



Third Edition

POWER SYSTEM DYNAMICS STABILITY AND CONTROL

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WILEY

Power System Dynamics

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Stability and Control

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Contents

About the Authors *xix*
List of Symbols & Abbreviations *xxi*

Part I

Introduction to Power Systems 1

1	Introduction	3
1.1	Stability and Control of a Dynamic System	3
1.2	Classification of Power System Dynamics	5
1.3	Two Pairs of Important Quantities	7
1.4	Stability of a Power System	8
1.5	Security of a Power System	9
2	Power System Components	13
2.1	Introduction	13
2.1.1	Reliability of Supply	13
2.1.2	Supplying Electrical Energy of Good Quality	14
2.1.3	Economic Generation and Transmission	14
2.1.4	Environmental Issues	14
2.2	Structure of the Electric Power System	14
2.2.1	Generation	16
2.2.2	Transmission	16
2.2.3	Distribution	17
2.2.4	Demand	17
2.3	Generating Units	17
2.3.1	Synchronous Generators	19
2.3.2	Exciters and Automatic Voltage Regulators	20
2.3.2.1	Excitation Systems	20
2.3.2.2	Automatic Voltage Regulators	22
2.3.3	Turbines and Their Governing Systems	24
2.3.3.1	Steam Turbines	24
2.3.3.2	Gas Turbines	26
2.3.3.3	Combined Cycle Gas Turbines	26
2.3.3.4	Hydro Turbines	27

2.3.3.5	Turbine Governing Systems	28
2.3.3.6	Turbine Characteristics	30
2.3.3.7	Governor Control Functions	33
2.4	Substations	33
2.5	Transmission and Distribution Network	34
2.5.1	Overhead Lines and Underground Cables	34
2.5.2	Transformers	34
2.5.2.1	Tap-changing Transformers	36
2.5.2.2	Phase Shifting Transformers	37
2.5.3	Shunt and Series Elements	39
2.5.3.1	Shunt Elements	39
2.5.3.2	Series Elements	40
2.5.4	FACTS Devices	41
2.5.4.1	Static VAR Compensator	42
2.5.4.2	Static Compensator	44
2.5.4.3	Energy Storage System	45
2.5.4.4	Thyristor-Controlled Braking Resistor	45
2.5.4.5	Series Compensators	46
2.5.4.6	Thyristor-controlled Phase Angle Regulator	47
2.5.4.7	Unified Power Flow Controller	48
2.6	Protection	49
2.6.1	Protection of Transmission Lines	50
2.6.2	Protection of Transformers	51
2.6.3	Protection of Busbars	52
2.6.4	Protection of Generating Units	53
2.7	Wide Area Measurement Systems	53
3	The Power System in the Steady State	57
3.1	Transmission Lines	57
3.1.1	Line Equations and the π -equivalent Circuit	58
3.1.2	Performance of the Transmission Line	59
3.1.2.1	Real Power Transmission	60
3.1.2.2	Reactive Power Considerations	61
3.1.3	Underground Cables	63
3.2	Transformers	64
3.2.1	Equivalent Circuit	64
3.2.2	Off-nominal Transformation Ratio	66
3.3	Synchronous Generators	68
3.3.1	Round-rotor Machines	68
3.3.1.1	The Generator on No Load	69
3.3.1.2	Armature Reaction and the Air-gap Flux	71
3.3.1.3	Equivalent Circuit and the Phasor Diagram	73
3.3.1.4	The Torque Creation Mechanism	74
3.3.2	Salient-pole Machines	75
3.3.2.1	Phasor Diagram and the Equivalent Circuit	77

3.3.2.2	The d- and q-axis Armature Coils	79
3.3.2.3	Torque in the Salient-pole Machine	79
3.3.3	Synchronous Generator as a Power Source	80
3.3.3.1	Equivalent Circuit of the Generator-transformer Unit	80
3.3.3.2	Real and Reactive Power of the Generator-transformer Unit	82
3.3.4	Reactive Power Capability Curve of a Round-rotor Generator	83
3.3.5	Voltage-reactive Power Capability Characteristic $V(Q)$	93
3.3.5.1	$I_f < I_{f \max}$ and AVR Controls the Voltage	94
3.3.5.2	Maximum Field Current	95
3.3.5.3	Maximum Power Angle	95
3.3.5.4	Maximum Stator Current	95
3.3.5.5	Combined Characteristic	95
3.3.5.6	Voltage-current Regulation Characteristic $V(I_Q)$	96
3.3.6	Including the Equivalent Network Impedance	97
3.3.6.1	Real Power	99
3.3.6.2	Reactive Power	100
3.3.6.3	Steady-state Power-angle Characteristic	100
3.4	Power System Loads	101
3.4.1	Lighting and Heating	102
3.4.2	Induction Motors	103
3.4.2.1	Power-slip Characteristic	103
3.4.2.2	Real Power-voltage Characteristic	104
3.4.2.3	Reactive Power-voltage Characteristic	105
3.4.2.4	Influence of Motor Protection and Starter Control	106
3.4.3	Static Characteristics of the Load	106
3.4.4	Load Models	107
3.4.4.1	Constant Power/Current/Impedance	108
3.4.4.2	Exponential Load Model	108
3.4.4.3	Piecewise Approximation	108
3.4.4.4	Frequency-dependent Load Model	109
3.4.4.5	Test Results	109
3.5	Network Equations	110
3.5.1	Linearization of Power Network Equations	112
3.5.2	Change of Reference Frame	114
3.6	Power Flows in Transmission Networks	114
3.6.1	Input Data	115
3.6.1.1	Power Mismatch Balanced by One Slack Node	115
3.6.1.2	Power Mismatch Balanced by a Number of Generation Nodes	116
3.6.2	Calculation of Power Flows	116
3.6.2.1	Gauss-Seidel Method	117
3.6.2.2	Newton-Raphson Method	117
3.6.3	Control of Power Flows	119

