

Contents

1	FACTS-Devices and Applications	1
1.1	Overview	2
1.2	Power Electronics	5
1.2.1	Semiconductors	6
1.2.2	Power Converters	8
1.3	Configurations of FACTS-Devices	13
1.3.1	Shunt Devices	13
1.3.1.1	SVC	14
1.3.1.2	STATCOM	15
1.3.2	Series Devices	18
1.3.2.1	Series Compensation	18
1.3.2.2	TCSC	19
1.3.2.3	SSSC	21
1.3.2.4	SCCL	22
1.3.3	Shunt and Series Devices	23
1.3.3.1	Dynamic Power Flow Controller	23
1.3.3.2	Unified Power Flow Controller	25
1.3.3.3	Interline Power Flow Controller	26
1.3.3.4	Generalized Unified Power Flow Controller	27
1.3.4	Back-to-Back Devices	28
	References	29
2	Modeling of Multi-Functional Single Converter FACTS in Power Flow Analysis.....	3
2.1	Power Flow Calculations	31
2.1.1	Power Flow Methods	31
2.1.2	Classification of Buses	32
2.1.3	Newton-Raphson Power Flow in Polar Coordinates	32
2.2	Modeling of Multi-Functional STATCOM	32
2.2.1	Multi-Control Functional Model of STATCOM for Power Flow Analysis	33
2.2.1.1	Operation Principles of the STATCOM	33
2.2.1.2	Power Flow Constraints of the STATCOM	34
2.2.1.3	Multi-Control Functions of the STATCOM	35
2.2.1.4	Voltage and Thermal Constraints of the STATCOM	39
2.2.1.5	External Voltage Constraints	40

2.2.2	Implementation of Multi-Control Functional Model of STATCOM in Newton Power Flow.....	40
2.2.2.1	Multi-Control Functional Model of STATCOM in Newton Power Flow.....	40
2.2.2.2	Modeling of Constraint Enforcement in Newton Power Flow	41
2.2.3	Multi-Violated Constraints Enforcement	42
2.2.3.1	Problem of Multi-Violated Constraints Enforcement.....	42
2.2.3.2	Concepts of Dominant Constraint and Dependent Constraint.....	43
2.2.3.3	Strategy for Multi-Violated Constraints Enforcement.....	43
2.2.4	Multiple Solutions of STATCOM with Current Magnitude Control	44
2.2.5	Numerical Examples	45
2.2.5.1	Multi-Control Capabilities of STATCOM	45
2.2.5.2	Multi-Violated STATCOM Constraints Enforcement	48
2.3	Modeling of Multi-Control Functional SSSC.....	50
2.3.1	Multi-Control Functional Model of SSSC for Power Flow Analysis	51
2.3.1.1	Operation Principles of the SSSC.....	51
2.3.1.2	Equivalent Circuit and Power Flow Constraints of SSSC	51
2.3.1.3	Multi-Control Functions and Constraints of SSSC	53
2.3.1.4	Voltage and Current Constraints of the SSSC.....	54
2.3.2	Implementation of Multi-Control Functional Model of SSSC in Newton Power Flow	55
2.3.2.1	Multi-Control Functional Model of SSSC in Newton Power Flow.....	55
2.3.2.2	Enforcement of Voltage and Current Constraints for SSSC.....	56
2.3.2.3	Initialization of SSSC in Newton Power Flow	57
2.3.3	Numerical Results	58
2.3.3.1	Power Flow, Voltage and Reactance Control by the SSSC	58
2.3.3.2	Enforcement of Voltage and Current Constraint of the SSSC	61
2.4	Modeling of SVC and TCSC in Power Flow Analysis	62
2.4.1	Representation of SVC by STATCOM in Power Flow Analysis	62
2.4.2	Representation of TCSC by SSSC in Power Flow Analysis	63
	References.....	64

