Contents

Preface to the SI Edition x	
Preface xi	
List of Symbols, Units, and Notation	xvii

CHAPTER 1

Introduction 1

Case Study: How the Free Market Rocked the Grid 2

- 1.1 History of Electric Power Systems 10
- 1.2 Present and Future Trends 17
- 1.3 Electric Utility Industry Structure 20
- 1.4 Computers in Power System Engineering 21
- 1.5 PowerWorld Simulator 22

CHAPTER 2

Fundamentals 31

Case Study: Key Connections 32

- **2.1** Phasors 40
- 2.2 Instantaneous Power in Single-Phase AC Circuits 42
- 2.3 Complex Power 47
- 2.4 Network Equations 52
- 2.5 Balanced Three-Phase Circuits 55
- 2.6 Power in Balanced Three-Phase Circuits 63
- 2.7 Advantages of Balanced Three-Phase versus Single-Phase Systems 68

CHAPTER 3

Power Transformers 87

Case Study: Power Transformers—Life Management and Extension 88

- 3.1 The Ideal Transformer 95
- 3.2 Equivalent Circuits for Practical Transformers 101
- 3.3 The Per-Unit System 107
- 3.4 Three-Phase Transformer Connections and Phase Shift 115
- 3.5 Per-Unit Equivalent Circuits of Balanced Three-Phase Two-Winding Transformers 120
- 3.6 Three-Winding Transformers 125
- 3.7 Autotransformers 129
- 3.8 Transformers with Off-Nominal Turns
 Ratios 131

CHAPTER 4

Transmission Line Parameters 161

Case Study: Integrating North America's Power Grid 162
Case Study: Grid Congestion - Unclogging the Arteries
of North America's Power Grid 167

	4.1	Transmission Line Design Considerations 173	
	4.2	Resistance 178	
	4.3	Conductance 181	
	4.4	Inductance: Solid Cylindrical Conductor 181	
	4.5	Inductance: Single-Phase Two-Wire Line	
		and Three-Phase Three-Wire Line with Equal Phase	
		Spacing 186	
	4.6	Inductance: Composite Conductors, Unequal Phase Spacing,	
		Bundled Conductors 188	
	4.7	Series Impedances: Three-Phase Line with Neutral Conductors	
		and Earth Return 196	
	4.8	Electric Field and Voltage: Solid Cylindrical Conductor 201	
	4.9	Capacitance: Single-Phase Two-Wire Line and Three-Phase	
		Three-Wire Line with Equal Phase Spacing 204	
	4.10	Capacitance: Stranded Conductors, Unequal Phase Spacing,	
		Bundled Conductors 206	
	4.11	Shunt Admittances: Lines with Neutral Conductors and Earth	
		Return 210	
	4.12	Electric Field Strength at Conductor Surfaces and	
		at Ground Level 215	
	4.13	Parallel Circuit Three-Phase Lines 218	
	Transı	nission Lines: Steady-State Operation 237	
	Case St	tudy: The ABCs of HVDC Transmission Technologies:	
		An Overview of High Voltage Direct Current Systems	
		and Applications 238	
	5.1	Medium and Short Line Approximations 258	
	5.2	Transmission-Line Differential Equations 265	
	5.3	Equivalent π Circuit 271	
	5.4	Lossless Lines 274	
	5.5	Maximum Power Flow 282	
	5.6	Line Loadability 284	
	5.7	Reactive Compensation Techniques 289	
Power Flows 309			
	Case St	rudy: Finding Flexibility: Cycling the Conventional	
		Fleet 310	
	6.1	Direct Solutions to Linear Algebraic Equations: Gauss Elimination 330	
	6.2	Iterative Solutions to Linear Algebraic Equations: Jacobi	
		and Gauss-Seidel 334	
	6.3	Iterative Solutions to Nonlinear Algebraic Equations:	
		Newton-Raphson 340	
	6.4	The Power Flow Problem 345	
	6.5	Power Flow Solution by Gauss-Seidel 351	
	6.6	Power Flow Solution by Newton-Raphson 353	
	6.7	Control of Power Flow 363	
	6.8	Sparsity Techniques 369	
	6.9	Fast Decoupled Power Flow 372	
	6.10	The "DC" Power Flow 372	
	6.11	Power Flow Modeling of Wind Generation 374	
	6.12	Economic Dispatch 376	
	6.13	Optimal Power Flow 389	
	Design 1	Projects 1–3 404–412	

