- Preface p. iii
- 1 Introduction and General Philosophies p. 1
- 1 Introduction p. 1
- 2 Classification of Relays p. 1
- 2.1 Analog/Digital/Numerical p. 2
- 3 Protective Relaying Systems and Their Design p. 2
- 3.1 Design Criteria p. 3
- 3.2 Factors Influencing Relay Performance p. 4
- 3.3 Zones of Protection p. 4
- 4 Applying Protective Relays p. 4
- 4.1 System Configuration p. 5
- 4.2 Existing System Protection and Procedures p. 5
- 4.3 Degree of Protection Required p. 5
- 4.4 Fault Study p. 5
- 4.5 Maximum Loads, Transformer Data, and Impedances p. 6
- 5 Relays and Application Data p. 6
- 5.1 Switchboard Relays p. 6
- 5.2 Rack-Mounted Relays p. 7
- 6 Circuit-Breaker Control p. 8
- 7 Comparison of Symbols p. 9
- 2 Technical Tools of the Relay Engineer: Phasors, Polarity, and Symmetrical Components p. 11
- 1 Introduction p. 11
- 2 Phasors p. 11
- 2.1 Circuit Diagram Notation for Current and Flux p. 11
- 2.2 Circuit Diagram Notation for Voltage p. 12
- 2.3 Phasor Notation p. 12
- 2.4 Phasor Diagram Notation p. 13
- 2.5 Phase Rotation vs. Phasor Rotation p. 15
- 3 Polarity in Relay Circuits p. 15
- 3.1 Polarity of Transformers p. 15
- 3.2 Polarity of Protective Relays p. 15
- 3.3 Characteristics of Directional Relays p. 16
- 3.4 Connections of Directional Units to Three-Phase Power Systems p. 17
- 4 Faults on Power Systems p. 18
- 4.1 Fault Types and Causes p. 18
- 4.2 Characteristics of Faults p. 20
- 5 Symmetrical Components p. 21
- 5.1 Basic Concepts p. 21
- 5.2 System Neutral p. 23
- 5.3 Sequences in a Three-Phase Power System p. 23
- 5.4 Sequence Impedances p. 24
- 5.5 Sequence Networks p. 26
- 5.6 Sequence Network Connections and Voltages p. 27

- 5.7 Network Connections for Fault and General Unbalances p. 28
- 5.8 Sequence Network Reduction p. 29
- 5.9 Example of Fault Calculation on a Loop-Type Power System p. 32
- 5.10 Phase Shifts Through Transformer Banks p. 37
- 5.11 Fault Evaluations p. 39
- 6 Symmetrical Components and Relaying p. 42
- 3 Basic Relay Units p. 43
- 1 Introduction p. 43
- 2 Electromechanical Units p. 43
- 2.1 Magnetic Attraction Units p. 43
- 2.2 Magnetic Induction Units p. 45
- 2.3 D'Arsonval Units p. 47
- 2.4 Thermal Units p. 47
- 3 Sequence Networks p. 47
- 3.1 Zero Sequence Networks p. 47
- 3.2 Composite Sequence Current Networks p. 48
- 3.3 Sequence Voltage Networks p. 49
- 4 Solid-State Units p. 50
- 4.1 Semiconductor Components p. 50
- 4.2 Solid-State Logic Units p. 52
- 4.3 Principal Logic Units p. 52
- 5 Basic Logic Circuits p. 54
- 5.1 Fault-Sensing Data Processing Units p. 54
- 5.2 Amplification Units p. 59
- 5.3 Auxiliary Units p. 59
- 6 Integrated Circuits p. 63
- 6.1 Operational Amplifier p. 63
- 6.2 Basic Operational Amplifier Units p. 65
- 6.3 Relay Applications of Operational Amplifier p. 68
- 7 Microprocessor Architecture p. 70
- 4 Protection Against Transients and Surges W. A. Elmore p. 71
- 1 Introduction p. 71
- 1.1 Electrostatic Induction p. 71
- 1.2 Electromagnetic Induction p. 72
- 1.3 Differential- and Common-Mode Classifications p. 72
- 2 Transients Originating in the High-Voltage System p. 73
- 2.1 Capacitor Switching p. 73
- 2.2 Bus Deenergization p. 73
- 2.3 Transmission Line Switching p. 74
- 2.4 Coupling Capacitor Voltage Transformer (CCVT) Switching p. 74
