, 294
  Synchronous emf 275
  Transient emf 275
Emergency
  Generators 3
  Load 3
  Lighting 459
Enclosure 78
  Copper bonding straps 371
  Direct and indirect entries 259
  For switchgear 143
  Forms of separation in switcher 148
  In relation to earthing 371
  Ingress protection for 78
  Open and closed types 120
  Plain or clearance hole entries 372
  Specification of 473
  Threaded entries 371
  Totally TE 120
End-of-curve condition of characteristic 122
End-of-curve operating point 14
Energy equation, compressor and turbine 32
Energy efficiency 385
Equivalent circuit
  Of a screening system in cables 375
  Of a transformer 132
  On an induction motor 100, 495, 500
  Of the earth loop impedance 366
  Pye, for long cables 217
  Tee, for long cables 214
Equivalent circuit, low voltage system 271
Equivalent transformer 278
Essential load 3
Events and alarms 158, 448
Extra-fast acting fuses 176
Excitation 61
Excitation voltage 88
Exciter 62, 78, 96
  Main 88
  Pilot 88, 89

Factor
  Correction for depth of the grid 593
  Correction for grid geometry 593
  Correction for mesh spacing 593
  Correction for rods within the grid 593
  Deceleration 118
  Deep-bar 102
  Derating for cable conductor current 202, 204, 206
  Derating of ground resistivity 589
  Doubling for fault current 151, 164
  Fusing 156, 225
  Load 10
  Marginal for MVA rating with future load 278
  Multiplying to change reactances 481
  Normal running load 9
  Overload 10
  Overall power 5
  Power 64
Factory built assemblies 143
Fans
  For transformer 12, 138, 145
  In induction motors 121
  Shaft mounted cooling 390
  Ventilating 345
Faults
  Busbars 332
  Cable internal line-to-line 333
  Cable internal three-phase 333
  Generator internal 323
  HV motor phase-to-phase 339
  Line-to-ground 364, 479, 483
  Line-to-line 479
  Transformer internal 329
Fault current 73
  Contribution from induction motors 292, 300, 493, 503
  Doubling, see current doubling
  Earth fault 324
  First cycle of 292
  Instantaneous 274
  Let-through 339
  Limited by transformer impedance 145
  Peak asymmetrical sub-transient 291
  Peak let-through 176
  Peak symmetrical 274
  Peak value of the 274
  rms value of asymmetrical 293
  Single line-to-ground 370
  Sub-transient 79
  Symmetrical 276
  Through fault 319, 329
  Total sub-transient symmetrical rms 281
  Transient and sub-transient 279

Fault making capacity 151
Feedback
  Derivative 84, 88
  Damping 84, 539
  Gain 399
  Regulation 389
  Signals 392
  Transfer function 42
Feedback regulation 389
Feedback signals 392
Feeders
  Cable 346
  High voltage 355
  To a switchboard 199
  Transformer 326, 406
Feeder cables, long route length and capacitance 340
Field current 64
Field winding 88, 480, 490
Filters, tuned and Q-factor 433
Final sub-circuits 163
Flame retardant 138
Flame retardant, material in switchgear 334
Flammable gas and vapour 251
Fluid couplings for speed control of machines 397
Flux
  Constant air gap 389, 393
  Density 140
  Leakage 131
  Linkages 482, 484, 487
  Linkage equations and variables 486
  Mutual or magnetising 131
  Negative phase sequence 322
  Raise in air gap 393
  Residual 140
  Trapped in machine 294
Forces, electromagnetic 142
Forward transfer function 42
Forward path gain 399
Fourier coefficients of current 409
Fourier coefficients of line current 414
Frequency, system 11
Frequency
  Error 447
  Nominal angular 481, 495
  Nominal cyclic 481
  Recovery of system 307
Fuel 23
  Air-fuel ratio and mixture 26
  Air-fuel ratio by mass 31
  Air-gas mixture 27
  Control valve 52, 58
  Control valve characteristic and limits 56
  Energy from the 32
  Mass flow rate of the 36
Fuel consumption of a gas turbines 36
Fuels for gas turbines 23
Function generators 316, 347
Functionality 470
Fuses and fusing 154, 173
  Arcing time 178
  Clearing time 178
  Factor 156, 225
  For induction motors 156
  High-speed 225
  Melting process 173
  Melting time 178
Fuse-contactor combinations 154
Fuse-switch combinations 154