Part II**Introduction to Power System Dynamics 123**

4	Electromagnetic Phenomena 125
4.1	Fundamentals 125
4.1.1	Swing Equation 125
4.1.2	Law of Constant Flux Linkages 129
4.2	Three-phase Short Circuit on a Synchronous Generator 130
4.2.1	Three-phase Short Circuit with the Generator on No Load and Winding Resistance Neglected 130
4.2.2	Including the Effect of Winding Resistance 133
4.2.3	Armature Flux Paths and the Equivalent Reactances 135
4.2.3.1	Quadrature-axis Reactances 138
4.2.4	Generator Electromotive Forces and Equivalent Circuits 140
4.2.4.1	Subtransient-state 141
4.2.4.2	Transient-state 142
4.2.4.3	Establishing Initial emf Values 143
4.2.4.4	Flux Decrement Effects 145
4.2.5	Short-circuit Currents with the Generator Initially on No Load 147
4.2.5.1	Influence of the Rotor Subtransient Saliency 149
4.2.6	Short-circuit Currents in the Loaded Generator 150
4.2.6.1	Influence of the AVR 150
4.2.7	Subtransient Torque 151
4.3	Phase-to-phase Short Circuit 153
4.3.1	Short-circuit Current and Flux with Winding Resistance Neglected 153
4.3.2	Influence of the Subtransient Saliency 157
4.3.2.1	Symmetrical Component Analysis of the Phase-to-phase Fault 158
4.3.2.2	Phase-to-phase Fault Current Harmonics Explained by Symmetrical Components 159
4.3.3	Positive- and Negative-sequence Reactances 160
4.3.4	Influence of Winding Resistance 161
4.3.5	Subtransient Torque 162
4.4	Switching Operations 164
4.4.1	Synchronization 164
4.4.2	Short Circuit in the Network and Its Clearing 166
4.4.3	Torsional Oscillations in the Drive Shaft 168
4.4.3.1	The Torsional Natural Frequencies of the Turbine-generator Rotor 169
4.4.3.2	Effect of System Faults 174
4.4.4	Switching Operations in Transmission Networks 176
4.4.4.1	Impedance Network Model 177
4.4.4.2	Thévenin's Theorem and the Nodal Impedance Method 179
4.4.4.3	Initial Switching Current as a Function of Switching Angle θ_{ab} 180
4.4.4.4	Changes in the Active Power of Synchronous Generators 181
4.4.4.5	Discussion of Methods Used in Practice 181
4.4.5	Synchro-check Device 183
4.5	Subsynchronous Resonance 191

5	Electromechanical Dynamics – Small Disturbances	195
5.1	Swing Equation	195
5.2	Damping Power	195
5.3	Equilibrium Points	199
5.4	Steady-state Stability of Unregulated System	200
5.4.1	Pull-out Power	200
5.4.2	Transient Power-angle Characteristics	202
5.4.2.1	Constant Flux Linkage Model	202
5.4.2.2	Classical Model	203
5.4.2.3	Steady-state and Transient Characteristics	204
5.4.3	Rotor Swings and Equal Area Criterion	207
5.4.4	Effect of Damper Windings	209
5.4.5	Effect of Rotor Flux Linkage Variation	210
5.4.5.1	Linearized Form of the Generator Equations	210
5.4.5.2	Equilibrium Point for $P_m < P_{E_q \text{ cr}}$	211
5.4.5.3	Equilibrium Point at $P_m = P_{E_q \text{ cr}}$	214
5.4.6	Analysis of Rotor Swings Around the Equilibrium Point	214
5.4.7	Mechanical Analogues of the Generator-infinite Busbar System	218
5.5	Steady-state Stability of the Regulated System	219
5.5.1	Steady-state Power-angle Characteristic of Regulated Generator	219
5.5.1.1	Physical Interpretation	221
5.5.1.2	Stability	222
5.5.1.3	Effect of the Field Current Limiter	222
5.5.2	Transient Power-angle Characteristic of the Regulated Generator	222
5.5.2.1	Stability	224
5.5.3	Effect of Rotor Flux Linkage Variation	225
5.5.4	Effect of AVR Action on the Damper Windings	227
5.5.5	Compensating the Negative Damping Components	228
6	Electromechanical Dynamics – Large Disturbances	229
6.1	Transient Stability	229
6.1.1	Fault Cleared Without a Change in the Equivalent Network Impedance	229
6.1.1.1	Reactance Values During the Pre-fault, Fault, and Post-fault State	230
6.1.1.2	Three-phase Fault	231
6.1.1.3	Unbalanced Faults	232
6.1.1.4	Effect of the Pre-fault Load	233
6.1.1.5	Influence of Fault Distance	233
6.1.2	Short-circuit Cleared with/without Auto-reclosing	234
6.1.3	Power Swings	237
6.1.4	Effect of Flux Decrement	238
6.1.5	Effect of the AVR	238
6.1.6	Simplified Angle Stability Criteria	240
6.2	Swings in Multi-machine Systems	243
6.3	Direct Method for Stability Assessment	246
6.3.1	Mathematical Background	247

6.3.2	Energy-type Lyapunov Function	249
6.3.2.1	Energy Function	249
6.3.3	Transient Stability Area	251
6.3.4	Equal Area Criterion	252
6.3.5	Lyapunov Direct Method for a Multi-machine System	253
6.3.5.1	Conservative Model	254
6.3.5.2	Energy Function Proposed by Gless	255
6.3.5.3	Energy Function Proposed by Lüders	257
6.3.5.4	Critical Value	260
6.4	Synchronization	262
6.5	Asynchronous Operation and Resynchronization	264
6.5.1	Transition to Asynchronous Operation	265
6.5.2	Asynchronous Operation	266
6.5.3	Possibility of Resynchronization	267
6.5.3.1	Influence of the Voltage Regulator	268
6.5.3.2	Other Possibilities of Resynchronization	268
6.6	Out-of-step Protection System	269
6.6.1	Concepts of Out-of-step Protection System	269
6.6.2	Impedance Loci During Power Swings	270
6.6.3	PSP of Synchronous Generator	272
6.6.4	Power Swings Blocking of Distance Protection	274
6.6.5	Protections Sensitive to Power Swings	278
6.6.6	Out-of-step Tripping in Transmission Network	280
6.6.7	Example of a Blackout	281
7	Wind Power	283
7.1	Wind Turbines	283
7.2	Generator Systems	287
7.3	Induction Machine Equivalent Circuit	291
7.4	Induction Generator Coupled to the Grid	294
7.5	Induction Generators with Slightly Increased Speed Range via External Rotor Resistance	297
7.6	Induction Generators with Significantly Increased Speed Range	299
7.6.1	Operation with the Injected Voltage in Phase with the Rotor Current	300
7.6.2	Operation with the Injected Voltage Out of Phase with the Rotor Current	303
7.6.3	The DFIG as a Synchronous Generator	303
7.6.4	Control Strategy for a DFIG	306
7.7	Fully Rated Converter Systems (Wide Speed Control)	307
7.7.1	Machine-side Inverter	307
7.7.2	Grid-side Inverter	308
7.8	Peak Power Tracking of Variable Speed Wind Turbines	309
7.9	Connections of Wind Farms	309
7.10	Fault Behavior of Induction Generators	310
7.10.1	Fixed-speed Induction Generators	310
7.10.2	Variable-speed Induction Generators	312
7.11	Influence of Wind Generators on Power System Stability	312

