

Table of Contents

Foreword	xvii
Introduction	xix
Part 1. Transmission Lines and Electric Power Networks	1
Chapter 1. The Two Paradigms of the World Electrical Power System	3
1.1. Introduction	3
1.2. The historical paradigm	5
1.2.1. Grouped generation: scale effect	5
1.2.2. Scattered consumption	6
1.2.3. Very limited means of energy storage	8
1.2.4. Transmission and distribution of electrical energy	8
1.3. New paradigm	12
1.3.1. Electric system operation in liberalized world	12
1.4. Distributed generation	15
Chapter 2. Production of Electrical Energy	17
Chapter 3. General Information on Electrical Power Networks	21
3.1. Transmission and distribution systems	21
3.2. Voltages	23
3.3. Power transfer	25

Chapter 4. Network Architecture	27
4.1. Network architecture: mesh or radial layout	27
4.1.1. Transmission networks	28
4.1.2. Subtransmission networks	29
4.1.3. Distribution networks	30
4.2. Line and cable technologies	33
4.2.1. Design and technology of overhead lines	33
4.2.2. Design and technology of insulated cables	38
4.3. Network components	40
4.3.1. Generators	40
4.3.2. Transformers	42
4.3.3. Electric load	47
4.3.4. The per-unit (pu) system	48
4.3.5. Exercise No. 1: per-unit system	50
4.4. Short-circuit power	51
4.4.1. Definition	51
4.4.2. Properties	51
4.4.3. Input impedance and short-circuit admittance	52
4.4.4. Voltage drop due to load connection with specific apparent power	53
4.5. Real and reactive power in sinusoidal situations	55
 Chapter 5. Operation of Electric Lines	 59
5.1. Operational equations (physical phenomena)	59
5.1.1. Line constants	60
5.1.2. Exercise No. 2: parameters of single-phase line	65
5.1.3. Basic equations	66
5.1.4. Equations of propagation	67
5.1.5. Important remarks	68
5.2. Modeling of lines under steady-state conditions	75
5.2.1. Steady-state equations – classification of lines	75
5.2.2. Exercise No. 3: power transfer	77
5.2.3. Short lines – model and representation	78
5.2.4. Apparatus of production or consumption of reactive power	85
5.2.5. Modification of line reactance	87
5.2.6. Medium lines – model and representation	90
5.2.7. Long lines – propagation	92
5.3. Exercises	108
5.3.1. Exercise No. 6: lossless long line	108
5.3.2. Exercise No. 7: long three-phase line with losses	109
5.3.3. Exercise No. 8: single-phase long line	109

5.3.4. Exercise No. 9: series compensation of long lines	110
5.3.5. Exercise No. 10: parameters of a single conductor	111
Chapter 6. High Voltage Direct Current (HVDC)	
Transmission	113
6.1. Advantages, disadvantages and fields of application	114
6.1.1. Underground or under water power transmission	114
6.1.2. Very long lines	114
6.1.3. Interconnections.	115
6.1.4. Networks with different frequencies.	115
6.1.5. Improving the operation of alternating current.	115
6.2. HVDC link between two points	115
6.2.1. Converter station	116
6.3. Operating equations	123
Chapter 7. Three-phase Transmission Lines	127
7.1. Line characteristics	127
7.1.1. Calculation of capacitance per unit length	128
7.1.2. Calculation of inductance per unit length.	131
7.2. Equations of three-phase lines.	134
7.3. Modes of propagation.	136
7.3.1. Line-to-line mode.	142
7.3.2. Homopolar mode	143
7.3.3. Values for various modes of propagation.	144
7.4. Exercise No. 11: calculation of parameters of three-phase lines	147
Chapter 8. Electrical Transients in Transmission	149
8.1. Transient analysis using Laplace transform	150
8.1.1. Definition and properties of Laplace transform	150
8.1.2. Equations of an open line when excited by a perfect generator	151
8.2. Method of traveling waves.	164
8.2.1. Example 1: open line.	167
8.2.2. Example 2: short-circuit line	168
8.2.3. Example 3: study of a surge arrester.	170