Gain 52
  Forward path 539
  Proportional in automatic voltage regulators 84
Gas and vapour in hazardous areas 251
Gas generator 19
Gas groups and temperature classes 266
Gas turbines
  Aero derivative 19
  Air compressor 20
  Block diagrams 51
  Closed-loop speed-torque characteristic 41
  Combustors 58
  Combustion temperature 26
  Compressor turbine 20
  Heavy industrial 19
  Inlet filter 33
  ISO rating 37
  Least signal selector device 59
  Light industrial 19
  Operating temperature 437, 441
  Open-loop speed-power characteristic 41
  Open-loop speed-torque characteristic 39, 41
  Packaged generators 37
  Power turbine 20
  Silencing, inlet and exhaust 32
  Simple or Joule cycle 24
  Single shaft 20, 51, 58, 539
  Starting 39
  Three shaft 23
  Two or twin shaft 20, 51, 58, 539
  Ungoverned speed-torque characteristic 39

Gate turn-off thyristors 405
Generator decrement curves, for fault currents 315
Generalised theory of electrical machines 479, 496
Generators
  Excitation 318
  Local captive 354
  Salient pole 291
Generators, sizing 13
Grids and rods for earthing 352, 369
Ground potential rise 369
Ground or soil thermal conductivity and resistivity 205

Hand-held equipment 235
Hand-to-foot resistance 352
Hand-to-hand resistance 352
Hard and soft limits in control valves 56
Harmonics
  Cancellation 418
  Currents 386
  Design of filters 431
  Distortion 401, 431
  Distortion in uninterruptible power supplies 449
  High frequency 136, 406
  Injected into a system 429
  Notches due to commutation 399
  Q-factor of filters 433
  Sharply tuned filers 433
  Spikes 387
  Voltdrops 386
Harmonic current in switchgear neutral busbars 146
Harmonisation of international standards 265
Hazardous areas 61, 78, 123, 125, 386, 460, 472
  Classification, earthing influenced by 358, 363
  Equipment 451
  Ex 'd' 78
  Ex 'de' 78
  Ex 'n' 78
  Ex 'p' 78
  Gases and vapours 251, 363
  Radar 466
  Use of four-pole circuit breakers and isolator 365
  Zone 1 and zone 2 78
  Zone 1 lighting fittings 460
Hazardous area classification 249
Hazardous area types, zones 0, 1 and 2 251
Hazardous area zones and divisions 253
Heat rate 35
Heat radiator 138
Heat exchanger 80
High conductivity copper 68
High impedance earth point 358
High power transistors 407
High-set setting 348
High voltage generator 78, 471
High voltage motor 78
Hysteresis 140

I-squared-t characteristic
  For negative phase sequence current 339
  Of a contractor 339
  Of a neutral earthing resistors 323
  Of a person 351
  Of cables 323
  Of copper cables 165
  Of downstream equipment 176
  Of fuses 164, 176
  Of molded case circuit breakers 164
  Of power equipment 337, 363
  Of transformers 329
I-squared-t duty of equipment, prospectively high 363
Impedance
  Armouring 366
  Earth loop, see earth loop impedance 200
  Earthing 355
  External, effect of short circuit currents 152
  In relation to armouring 186
  Induction motor sub-transient 294
  Induction motor transient 294
  Leakage, of a transformer 145
  Operational 486, 491, 493
  Operational in the D-axis 489
  Operational in the Q-axis 489
  Per-unit of a transformer 133
  Shield transfer in screening 380
  Source 366, 492
  Sub-transient 64
  Transient 64
Increased safety, type of protection 256
Indication and control for switchgear 158
Induced emf 79
Inductive reactance 99

Induction
  Rotational type of 273
  Transformer type of 273
Induction motors 99
  Double cage 101, 108, 490
  Maximum torque 106
  Pole amplitude modulated 390
  Pole changing 390
  Squirrel or single cage 385, 387, 479, 485, 490
  Torque 103
  Wound rotor 385, 387, 391
Inductance, series connected external 480
Inductance in the DC circuit 413
Inductances, mutual 484, 493
Inductances, self or total 481
Induction by rotating action 483
Induction by transformer action 482
Inertia 122, 441
Inertia characteristics 304
Inertia constant 54, 78, 306
Inertia of the fuel mass 58
Inertia, of the rotor system of masses 52, 539
Ingress protection 473
  For switchgear 144, 147
Ingress of water and particles 121
Ingress protection for liquids and dust 78
Inlet and exhaust ducting 32
Inlet and exhaust silences 32
Inlet and exhaust silencing and filtering 38
Inlet filter and ducting 24
Inlet silencer 24
Inrush current of a motor 340
Inrush current of transformers 141
Installations, see offshore and onshore
Instantaneous
  Currents 483
  Emf 483
  Setting 348
  Voltages 483
Insulation classes B and F 121
Iterative solution 117
Interfaces, engineering disciplines 16
Interfacing with switchgear 159, 161
Integral controller 444
Interlocking
  Safety devices 157
  Systems 16, 161
  Two-out-of-three feeder paralleling scheme 157
Inverter
  Current source 422
  Single-phase 421
  Square wave type 421
  Three-phase 422
  Voltage source 422
Iron circuit 62
Iron core 88
  Damage to laminations 318, 355
  Earth faults in laminations 340
  Eddy current loss 100
  Of a transformer 131, 140
  Over-heating laminations 324
Island mode operation of a plant 36, 300
Isochronous governing 325
Isochronous control of frequency 443
Isochronous control of voltage 444
ISO conditions 35