8	Voltage Stability	315
8.1	Network Feasibility	315
8.1.1	Ideally Stiff Load	316
8.1.2	Influence of the Load Characteristics	319
8.2	Stability Criteria	320
8.2.1	The dQ/dV Criterion	320
8.2.2	The dE/dV Criterion	323
8.2.3	The dQ_G/dQ_L Criterion	324
8.3	Critical Load Demand and Voltage Collapse	325
8.3.1	Effects of Increasing Demand	326
8.3.2	Effect of Network Outages	328
8.3.3	Influence of the Shape of the Load Characteristics	330
8.3.4	Influence of the Voltage Control	331
8.4	Static Analyses	332
8.4.1	Simplified Voltage Stability Criterion	332
8.4.2	Voltage Stability and Load Flow	334
8.4.2.1	Nose Curve and Critical Power Demand	335
8.4.2.2	Sensitivity and Modal Analyses	338
8.4.2.3	Other Methods	340
8.4.3	Voltage Stability Indices	341
8.5	Dynamic Analysis	342
8.5.1	The Dynamics of Voltage Collapse	342
8.5.1.1	Scenario 1: Load Build-up	342
8.5.1.2	Scenario 2: Network Outages	342
8.5.1.3	Scenario 3: Voltage Collapse and Asynchronous Operation	343
8.5.1.4	Scenario 4: Phenomena Inside the Composite Load	343
8.5.2	Examples of Power System Blackouts	344
8.5.2.1	Athens Blackout in 2004	344
8.5.2.2	US/Canada Blackout in 2003	345
8.5.2.3	Scandinavian Blackout in 2003	346
8.5.3	Computer Simulation of Voltage Collapse	346
8.6	Prevention of Voltage Collapse	348
8.7	Self-excitation of a Generator Operating on a Capacitive Load	349
8.7.1	Parametric Resonance in RLC Circuits	349
8.7.2	Self-excitation of a Generator with Open-circuited Field Winding	350
8.7.3	Self-excitation of a Generator with Closed Field Winding	353
8.7.4	Practical Possibility of Self-excitation	354
9	Frequency Stability and Control	355
9.1	Automatic Generation Control	355
9.1.1	Generation Characteristic	356
9.1.2	Primary Control	358
9.1.3	Secondary Control	360
9.1.4	Tertiary Control	364
9.1.5	AGC as a Multi-level Control	365

9.1.6	Defense Plan Against Frequency Instability	366
9.1.7	Quality Assessment of Frequency Control	367
9.2	Stage I – Rotor Swings in the Generators	368
9.3	Stage II – Frequency Drop	371
9.4	Stage III – Primary Control	373
9.4.1	The Importance of the Spinning Reserve	374
9.4.2	Frequency Collapse	376
9.4.3	Underfrequency Load Shedding	377
9.5	Stage IV – Secondary Control	378
9.5.1	Islanded System	378
9.5.1.1	The Energy Balance over the Four Stages	380
9.5.2	Interconnected Systems and Tie-line Oscillations	381
9.5.2.1	Ideal Settings of the Regulators	383
9.5.2.2	Nonideal Settings of the Central Regulator	384
9.5.2.3	Insufficient Available Regulation Power	385
9.6	Simplified Simulation Models	387
9.6.1	Simplified Model of Islanded System	387
9.6.2	Simplified Model of Two Connected Subsystems	388
9.7	Series FACTS Devices in Tie-lines	392
9.7.1	Incremental Model of a Multi-machine System	393
9.7.2	State-variable Control Based on Lyapunov Method	397
9.7.3	Simulation Model of Three Connected Subsystems	400
9.7.4	Example of Simulation Results	400
9.7.5	Coordination Between AGC and Series FACTS Devices in Tie-lines	403
9.8	Static Analysis by Snapshots of Power Flow	404
10	Stability Enhancement	407
10.1	Excitation Control System	408
10.1.1	Transient Gain Reduction	408
10.1.2	Power System Stabilizers	410
10.1.2.1	PSS Based on $\Delta\omega$	411
10.1.2.2	PSS Based on P_e	412
10.1.2.3	PSS Based on P_e and $\Delta\omega$	413
10.1.2.4	PSS Based on f_{V_g} and $f_{E'}$	414
10.1.2.5	Influence of PSS on Electromechanical Swings in Transient State	414
10.1.2.6	PSS Design	414
10.2	Turbine Control System	415
10.2.1	PSS Applied to the Turbine Governor	415
10.2.2	Fast Valving	416
10.3	Braking Resistors	419
10.4	Generator Tripping	421
10.4.1	Preventive Tripping	421
10.4.2	Restitutive Tripping	423
10.5	Shunt FACTS Devices	423
10.5.1	Power-angle Characteristic	423

10.5.2	State-variable Stabilizing Control	426
10.5.2.1	Energy Dissipation	426
10.5.2.2	Continuous Control	427
10.5.2.3	Bang-Bang Control	428
10.5.2.4	Interpretation of Shunt Element Control Using the Equal Area Criterion	428
10.5.3	Control Based on Local Measurements	429
10.5.3.1	Dynamic Properties of Local Measurements	429
10.5.3.2	Voltage-based Quantities	430
10.5.3.3	Control Schemes	431
10.5.4	Examples of Controllable Shunt Elements	432
10.5.4.1	Supplementary Control of SVC and STATCOM	432
10.5.4.2	Control of BR	432
10.5.4.3	STATCOM + BR as a More Effective Device	433
10.5.4.4	Modulation of Energy Storage SMES or BESS	433
10.5.5	Generalization to Multi-machine Systems	433
10.5.5.1	Mathematical Model	433
10.5.5.2	Control Strategy	434
10.5.5.3	Wide Area Control System WAMPAC	437
10.5.5.4	Emulation of State-variable Control by Local Control	437
10.5.6	Example of Simulation Results	440
10.6	Series Compensators	442
10.6.1	State-variable Control	443
10.6.2	Interpretation Using the Equal Area Criterion	445
10.6.3	Control Strategy Based on the Squared Current	446
10.6.4	Control Based on Other Local Measurements	447
10.6.4.1	Controller Based on Active Power	448
10.6.4.2	Controller Based on Current	448
10.6.4.3	Controller Cased on Squared Current	448
10.6.5	Simulation Results	449
10.7	Unified Power Flow Controller	449
10.7.1	Power-angle Characteristic	450
10.7.2	State-variable Control	452
10.7.3	Control Based on Local Measurements	453
10.7.4	Examples of Simulation Results	454
10.8	HVDC Links in Transmission Network	455
10.8.1	Mathematical Model	456
10.8.2	State-variable Stabilizing Control	458
10.8.2.1	Lyapunov Function	458
10.8.2.2	Control Formulas	459
10.8.2.3	Controllability	461
10.8.2.4	Additive Damping	461
10.8.2.5	Simulation Results	461
10.8.2.6	Robustness	463
10.8.3	Control Based on Local Measurements	463