3 Modeling of Multi-Converter FACTS in Power Flow Analysis.....	67
3.1 Modeling of Multi-Control Functional UPFC.....	67
3.1.1 Advanced UPFC Models for Power Flow Analysis.....	68
3.1.1.1 Operating Principles of UPFC.....	68
3.1.1.2 Power Flow Constraints of UPFC	69
3.1.1.3 Active Power Balance Constraint of UPFC.....	70
3.1.1.4 Novel Control Modes of UPFC	70
3.1.2 Implementation of Advanced UPFC Model in Newton Power Flow	75
3.1.2.1 Modeling of UPFC in Newton Power Flow	75
3.1.2.2 Modeling of Voltage and Current Constraints of the UPFC	76
3.1.2.3 Initialization of UPFC Variables in Newton Power Flow	76
3.1.3 Numerical Results.....	77
3.2 Modeling of Multi-Control Functional IPFC and GUPFC.....	79
3.2.1 Mathematical Modeling of IPFC in Newton Power Flow under Practical Constraints	80
3.2.1.1 Mathematical Model of the IPFC	80
3.2.1.2 Modeling of IPFC in Newton Power Flow	83
3.2.1.3 Initialization of IPFC Variables in Newton Power Flow	84
3.2.2 Mathematical Modeling of GUPFC in Newton Power Flow under Practical Constraints	85
3.2.2.1 Mathematical Model of GUPFC	85
3.2.2.2 Modeling of the GUPFC in Newton Power Flow	88
3.2.2.3 Initialization of GUPFC Variables in Newton Power Flow	89
3.2.3 Numerical Examples	89
3.2.3.1 Initialization of the Power Flow with FACTS-Devices	90
3.2.3.2 Enforcement of Practical Constraints of FACTS	91
3.2.3.3 Enforcement of Practical Constraints of Series Converters	92
3.2.3.4 Enforcement of Practical Constraints of the Shunt Converter.....	92
3.2.3.5 Enforcement of Series and Shunt Converter Constraints	92
3.3 Multi-Terminal Voltage Source Converter Based HVDC.....	93
3.3.1 Mathematical Model of M-VSC-HVDC with Converters Co-located in the Same Substation	94
3.3.1.1 Operating Principles of M-VSC-HVDC.....	94
3.3.1.2 Power Flow Constraints of M-VSC-HVDC.....	95
3.3.1.3 Active Power Balance of M-VSC-HVDC.....	96

3.3.1.4	Voltage and Power Flow Control of M-VSC-HVDC	96
3.3.1.5	Voltage and Current Constraints of M-VSC-HVDC	98
3.3.1.6	Modeling of M-VSC-HVDC in Newton Power Flow	98
3.3.1.7	Handling of Internal Voltage and Current Limits of M-VSC-HVDC	99
3.3.1.8	Comparison of M-VSC-HVDC and GUPFC	99
3.3.2	Generalized M-VSC-HVDC Model with Incorporation of DC Network Equation	100
3.3.2.1	Generalized M-VSC-HVDC	100
3.3.2.2	DC Network Equation	101
3.3.2.3	Incorporation of DC Network Equation into Newton Power Flow	102
3.3.3	Numerical Examples	103
3.3.3.1	Comparison of the M-VSC-HVDC to the GUPFC	103
3.3.3.2	Power Flow and Voltage Control by M-VSC-HVDC	104
3.4	Handling of Small Impedances of FACTS in Power Flow Analysis	107
3.4.1	Numerical Instability of Voltage Source Converter FACTS Models	107
3.4.2	Impedance Compensation Model	108
	References	110
4	Modeling of FACTS-Devices in Optimal Power Flow Analysis.....	113
4.1	Optimal Power Flow Analysis.....	113
4.1.1	Brief History of Optimal Power Flow	113
4.1.2	Comparison of Optimal Power Flow Techniques	114
4.1.2.1	Gradient Methods	114
4.1.2.2	Linear Programming Methods	114
4.1.2.3	Quadratic Programming Methods	115
4.1.2.4	Newton's Methods	115
4.1.2.5	Interior Point Methods	116
4.1.3	Overview of OPF-Formulation	116
4.2	Nonlinear Interior Point Optimal Power Flow Methods.....	118
4.2.1	Power Mismatch Equations	118
4.2.2	Transmission Line Limits	118
4.2.3	Formulation of the Nonlinear Interior Point OPF	119
4.2.4	Implementation of the Nonlinear Interior Point OPF	123
4.2.4.1	Eliminating Dual Variables π_l, π_u of the Inequalities	123
4.2.4.2	Eliminating Generator Variables P_g and Q_g	124
4.2.5	Solution Procedure for the Nonlinear Interior Point OPF	126