Key single line diagram 1
  Generators 15
  High voltage motors 15
  Large low voltage motors 15
  Motor control centers 15
  Switchboards 15
  Transformer feeders 15

Lead metal 186
Lead-tin-antimony alloy
  sheathing material of cables 186
Leakage flux 131
Leakage reactances
  Armature or stator winding 480
  D-axis damper winding 481
  D-axis field winding 481
  Q-axis damper winding 481
Leakage inductances
  Armature or stator winding 480
  D-axis damper winding 480
  D-axis field winding 480
  Q-axis damper winding 480
Least single selector control device 59, 539
Let-through current 224
Let-through current in capability 155
Let-through current in fuses 176
Let-through fault withstand capability, of cables 124
Lighting
  Emergency 459
  Escape 459
  Flood 460
  Fluorescent lamp fittings 460
  Helideck 463
  High pressure sodium 460

  Levels of illumination 461
  Low pressure sodium 461
  Normal 459
  Stroboscopic effect 459
  Types of fittings generally used 461
Limits 97
Load 3
  Angle across a reactance 303
  Belt-driven 122
  Break switches 154
  Current in rectifiers 404
  Emergency 3
  End-of-curve condition 122
  Essential 3
  Future expansion 8
  Initial consumption 8
  Non-essential 3
  Normal 3
  Seasonal demand 5
  Static 345
  Total 5
  Total of the system 49
  Total plant peak, TPPL 5
  Total plant running, TPRL 5
  Uninterruptible 452
  Vital 3
Loading
  Fully loaded system 311
  Lightly loaded system 311
  Single phase, unbalanced 479, 483
Load factor 438
  Decreasing 446
Loads
  Sharing of 46, 443
  Unbalanced 323
Load schedule 5, 445
Load shedding
  High speed 436
  Low speed 436, 440
  Priority table 439
Locked rotor apparent power 107
Locked rotor current 109
Locked rotor torque 109
Long delay setting 348
Long delay time 348
Loss of accuracy 486
Losses
  Active power 70
  Core-loss in a transformer 134
  Dirty engine 38
  Eddy current 100
  Fans and bearings 500
  Gearbox 13, 38
  Generator 38
  Heat in motors 121
  Ohmic power, in harmonic systems 410
  Power dissipation from harmonic filters 431
  Resistive 500
  Reactive power 70
  Silencer, filter and ducting 38
  Turbine 29
Lower calorific value 35
Lower explosive limit 252

Machines, centrifugal 122
Magnetic flux 99
Magnetic saturation knee-point 401
Magnetic saturation in generators 401
Magnetic saturation in transformers 401
Magnetising current 140
  In induction motors 393
  Of transformer 324
Magneto-motive force, MMF 63
Master load schedule 2
Materials
  Cable insulation 188, 192
  Cable sheathing 188, 192
Mathematical models
  of machines and control systems 33
  transient and sub-transient power equations 53
Maximum asymmetrical current in fuses 176
Melting time 174
Merz-price, see protection 333, 334
  Differential current 340
Micro-computer based intelligence, for switchgear 159
Micro-computer chips 347
Micro-computer control system 397
Modules
  Electronic relay, in switchgear 159
  Solid state, for use in switchgear 164
Molded case circuit breakers 144, 162, 163, 164, 165
Moment of inertia 11
Motor control center 143, 144, 155, 157, 158, 209
Motor feeder cable 123
Motor run-up time 318
Motors
  AC commutator 388
  Commutator 385

Motors (*Continued*)
  DC shunt, series and compound wound 385
  Pole amplitude modulation 390
  Pole changing 388, 390
  Synchronous 385
Multi-generator system 306
Multiplying factors for peak fault currents 292
Mutual coupling 67, 406
Mutual inductances 374, 481, 485, 493
  Between winding in D-axis 480
  Between winding in Q-axis 480
Mutual or magnetising flux 131
Mutual reactances
  Between winding in D-axis 480
  Between winding in Q-axis 480