Part III**Advanced Topics in Power System Dynamics 467**

11	Advanced Power System Modeling 469
11.1	Synchronous Generator 469
11.1.1	Assumptions 470
11.1.2	The Flux Linkage Equations in the Stator Reference Frame 470
11.1.3	The Flux Linkage Equations in the Rotor Reference Frame 472
11.1.4	Voltage Equations 475
11.1.5	Generator Reactances in Terms of Circuit Quantities 478
11.1.5.1	Steady State 478
11.1.5.2	Transient State 478
11.1.5.3	Subtransient State 480
11.1.6	Synchronous Generator Equations 481
11.1.6.1	Steady-state Operation 482
11.1.6.2	Transient Operation 482
11.1.6.3	Subtransient Operation 484
11.1.6.4	The Generator (d, q) Reference Frame and the System (a, b) Reference Frame 485
11.1.6.5	Power, Torque, and the Swing Equation 487
11.1.6.6	Per-unit Notation 487
11.1.7	Synchronous Generator Models 488
11.1.7.1	Sixth-order Model – $(\dot{\delta}, \dot{\omega}, \dot{E}''_d, \dot{E}''_q, \dot{E}'_d, \dot{E}'_q)$ 489
11.1.7.2	Fifth-order Model – $(\dot{\delta}, \dot{\omega}, \dot{E}''_d, \dot{E}''_q, \dot{E}'_q)$ 490
11.1.7.3	Fourth-order Model – $(\dot{\delta}, \dot{\omega}, \dot{E}'_d, \dot{E}'_q)$ 490
11.1.7.4	Third-order Model – $(\dot{\delta}, \dot{\omega}, \dot{E}'_q)$ 491
11.1.7.5	Second-order Model – The Classical Model $(\dot{\delta}, \dot{\omega})$ 491
11.1.7.6	Summary 492
11.1.8	Saturation Effects 492
11.1.8.1	Saturation Characteristic 492
11.1.8.2	Calculation of the Saturation Factor 493
11.1.8.3	Sensitivity of Parameters to Saturation 495
11.2	Excitation Systems 496
11.2.1	Transducer and Comparator Model 497
11.2.2	Exciters and Regulators 497
11.2.2.1	DC Exciters 497
11.2.2.2	AC Rotating Exciters 500
11.2.2.3	Static Exciters 502
11.2.3	Power System Stabilizer (PSS) 503
11.3	Turbines and Turbine Governors 505
11.3.1	Steam Turbines 505
11.3.1.1	Governing System for Steam Turbines 508
11.3.1.2	Boiler Control 510
11.3.2	Hydraulic Turbines 511
11.3.2.1	Linear Turbine Model 513

11.3.2.2	Governing System for Hydraulic Turbines	514
11.3.3	Gas-steam Combined-cycle Power Plants	516
11.3.3.1	Gas Turbine Model	518
11.3.3.2	Steam Turbine Model	520
11.3.3.3	Simplified Models	521
11.4	Wind Turbine Generator Systems and Wind Farms	522
11.4.1	Wind Energy Systems	522
11.4.2	Wind Speed	524
11.4.3	Wind Turbine Generator System with Induction Generator	525
11.4.3.1	Wind Turbine	525
11.4.3.2	Asynchronous Machine	527
11.4.3.3	Power Electronic Converter	532
11.4.3.4	Control System	533
11.4.4	WTGS with Synchronous Generator	541
11.4.4.1	Control System	541
11.5	Photovoltaic Power Plants	544
11.6	HVDC Links	548
11.6.1	HVDC Link Structure	548
11.6.2	Power Electronic Converter Models	549
11.6.3	Control of HVDC Links	552
11.6.3.1	Control of Thyristor-based Converter HVDC Link	553
11.6.3.2	Control of Transistor-based Converter HVDC Link	554
11.7	Facts Devices	557
11.7.1	Shunt FACTS Devices	557
11.7.2	Series FACTS Devices	557
11.8	Dynamic Load Models	559
12	Steady-state Stability of Multi-machine Systems	561
12.1	Mathematical Background	561
12.1.1	Eigenvalues and Eigenvectors	561
12.1.2	Diagonalization of a Square Real Matrix	565
12.1.3	Solution of Matrix Differential Equation	568
12.1.4	Modal and Sensitivity Analysis	575
12.1.5	Modal Form of the State Equation with Inputs	579
12.1.6	Nonlinear System	579
12.2	Steady-state Stability of Unregulated System	580
12.2.1	State-space Equation	580
12.2.2	Simplified Steady-state Stability Conditions	583
12.2.3	Including the Voltage Characteristics of the Loads	587
12.2.4	Transfer Capability of the Network	588
12.3	Steady-state Stability of the Regulated System	589
12.3.1	Generator and Network	589
12.3.2	Including Excitation System Model and Voltage Control	593
12.3.3	Linear State Equation of the System	594
12.3.4	Examples	596