Part 2. Analysis Methods of Electrical Power Systems	173
Chapter 9. Functions of Electrical Energy Systems	175
9.1. Introduction.	175
9.2. Hierarchy and representation of electrical power systems	179
9.2.1. Transmission lines and apparatus	181
9.2.2. Transformers	181
9.2.3. Electric loads	181
9.2.4. Generators	182
Chapter 10. Network Representation	183
10.1. Graphical and topological description of a network	183
10.1.1. Review of graph theory	183
10.2. Network global modeling: the CIM model.	186
10.3. Matrix representation of networks.	187
10.3.1. Network matrices	188
Chapter 11. Formation of Network Matrices	207
11.1. Formation of the Y_{bus} matrix	208
11.2. Formation of the Z_{bus} matrix	210
11.2.1. Adding branches.	210
11.2.2. Adding cords.	215
11.3. Exercises.	220
11.3.1. Exercise No. 12: construction of a Z_{bus} matrix.	220
11.3.2. Exercise No. 13: construction of network matrices	221
Chapter 12. Load Flow Calculations	223
12.1. Objectives	223
12.1.1. Definition of network state	223
12.1.2. Calculation of current flow	223
12.1.3. Line losses	224
12.1.4. Strategy for adjustment and control	224
12.1.5. Optimizing power transfer capacity	224
12.2. Model of network elements.	224
12.2.1. Lines and transformers	224
12.2.2. Generators and loads	225
12.2.3. Representation of voltage	226

12.3. Problem formulation	226
12.3.1. General equations	226
12.3.2. Simplified models	228
12.4. Solution methods	228
12.4.1. Gauss-Seidel method	229
12.4.2. Newton-Raphson method	232
12.4.3. Calculation of power flows	238
12.5. Software tools for load flow analysis	241
12.6. Principle of numerical iterative methods	241
12.6.1. Gauss-Seidel method	241
12.6.2. Newton-Raphson method	242
12.7 Exercises	244
12.7.1. Exercise No. 14: load flow calculations	244
12.7.2 Exercise No. 15: power flow	245
12.7.3. Exercise No. 16: matrices and load flow	247
Chapter 13. Transient Analysis Methods	249
13.1. Interest in transient analysis	249
13.2. Transient network analyzer	251
13.2.1. Principle of operation	251
13.2.2. Advantages and disadvantages	251
13.3. The method of traveling waves	253
13.3.1. Principle	253
13.3.2. Representation of a line (or cable)	254
13.3.3. Representation of a resistor	256
13.3.4. Representation of an inductor	257
13.3.5. Representation of a capacitor	258
13.3.6. Representation of a voltage source	260
13.3.7. Operating principle	260
13.3.8. Illustration example	263
13.4. Conclusions	265
13.5. Exercises	266
13.5.1. Exercise No. 17: transient analysis on a line	266
13.5.2. Exercise No. 18: matrices and transient analysis	267
13.5.3. Exercise No. 19: transient analysis under lightning strike	268
Chapter 14. Fault Current Calculations	271
14.1. Definition	271
14.2. Effects of short-circuit conditions	271
14.3. Common causes of faults	272
14.4. Importance of short-circuit current calculations	273
14.5. Types of short circuits	273

14.6. Notion of short-circuit power	275
14.7. Polyphase balanced and unbalanced systems	276
14.7.1. Balanced three-phase systems.	276
14.7.2. Complex representation	277
14.7.3. Symmetrical components	278
14.7.4. Powers in terms of symmetrical components.	282
14.7.5. Symmetrical components and impedance/admittance matrices	283
14.7.6. Notion of circulating matrices.	284
14.7.7. Case of synchronous machines	285
14.7.8. Short-circuit current calculations	287
14.7.9. Other types of faults	295
14.8. Generalization of fault calculation in complex networks	296
14.9. Three-phase symmetrical fault current calculations	296
14.10. Symmetrical fault current: systematic approach.	298
14.11. Expression of short-circuit current and short-circuit power	302
14.12. Asymmetrical fault current calculations	303
14.12.1. Generalization of symmetrical components	303
14.12.2. Neutral and homopolar currents	304
14.12.3. Impedances of network components	306
14.12.4. Example of generalization on a complex network	311
14.12.5. Systematic calculation of asymmetrical fault currents.	313
14.13 Exercises	319
14.13.1 Exercise No. 20: fault current in a simple network	319
14.13.2 Exercise No. 21: symmetrical fault on a network	320
Chapter 15. Stability Analysis of Power Systems.	323
15.1. Objective	323
15.2. Introduction	323
15.3. Categories and classes of stability problems.	324
15.4. The equation of motion	326
15.5. Simplified model of a synchronous machine	331
15.6. Power-angle considerations at steady state	333
15.7. Case of small perturbations.	337
15.8. Transient stability	339
15.9. Application of equal-area criteria	343
15.9.1. Case of a short circuit at generator terminals	344
15.9.2. Critical fault clearing time	346
15.9.3. Case of a short circuit on a line	348
15.10. Case of a multi-machine system	351
15.11 Exercise No. 22: stability and critical fault clearing time.	352