Nameplate
  Rating of loads 437
  Total power 439
  Voltage of motors 210
Nameplates,
  markings for hazardous area equipment 266
Navigation aids 463
  Aircraft warning lights 465
  Buoys 465
  Echo-sounding devices 466
  Flashing marker lights 464
  Identification panels for offshore platforms 465
  Synchronization of flashing lights 465
  White and red flashing lights 464
Neutral busbars 146
Neutral earthing resistance 80, 355, 357, 585, 596
Neutral earthing
  High impedance 355
  Resistor 333, 355, 370
Noise
  As harmonic currents and voltages 387
  Electromagnetic 372, 379
  Pick-up 373, 382
  Voltages in current source inverters 423
Nomographs for voltage drop when starting motors 571
Non-drive end 78, 80, 120
Non-essential load 3
Non-hazardous area 253
Normal load 3
Notation,
  Cable composition 192
  Earthing and grounding 355
  Numbering system of transformer windings 137
  Transient and sub-transient impedances of motors 493
Notching distortion 406

Overhead
  Earthing conductor 370
  Power lines 329
  Line pole and fences 367, 369
  Transmission line 422, 432, 585
Operating temperature of a gas turbine 437, 441

Parallel redundant uninterruptible power supplies 457
Partial discharging in insulation 373
Peak asymmetrical current 151
Peak let-through current in fuses 176
Permanent magnet 89
Per-unit
  System base parameters 579
  Torque 486
Phase-to-neutral emf 407
Phase angle displacement 137
Phasor diagram 64, 275
Philosophy, N-1 9, 12
Phosphor bronze, in cables used as armouring 185
Plants
  Land-based 78, 353, 354
  Land-based, earthing systems 367
  Land-based installations 363
  Liquified natural gas, emergency generators 325
  Liquified natural gas, large compressors in 336
  Off-shore 138
  Off-shore and marine installations 363
  Self-contained generating 273
  Utility power 332
Plastic 184, 188
Point of connection, to a utility supply 356
Poles 99
Portable lambs and torches 460
Power
  Active 69, 441, 443
  Active, in harmonic systems 410
  Active, summation in estimating load 199

  Amplifier 54, 84
  Consumption 9
  Factor of load 5
  Factor of the fundamental current 410
  Invariance in generalised machines 484
  Management system 435
  Net available from the power turbine 26
  Reactive 69, 83, 443
  Reactive in harmonic systems 410
  Reactive, summation in estimating load 199
  System frequency 441
  System, fully loaded 311
  System, lightly loaded 311
  Systems, national grid 431
  Transistors and thyristors 385, 402
  Transistors controllers 391, 394
  Utility company 328
Potential gradient, maximum in cable insulation 373
Potential difference in earthed systems 355
Power angle chart 72
Power factor 64, 85
Power factor leading 73
Power factor of a transformer 140
Power factor of short circuit current 174
Power-to-weight ratio 20
Power-to-weight ratio, high 19, 20
Power turbine 19
Power utility company 8, 20
Pre-arcing time 174
Pressure drops 32
  Combustion chamber 33
  Compressor discharge 33
  Turbine exhaust 33
Pressure ratio 31, 33
Prime-movers 13, 304
  Gas turbines 41
  Under and over frequency 325
  Upgrading 13
Projects, new 5
Prospective current in fuses 176
Prospective fault current 79
Protective relays
  Admittance type 320
  Buchholz 139, 398
  Coordination 312
  Differential stator current 80, 318, 326
  Earth fault 124
  Earth leakage current 451
  Earth leakage detection 242, 323
  Electronic 336
  Field winding earth fault 326
  Inverse time 124
  Lock-out 436
  Long time delay characteristic 163
  Negative phase sequence current 322, 326
  Nominal current 348
  Overvoltage 318
  Restricted earth fault 323
  Reverse power 448
  Sensitive earth current 596
  Short time delay characteristic 163
  Synchronising check 158
  Thermal 124, 337
  Undervoltage 159, 318, 335
  Voltage restrained overcurrent 316
Protective relays and devices 311
  Cascaded devices 451
  IEEE numbers 313
  Notation used for 313
Protection schemes and systems
  Back-up 318, 333
  Cold and hot thermal, for motors 340, 344
  Coordination 312
  Coordination of earth fault devices 333
  Core-balance 242, 333, 345
  Core-balance for fluorescent lighting 346
  Core-balance for static loads 346
  Core-balance for welding socket outlets 346
  Definite time 316
  Differential busbar zone 334
  Excessive vibration in motors 342
  Fuses 333
  High-set overcurrent for static loads 346
  High-set current 330
  High bearing temperature of motor 342
  High speed differential current 333
  Instantaneous current 330, 332
  Instantaneous overcurrent for static loads 346
  Instantaneous tripping function 339
  Inverse square law 330
  Loss of excitation 320
  Merz-price scheme 333
  Multi-zone distance 332
  Of high voltage motors 336
  Overcurrent and overvoltage in battery charger 452
  Overcurrent in cables 332
  Overcurrent in inverters 450
  Overcurrent in the bus-section circuit 335
  Overloading for motors 336