- 2.5 Other Transient Sources p. 74
- 3 Transients Originating in the Low-Voltage System p. 74
- 3.1 Direct Current Coil Interruption p. 74
- 3.2 Direct Current Circuit Energization p. 75

- 3.3 Current Transformer Saturation p. 75
- 3.4 Grounding of Battery Circuit p. 75
- 4 Protective Measures p. 75
- 4.1 Separation p. 75
- 4.2 Suppression at the Source p. 77
- 4.3 Suppression by Shielding p. 77
- 4.4 Suppression by Twisting p. 77
- 4.5 Radial Routing of Control Cables p. 78
- 4.6 Buffers p. 78
- 4.7 Optical Isolators p. 78
- 4.8 Increased Energy Requirement p. 79
- 5 Instrument Transformers for Relaying W. A. Elmore p. 81
- 1 Introduction p. 81
- 2 Current Transformers p. 81
- 2.1 Saturation p. 81
- 2.2 Effect of dc Component p. 82
- 3 Equivalent Circuit p. 82
- 4 Estimation of Current Transformer Performance p. 82
- 4.1 Formula Method p. 83
- 4.2 Excitation Curve Method p. 83
- 4.3 ANSI Standard: Current Transformer Accuracy Classes p. 85
- 5 European Practice p. 87
- 5.1 TPX p. 88
- 5.2 TPY p. 88
- 5.3 TPZ p. 88
- 6 Direct Current Saturation p. 88
- 7 Residual Flux p. 89
- 8 MOCT p. 91
- 9 Voltage Transformers and Coupling Capacitance Voltage Transformers p. 91
- 9.1 Equivalent Circuit of a Voltage Transformer p. 91
- 9.2 Coupling Capacitor Voltage Transformers p. 92
- 9.3 MOVT/EOVT p. 93
- 10 Neutral Inversion p. 93
- 6 Microprocessor Relaying Fundamentals W. A. Elmore p. 95
- 4 How to Overcome Aliasing p. 98
- 1 Introduction p. 95
- 2 Sampling Problems p. 97
- 3 Aliasing p. 97
- 4.1 Antialiasing Filters p. 98
- 4.2 Nonsynchronous Sampling p. 98
- 5 Choice of Measurement Principle p. 99
- 5.1 rms Calculation p. 100
- 5.2 Digital Filters p. 100
- 5.3 Fourier-Notch Filter p. 100

- 5.7 Leading-Phase Identification p. 102
- 5.4 Another Digital Filter p. 101
- 5.5 dc Offset Compensation p. 101
- 5.6 Symmetrical Component Filter p. 102
- 5.8 Fault Detectors p. 102
- 6 Self-Testing p. 103
- 6.1 Dead-Man Timer p. 103
- 6.2 Analog Test p. 103
- 6.3 Check-Sum p. 103
- 6.4 RAM Test p. 103
- 6.5 Nonvolatile Memory Test p. 103
- 7 Conclusions p. 104
- 7 System Grounding and Protective Relaying p. 105
- 1 Introduction p. 105
- 2 Ungrounded Systems p. 105
- 2.1 Ground Faults on Ungrounded Systems p. 105
- 2.2 Ground Fault Detection on Ungrounded Systems p. 107
- 3 Reactance Grounding p. 108
- 3.1 High-Reactance Grounding p. 108
- 3.2 Resonant Grounding (Ground Fault Neutralizer) p. 109
- 3.3 Low-Reactance Grounding p. 109
- 4 Resistance Grounding p. 110
- 4.1 Low-Resistance Grounding p. 110
- 4.2 High-Resistance Grounding p. 111
- 5.3 Ground Overcurrent Relay with Zero Sequence Current Transformers p. 114
- 5 Sensitive Ground Relaying p. 112
- 5.1 Ground Overcurrent Relay with Conventional Current Transformers p. 112
- 5.2 Ground Product Relay with Conventional Current Transformers p. 113
- 6 Ground Fault Protection for Three-Phase, Four-Wire Systems p. 114
- 6.1 Unigrounded Four-Wire Systems p. 114
- 6.2 Multigrounded Four-Wire Systems p. 115
- 8 Generator Protection p. 117
- 1 Introduction p. 117
- 2 Choice of Technology p. 117
- 3 Phase Fault Detection p. 117
- 3.1 Percentage Differential Relays (Device 87) p. 118
- 3.2 High Impedance Differential Relays (Device 87) p. 119