4.3	Modeling of FACTS in OPF Analysis.....	126
4.3.1	IPFC and GUPFC in Optimal Voltage and Power Flow Control	127
4.3.2	Operating and Control Constraints of GUPFC.....	127
4.3.2.1	Power Flow Constraints of GUPFC	128
4.3.2.2	Operating Control Equalities of GUPFC.....	130
4.3.2.3	Operating Inequalities of GUPFC	130
4.3.3	Incorporation of GUPFC into Nonlinear Interior Point OPF	131
4.3.3.1	Constraints of GUPFC.....	131
4.3.3.2	Variables of GUPFC	131
4.3.3.3	Augmented Lagrangian Function of GUPFC in Nonlinear Interior OPF	133
4.3.3.4	Newton Equation of Nonlinear Interior OPF with GUPFC.....	134
4.3.3.5	Implementation of Multi-Configurations and Multi-Control Functions of GUPFC	135
4.3.3.6	Initialization of GUPFC Variables in Nonlinear Interior OPF	136
4.3.4	Modeling of IPFC in Nonlinear Interior Point OPF.....	137
4.4	Modeling of Multi-Terminal VSC-HVDC in OPF.....	139
4.4.1	Multi-Terminal VSC-HVDC in Optimal Voltage and Power Flow	139
4.4.2	Operating and Control Constraints of the M-VSC-HVDC	140
4.4.3	Modeling of M-VSC-HVDC in the Nonlinear Interior Point OPF.....	141
4.5	Comparison of FACTS-Devices with VSC-HVDC	143
4.5.1	Comparison of UPFC with BTB-VSC-HVDC	143
4.5.2	Comparison of GUPFC with M-VSC-HVDC.....	145
4.6	Appendix: Derivatives of Nonlinear Interior Point OPF with GUPFC	148
4.6.1	First Derivatives of Nonlinear Interior Point OPF	148
4.6.2	Second Derivatives of Nonlinear Interior Point OPF.....	150
	References	153
5	Modeling of FACTS in Three-Phase Power Flow and Three-Phase OPF Analysis.....	157
5.1	Three-Phase Newton Power Flow Methods in Rectangular Coordinates	158
5.1.1	Classification of Buses.....	158
5.1.2	Representation of Synchronous Machines	159
5.1.3	Power and Voltage Mismatch Equations in Rectangular Coordinates	160
5.1.3.1	Power Mismatch Equations at Network Buses.....	160
5.1.3.2	Power and Voltage Mismatch Equations of Synchronous Machines	161