13	Power System Dynamic Simulation	601
13.1	Numerical Integration Methods	602
13.2	The Partitioned Solution	606
13.2.1	Partial Matrix Inversion	609
13.2.2	Matrix Factorization	611
13.2.3	Newton's Method	613
13.2.4	Ways of Avoiding Iterations and Multiple Network Solutions	616
13.3	The Simultaneous Solution Methods	618
13.4	Comparison Between the Methods	619
13.5	Modeling of Unbalanced Faults	620
13.6	Evaluation of Power System Dynamic Response	622
14	Stability Studies in Power System Planning	625
14.1	Purposes and Kinds of Analyses	625
14.1.1	Static Analyses	626
14.1.2	Dynamic Analyses	627
14.2	Planning Criteria	629
14.2.1	Contingency Events and Initial Conditions	629
14.2.2	Allowed Constraints in System Operation	631
14.2.3	Performance Standard	632
14.2.4	Examples	634
14.3	Automation of Analyses and Reporting	641
15	Optimization of Control System Parameters	643
15.1	Grid Code Requirements	643
15.2	Optimization Methods	644
15.3	Linear Regulators	647
15.3.1	Linear Regulator Design	647
15.3.2	Voltage Regulators	655
15.3.3	Power System Stabilizers	668
15.3.3.1	Selection of Low-pass $G_f(s)$ and High-pass $G_w(s)$ Filters Parameters	672
15.3.3.2	Selection of Time Constants of Compensating Elements $G_c(s)$	674
15.3.3.3	Selection of the Gain	678
15.3.3.4	Selection of Limits for the Output Signal V_{PSS} and the PSS Blocking	681
15.4	Optimal Regulators LQG, LQR, and LQI	681
15.5	Robust Regulators H_2 , h_∞	685
15.6	Nonlinear Regulators	693
15.7	Adaptive Regulators	694
15.8	Real Regulators and Field Tests	700
16	Wide-Area Monitoring and Control	709
16.1	Wide Area Measurement Systems	709
16.1.1	Phasors	709
16.1.2	Structure of the WAMS	713

16.2	Examples of WAMS Applications	718
16.2.1	Evaluation of Power System Operation	718
16.2.1.1	Identification of Modes of Electromechanical Oscillations	719
16.2.1.2	Monitoring of Electromechanical Oscillations	721
16.2.1.3	Identification of Subsynchronous Oscillations	722
16.2.2	Detection of Power System Islanding	723
16.2.3	Stability Monitoring and Instability Prediction	726
16.2.3.1	Steady-state Inherent Stability	726
16.2.3.2	Transient Instability	727
16.2.4	Damping of Electromechanical Oscillations	728
17	Impact of Renewable Energy Sources on Power System Dynamics	735
17.1	Renewable Energy Sources	735
17.1.1	Wind Turbine Generator Systems	736
17.1.1.1	WTGS with a DFIG	736
17.1.1.2	WTGS with Synchronous Generator and an FRC	739
17.1.1.3	Summary Remarks	740
17.1.2	Photovoltaic Power Plants	741
17.2	Inertia in the Electric Power System	742
17.2.1	Variability of the Power System Inertia	742
17.2.1.1	Definition of <i>RoCoF</i>	743
17.2.1.2	Assessment of the EPS Inertia Constant and <i>RoCoF</i>	745
17.2.1.3	Calculation of <i>RoCoF</i> for Individual Generating Units	749
17.2.2	Impact of Inertia Constant on Power System Dynamics	752
17.3	Virtual Inertia	758
17.3.1	The Algorithm of a Virtual Inertia	759
17.3.2	The Impact of Virtual Inertia on Power System Dynamics	763
17.3.3	Virtual Inertia and Dynamics of Interconnected Systems	769
18	Power System Model Reduction – Equivalents	775
18.1	Types of Equivalents	775
18.2	Network Transformation	776
18.2.1	Elimination of Nodes	776
18.2.1.1	Sparse Matrix Techniques	777
18.2.2	Aggregation of Nodes Using Dimo’s Method	779
18.2.3	Aggregation of Nodes Using Zhukov’s Method	780
18.2.4	Coherency	782
18.3	Aggregation of Generating Units	784
18.4	Equivalent Model of External Subsystem	785
18.5	Coherency Recognition	786
18.6	Properties of Coherency Based Equivalents	790
18.6.1	Electrical Interpretation of Zhukov’s Aggregation	790
18.6.2	Incremental Equivalent Model	791
18.6.2.1	Aggregation in the Linear Model	793

- 18.6.2.2 Linearization of the Reduced Nonlinear Model 793
- 18.6.3 Modal Interpretation of Exact Coherency 794
- 18.6.4 Eigenvalues and Eigenvectors of the Equivalent Model 798
- 18.6.5 Equilibrium Points of the Equivalent Model 804

Appendix 809

- A.1 Per-unit System 809
 - A.1.1 Stator Base Quantities 809
 - A.1.2 Power Invariance 811
 - A.1.3 Rotor Base Quantities 811
 - A.1.4 Power System Base Quantities 814
 - A.1.5 Transformers 815
- A.2 Partial Inversion 816
- A.3 Linear Ordinary Differential Equations 817
 - A.3.1 Fundamental System of Solutions 817
 - A.3.2 Real and Distinct Roots 819
 - A.3.3 Repeated Real Roots 820
 - A.3.4 Complex and Distinct Roots 821
 - A.3.5 Repeated Complex Roots 825
 - A.3.6 First-order Complex Differential Eq. 825
- A.4 Prony Analysis 826
- A.5 Limiters and Symbols in Block Diagrams 832
 - A.5.1 Addition, Multiplication, and Division 832
 - A.5.2 Simple Integrator 833
 - A.5.3 Simple Time Constant 833
 - A.5.4 Lead-lag Block 834

References 835**Index 847**

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List of Symbols & Abbreviations

Notation

Italic type denotes scalar physical quantity (e.g. R , L , C) or numerical variable (e.g. x , y).

Phasor or complex quantity or numerical variable is underlined (e.g. \underline{I} , \underline{V} , \underline{S}).

Italic with arrow on top of a symbol denotes a spatial vector (e.g. \vec{F}).

Italic boldface denotes a matrix or a vector (e.g. \mathbf{A} , \mathbf{B} , \mathbf{x} , \mathbf{y}).

Unit symbols are written using roman type (e.g. Hz, A, kV).

Standard mathematical function are written using roman type (e.g. sin, cos).

Numbers are written using roman type (e.g. 5, 6).

Symbols representing numbers are written using roman type (e.g. π , $e = 2.718282$ – John Napier number, j – angular shift by 90° , a – angular shift by 120°).

Matrix transposition T is written using roman type.

Differential and partial differential coefficients are written using roman type (e.g. $\frac{df}{dx}$, $\frac{\partial f}{\partial x}$).

Symbols describing objects are written using roman type (e.g. TRAFO, LINE).

Subscript relating to objects is written using roman type (e.g. I_{TRAFO} , I_{LINE}).

