

Preface ix List of Symbols, Units, and Notation xiii

CHAPTER | Introduction |

- *Case Study: Restructuring and Reregulation of the U.S. Electric Utility
 Industry 2
- 1.1 History of Electric Power Systems 5
- ⁴ 1.2 Present and Future Trends 12
 - 1.3 Electric Utility Industry Structure 15
 - 1.4 Computers in Power System Engineering 16
 - 1.5 PowerWorld Simulator 17

CHAPTER 2 Fundamentals 25

Case Study: Restructuring the Thin-Stretched Grid 26

- 2.1 Phasors 34
- 2.2 Instantaneous Power in Single-Phase ac Circuits 36
- 2.3 Complex Power 41
- 2.4 Network Equations 46
- 2.5 Balanced Three-Phase Circuits 49
- 2.6 Power in Balanced Three-Phase Circuits 57
- 2.7 Advantages of Balanced Three-Phase versus Single-Phase Systems 61

CHAPTER 3 Power Transformers 7

Case Study: How Electric Utilities Buy Quality When They Buy
Transformers 72

- 3.1 The Ideal Transformer 76
- 3.2 Equivalent Circuits for Practical Transformers 82
- 3.3 The Per-Unit System 88
- 3.4 Three-Phase Transformer Connections and Phase Shift 96
- 3.5 Per-Unit Equivalent Circuits of Balanced Three-Phase Two-Winding
 Transformers 101
- 3.6 Three-Winding Transformers 106
- 3.7 Autotransformers 109
- 3.8 Transformers with Off-Nominal Turns Ratios 111

CHAPTER 4 Transmission-Line Parameters 130

Care	Chuche	Special	Denort	Transmission	Structures	121
Case	SILION:	Special	Kenori	i ransmission	SITUCTURES	1.31

- 4.1 Transmission Line Design Considerations 145
- 4.2 Resistance 151
- 4.3 Conductance 154
- 4.4 Inductance: Solid Cylindrical Conductor 154
- 4.5 Inductance: Single-Phase Two-Wire Line and Three-Phase Three-Wire Line with Equal Phase Spacing 159
- 4.6 Inductance: Composite Conductors, Unequal Phase Spacing, Bundled Conductors 162
- 4.7 Series Impedances: Three-Phase Line with Neutral Conductors and Earth Return 170
- 4.8 Electric Field and Voltage: Solid Cylindrical Conductor 175
- 4.9 Capacitance: Single-Phase Two-Wire Line and Three-Phase Three-Wire Line with Equal Phase Spacing 178
- 4.10 Capacitance: Stranded Conductors, Unequal Phase Spacing, Bundled Conductors 180
- 4.11 Shunt Admittances: Lines with Neutral Conductors and Earth Return 184
- 4.12 Electric Field Strength at Conductor Surfaces and at Ground Level 189
- 4.13 Parallel Circuit Three-Phase Lines 192

CHAPTER 5 Transmission Lines: Steady-State Operation 199

Case Study: FACTS Technology Development: An Update 200

- 5.1 Medium and Short Line Approximations 208
- 5.2 Transmission-Line Differential Equations 215
- 5.3 Equivalent π Circuit 221
- 5.4 Lossless Lines 223
- 5.5 Maximum Power Flow 232
- 5.6 Line Loadability 234
- 5.7 Reactive Compensation Techniques 239

CHAPTER 6 Power Flows 250

Case Study: Visualizing the Electric Grid 251

- 6.1 Direct Solutions to Linear Algebraic Equations: Gauss Elimination 261
- 6.2 Iterative Solutions to Linear Algebraic Equations: Jacobi and Gauss-Seidel 265
- 6.3 Iterative Solutions to Nonlinear Algebraic Equations: Newton-Raphson 271
- **6.4** The Power-Flow Problem 275
- 6.5 Power-Flow Solution by Gauss-Seidel 281
- 6.6 Power-Flow Solution by Newton-Raphson 284
- 6.7 Control of Power Flow 292