5.1.4	Formulation of Newton Equations in Rectangular Coordinates	162
5.2	Three-Phase Newton Power Flow Methods in Polar Coordinates.....	168
5.2.1	Representation of Generators	168
5.2.2	Power and Voltage Mismatch Equations in Polar Coordinates	169
5.2.2.1	Power Mismatch Equations at Network Buses.....	169
5.2.2.2	Power and Voltage Mismatch Equations of Synchronous Machines	169
5.2.3	Formulation of Newton Equations in Polar Coordinates	170
5.3	SSSC Modeling in Three-Phase Power Flow in Rectangular Coordinates	171
5.3.1	Three-Phase SSSC Model with Delta/Wye Connected Transformer.....	172
5.3.1.1	Basic Operation Principles	172
5.3.1.2	Equivalent Circuit of Three-Phase SSSC	173
5.3.1.3	Power Equations of the Three-Phase SSSC	174
5.3.1.4	Three-Phase SSSC Model with Independent Phase Power Control	176
5.3.1.5	Three-Phase SSSC Model with Total Three-Phase Power Control	177
5.3.1.6	Three-Phase SSSC Model with Symmetrical Injected Voltage Control	178
5.3.2	Single-Phase/Three-Phase SSSC Models with Separate Single Phase Transformers.....	180
5.3.2.1	Basic Operating Principles of Single Phase SSSC	180
5.3.2.2	Equivalent Circuit of Single Phase SSSC.....	180
5.3.2.3	Single-Phase SSSC.....	181
5.3.2.4	Three-Phase SSSC Model with Three Separate Single Phase Transformers.....	182
5.3.3	Numerical Examples	182
5.3.3.1	Test Results for the 5-Bus System.....	183
5.3.3.2	Test Results for the IEEE 118-Bus System	186
5.4	UPFC Modeling in Three-Phase Newton Power Flow in Polar Coordinates	187
5.4.1	Operation Principles of the Three-Phase UPFC.....	188
5.4.2	Three-Phase Converter Transformer Models	189
5.4.3	Power Flow Constraints of the Three-Phase UPFC	190
5.4.3.1	Power Flow Constraints of the Shunt Converter	190
5.4.3.2	Power Flow Constraints of the Series Converter.....	192
5.4.3.3	Active Power Balance of the UPFC	194
5.4.4	Symmetrical Components Control Model for Three-Phase UPFC	195
5.4.4.1	PQ Flow Control by the Series Converter	195
5.4.4.2	Voltage Control by the Shunt Converter	196

5.4.4.3	Transformer Models	197
5.4.4.4	Modeling of Three-Phase UPFC in Newton Power Flow	197
5.4.5	General Three-Phase Control Model for Three-Phase UPFC	198
5.4.5.1	PQ Flow Control by the Series Converter	198
5.4.5.2	Voltage Control by the Shunt Converter	198
5.4.5.3	Operating Constraints of the Shunt Transformer....	198
5.4.5.4	Transformer Models	199
5.4.5.5	Modeling of Three-Phase UPFC in Newton Power Flow	199
5.4.6	Hybrid Control Model for Three-Phase UPFC	200
5.4.6.1	PQ Flow Control by the Series Converter	200
5.4.6.2	Voltage Control by the Shunt Converter	200
5.4.6.3	Transformer Models	201
5.4.6.4	Modeling of Three-Phase UPFC in the Newton Power Flow	201
5.4.7	Numerical Examples	202
5.4.7.1	Results for the 5-Bus System	202
5.4.7.2	Results for the Modified IEEE 118-Bus System	206
5.5	Three-Phase Newton OPF in Polar Coordinates.....	207
5.6	Appendix A - Definition of Y_{gi}	209
5.7	Appendix B - 5-Bus Test System	210
	References	211
6	Steady State Power System Voltage Stability Analysis and Control with FACTS.....	213
6.1	Continuation Power Flow Methods for Steady State Voltage Stability Analysis	214
6.1.1	Formulation of Continuation Power Flow	214
6.1.2	Modeling of Operating Limits of Synchronous Machines	216
6.1.3	Solution Procedure of Continuation Power Flow.....	217
6.1.4	Modeling of FACTS-Control in Continuation Power Flow....	218
6.1.5	Numerical Results	218
6.1.5.1	System Loadability with FACTS-Devices	218
6.1.5.2	Effect of Load Models	220
6.1.5.3	System Transfer Capability with FACTS-Devices	222
6.2	Optimization Methods for Steady State Voltage Stability Analysis....	223
6.2.1	Optimization Method for Voltage Stability Limit Determination	224
6.2.2	Optimization Method for Voltage Security Limit Determination	225
6.2.3	Optimization Method for Operating Security Limit Determination	225
6.2.4	Optimization Method for Power Flow Unsolvability.....	226