Subscript relating to physical quantity or numerical variable is written using italic type (e.g. A_{ij} , x_k).

Subscripts A, B, C refer to three-phase axes of a generator.

Subscripts d, q refer to the direct- (d-axis) and quadrature-axis (q-axis) components.

Lower case symbols normally denote instantaneous values (e.g. v , i).

Upper case symbols normally denote RMS or peak values (e.g. V , I).

Symbols

a , a^2 operators shifting the angle by 120° and 240° , respectively.

B_μ magnetizing susceptance of a transformer.

B_{sh} susceptance of a shunt element.

D damping coefficient.

E_k kinetic energy of the rotor relative to the synchronous speed.

E_p potential energy of the rotor with respect to the equilibrium point.

e_f field voltage referred to the fictitious q-axis armature coil.

e_q steady-state emf induced in the fictitious q-axis armature coil proportional to the field winding self-flux linkages.

e'_d transient emf induced in the fictitious d-axis armature coil proportional to the flux linkages of the q-axis coil representing the solid steel rotor body (round-rotor generators only).

e'_q	transient emf induced in the fictitious q-axis armature coil proportional to the field winding flux linkages.
e''_d	subtransient emf induced in the fictitious d-axis armature coil proportional to the total q-axis rotor flux linkages (q-axis damper winding and q-axis solid steel rotor body).
e''_q	subtransient emf induced in the fictitious q-axis armature coil proportional to the total d-axis rotor flux linkages (d-axis damper winding and field winding).
E	steady-state internal emf.
E_f	excitation emf proportional to the excitation voltage V_f .
E_{fm}	peak value of the excitation emf.
E_d	d-axis component of the steady-state internal emf proportional to the rotor self-linkages due to currents induced in the q-axis solid steel rotor body (round-rotor generators only).
E_q	q-axis component of the steady-state internal emf proportional to the field winding self-flux linkages (i.e. proportional to the field current itself).
E'	transient internal emf proportional to the flux linkages of the field winding and solid steel rotor body (includes armature reaction).
E'_d	d-axis component of the transient internal emf proportional to flux linkages in the q-axis solid steel rotor body (round-rotor generators only).
E'_q	q-axis component of the transient internal emf proportional to the field winding flux linkages.
E''	subtransient internal emf proportional to the total rotor flux linkages (includes armature reaction).
E''_d	d-axis component of the subtransient internal emf proportional to the total flux linkages in the q-axis damper winding and q-axis solid steel rotor body.
E''_q	q-axis component of the subtransient internal emf proportional to the total flux linkages in the d-axis damper winding and the field winding.
E_r	resultant air-gap emf.
E_{rm}	amplitude of the resultant air-gap emf.
E_G	vector of the generator emf's.
f	mains frequency.
f_n	rated frequency.
\vec{F}	magnetomotive force (mmf) due to the field winding.
\vec{F}_a	armature reaction mmf.
$F_{a\ ac}$	ac armature reaction mmf (rotating).
$F_{a\ dc}$	dc armature reaction mmf (stationary).
$\vec{F}_{ad}, \vec{F}_{aq}$	d- and q-axis components of the armature reaction mmf.
\vec{F}_f	resultant mmf.
G_{Fe}	core loss conductance of a transformer.
G_{sh}	conductance of a shunt element.
H_{ii}, H_{ij}	self and mutual synchronizing power.
i_A, i_B, i_C	instantaneous currents in phases A, B, and C.
$i_{A\ dc}, i_{B\ dc}, i_{C\ dc}$	DC component of the current in phases A, B, and C.
$i_{A\ ac}, i_{B\ ac}, i_{C\ ac}$	ac component of the current in phases A, B, and C.
i_d, i_q	currents flowing in the fictitious d- and q-axis armature coils.
i_D, i_Q	instantaneous d- and q-axis damper winding current.
i_f	instantaneous field current of a generator.

\mathbf{i}_{ABC}	vector of instantaneous phase currents.
\mathbf{i}_{fDQ}	vector of instantaneous currents in the field winding and the d- and q-axis damper windings.
\mathbf{i}_{odq}	vector of armature currents in the rotor reference frame.
\underline{I}	armature current.
$\underline{I}_d, \underline{I}_q$	d- and q-axis component of the armature current.
$\underline{I}_S, \underline{I}_R$	currents at the sending and receiving end of a transmission line.
$\underline{I}_R, \underline{I}_E$	vector of complex current injections to the retained and eliminated nodes.
$\underline{I}_G, \underline{I}_L$	vector of complex generator and load currents.
$\Delta \underline{I}_L$	vector of load corrective complex currents.
J	moment of inertia.
j	operator shifting the angle by 90° .
k_{PV}, k_{QV}	voltage sensitivities of the load (the slopes of the real and reactive power demand characteristics as a function of voltage).
k_{PF}, k_{QF}	frequency sensitivities of the load (the slopes of the real and reactive power demand characteristics as a function of frequency).
K_{E_q}	steady-state synchronizing power coefficient (the slope of the steady-state power angle curve $P_{E_q}(\delta)$).
$K_{E'_q}$	transient synchronizing power coefficient (the slope of the transient power angle curve $P_{E'_q}(\delta')$).
$K_{E'}$	transient synchronizing power coefficient (the slope of the transient power angle curve $P_{E'}(\delta')$).
K_i	reciprocal of droop for the i -th generating unit.
K_L	frequency sensitivity coefficient of the system real power demand.
K_T	reciprocal of droop for the total system generation characteristic.
l	length of a transmission line.
L_{AA}, L_{BB}, L_{CC}	self-inductances of the windings of the phase windings A, B, and C; the field winding; and the
L_{ff}, L_{DD}, L_{QQ}	d- and the q-axis damper winding.
L_d, L_q	inductances of the fictitious d- and q-axis armature windings.
L'_d, L'_q, L''_d, L''_q	d- and q-axis transient and subtransient inductances.
L_{xy}	where $x, y \in \{A, B, C, D, Q, f\}$ and $x \neq y$ are the mutual inductances between the windings denoted by the indices as described above.
L_S	minimum value of the self-inductance of a phase winding.
ΔL_S	amplitude of the variable part of the self-inductance of a phase winding.
\mathbf{L}_R	submatrix of the rotor self- and mutual inductances.
\mathbf{L}_S	submatrix of the stator self- and mutual inductances.
$\mathbf{L}_{SR}, \mathbf{L}_{RS}$	submatrices of the stator-to-rotor and rotor-to-stator mutual inductances.
M	coefficient of inertia.
M_f, M_D, M_Q	amplitude of the mutual inductance between a phase winding and, respectively, the field winding and the d- and q-axis damper winding.
N	generally, number of turns of a winding.
p	number of poles.
P, Q	active (real) and reactive power, respectively.
P_{acc}	accelerating power.
P_D	damping power.
P_e	electromagnetic air-gap power.