Protection schemes and systems (*Continued*)
  Over-temperature 540
  Repeated starting of motors 341
  Single-phase for motors 344
  Thermal image 343
  Thermal image for motors 336, 343
  Time delayed overcurrent for static loads 346
  Underfrequency 11, 540
  Underfrequency multi-stage 540
  Undervoltage at high voltage busbars 335
Pumps 385, 386, 402
  Centrifugal 108, 396
  For transformers 138
  Submersible 394
  Variable speed drives for 433, 495
Purging systems for motors 386

Radial interconnecting circuits in relation to earthing 277, 382
Radial, stress pattern in the insulation of cables 373
Radiator, for transformers 138
Ratings
  Motors 13
  ISO for gas turbines 37
Ratio
  Dynamic to static 306
  Generator to motor ratings 581
  Power to weight 19
  Starting to rated current of an induction motor 107, 280, 573, 584
  Three-speed induction motors 391
  Two-speed induction motors 390
  Voltage-to-frequency, control of air gap flux 399
Ratio, X-to-R, see X-to-R ratio 108
Reacceleration of motors 159, 210, 335, 447, 540
Reactance
  Commutating 407
  D-axis sub-transient 488
  D-axis synchronous 488
  D-axis transient 488
  Derived 62, 491, 492, 495
  Direct axis 62
  Direct axis sub-transient 63
  Direct axis synchronous 62
  Direct axis transient 63
  External 492
  Field leakage 68
  Inductive 99, 174
  Negative phase sequence 489
  Q-axis sub-transient 488
  Q-axis synchronous 488
  Quadrature 274
  Quadrature axis 62
  Quadrature axis sub-transient 63
  Quadrature axis synchronous 62
  Quadrature axis transient 63
  Rotor leakage 101
  Series connected external 481
  Stator winding leakage, armature leakage 67
  Sub-transient 79, 153, 273, 274, 501, 502
  Synchronous 71, 87, 273, 479
  Transient 273, 274, 479, 502, 573
  Zero-phase sequence 489
Reactive power 4, 5
Reactors
  Use of 294
  Air-cored 299
  Dry-type 299
  Liquid immersed 299
  Fault current limiting 295
  Iron-cored 299
  Zig-zag connected for earthing 358
Receiving end of a cable 333
Receiving end of a transmission link 301
Receiving end of voltage 303
Reciprocating compressors 345
Reciprocating machinery 307
Rectifier-inverter system for soft starting motors 127, 397
Reference
  Voltage 84
  Points in earthing 382
Refrigeration, LNG plants 3
Regulation 84
  Speed 106
  Feedback 389
  Of speed 325
  Voltage 89
  Voltage, of a transformer 135
Relative vapour density 252
Relay coordination, see Protection
Relays, under and over frequency protective 11
Reluctance 67
Residual magnetism 88
Resistances
  Armature or stator winding 480
  D-axis damper winding 480