6.2.5	Numerical Examples	228
6.2.5.1	IEEE 30-Bus System Results	228
6.2.5.2	IEEE 118-Bus System Results	229
6.3	Security Constrained Optimal Power Flow for Transfer Capability Calculations	230
6.3.1	Unified Transfer Capability Computation Method with Security Constraints	231
6.3.2	Solution of Unified Security Constrained Transfer Capability Problem by Nonlinear Interior Point Method	233
6.3.3	Solution Procedure of the Security Constrained Transfer Capability Problem	239
6.3.4	Numerical Results	239
6.3.4.1	IEEE 30-Bus System Results	240
6.3.4.2	Discussion of the Results	241
	References	243
7	Steady State Voltage Stability of Unbalanced Three-Phase Power Systems.....	245
7.1	Steady State Unbalanced Three-Phase Power System Voltage Stability.....	245
7.2	Continuation Three-Phase Power Flow Approach	246
7.2.1	Modeling of Synchronous Machines with Operating Limits	246
7.2.2	Three-Phase Power Flow in Polar Coordinates.....	247
7.2.3	Formulation of Continuation Three-Phase Power Flow	249
7.2.4	Solution of the Continuation Three-Phase Power Flow	251
7.2.5	Implementation Issues of Continuation Three-Phase Power Flow	252
7.2.5.1	The Structure of Jacobian Matrix	252
7.2.5.2	Improvement of Computational Speed	252
7.2.5.3	Comparison of Balanced Three-Phase Systems and Single-Phase Systems	252
7.2.6	Numerical Results	253
7.2.6.1	Results for the 5-Bus System without Line Outages	253
7.2.6.2	Results for the 5-Bus System with Line Outages	256
7.2.6.3	Results for the Modified IEEE 118-Bus System	258
7.2.6.4	Reactive Power Limits	259
7.3	Steady State Unbalanced Three-Phase Voltage Stability with FACTS.....	261
7.3.1	STATCOM	262
7.3.2	SSSC	263
7.3.3	UPFC	265
	References	266

8 Congestion Management and Loss Optimization with FACTS.....	269
8.1 Fast Power Flow Control in Energy Markets	269
8.1.1 Operation Strategy	269
8.1.2 Control Scheme.....	271
8.2 Placement of Power Flow Controllers.....	272
8.3 Economic Evaluation Method	275
8.3.1 Modelling of PFC for Cross-Border Congestion Management.....	276
8.3.1.1 Basic Network Model.....	276
8.3.1.2 Inclusion of 'Slow' PFC	278
8.3.1.3 Inclusion of 'Fast' PFC.....	279
8.3.2 Determination of Cross-Border Transmission Capacity	280
8.3.3 Estimation of Economic Benefits through PFC	281
8.4 Quantified Benefits of Power Flow Controllers	284
8.4.1 Transmission Capacity Increase.....	284
8.4.2 Loss Reduction.....	286
8.5 Appendix	289
References	290
9 Non-intrusive System Control of FACTS.....	291
9.1 Requirement Specification	291
9.1.1 Modularized Network Controllers	292
9.1.2 Controller Specification	293
9.2 Architecture	294
9.2.1 NISC-Approach for Regular Operation	296
9.2.2 NISC-Approach for Contingency Operation.....	298
References	299
10 Autonomous Systems for Emergency and Stability Control of FACTS.....	301
10.1 Autonomous System Structure	301
10.2 Autonomous Security and Emergency Control	303
10.2.1 Model and Control Structure	303
10.2.2 Generic Rules for Coordination	304
10.2.3 Synthesis of the Autonomous Control System.....	307
10.2.3.1 Bay Control Level.....	307
10.2.3.2 Substation and Network Control Level.....	309
10.2.3.3 Preventive Coordination	311
10.3 Adaptive Small Signal Stability Control	313
10.3.1 Autonomous Components for Damping Control.....	313
10.4 Verification.....	314
10.4.1 Failure of a Transmission Line.....	316
10.4.2 Increase of Load	318
References	320