- 3.3 Machine Connections p. 119
- 3.4 Split-Phase p. 119
- 4 Stator Ground Fault Protection p. 120
- 4.1 Unit-Connected Schemes p. 120
- 4.2 95% Ground Relays p. 120
- 4.3 Neutral-to-Ground Fault Detection (Device 87N3) p. 121
- 4.4 100% Winding Protection p. 122

- 5 Backup Protection p. 123
- 5.1 Unbalanced Faults p. 123
- 5.2 Balanced Faults p. 124
- 6 Overload Protection p. 126
- 6.1 RTD Schemes (Device 49) p. 126
- 6.2 Thermal Replicas (Device 49) p. 126
- 7 Volts per Hertz Protection p. 126
- 8 Overspeed Protection p. 126
- 9 Loss-of-Excitation Protection p. 127
- 9.1 Causes of Machine Loss of Field p. 127
- 9.2 Hazard p. 127
- 9.3 Loss-of-Field Relays p. 128
- 9.4 KLF and KLF-1 Curves p. 129
- 9.5 Two-Zone KLF Scheme p. 129
- 10 Protection Against Generator Motoring p. 130
- 10.1 Steam Turbines p. 131
- 10.2 Diesel Engines p. 131
- 10.3 Gas Turbines p. 131
- 10.4 Hydraulic Turbines p. 131
- 11 Inadvertent Energization p. 132
- 12 Field Ground Detection p. 134
- 12.1 Brush-Type Machine p. 135
- 12.2 Brushless Machines p. 136
- 12.3 Injection Scheme for Field Ground Detection p. 136
- 13 Alternating-Current Overvoltage Protection for Hydroelectric Generators p. 136
- 14 Generator Protection at Reduced Frequencies p. 136
- 15 Off-Frequency Operation p. 138
- 16 Recommended Protection p. 139
- 17 Out-of-Step Protection p. 139
- 18 Bus Transfer Systems for Station Auxiliaries p. 139
- 18.1 Fast Transfer p. 139
- 18.2 Choice of Fast Transfer Scheme p. 140
- 18.3 Slow Transfer p. 142
- 19 Microprocessor-Based Generator Protection p. 143
- 9 Motor Protection p. 145
- 1 Introduction p. 145
- 1.1 General Requirements p. 145
- 1.2 Induction Motor Equivalent Circuit p. 146
- 1.3 Motor Thermal Capability Curves p. 146
- 2 Phase-Fault Protection p. 147
- 3 Ground-Fault Protection p. 147
- 4 Locked-Rotor Protection p. 149
- 5 Overload Protection p. 153
- 6 Thermal Relays p. 153

- 6.1 RTD-Input-Type Relays p. 154
- 6.2 Thermal Replica Relays p. 154
- 7 Low-Voltage Protection p. 155
- 8 Phase-Rotation Protection p. 155
- 9 Negative Sequence Voltage Protection p. 155
- 10 Phase-Unbalance Protection p. 156
- 11 Negative Sequence Current Relays p. 157
- 12 Jam Protection p. 157
- 13 Load Loss Protection p. 157
- 14 Out-of-Step Protection p. 158
- 15 Loss of Excitation p. 158
- 16 Typical Application Combinations p. 159
- 2.1 Initial Inrush p. 163
- 10 Transformer and Reactor Protection p. 163
- 1 Introduction p. 163
- 2 Magnetizing Inrush p. 163
- 2.2 Recovery Inrush p. 163
- 2.3 Sympathetic Inrush p. 165
- 3 Differential Relaying for Transformer Protection p. 166
- 3.1 Differential Relays for Transformer Protection p. 166
- 3.2 General Guidelines for Transformer Differential Relaying Application p. 171
- 4 Sample Checks for Applying Transformer Differential Relays p. 173
- 4.1 Checks for Two-Winding Banks p. 173
- 4.2 Checks for Multiwinding Banks p. 178
- 4.3 Modern Microprocessor Relay p. 180
- 5 Typical Application of Transformer Protection p. 180
- 5.1 Differential Scheme with Harmonic Restraint Relay Supervision p. 180
- 5.2 Ground Source on Delta Side p. 182
- 5.3 Three-Phase Banks of Single-Phase Units p. 183
- 5.4 Differential Protection of a Generator-Transformer Unit p. 183