  D-axis field winding 480
  Q-axis damper winding 480
  Series connected external 480
Resistance armature 71
Resistance of the human body 352
Resistance temperature detectors 139
Resistance to earth 368, 590
Resonance 402
Restarting of motors 159
Retardation angle 404
Ring interconnecting circuits in relation to earthing 382
Ring main station 277, 369
Ripple, average voltage 408
Ripple number 408
Rotationally induced 483
Rotor, see induction motors 61
  Field 61
  High resistance, induction motor 389
  Pole face 294
  Wound type, induction motor 389
Rotor angular position 306, 484
Rotor bars 101
Rotor bars, caged 78
Rotor poles and damper bars 322
Rubber 187
  Natural 187
  Silicon 196
  Synthetic 187
  Vulcanized 187
Rubber, mats used in switchrooms 367
Rule-of-thumb,
  Auxiliary power 37
  Dirty engine losses 38
  Drop terminal voltage 122
  For cascaded devices 451
  For charging current of batteries 454
  For extra capacity in switchgear 149
  Letters and numbers for windings 136
  Losses due to silencing and filtering 39
  Power factor of bridges 413
  Ratio of motor kW to supply kW capacity 124
  Ratio of ratings of generators to motors 442
  Sizing induction motors 14
  Spacing of cables to avoid harmonic coupling 406
Run-up time, long 325, 329
Safety 234
Safety of personnel 3
Saliency of the pole surface, sub-transient current due to 150
Saliency, sub-transient 492
Salient pole rotor construction 61
Safety 325
Salient pole generators 322
Saturation constants 93
Saturation function 89
Scheduling the shutting-down of main generators 445
Scheduling the starting-up of main generators 445
Screening
  Aluminium foil in cables 381
  Braided armouring 379
  Braided armour in cables 381
  Common circuit conduction 373
  Cut-off at high frequencies 380
  Eddy currents 381
  Effectiveness 379
  Electromagnetic or mutual inductive coupling 373
  Electrostatic discharging 380
  Electrostatic or capacitive coupling 373
  Fault currents 374
  Harmonic currents 374
  High frequency attenuation 379
  Holes in braiding 381
  Low frequency interference 379
  Noise cancellation 379
  Off-shore signal cables 379
  Pick-up of noise 382
  Shield transfer impedance 380
  Signal conditioning units 382
  Surge currents 374
  Source of interference 375
  Unbalanced core and screen currents 379
  Unbalanced currents 374
  Virtual earth in an electronic amplifier 379
Self-excitation 88
Sending end of a cable 333
Sending end of a transmission link 301
Sending end voltage 303
Sensitive earth leakage current detectors 356
Series reactor for starting motors 128
Series resonant branch of a filter 433
Set-points
  For the inverter 399
  Of automatic voltage regulation 448
  Of speed governors 448

Shaft torque and shaft power 486
Sharing of active power 444, 448
Sharing of reactive power 444, 447
Short circuit current 223, 269
  Current doubling 283
  DC part 150, 502
  Double frequency AC part 150
  Fundamental AC part 150
  Impedance 99
  Instantaneous 492
  Peak 145, 274, 293
  Peak let-through 176, 225
  RMS 274, 293
Short circuit,
  Line-to-line-to-line or three-phase 282, 492
  Not involving earth 333
Short delay setting 348
Short delay time 348
Shutdown, of gas turbine generators 20
Signals
  Raise and lower 84
  Least selector device 59
Silencing, inlet and exhaust 32
Silicon controlled rectifiers 385
Single line diagram 14
Single-phase protection 155
Single-phase transformer 131
Slewing characteristics in control systems 56
Slip 104
  At harmonic frequencies 423
  Full-load 101
  Rings 88, 490
Slip energy recovery 388
Slots, in induction motor stator 129
Soft starting of submersible pumps 396
Soil resistivity 367, 368
Solidly earthed secondary winding 328
Solidly earthed start points 358
Source of ignition 251
Spare
  Feeder 8
  Generator 8
  N-1 philosophy 9
Sparks, electrical and mechanical 251, 252
Spark, in a neutral circuit 365
Specifications
  Abbreviated tests 474
  Desirable requirements 470
  Essential requirements 470
  Hazardous areas 472
  High ambient temperatures 471, 472
  Incidental requirements 470
  Ingress protection 473
  Inspection and testing 474
  Modes of operation of the power system 472
  Performance tests 474
  Production tests 474
  Routine tests 474
  Short circuit withstand performance 473
  Special tests 474
  Temperature rise limits 473
  Type tests 474
  Typical format 470
Specific heat
  At constant pressure 26, 27, 31
  At constant volume 26
Speed governing 39
  Closed-loop 41
  Derivative damping 56
  Droop control 43, 44
  Gain 52
  Integral control 44
  Isochronous control 43, 44
  Load sharing 46
  Open-loop 39
  Power or load sharing between gas turbines 44
  Proportional control 44
  Transfer function gain 43
Speed or frequency versus load sharing between gas turbines 46
Speed regulation in a variable speed drive system 400
Stability
  And hunting 295
  Limit of transient 306
  Of relays 319
  Steady state 300
  Studies 300
Stalling time, maximum for an induction motor 125, 341
  Steel wire braid armour 186
  Steel wire armour 186
Standard voltages 191
Standby redundant uninterruptible power supplies 457
Standing load at a switchboard 312
Star, connected winding 100
Star connected motors 192
Star-delta stator winding 388
Star-delta transformer 328