11 Multi-agent Systems for Coordinated Control of FACTS-Devices.....	321
11.1 Challenges for Coordinated Control	321
11.2 Multi-agent System Structure	322
11.2.1 Communication Model	322
11.2.1.1 Principle communication among Agents.....	323
11.2.1.2 Communication Rules	324
11.2.2 Influence Area of a PFC	325
11.2.2.1 Calculating the Sensitivity	325
11.2.2.2 Assigning the Direction of Impact.....	326
11.2.3 Distributed Coordination	327
11.2.3.1 Weighting Function	328
11.2.3.2 Control of PFCs.....	330
11.3 Verification	331
11.3.1 Tripping of a Transmission Line.....	331
11.3.2 Increase of Load.....	334
References	336
12 Wide Area Control of FACTS	339
12.1 Wide Area Monitoring and Control System.....	339
12.2 Wide Area Monitoring Applications	342
12.2.1 Corridor Voltage Stability Monitoring	342
12.2.2 Thermal Limit Monitoring	346
12.2.3 Oscillatory Stability Monitoring	347
12.2.4 Topology Detection and State Calculation.....	352
12.2.5 Loadability Calculation Based on OPF Techniques.....	354
12.2.6 Voltage Stability Prediction	355
12.3 Wide Area Control Applications	358
12.3.1 Predictive Control with Setpoint Optimization	359
12.3.2 Remote Feedback Control	362
References	369
13 Modeling of Power Systems for Small Signal Stability Analysis with FACTS	371
13.1 Small Signal Modeling	372
13.1.1 Synchronous Generators	372
13.1.2 Excitation Systems	374
13.1.3 Turbine and Governor Model.....	376
13.1.4 Load Model	376
13.1.5 Network and Power Flow Model	379
13.1.6 FACTS-Models	379
13.1.6.1 SVC-Model	380
13.1.6.2 TCPS-Model	381
13.1.6.3 TCSC-Model.....	384
13.1.7 Study System.....	386
13.2 Eigenvalue Analysis	387
13.2.1 Small Signal Stability Results of Study System	387

13.2.2	Eigenvector, Mode Shape and Participation Factor	393
13.3	Modal Controllability, Observability and Residue.....	396
	References.....	400
14	Linear Control Design and Simulation of Power System Stability with FACTS	401
14.1	H-Infinity Mixed-Sensitivity Formulation	402
14.2	Generalized H-Infinity Problem with Pole Placement	403
14.3	Matrix Inequality Formulation	405
14.4	Linearization of Matrix Inequalities	406
14.5	Case Study.....	408
14.5.1	Weight Selection	408
14.5.2	Control Design	409
14.5.3	Performance Evaluation	412
14.5.4	Simulation Results.....	413
14.6	Case Study on Sequential Design.....	416
14.6.1	Test System	416
14.6.2	Control Design	417
14.6.3	Performance Evaluation	418
14.6.4	Simulation Results.....	419
14.7	H-Infinity Control for Time Delayed Systems	422
14.8	Smith Predictor for Time-Delayed Systems	423
14.9	Problem Formulation Using Unified Smith Predictor	427
14.10	Case Study.....	429
14.10.1	Control Design	429
14.10.2	Performance Evaluation	432
14.10.3	Simulation Results	432
	References.....	436
15	Power System Stability Control Using FACTS with Multiple Operating Points.....	439
15.1	Introduction.....	439
15.1.1	LMI Based Techniques for Damping Control Design	439
15.1.2	The Technical Challenges of LMI Based Damping Control Design for Multi-model Systems	440
15.2	Nonlinear Matrix Inequalities Formulation of FACTS Stability Control Considering Multiple Operating Points	441
15.2.1	Multi-model System	441
15.3	A Two-Step Design Approach for the Output Feedback Controller.....	442
15.3.1	First Step: Determination of the Variable K	443
15.3.2	Second Step: Determination of Variables A_k and B_k	445
15.4	Extension to H_2 and H_∞ Performances	449
15.4.1	First Step: Determining K for Multi-objective Control	450
15.4.2	Second Step: Determining A_k and B_k for Multi-objective Control	451