- 5.5 Overexcitation Protection of a Generator-Transformer Unit p. 184
- 5.6 Sudden-Pressure Relay (SPR) p. 185
- 5.7 Overcurrent and Backup Protection p. 185
- 5.8 Distance Relaying for Backup Protection p. 192
- 5.9 Overcurrent Relay with HRU Supplement p. 192
- 6 Typical Protective Schemes for Industrial and Commercial Power Transformers p. 193
- 7 Remote Tripping of Transformer Bank p. 197
- 8 Protection of Phase-Angle Regulators and Voltage Regulators p. 197
- 9 Zig-Zag Transformer Protection p. 202
- 10 Protection of Shunt Reactors p. 203
- 10.1 Shunt Reactor Applications p. 203
- 10.2 Rate-of-Rise-of-Pressure Protection p. 205
- 10.3 Overcurrent Protection p. 205
- 10.4 Differential Protection p. 206

- 10.5 Reactors on Delta System p. 207
- 10.6 Turn-to-Turn Faults p. 209
- 11 Station-Bus Protection p. 213
- 1 Introduction p. 213
- 1.1 Current Transformer Saturation Problem and Its Solutions on Bus Protection p. 213
- 1.2 Information Required for the Preparation of a Bus Protective Scheme p. 215
- 1.3 Normal Practices on Bus Protection p. 215
- 2 Bus Differential Relaying with Overcurrent Relays p. 216
- 2.1 Overcurrent Differential Protection p. 216
- 2.2 Improved Overcurrent Differential Protection p. 216
- 3 Multirestraint Differential System p. 217
- 4 High Impedance Differential System p. 219
- 4.1 Factors that Relate to the Relay Setting p. 221
- 4.2 Factors that Relate to the High-Voltage Problem p. 221
- 4.3 Setting Example for the KAB Bus Protection p. 222
- 5 Differential Comparator Relays p. 222
- 6 Protecting a Bus that Includes a Transformer Bank p. 223
- 8.2 Directional Comparison Relaying p. 227
- 7 Protecting a Double-Bus Single-Breaker with Bus Tie Arrangement p. 224
- 8 Other Bus Protective Schemes p. 226
- 8.1 Partial Differential Relaying p. 226
- 8.3 Fault Bus (Ground-Fault Protection Only) p. 227
- 12 Line and Circuit Protection p. 229
- 1 Introduction p. 229
- 1.1 Classification of Electric Power Lines p. 229
- 1.2 Techniques for Line Protection p. 229
- 1.3 Seleting a Protective System p. 229
- 1.4 Relays for Phase- and Ground-Fault Protection p. 230
- 1.5 Multiterminal and Tapped Lines and Weak Feed p. 230
- 2 Overcurrent Phase- and Ground-Fault Protection p. 231
- 2.1 Fault Detection p. 231
- 2.2 Time Overcurrent Protection p. 232
- 2.3 Instantaneous Overcurrent Protection p. 237
- 2.4 Overcurrent Ground-Fault Protection p. 238
- 3 Directional Overcurrent Phase- and Ground-Fault Protection p. 239
- 3.1 Criteria for Phase Directional Overcurrent Relay Applications p. 239
- 3.2 Criteria for Ground Directional Overcurrent Relay Applications p. 239
- 3.3 Directional Ground-Relay Polarization p. 239
- 3.4 Mutual Induction and Ground-Relay Directional Sensing p. 243
- 3.5 Applications of Negative Sequence Directional Units for Ground Relays p. 244
- 3.6 Selection of Directional Overcurrent Phase and Ground Relays p. 244
- 4 Distance Phase and Ground Protection p. 247
- 4.1 Fundamentals of Distance Relaying p. 247
- 4.2 Phase-Distance Relays p. 250

- 4.3 Ground-Distance Relays p. 254
- 4.4 Effect of Line Length p. 257
- 4.5 The Infeed Effect on Distance-Relay Application p. 260
- 4.6 The Outfeed Effect on Distance-Relay Applications p. 261