CHAPTER 5

CHAPTER 6

CHAPTER 7	Symmetrical Faults 415
	Case Study: Short-Circuit Modeling of a Wind Power Plant 416 7.1 Series R-L Circuit Transients 435 7.2 Three-Phase Short Circuit—Unloaded Synchronous Machine 438 7.3 Power System Three-Phase Short Circuits 442 7.4 Bus Impedance Matrix 445 7.5 Circuit Breaker and Fuse Selection 455 Design Project 3 (continued) 472
CHAPTER 8	Symmetrical Components 475
	Case Study: Technological Progress in High-Voltage
	Gas-Insulated Substations 476 8.1 Definition of Symmetrical Components 493 8.2 Sequence Networks of Impedance Loads 499 8.3 Sequence Networks of Series Impedances 506
	8.4 Sequence Networks of Three-Phase Lines 508
	8.5 Sequence Networks of Rotating Machines 510
	8.6 Per-Unit Sequence Models of Three-Phase Two-Winding Transformers 516
	 8.7 Per-Unit Sequence Models of Three-Phase Three-Winding Transformers 522 8.8 Power in Sequence Networks 524
CHAPTER 9	Unsymmetrical Faults 539
	Case Study: Innovative Medium Voltage Switchgear for Today's Applications 540 9.1 System Representation 547 9.2 Single Line-to-Ground Fault 553 9.3 Line-to-Line Fault 557 9.4 Double Line-to-Ground Fault 560 9.5 Sequence Bus Impedance Matrices 567 Design Project 3 (continued) 588 Design Project 4 589
CHAPTER 10	System Protection 593
led suist) silved an another second	Case Study: Upgrading Relay Protection Be Prepared for the Next Replacement or Upgrade Project 594 10.1 System Protection Components 612 10.2 Instrument Transformers 614 10.3 Overcurrent Relays 620 10.4 Radial System Protection 625 10.5 Reclosers and Fuses 629 10.6 Directional Relays 633 10.7 Protection of a Two-Source System with Directional Relays 634 10.8 Zones of Protection 635 10.9 Line Protection with Impedance (Distance) Relays 639 10.10 Differential Relays 645 10.11 Bus Protection with Differential Relays 647
	10.12 Transformer Protection with Differential Relays 648

	10.13 Pilot Relaying 653
	10.14 Numeric Relaying 654
CHAPTER 11	Transient Stability 669
	Case Study: Down, but Not Out 671
	11.1 The Swing Equation 689
	11.2 Simplified Synchronous Machine Model and System
	Equivalents 695
	11.3 The Equal-Area Criterion 697
	11.4 Numerical Integration of the Swing Equation 707
	11.5 Multimachine Stability 711
	11.6 A Two-Axis Synchronous Machine Model 719
	11.7 Wind Turbine Machine Models 724
	11.8 Design Methods for Improving Transient Stability 730
CHAPTER 12	Power System Controls 739
	Case Study: No Light in August: Power System Restoration Following the
	2003 North American Blackout 742
	12.1 Generator-Voltage Control 757
	12.2 Turbine-Governor Control 761
	12.3 Load-Frequency Control 767
CHAPTER 13	Transmission Lines: Transient Operation 779
	Case Study: Surge Arresters 780
	Case Study: Emergency Response 794
	13.1 Traveling Waves on Single-Phase Lossless Lines 809
	13.2 Boundary Conditions for Single-Phase Lossless Lines 813
	13.3 Bewley Lattice Diagram 822
	13.4 Discrete-Time Models of Single-Phase Lossless Lines and Lumped
	RLC Elements 828
	13.5 Lossy Lines 834
	13.6 Multiconductor Lines 838
	13.7 Power System Overvoltages 841
	13.8 Insulation Coordination 847
CHAPTER 14	Power Distribution 859
	Case Study: It's All in the Plans 860
	14.1 Introduction to Distribution 875
	14.2 Primary Distribution 878
	14.3 Secondary Distribution 885
	14.4 Transformers in Distribution Systems 890
	14.5 Shunt Capacitors in Distribution Systems 900
	14.6 Distribution Software 905
	14.7 Distribution Reliability 906
	14.8 Distribution Automation 910
	140 Smart Crid- 012

Appendix 921

Smart Grids 913

Index 925

14.9