

Contents

Preface	x
1 General Background	1
1.1 Brief Historical Review of Electricity	2
1.2 Evolution of Modern Power System	4
1.3 Electric Energy Generation and Demand	6
1.4 Transmission and Distribution and the Substation	7
1.5 Load Studies	8
1.6 Fault Calculations	9
1.7 System Protection	10
1.8 Economic Dispatch	11
1.9 Stability Studies	11
1.10 Power System Operations and Control	12
1.11 Electric Utility Deregulation and Restructuring	13
1.12 Smart Grid	14
1.13 Summary	17
2 Basic Concepts	19
2.1 Introduction	20
2.2 Single-Phase AC Circuits	21
2.3 Three-Phase AC Circuits	31
2.4 Per-Unit Quantities	41
2.5 The One-Line Diagram	46
2.6 Impedance and Reactance Diagrams	48
2.7 Summary	49
Review Questions	49
Problems	51
3 Transformers and Synchronous Machines	53
3.1 The Ideal Transformer	54
3.2 The Equivalent Circuit of a Single-Phase Transformer	61
3.3 The Autotransformer	66

3.4	Per-Unit Impedances in Single-Phase Transformer Circuits	67
3.5	Three-Phase Transformers	71
3.6	The Three-Winding Transformers	76
3.7	Three-Phase Transformers: Phase Shift and Equivalent Circuits	79
3.8	Tap-Changing and Regulating Transformers	85
3.9	Description of the Synchronous Machine	90
3.10	Operation Principles of the Synchronous Machine	93
3.11	The Equivalent Circuit of a Synchronous Machine	96
3.12	Real and Reactive Power Control	105
3.13	Operation Limits of a Synchronous Machine	109
3.14	Summary	115
	Review Questions	116
	Problems	118
4	Parameters of Transmission Lines	125
4.1	Resistance of Conductors	127
4.2	Series Impedance of Transmission Lines	131
4.3	Transposition of Transmission Lines	142
4.4	Shunt Admittance of Transmission Lines	146
4.5	Effect of Earth on the Capacitance of Three-phase Transmission Lines	156
4.6	Summary	163
	Review Questions	164
	Problems	165
5	Modeling Transmission Lines	169
5.1	The Short Transmission Line	170
5.2	The Medium-Length Transmission Line	174
5.3	The Long Transmission Line	176
5.4	The Equivalent Circuit of a Long Transmission Line	185
5.5	Power Flow Through a Transmission Line	188
5.6	Reactive Compensation of Transmission Lines	190
5.7	Direct-Current Transmission	193
5.8	Summary	194
	Review Questions	194
	Problems	196
6	Network Calculations	199
6.1	Nodal Analysis and Admittance Matrix	200
6.2	Node Elimination by Kron Reduction	208
6.3	The Bus Impedance Matrix	214

6.4	Thévenin's Theorem and the Bus Impedance Matrix	215
6.5	Modification of an Existing Z_{bus}	220
6.6	Direct Determination of the Bus Impedance Matrix	227
6.7	Calculation of Z_{bus} Elements from Y_{bus} by Triangular Factorization	231
6.8	Power Invariant Transformations	236
6.9	Summary	241
	Review Questions	241
	Problems	242
7	Power Flow Studies	245
7.1	Gauss-Seidel Iterative Method	246
7.2	Newton-Raphson Method	251
7.3	The Power-Flow Problem	257
7.4	The Gauss-Seidel Power-Flow Method	262
7.5	The Newton-Raphson Power-Flow Method	271
7.6	The Fast Decoupled Power-Flow Method	288
7.7	Summary	295
	Review Questions	295
	Problems	296
8	Symmetrical Faults	301
8.1	Transients in RL Series Circuits	302
8.2	Internal Voltages of Loaded Machines Under Fault Conditions	304
8.3	Fault Calculations Using the Bus Impedance Matrix, Z_{bus}	311
8.4	Fault Calculations Using Z_{bus} Equivalent Circuits	315
8.5	The Selection of Circuit Breakers	321
8.6	Summary	329
	Review Questions	330
	Problems	331
9	Symmetrical Components and Sequence Networks	335
9.1	Fundamentals of Symmetrical Components	336
9.2	Symmetrical Wye (Y) and Delta (Δ) Circuits	340
9.3	Power in Terms of Symmetrical Components	346
9.4	Sequence Circuits of Wye (Y) and Delta (Δ) Impedances	349
9.5	Sequence Circuits of a Symmetrical Transmission Line	353
9.6	Sequence Circuits of the Synchronous Machine	358
9.7	Sequence Circuits of Wye-Delta (Y- Δ) Transformers	365
9.8	Unsymmetrical Series Impedances	373
9.9	Sequence Networks	375
9.10	Summary	379

	Review Questions	380
	Problems	382
10	Unsymmetrical Faults	385
	10.1 Unsymmetrical Faults on Power Systems	386
	10.2 Single Line-to-Ground Faults	395
	10.3 Line-to-Line Faults	401
	10.4 Double Line-to-Ground Faults	405
	10.5 Demonstration Problems	411
	10.6 Open-Conductor Faults	422
	10.7 Summary	430
	Review Questions	434
	Problems	435
11	Power System Protection	439
	11.1 Attributes of Protection Systems	440
	11.2 Zones of Protection	442
	11.3 Transducers	444
	11.4 Protective Relays Based on Logic	447
	11.5 Primary and Backup Protection	454
	11.6 Transmission Line Protection	455
	11.7 Protection of Power Transformers	467
	11.8 Evolution of Protective Relays	471
	11.9 Summary	472
	Review Questions	472
	Problems	473
12	Economic Dispatch and Automatic Generation Control	475
	12.1 Distribution of Load Between Units Within a Plant	476
	12.2 Distribution of Load Between Units Within a Plant Considering Unit Generation Limits	484
	12.3 Distribution of Load Between Plants	490
	12.4 The Transmission-Loss Equation	502
	12.5 Automatic Generation Control	511
	12.6 Summary	520
	Review Questions	520
	Problems	522
13	Power System Stability	525
	13.1 The Stability Problem	526

13.2	Rotor Dynamics and the Swing Equation	528
13.3	Further Considerations of the Swing Equation	531
13.4	The Power-Angle Equation	535
13.5	Synchronizing Power Coefficients	541
13.6	Equal-Area Criterion of Stability	544
13.7	Further Applications of the Equal-Area Criterion	549
13.8	Multimachine Stability Studies: Classical Representation	551
13.9	Step-By-Step Solution of the Swing Curve	558
13.10	Computer Programs for Transient Stability Studies	567
13.11	Factors Affecting Transient Stability	569
13.12	Summary	571
	Review Questions	571
	Problems	573
Appendix A		575
Table A1:	Typical Range of Transformer Reactances	575
Table A2:	Typical Reactances of Three-phase Synchronous Machines	575
Table A3:	Electrical Characteristics of Bare Aluminum Conductors Steel-Reinforced (ACSR)	576
Table A4:	Inductive Reactance Spacing Factor X_d at 60 Hz (ohms per mile per conductor)	577
Table A5:	Shunt Capacitance-Reactance Spacing Factor X_d at 60 Hz (megaohm-miles per conductor)	578
Table A6:	ABCD Constants for Various Networks	579
Index		581