6.8 Sparsity Techniques 2966.9 Fast Decoupled Power Flow	299				
Design Projects 1-5 307					
C					

CHAPTER 7 Symmetrical Faults 319

Case Study: The Problem of Arcing Faults in Low-Voltage Power Distribution Systems 320

- 7.1 Series R-L Circuit Transients 322
- 7.2 Three-Phase Short Circuit—Unloaded Synchronous Machine 325
- 7.3 Power System Three-Phase Short Circuits 328
- 7.4 Bus Impedance Matrix 332
- 7.5 Circuit Breaker and Fuse Selection 340

Design Project 4 (continued) 354

CHAPTER 8 Symmetrical Components 356

- 8.1 Definition of Symmetrical Components 357
- 8.2 Sequence Networks of Impedance Loads 362
- 8.3 Sequence Networks of Series Impedances 370
- 8.4 Sequence Networks of Three-Phase Lines 372
- 8.5 Sequence Networks of Rotating Machines 374
- 8.6 Per-Unit Sequence Models of Three-Phase Two-Winding
 Transformers 380
- 8.7 Per-Unit Sequence Models of Three-Phase Three-Winding
 Transformers 385
- 8.8 Power in Sequence Networks 388

CHAPTER 9 Unsymmetrical Faults 396

Case Study: Fires at U.S. Utilities 397

- 9.1 System Representation 398
- 9.2 Single Line-to-Ground Fault 403
- 9.3 Line-to-Line Fault 408
- 9.4 Double Line-to-Ground Fault 410
- 9.5 Sequence Bus Impedance Matrices 417

Design Project A (continued) 435

Design Project 6 436

CHAPTER 10 System Protection 438

Case Study: Digital Relay Reports Verify Power System Models 439

- 10.1 System Protection Components 449
- 10.2 Instrument Transformers 450
- 10.3 Overcurrent Relays 457
- 10.4 Radial System Protection 461
- 10.5 Reclosers and Fuses 466
- 10.6 Directional Relays 469

	 10.7 Protection of Two-Source System with Directional Relays 471 10.8 Zones of Protection 472 10.9 Line Protection with Impedance (Distance) Relays 475 10.10 Differential Relays 482 10.11 Bus Protection with Differential Relays 484 10.12 Transformer Protection with Differential Relays 485 10.13 Pilot Relaying 490 10.14 Digital Relaying 491 				
CHAPTER II	Power System Controls 504				
	Case Study: Meet the Emerging Transmission Market Segments 507 11.1 Generator-Voltage Control 516 11.2 Turbine-Governor Control 517 11.3 Load-Frequency Control 521 11.4 Economic Dispatch 525 11.5 Optimal Power Flow 538				
CHAPTER 12	Transmission Lines: Transient Operation 547				
	Case Study: Protecting Computer Systems Against Power Transients 548 Case Study: VariSTAR® Type AZE Surge Arresters 555 12.1 Traveling Waves on Single-Phase Lossless Lines 558 12.2 Boundary Conditions for Single-Phase Lossless Lines 561 12.3 Bewley Lattice Diagram 570 12.4 Discrete-Time Models of Single-Phase Lossless Lines and Lumped RLC Elements 575 12.5 Lossy Lines 582 12.6 Multiconductor Lines 586 12.7 Power System Overvoltages 589 12.8 Insulation Coordination 596				
CHAPTER 13	Transient Stability 608				
	Case Study: The Great Blackout 610 13.1 The Swing Equation 613 13.2 Simplified Synchronous Machine Model and System Equivalents 619 13.3 The Equal-Area Criterion 621 13.4 Numerical Integration of the Swing Equation 628 13.5 Multimachine Stability 633 13.6 Design Methods for Improving Transient Stability 638				
	Appendix 644 Index 648				