Star point
  At the sending end 333
  Connection to earth 323
  Earthing of 224
  Earthing through an impedance 328, 333, 358
  Low voltage system 355
  See also neutral point 80
Starting
  Auto-transformer method 126
  Korndorfer method 126, 573
  Part winding method 129
  Reduced voltage 126, 573
  Series reactor method 128
  Soft-start method 127
  Star-delta method 126
Starting and run-up current 107
Starting current 106
Starting gas turbines,
  DC motors, air motors, batteries 39
Starting or run-up time, induction motor 125, 225, 329
Starting times, long 336
States
  Dynamic 64
  No-load 108
  Steady 64
  Sub-transient 70
  Transient 70
State, dirty engine 439, 445
Static resistance bank, for slip ring motors 391
Stator 99
  Armature 61
  Slots 67
Stator current
  Peak-to-peak value 63
  Root-mean-square value 63
Stator current versus speed 100
Steel
  Carbon 185
  Galvanised 185
  Mild 185
Stiction 108
Still air conditions 252
Structures
  Made of concrete and brick 353
  Made of steel 353
Studies
  Preliminary 73
  Transient stability 73
Studies, stability 300, 335
Submarine cable 73, 185, 402
Submersible pumps 394
Sub-system, unearthed 353
Sulphur,
  Hexafluoride gas 147
  In cables 187
Switchgear 143
  Metal clad type 144
  Neutral busbars 146
  Switching devices 154
Switchboard 3
Switchboard, main 277
Symmetrical component theory 483, 585
Synchronising facilities 3
Synchronous
  Generators 72, 83, 273, 479, 480
  Machines 62
  Motors 61, 294
  Reactance 62, 85
  Reference frame 487, 496
  Source and sink 302
  Speed 55, 63, 100, 487, 496
System
  Control and data acquisition, SCADA 159, 336, 435, 448
  Earthing 356
  Frequency 48, 540
  Governor control 322
  Grids and rods for an earthing 352
  Interconnected 305
  Interconnected, tightness and looseness 306
  Meshed or looped 277
  Modes of operation 472
  Multi-machine 306
  Power management 435
  Radial 276, 292, 311
  Ring-main 277
  Selv and Pelv, in relation to earthing 364
  Solidly earthed low voltage 365
  Three-phase star connected 356
  Transmission 72
  Unearthed 329
    drilling rigs and low voltage supplies 323
System control and data acquisition,
  interfacing with switchgear 159
Systems and schemes
  Interlocking 16
  Synchronising 16

Tacho-generator for feedback of speed 399
Temperature
  Ambient 471, 472
  Ambient air 199
  Ambient for batteries 456
  Cable conductors 199, 223
  Class, in hazardous area classification 252
  Combustion 11, 26
  High ambient 121
  Initial, for cable conductors 222
  Maximum surface, for cable conductors 222
  Operating, of a gas turbine 437, 441
  Standard ground 199
Temperature rise 473
  Insulation Class B, Class F 79
Teredo worms, damage to cables 185
Terminal boxes 80
Terminal voltage 64, 85, 315, 324
  Transformer at full-load 135
  Transformer at no-load 135
Termites and ants, damage to cables 185
Thermal withstand time of neutral earthing resistors 323
Thermocouples 342
Thermodynamic
  Adiabatic compression 24
  Entropy 24
  Joule cycle or simple cycle 24
  Relationships, P, V, T and S 24
Third harmonic current 323
Three-phase
  Fault 80, 492
  Fault inside a terminal box 123
  Transformer 140
  Winding 99, 129
Threshold limit of fibrillation 351, 367
Throttle valve control for pumps 397
Thyristor 385, 422, 450
  Controllers 387
  Controllers for DC motors on drilling rigs 394
  Inverters 387, 450
  Rectifier 392
  Rectifier-inverter 392
Time characteristics of relays
  Definite 329
  Extremely inverse 329, 330, 333, 347
  Standard inverse 329, 330, 333, 347
  Very inverse 329, 330, 333, 347
Time constants 73, 83, 479, 488, 491
  Armature 489, 493, 502
  Armature, of AC machines 153
  D-axis damper leakage 488
  D-axis sub-transient open-circuit 488
  D-axis sub-transient short-circuit 488
  D-axis transient open-circuit 488
  D-axis transient short-circuit 488
  Q-axis damper leakage 489
  Q-axis sub-transient open-circuit 489
  Q-axis sub-transient short-circuit 489
Thermal, of high voltage motors 337
Thermal, of low voltage motors 343
Transient and sub-transient direct axis 332
Time
  Critical, of motors 125
  Disconnection 236
  Margin between relays and devices 335
  Stalling, of motors 341
Time multiplier setting 316, 318, 322, 348
Tin, in cables used with conductors and armouring 184
Tolerances 78, 109
  Data for computer programs 481
  Level of harmonic voltages and currents 531
  Of harmonics 398
  Power system data 479
  Wider for the Q-axis data 480
Torque 99, 103
  Breakdown for an induction motor 106
  Constant versus speed 108
  Full-load 104
  Maximum for an induction motor 106
  Pull up an induction motor 106
  Quadratic versus speed 108
  Starting 104
Torque versus speed 108
Torque versus speed curve of a motor 399
Transformers 12
  Current 83
  Delta-star, in rectifier bridges 417, 419
  Double-wound isolating 364
  Equivalent 278
  Feeders 326
  Induction 63
  Leakage reactance 402
  Phase shift in rectifier 417
  Single phase 131
  Star point 328
  Star-star, in rectifier bridges 419
  Three-winding type 328