Part 3. Management of Electricity Networks in a Competitive Environment	355
Chapter 16. Basic Electrical System	357
16.1. Introduction	357
16.2. Means of power generation.	361
16.2.1. Nuclear power	362
16.2.2. Conventional thermal power	364
16.2.3. Hydropower	367
16.2.4. Decentralized generation.	369
16.3. Transmission network	372
16.4. Distribution network.	375
16.5. Consumption	377
16.5.1 Notions and constraints of electric load	379
16.5.2. Characteristics of electric load	380
16.6. System monitoring	381
16.6.1. Frequency control	382
16.6.2. Voltage regulation.	384
16.7. Need for network interconnections	385
16.7.1. Economic benefits.	386
16.7.2. Advantages of interconnections.	386
16.7.3. Disadvantages of interconnections	387
16.8. Conclusion	390
Chapter 17. Liberalization of Energy Markets	391
17.1. Introduction	391
17.2. Main electrical system features	393
17.3. Case prior to liberalization: monopoly regime	393
17.4. Liberalization of energy markets: reasons for change	396
17.5. Guidelines and regulations	399
17.5.1. <i>European Directive 96/92/EC</i>	399
17.5.2. <i>US FERC orders 888 and 889</i>	400
17.6. Liberalization of energy markets: the concept of unbundling	401
17.7. Liberalization of energy markets: industrial movement	405
17.8. Liberalization of energy markets: different market segments and players	405
17.8.1. Market players and the electrical system.	407
17.9. Conclusion	418

Chapter 18. Description and Models of Energy Markets	419
18.1. Introduction	419
18.2. Organized market model type	420
18.3. Bilateral market model	424
18.4. Other models	424
18.4.1. Hybrid model	425
18.4.2. Single-buyer model	426
18.4.3. Mixed generation model	426
18.5. Different markets.	427
18.5.1. Day-ahead market (spot market)	427
18.5.2 Hour-ahead market	427
18.5.3. Market ‘derivatives’	428
18.6. Interaction and coupling of markets.	430
18.7. Market adjustment	431
18.7.1. Adjustment mechanism	431
18.7.2. Mobilization of adjustment bids: France as an example	431
18.7.3. Participants involved in the adjustment mechanism.	432
18.7.4. Transmission of adjustment bids	432
18.8. Responsibilities, different markets and interactions	433
18.9. Treatment of losses	433
18.9.1. Physical and financial compensation of Joule losses	435
18.9.2. Cost allocation of Joule losses	436
18.10. Factors influencing prices and their variation	436
18.11. Conclusion.	441
Chapter 19. Ancillary Services	443
19.1. Introduction	443
19.2. Some definitions	444
19.3. Frequency adjustment and control.	445
19.3.1. Primary control	446
19.3.2. Secondary control	448
19.3.3. Tertiary control	448
19.3.4. Technical and economic characteristics of reserves	450
19.3.5. Value of frequency adjustment	450
19.4. Voltage control	451
19.4.1. Characteristics of reactive power reserves and voltage adjustment	453
19.5. System recovery	455
19.6. Management of ancillary services.	455
19.6.1. Provision of ancillary services	456
19.7. Market-based mechanisms for ancillary services	456
19.7.1. Example of market mechanisms	457