- 4.7 Effect of Tapped Transformer Bank on Relay Application p. 261
- 4.8 Distance Relays with Transformer Banks at the Terminal p. 262
- 4.9 Fault Resistance and Ground-Distance Relays p. 265
- 4.10 Zero Sequence Mutual Impedance and Ground-Distance Relays p. 265
- 5 Loop-System Protection p. 267
- 6.1 Definition of Short Line p. 270
- 5.1 Single-Source Loop-Circuit Protection p. 267
- 5.2 Multiple-Source Loop Protection p. 269
- 6 Short-Line Protection p. 270
- 6.2 Problem Associated with Short-Line Protection p. 270
- 6.3 Current-Only Scheme for Short-Line Protection p. 270
- 6.4 Distance Relay for Short-Line Protection p. 270
- 7 Series-Capacitor Compensated-Line Protection p. 273
- 7.1 A Series-Capacitor Compensated Line p. 273
- 7.2 Relaying Quantities Under Fault Conditions p. 273
- 7.3 Distance Protection Behavior p. 275
- 7.4 Practical Considerations p. 276
- 8 Distribution Feeder Protection p. 276
- 8.1 Relay Coordination with Reclosers and Sectionalizers on a Feeder p. 277
- 8.2 Coordinating with Low-Voltage Breaker and Fuse p. 277
- Appendix A Equation (12-2) p. 281
- Appendix B Impedance Unit Characteristics p. 281
- B.1 Introduction p. 281
- B.2 Basic Application Example of a Phase Comparator p. 284
- B.3 Basic Application Example of a Magnitude Comparator p. 285
- B.4 Practical Comparator Applications in Distance Relaying p. 285
- B.5 Reverse Characteristics of an Impedance Unit p. 294
- B.6 Response of Distance Units to Different Types of Faults p. 298
- B.7 The Influence of Current Distribution Factors and Load Flow p. 302
- B.8 Derived Characteristics p. 305
- B.9 Apparent Impedance p. 305
- B.10 Summary p. 306
- Appendix C Infeed Effect on Ground-Distance Relays p. 306
- C.1 Infeed Effect on Type KDXG, LDAR, and MDAR Ground-Distance Relays p. 306
- C.2 Infeed Effect on Type SDG and LDG Ground-Distance Relays p. 307
- Appendix D Coordination in Multiple-Loop Systems p. 308
- D.1 System Information p. 308
- D.2 Relay Type Selection p. 308
- D.3 Relay Setting and Coordination p. 309
- 13 Backup Protection p. 323

- 1 Introduction p. 323
- 2 Remote vs. Local Backup p. 323
- 2.1 Remote Backup p. 323
- 2.2 Local Backup and Breaker Failure p. 324
- 2.3 Applications Requiring Remote Backup with Breaker-Failure Protection p. 326
- 3 Breaker-Failure Relaying Applications p. 327
- 3.1 Single-Line/Single-Breaker Buses p. 327
- 3.2 Breaker-and-a-Half and Ring Buses p. 328
- 4 Traditional Breaker-Failure Scheme p. 329
- 4.1 Timing Characteristics of the Traditional Breaker-Failure Scheme p. 329
- 4.2 Traditional Breaker-Failure Relay Characteristics p. 330
- 4.3 Microprocessor Relays p. 331
- 5 An Improved Breaker-Failure Scheme p. 332
- 5.1 Problems in the Traditional Breaker-Failure Scheme p. 332
- 7 Special Breaker-Failure Scheme for Single-Pole Trip-System Application p. 337
- 5.2 The Improved Breaker-Failure Scheme p. 333
- 5.3 Type SBF-1 Relay p. 334
- 6 Open Conductor and Breaker Pole Disagreement Protection p. 336
- 14 System Stability and Out-of-Step Relaying W. A. Elmore p. 339
- 1 Introduction p. 339
- 2 Steady-State Stability p. 339
- 3 Transient Stability p. 340
- 4 Relay Quantities During Swings p. 341
- 5 Effect of Out-of-Step Conditions p. 343
- 5.1 Distance Relays p. 343
