
Contents

Preface	v
List of figures	xiv
List of tables	xxiv
Contributors	xxvii
 Part I Modelling	
1 Telegrapher's equations for field-to-transmission line interaction	3
1.1 Transmission line approximation	3
1.2 Single-wire line above a perfectly conducting ground	5
1.2.1 Taylor, Satterwhite and Harrison model	6
1.2.2 Agrawal, Price and Gurbaxani model	10
1.2.3 Rachidi model	12
1.3 Contribution of the different electromagnetic field components	13
1.4 Inclusion of losses	13
1.5 Case of multi-conductor line	15
1.6 Time-domain representation of the coupling equations	17
1.7 Solutions with particular reference to time-domain numerical solutions	18
1.8 Application of theory to the case of lightning-induced voltages on distribution overhead lines	22
1.8.1 The LIOV code	22
1.8.2 The LIOV-EMTP-RV code	23
1.8.3 LEMP response of electrical distribution systems	29
1.9 Summary and concluding remarks	39
Acknowledgements	40
Bibliography	40
 2 An affine arithmetic-based methodology for uncertain power flow and optimal power flow analyses	45
2.1 Introduction	45
2.2 Overview of existing approaches	46
2.2.1 Sampling methods	46
2.2.2 Analytical methods	47
2.2.3 Approximate methods	48
2.2.4 Non-probabilistic methods	49
2.2.5 AA-based methods	50

2.3	Mathematical background	51
2.3.1	PF analysis	51
2.3.2	OPF analysis	52
2.4	Self-validated computing	54
2.4.1	Interval arithmetic	54
2.4.2	Affine arithmetic	56
2.5	AA-based PF and OPF analyses	58
2.5.1	Theoretical framework	59
2.5.2	Applications	64
2.6	Numerical results	65
2.6.1	PF analysis	66
2.6.2	Reactive power dispatch	68
2.7	Computational requirements	69
2.8	Conclusions	71
	Bibliography	73
3	DFT-based synchrophasor estimation processes for Phasor Measurement Units applications: algorithms definition and performance analysis	77
3.1	Literature review	78
3.2	Definitions	79
3.2.1	Signal model	79
3.2.2	Phasor	81
3.2.3	Synchrophasor	81
3.2.4	Frequency and rate of change of frequency	83
3.2.5	Phasor measurement unit	84
3.3	The discrete Fourier transform	86
3.3.1	From the Fourier transform to the DFT	86
3.3.2	DFT interpretation and relevant properties	87
3.3.3	DFT effects	89
3.3.4	DFT parameters	95
3.3.5	DFT calculation in real time	98
3.4	DFT-based SE algorithms	102
3.4.1	The Interpolated-DFT technique	103
3.4.2	The iterative-Interpolated DFT technique	110
3.5	Performance analysis of SE algorithm	112
3.5.1	The IEEE Std. C37.118	112
3.5.2	Performance assessment of the i-IPDFT SE algorithm	121
3.6	Conclusions	126
	Bibliography	126
4	Modelling power systems with stochastic processes	131
4.1	Literature review	131
4.2	Outlines on SDEs	133

4.3	Design of SDE-based models	136
4.3.1	Method based on the solution of the stationary Fokker–Planck equation	136
4.3.2	Examples	139
4.3.3	Method based on translation processes	143
4.3.4	Application to wind speed modelling	144
4.4	Modelling power systems as SDAEs	145
4.4.1	Modelling stochastic perturbations in power systems	147
4.4.2	Examples	149
4.5	Time-domain integration of SDAEs	152
4.5.1	IEEE 145-bus 50-machine system	155
4.6	Conclusions	159
	Bibliography	159
 Part II Control		
5	Optimization methods for preventive/corrective control in transmission systems	163
5.1	Formulation of a time-continuous dynamic optimization problem for corrective control	163
5.2	Formulation of a time-discrete static optimization problem for corrective control	166
5.3	Application to power system DAEs	169
5.3.1	Control variables	173
5.3.2	Control effort minimization	173
5.3.3	Kinetic energy cost function	174
5.3.4	Voltage penalty functions	175
5.3.5	Distance relays penalty function	176
5.4	Application of the proposed methodology for the corrective control of a realistically sized power system (test results)	178
5.5	Application to preventive control problems	183
	Bibliography	186
6	Static and recursive PMU-based state estimation processes for transmission and distribution power grids	189
6.1	State estimation measurement and process model	190
6.1.1	Measurement model	191
6.1.2	Network observability	201
6.1.3	Process model	202
6.2	Static state estimation: the weighted least squares	203
6.2.1	Linear weighted least squares state estimator	204
6.2.2	Non-linear weighted least squares	205
6.3	Recursive state estimation: the Kalman filter	206
6.3.1	Discrete Kalman filter	206
6.3.2	Extended Kalman filter	210