$P_{E_q \text{ cr}}$	critical (pull-out) air-gap power developed by a generator.
$P_{E_q}(\delta), P_{E'}(\delta'), P_{E'_q}(\delta')$	air-gap power curves assuming $E_q = \text{constant}$, $E' = \text{constant}$, and $E'_q = \text{constant}$.
P_g	in induction machine (Chapter 7), real power supplied from the grid (motoring mode) or supplied to the grid (generating mode).
P_L	real power absorbed by a load or total system load.
P_m	mechanical power supplied by a prime mover to a generator; also mechanical power supplied by a motor to a load (induction machine in motoring mode, Chapter 7).
P_n	real power demand at rated voltage.
P_R	real power at the receiving end of a transmission line.
$P_{rI}, P_{rII}, P_{rIII}, P_{rIV}$	contribution of the generating units remaining in operation toward covering the real power imbalance during the first, second, third, and fourth stage of load frequency control.
$P_{sI}, P_{sII}, P_{sIII}, P_{sIV}$	contribution of the system toward covering the real power imbalance during the first, second, third, and fourth stage of load frequency control.
P_s	stator power of induction machine (Chapter 7).
P_S	real power at the sending end of a transmission line or real power supplied by a source to a load or real power supplied to the infinite busbar.
P_{SIL}	surge impedance (natural) load.
$P_{SE_q}(\delta)$	curve of real power supplied to the infinite busbar assuming $E_q = \text{constant}$.
P_T	total power generated in a system.
P_{tie}	net tie-line interchange power.
$P_{V_g}(\delta)$	air-gap power curve assuming $V_g = \text{constant}$.
$P_{V_g \text{ cr}}$	critical value of $P_{V_g}(\delta)$.
Q_L	reactive power absorbed by a load.
Q_G	reactive power generated by a source (the sum of Q_L and the reactive power loss in the network).
Q_n	reactive power demand at rated voltage.
Q_R	reactive power at the receiving end of a transmission line.
Q_S	reactive power at the sending end of a transmission line or reactive power supplied by a source to a load.
R	resistance.
r	total resistance between (and including) the generator and the infinite busbar.
$R_A, R_B, R_C, R_D, R_Q, R_f$	resistances of the phase windings A, B, and C; the d- and q-axis damper winding; and the field winding.
\mathbf{R}_{ABC}	diagonal matrix of phase winding resistances.
\mathbf{R}_{fDQ}	diagonal matrix of resistances of the field winding and the d- and q-axis damper windings.
s	Laplace operator.
s	slip of induction motor.
s_{cr}	critical slip of induction motor.
S_n	rated apparent power.
S_{SHC}	short-circuit power.
t	time.
T'_d, T''_d	short-circuit d-axis transient and subtransient time constants.
T'_{do}, T''_{do}	open-circuit d-axis transient and subtransient time constants.
T'_q, T''_q	short-circuit q-axis transient and subtransient time constants.

T'_{q0}, T''_{q0}	open-circuit q-axis transient and subtransient time constants.
T_a	armature winding time constant.
\mathbf{T}	transformation matrix between network (a, b) and generator (d, q) coordinates.
v_A, v_B, v_C, v_f	instantaneous voltages across phases A, B, and C and the field winding.
v_d, v_q	voltages across the fictitious d- and q-axis armature coils.
v_w	wind speed.
\mathbf{v}_{ABC}	vector of instantaneous voltages across phases A, B, and C.
\mathbf{v}_{fDQ}	vector of instantaneous voltages across the field winding and the d- and q-axis damper windings.
V	Lyapunov function.
V_{cr}	critical value of the voltage.
$\underline{V}_d, \underline{V}_q$	d- and q-axis component of the generator terminal voltage.
V_f	voltage applied to the field winding.
\underline{V}_g	voltage at the generator terminals.
\underline{V}_s	infinite busbar voltage.
$\underline{V}_{sd}, \underline{V}_{sq}$	d- and q-axis component of the infinite busbar voltage.
$\underline{V}_S, \underline{V}_R$	voltage at the sending and receiving end of a transmission line.
V_{sh}	local voltage at the point of installation of a shunt element.
$\underline{V}_i = V_i \angle \delta_i$	complex voltage at node i .
$\underline{V}_R, \underline{V}_E$	vector of complex voltages at the retained and eliminated nodes.
W	work.
\mathbf{W}	Park's modified transformation matrix.
\mathbf{W}, \mathbf{U}	modal matrices of right and left eigenvectors.
X_a	armature reaction reactance (round-rotor generator).
X_C	reactance of a series compensator.
X_D	reactance corresponding to the flux path around the damper winding.
X_d, X'_d, X''_d	d-axis synchronous, transient, and subtransient reactance.
x_d, x'_d, x''_d	total d-axis synchronous, transient, and subtransient reactance between (and including) the generator and the infinite busbar.
$x'_{d \text{ PRE}}, x'_{d \text{ F}}, x'_{d \text{ POST}}$	pre-fault, fault, and post-fault value of x'_d .
X_f	reactance corresponding to the flux path around the field winding.
X_l	armature leakage reactance of a generator.
X_q, X'_q, X''_q	q-axis synchronous, transient and subtransient reactance.
x_q, x'_q, x''_q	total q-axis synchronous, transient, and subtransient reactance between (and including) the generator and the infinite busbar.
X_{SHC}	short-circuit reactance of a system as seen from a node.
Y_T	admittance of a transformer.
\mathbf{Y}	admittance matrix.
$\underline{Y}_{GG}, \underline{Y}_{LL}, \underline{Y}_{LG}$	admittance submatrices, where subscript G corresponds to fictitious generator nodes and subscript L corresponds to all the other nodes (including generator terminal nodes).
\underline{Y}_{LG}	admittance submatrix between generator terminal nodes and other nodes.
$\underline{Y}_{ij} = G_{ij} + jB_{ij}$	element of the admittance matrix.
$\underline{Y}_{RR}, \underline{Y}_{EE}, \underline{Y}_{RE}$	complex admittance submatrices, where subscript E refers to eliminated and subscript R to retained nodes. $Z = \sqrt{r^2 + x_d x_q}$.
\underline{Y}_{ER}	admittance submatrix between retained and eliminated nodes.
Z_c	characteristic impedance of a transmission line.