- 5.2 Directional Comparison Systems p. 344
- 5.3 Phase-Comparison or Pilot-Wire Systems p. 344
- 5.4 Underreaching Transfer-Trip Schemes p. 344
- 5.5 Circuit Breakers p. 344
- 5.6 Overcurrent Relays p. 344
- 5.7 Reclosing p. 344
- 6 Out-of-Step Relaying p. 345
- 6.1 Generator Out-of-Step Relaying p. 345
- 6.2 Transmission-Line Out-of-Step Relaying p. 346
- 7 Philosophies of Out-of-Step Relaying p. 346
- 7.1 Utility Practice p. 347
- 8 Types of Out-of-Step Schemes p. 347
- 8.1 Concentric Circle Scheme p. 347
- 8.2 Blinder Scheme p. 348
- 9 Relays for Out-of-Step Systems p. 348
- 9.1 Electromechanical Types p. 348
- 9.2 Solid-State Types p. 349
- 10 Selection of an Out-of-Step Relay System p. 351
- 15 Voltage Stability L. Wang p. 353

- 1 Introduction p. 353
- 1.1 Small-Disturbance Instability p. 353
- 1.2 Large-Disturbance Instability p. 355
- 1.3 Voltage Instability Incidents p. 356
- 2 Voltage Instability Indices p. 357
- 2.1 Indices Based on Current Operating Condition p. 357
- 2.2 Indices Based on Stressed System Conditions p. 360
- 2.3 Summary p. 362
- 3 Voltage Instability Protection p. 362
- 3.1 Reactive Power Control p. 362
- 3.2 Load Tap Changer Blocking Schemes p. 362
- 3.3 Load Shedding p. 362
- 3 Reclosing System Considerations p. 366
- 16 Reclosing and Synchronizing p. 365
- 1 Introduction p. 365
- 2 Reclosing Precautions p. 365
- 3.1 One-Shot vs. Multiple-Shot Reclosing Relays p. 366
- 3.2 Selective Reclosing p. 366
- 3.3 Deionizing Times for Three-Pole Reclosing p. 366
- 3.4 Synchronism Check p. 366
- 3.5 Live-Line/Dead-Bus, Live-Bus/Dead-Line Control p. 367
- 3.6 Instantaneous-Trip Lockout p. 367
- 3.7 Intermediate Lockout p. 367
- 3.8 Compatibility with Supervisory Control p. 367
- 3.9 Inhibit Control p. 368
- 3.10 Breaker Supervision Functions p. 368
- 3.11 Factors Governing Application of Reclosing p. 368
- 4 Considerations for Applications of Instantaneous Reclosing p. 368
- 4.1 Feeders with No-Fault-Power Back-Feed and Minimum Motor Load p. 369
- 4.2 Single Ties to Industrial Plants with Local Generation p. 369
- 4.3 Lines with Sources at Both Ends p. 369
- 5 Reclosing Relays and Their Operation p. 369
- 5.1 Review of Breaker Operation p. 369
- 5.2 Single-Shot Reclosing Relays p. 369
- 5.3 Multishot Reclosing Relays p. 371
- 6 Synchronism Check p. 377
- 6.1 Phasing Voltage Synchronism Check Characteristic p. 377
- 6.2 Angular Synchronism Check Characteristic p. 378
- 7 Dead-Line or Dead-Bus Reclosing p. 379
- 2 Rate of Frequency Decline p. 381
- 8 Automatic Synchronizing p. 379
- 17 Load-Shedding and Frequency Relaying p. 381
- 1 Introduction p. 381
- 3 Load-Shedding p. 383

- 4 Frequency Relays p. 384
- 4.1 KF Induction-Cylinder Underfrequency Relay p. 384
- 4.2 Digital Frequency Relays p. 385
- 4.3 Microprocessor-Based Frequency Relay p. 385
- 5 Formulating a Load-Shedding Scheme p. 385
- 5.1 Maximum Anticipated Overload p. 385
- 5.2 Number of Load-Shedding Steps p. 386
- 5.3 Size of the Load Shed at Each Step p. 386
- 5.4 Frequency Settings p. 387
- 5.5 Time Delay p. 388
- 5.6 Location of the Frequency Relays p. 388
- 6 Special Considerations for Industrial Systems p. 389
- 7 Restoring Service p. 390
- 8 Other Frequency Relay Applications p. 391
- Bibliography p. 395
- Index p. 399