6.3.3	Kalman Filter sensitivity with respect to the measurement and process noise covariance matrices	211
6.3.4	Assessment of the process noise covariance matrix	212
6.4	Assessment of the measurement noise covariance matrix	212
6.5	Data conditioning and bad data processing in PMU-based state estimators	219
6.6	Kalman filter vs. weighted least squares	222
6.7	Numerical validation and performance assessment of the state estimation	223
6.7.1	Linear state estimation case studies	223
6.7.2	Non-linear SE case studies	232
6.8	Kalman filter process model validation	234
6.9	Numerical validation of Theorem 6.1	235
	Bibliography	236
7	Real-time applications for electric power generation and voltage control	241
7.1	Introduction	241
7.2	Outlines of real-time system concepts	242
7.2.1	Real-time operating systems	244
7.2.2	Real-time communications	250
7.3	Voltage control	254
7.3.1	Excitation control systems	256
7.3.2	Secondary voltage control	259
7.3.3	Voltage control with distributed generation	265
7.4	Conclusions	270
	Bibliography	270
8	Optimal control processes in active distribution networks	275
8.1	Typical architecture of ADN grid controllers	276
8.1.1	Control architecture	276
8.1.2	Controller's actions	278
8.2	Classic computation of sensitivity coefficients in power networks	280
8.3	Efficient computation of sensitivity coefficients of bus voltages and line currents in unbalanced radial electrical distribution networks	282
8.3.1	Voltage sensitivity coefficients	282
8.3.2	Current sensitivity coefficients	285
8.3.3	Sensitivity coefficients with respect to transformer's ULTC	286
8.4	Application examples	287
8.4.1	Distribution network case studies	287
8.4.2	Numerical validation	289
8.4.3	Voltage control and lines congestion management examples	295
8.5	Conclusions	308
	Bibliography	308

Part III Stability Analysis

9 Time-domain simulation for transient stability analysis	313
9.1 Introduction	313
9.2 Time-domain simulations and transient stability	315
9.3 Transient stability and high-performance computing	321
9.4 A new class of algorithms: from step-by-step solutions to parallel-in-time computations	324
9.5 Performances in parallel-in-time computations	332
9.6 Conclusions	335
Bibliography	335
10 Voltage security in modern power systems	339
10.1 Introduction	339
10.2 The power flow problem in rectangular coordinated	344
10.2.1 The power flow with SVC constraints	345
10.3 The OPF with SVC constraints	349
10.3.1 The maximum loadability with SVC constraints	350
10.3.2 Minimisation of the squared deviation of the bus voltage magnitude from a reference value	351
10.3.3 Constrained maximisation of the loadability with SVC	355
10.4 Solution of the optimisation problem	356
10.4.1 Primal-dual interior point method	356
10.4.2 Reduction of the linear system	359
10.5 Numerical results	360
10.5.1 The New England 39 buses network case	361
10.5.2 The Italian case	363
10.6 Conclusions	367
Bibliography	367
11 Small-signal stability and time-domain analysis of delayed power systems	371
11.1 Introduction	371
11.1.1 Time-domain methods	372
11.1.2 Frequency-domain methods	372
11.2 A general model for power systems with time delays	373
11.2.1 Steady-state DDAE	374
11.3 Numerical techniques for DDAEs	376
11.3.1 Padé approximants	376
11.3.2 Numerical integration of DDAEs	378
11.3.3 Methods to approximate the characteristic roots of DDAEs	380
11.3.4 Discretization of the TIO	382
11.3.5 LMS approximation	384
11.4 Impact of delays on power system control	385

11.5 Case studies	388
11.5.1 IEEE 14-bus system	388
11.5.2 All-island 1479-bus Irish system	394
Bibliography	400
12 Shooting-based stability analysis of power system oscillations	405
12.1 Introduction	406
12.2 Mathematical background	408
12.2.1 The time-domain shooting method	408
12.2.2 The state transition matrix for hybrid dynamical systems	410
12.2.3 Bordering the Jacobian	413
12.2.4 The probe-insertion technique	414
12.3 Revisited PSM	417
12.3.1 Outlines of standard PSMs	417
12.3.2 From polar to rectangular coordinates	420
12.3.3 On the unit multipliers of the PSM periodic orbits	422
12.3.4 Bordering based on the COI	423
12.4 Case studies	424
12.4.1 IEEE 14-bus test system	424
12.4.2 WSCC 9-bus test system	426
12.4.3 A switching two-area PSM	427
12.5 Conclusions	431
Bibliography	431
Part IV Appendices	
Appendix A Outlines of stochastic calculus	437
A.1 Stationary Markov processes	437
A.2 Regression theorem	438
A.3 Change of variables in stochastic calculus: the Itô formula	438
A.4 Memoryless transformations: translation Processes	439
A.5 Fokker–Planck equation	440
Bibliography	440
Appendix B Data of lines, loads and distributed energy resources	441
B.1 IEEE 34-bus distribution test feeder data	441
B.2 IEEE 13-bus distribution test feeder data	442
B.3 IEEE 39-bus transmission test system data	445
Bibliography	446
Appendix C Proofs and tools for DDAEs	447
C.1 Determination of A_0 , A_1 and A_2	447
C.2 Chebyshev's differentiation matrix	448
C.3 Kronecker's product	448
Bibliography	449

Appendix D Numerical aspects of the probe-insertion technique	451
D.1 Parameters of the probe-insertion technique	451
D.2 Integration of (12.44)	451
Bibliography	452
Index	453