19.8. Cost allocation of ancillary services	461
19.9. Example of cost of ancillary services	461
19.10. Conclusion.	461
Chapter 20. Available Transmission Capability (ATC)	465
20.1. Introduction	465
20.2. Calculation of maximum power transfer capabilities	467
20.2.1. Calculation method	468
20.3. Directional aspects and time line in calculating ATC	474
20.4. Availability of information on ATC to market participants	475
20.5. Mechanisms for allocating cross-border capacities.	476
20.6. Conclusion	477
Chapter 21. Congestion Management.	479
21.1. Introduction	479
21.2. Congestion phenomenon in transmission networks	480
21.2.1. Limits imposed on transmission networks for maximum transfers.	480
21.2.2. Concept of congestion	481
21.3. Factors influencing congestion.	481
21.4. Congestion and the market	483
21.4.1. Model based on bilateral transactions	484
21.4.2. Model based on pool or power exchange	484
21.5. Technical resolution of congestion	485
21.5.1. Network configuration	485
21.5.2. Curtailment of bilateral transactions	485
21.5.3. Change in generation or load: re-dispatching.	486
21.6. Principle of nodal pricing	486
21.6.1. Summary	487
21.7. Principle of market splitting and zonal pricing	488
21.8. Case of a bilateral market.	490
21.8.1. Example: California model (CAISO)	490
21.9. Case of re-dispatching without taking into account balance constraints of SCs.	494
21.10. General formulation of the re-dispatching problem.	495
21.11. Case of pool based on the calculation of nodal marginal prices	498
21.11.1. Calculation of locational marginal pricing (LMP)	499
21.11.2. Mathematical formulation of the LMP algorithm	500
21.12. Hedging the risk of congestion cost	500
21.12.1. Congestion revenues	501
21.13. Conclusion.	501

Chapter 22. Network Access and Charges	503
22.1. Introduction	503
22.2. Main costs and expenses of electricity transmission	505
22.3. Tariff objectives for electricity transmission	505
22.3.1. Economic efficiency	506
22.3.2. Fairness of treatment and non-discriminatory access	506
22.3.3. Simplicity and transparency	506
22.4. Methods of determining costs and price setting	506
22.4.1. Methods based on average costs	507
22.4.2. Methods based on incremental (or marginal) cost	510
22.5. Some regulation aspects of cost allocation	515
22.5.1. Regulation of income	516
22.5.2. Regulation of prices	516
22.5.3. Incentive regulation	516
22.6. French example: principles of tariffs on the public transmission system	517
22.6.1. Objectives of network use tariff	517
22.6.2. Pricing based on physical flows	518
22.6.3. Network access contract and classification of voltage levels	518
22.6.4. Tariff structure	519
22.7. Tariff for network access in Europe	521
22.8. Conclusion	521
Part 4. Exercise Solutions	525
Chapter 23. Exercise Solutions	527
23.1. Exercise No. 1: per-unit system	527
23.2. Exercise No. 2: parameters of single-phase line	532
23.3. Exercise No. 3: power transfer	541
23.4. Exercise No. 4	550
23.5. Exercise No. 5	554
23.6. Exercise No. 6: lossless long line	559
23.7. Exercise No. 7: long three-phase line with losses	570
23.8. Exercise No. 8: single-phase long line	577
23.9. Exercise No. 9: series compensation of long lines	587
23.10. Exercise No. 10: parameters of a single conductor	593
23.11. Exercise No. 11: calculation of parameters of three-phase lines	597
23.12. Exercise No. 12: construction of Z_{bus} matrix	607
23.13. Exercise No. 13: construction of network matrices	612
23.14. Exercise No. 14: load flow calculations	617

23.15. Exercise No. 15: power flow	630
23.16. Exercise No. 16: matrices and load flow	630
23.17. Exercise No. 17: transient analysis of a line	631
23.18. Exercise No. 18: matrices and transient analysis	632
23.19. Exercise No. 19: transfer analysis under lightning strike.	632
23.20. Exercise No. 20: fault current in a simple network	633
23.21. Exercise No. 21: symmetrical fault on a network	648
23.22 Exercise No. 22: stability and critical fault clearing time	659
References	665
R.1. Websites	665
R.2. Bibliography	666
R.3. Suggested further reading	668
Index	671