- Voltage 83
- Zig-zag connected for earthing 358

Transformer construction
- Conservator type 139
- Dry-type 137
- Liquid immersed type 137
- Oil 138
- Resin insulated 138
- Sealed tank type 140
- Synthetic liquids 138

Transformer induced 482
Transient stability studies 70, 300
Transmission link 70
Transmission network 332
Transmission power, long distance 422
Transmission system 72
- Capacitance charging current 72

Trending of
- Active power 448
- Engine parameters 448
- Generator parameters 448
- Reactive power 448

Turbine
- High pressure 22
- Low pressure 22

Typical data 73
- For switchgear busbars 145
- Impedances of a transformer 133

Unbalanced loads 145
Unbalanced stator currents 322
Unearthed systems 329
Uninterruptible power supplies, AC 449
Uninterruptible power supplies, DC 451
Uninterruptible power supplies, UPS 3
Upper explosive limit 352
Upstream
- Coordination of contactor with its fuses 343, 344
- Devices 348
- Inverter 450
- Source protection characteristics 332

Upsteam, fuses 330
Upstream switchgear 157, 163
Utility grid 72
Utility, large public 306

Vacuum 147
Variables
- Receiving-end 68
- Sending-end 68

Variable pumping capability for submersible pumps 396
Variable speed motors and drivers 471, 385, 495
Variable torque control for submersible pumps 396
Ventricular fibrillation of the human heart 351
Vertical rods 355
Virtual time 178
Vital load 3
Volt drop 64, 79
- At main switchboard busbars 79
- Calculation 559
- Compensation in motor cables 399
- Effect of generator impedance 577
- Full-load running current of motors 220
- Graphical estimation 125, 580
- Harmonic 406
- In a transformer 131, 135
- In cables 209
- In long cables 213
- In long motor feeder cables 159
- In motor feeder cables 220
- In short cables 209
- Maximum route length of a motor feeder cable 220, 223
- Nomographical method 125, 584
- Per-unit 571
- Reactive 295
- Resistive 484, 490
- Starting current of motors 220

Voltage
- Control of the rectifier 399
- Depressions 210
- Dip at generator terminals 318
- Driving earth fault current 366
- Feedback 399
- Magnitude error 447
- Phase angle error 447
- Phase-to-neutral 235, 339, 499, 502
- Phase-to-neutral, for lighting circuits 460
- Phase-to-phase 339
- Receiving end 303
- Recovery of system 307
- Reference for AVR 84
- Regulation 89
- Restrained relay 324
- Restraining element 326
- Restraint of overcurrent relays 316
- Sending end 303

Voltage (*Continued*)
  Standard 191
  Transformer 83
  To frequency ratio 399
  Unbalanced 339
Voltage source, constant 269

Water table, burial of cables 186
Windings
  Connections 136
  Delta 136
  Letters and numbers 136
  Primary of machines 496
  Primary of a transformer 131
  Secondary of machines 496
  Secondary of a transformer 131
  Star 136
  Zig-zag 136
Work done on the generator 32
Worst case situation
  For DC off-set of fault current 287, 503
  For design of earth loop impedance 366
  For fault making current 149, 492
  For generator parameters 73
  Fully asymmetrical current 174
  Maximum fault making duty 277
  Overall derating of cables 206
  Slip 122
  Still air conditions 252

X-to-R ratio 108, 151, 174, 271, 274, 291, 293, 294, 320, 393

Zenor diodes 347
Zero reference potential 351
Zone 0 hazardous area 254
Zone 1 hazardous area 253
Zone 2 hazardous area 253