$\underline{Z}_s = R_s + jX_s$	internal impedance of the infinite busbar.
$\underline{Z}_T = R_T + jX_T$	series impedance of the transformer.
$\Delta\omega$	rotor speed deviation equal to $(\omega - \omega_s)$.
γ	instantaneous position of the generator d-axis relative to phase A.
γ_0	position of the generator d-axis at the instant of a fault.
Φ_a	armature reaction flux.
Φ_{ad}, Φ_{aq}	d- and q-axis component of the armature reaction flux.
$\Phi_{a\ ac}$	ac armature reaction flux (rotating).
$\Phi_{a\ dc}$	dc armature reaction flux (stationary).
Φ_f	excitation (field) flux.
Ψ_A, Ψ_B, Ψ_C	total flux linkage of phases A, B, and C.
$\Psi_{AA}, \Psi_{BB}, \Psi_{CC}$	self-flux linkage of phases A, B, and C.
$\Psi_{a\ ac\ r}$	rotor flux linkages produced by $\Phi_{a\ ac}$.
$\Psi_{a\ dc\ r}$	rotor flux linkages produced by $\Phi_{a\ dc}$.
$\Psi_{a\ r}$	rotor flux linkages produced by the total armature reaction flux.
Ψ_D, Ψ_Q	total flux linkage of damper windings in axes d- and q.
Ψ_d, Ψ_q	total d- and q-axis flux linkages.
Ψ_f	total flux linkage of the field winding.
Ψ_{fa}	excitation flux linkage with armature winding.
$\Psi_{fA}, \Psi_{fB}, \Psi_{fC}$	excitation flux linkage with phases A, B, and C.
Ψ_{ABC}	vector of phase flux linkages.
Ψ_{fDQ}	vector of flux linkages of the field winding and the d- and q-axis damper windings.
Ψ_{0dq}	vector of armature flux linkages in the rotor reference frame.
τ_e	electromagnetic torque.
τ_m	mechanical torque.
τ_ω	fundamental-frequency subtransient electromagnetic torque.
$\tau_{2\omega}$	double-frequency subtransient electromagnetic torque.
τ_d, τ_q	d- and q-axis component of the electromagnetic torque.
τ_R, τ_r	subtransient electromagnetic torque due to stator and rotor resistances.
ϵ	rotor acceleration.
φ_g	power factor angle at the generator terminals.
δ	power (or rotor) angle with respect to the infinite busbar.
δ_g	power (or rotor) angle with respect to the voltage at the generator terminals.
$\hat{\delta}_s$	stable equilibrium value of the rotor angle.
δ'	transient power (or rotor) angle between E' and V_s .
δ_{fr}	angle between the resultant and field mmf's.
λ_R	frequency bias factor.
$\lambda_i = \alpha_i + j\Omega_i$	eigenvalue.
ω	angular velocity of the generator (in electrical radians).
ω_s	synchronous angular velocity in electrical radians (equal to $2\pi f$).
ω_T	rotor speed of wind turbine (in rad/s).
Ω	frequency of rotor swings (in rad/s).
$\mathbf{\Omega}$	rotation matrix.
ρ	static droop of the turbine-governor characteristic.
ρ_T	droop of the total system generation characteristic.
ϑ	transformation ratio.

γ	propagation constant of a transmission line.
β	phase constant of a transmission line.
\mathfrak{R}	reluctance.
$\mathfrak{R}_d, \mathfrak{R}_q$	reluctance along the d- and q-axis.
ζ	damping ratio.

Abbreviations

AC	alternating current
ACE	area control error
AGC	automatic generation control
AGSS	automatic generation shedding scheme
ANN	artificial neural network
AR	autoregressive
ARMAX	autoregressive moving average with exogenous input model
ARX	autoregressive with exogenous input model
AVR	automatic voltage regulator
BESS	battery energy storage system
BFP	breaker failure protection
BIMP	Bureau international des poids et mesures
BTA	balanced truncation approximation
CCGT	combined cycle gas turbine
CCPP	combined-cycle power plant
CCT	critical clearing time
CESA	continental Europe synchronous area
CIM	current injection model
COI	center of inertia
CSC	controlled series capacitor
CT	current transformer
d-axis	direct-axis of a generator
DC	direct current
DFIG	doubly-fed induction generator
DFIM	doubly-fed induction machine
DSA	dynamic security assessment
DSO	distribution system operator
EHV	extra high voltage
emf	electromotive force
EMS	energy management system
ENTSO-E	European Network of Transmission System Operators for Electricity
EPS	electric power system
FACTS	flexible AC transmission system
FC	fixed capacitor
FRC	fully rated converter
FRT	fault ride through

GEP	generator-exciter-power system
GV	governor valves
GPS	global positioning system
GTO	gate turn-off thyristor
HAWT	horizontal-axis wind turbine
HP	high pressure
HRB	heat-recovery boiler
HRSG	heat-recovery steam generator
HV	high voltage
HVDC	high voltage direct current
HVRT	high-voltage ride through
IGBT	insulated gate bipolar transistor
IGCT	integrated gate-commutated thyristor
IGV	inlet guide vanes
Im	imaginary axis
IP	intermediate pressure
IV	intercept valves
K3, K2E, K2, K1	short circuits: three-phase, two-phase-ground, two-phase, single-phase
LFC	load and frequency control
LLFT	lower linear fractional transformation
LP	low pressure
LQE	linear-quadratic estimator
LQI	linear-quadratic-Gaussian regulator with tracking loop based on integral element
LQR	linear-quadratic regulator
LTC	load tap changer
LVRT	low-voltage ride through
MAWS	mean annual wind speed
MIMO	multiple inputs and multiple outputs
mmf	magnetomotive force
MSV	main emergency stop valves
OEL	overexcitation limiter
OLEC	overload emergency state control
OLTC	on-load tap changer
OPF	optimal power flow
OST	out-of-step tripping
PCC	point of common coupling
PCS	power conditioning system
PDC	phasor data concentrator
PMU	phasor measurement unit
POD	power oscillation damper
PSB	power swing blocking
PSD	power swing detection
PSP	pole-slip protection
PSS	power system stabilizer
pu	per unit