15.4.3	H _∞ Performance	453
15.4.4	H ₂ Performance.....	454
15.4.5	Remarks on the Two-Step Control Design Approach.....	457
15.5	Two-Step Control Design Approach for the Single-Machine-Infinite-Bus.....	457
15.5.1	Single-Machine-Infinite-Bus (SMIB)	457
15.5.2	Pole Placement Based Damping Controller Design Using the Two-Step Approach.....	459
15.5.3	Comparison MLMI with SLMI Using Nonlinear Simulations.....	462
15.6	Two-Step Control Design Approach for the Multi-machine System.....	463
15.6.1	Multi-machine Test System	463
15.6.2	Two-Step Damping Controller Design for the Multi-machine System	464
15.6.3	Performance Evaluation.....	466
15.6.4	Nonlinear Simulations	467
15.6.4.1	Closed-Loop Performance under Small Disturbances	467
15.6.4.2	Closed-Loop Performance under Three-Phase Fault Conditions.....	468
15.7	Alternative Two-Step Control Design Approach for the Multi-machine System.....	469
15.7.1	Introduction of SCADA/EMS.....	469
15.7.2	Alternative Two-Step Damping Controller Design Approach.....	470
15.7.3	Numerical Examples.....	471
15.8	Summary	473
	References	474
16	Control of a Looping Device in a Distribution System	477
16.1	Overview of a Looping Device in a Distribution System.....	477
16.2	Local Control of Looping Device.....	480
16.2.1	Estimation of Line Voltage	480
16.2.2	Loop Power Flow Control	481
16.2.3	Reactive Power Control.....	482
16.3	Approximation Control	483
16.3.1	Objective Function and Optimal Control	483
16.3.2	Approximation Using the Least-Squares Method	485
16.4	Simulation	486
16.5	Demonstration	492
16.5.1	Field Test System	492
16.5.2	Simple Control for Testing.....	493
16.5.3	Testing Conditions	494
16.5.4	Testing Results	495
	References	497

17	Power Electronic Control for Wind Generation Systems	499
17.1	Introduction	499
17.2	WT with DFIG	501
17.2.1	Modelling and Control of WT with DFIG	501
17.2.1.1	Selection of Models of DFIG for Power System Analysis	501
17.2.1.2	Decoupling Control of DFIG	502
17.2.1.3	Impacts of WT with DFIG on Power System Stability	504
17.2.2	Model of WT with DFIG.....	505
17.2.2.1	Model of DFIG	505
17.2.2.2	Model of Drive Train	507
17.2.2.3	Model of the Back-to-Back Converters	509
17.2.2.4	Rotor Side Converter Controller Model.....	509
17.2.2.5	Grid Side Converter Controller Model	511
17.2.2.6	Pitch Controller	511
17.2.2.7	Interfacing with Power Grid	512
17.3	Small Signal Stability Analysis of WT with DFIG	512
17.3.1	Dynamic Model of WT with DFIG	512
17.3.2	Small Signal Stability Analysis Model of WT with DFIG.....	513
17.3.3	Small Signal Stability Analysis of WT with DFIG	514
17.3.3.1	Small Signal Stability Analysis Techniques [6][19]	514
17.3.3.2	Small Signal Stability Analysis with PI Controllers.....	515
17.3.3.3	Small Signal Stability Analysis with Optimized PI Controllers	516
17.3.4	Dynamic Simulations	517
17.3.4.1	Four-Machine System - Small Disturbance	517
17.3.4.2	Four-Machine System - Large Disturbance	519
17.4	Model of WT with DDPMG	519
17.4.1	Model of WT with DDPMG	520
17.4.1.1	Model of DDPMG	520
17.4.1.2	Model of Drive Train	521
17.4.1.3	Model of Converter.....	522
17.4.1.4	Generator Side Converter Controller Model ...	522
17.4.1.5	Grid Side Converter Controller.....	524
17.4.1.6	Interfacing with Power Grid	524
17.4.1.7	Dynamic Model of WT with DDPMG System.....	525
17.5	Small Signal Stability Analysis of WT with DDPMG	525
17.5.1	Small Signal Stability Analysis Model.....	525
17.5.2	Small Signal Stability Analysis of WT with DDPMG	526
17.5.2.1	Small Signal Stability Analysis with PI Controller	526

17.5.2.2	Small Signal Stability Analysis of the WT with DDPMG Using Optimized PI Controllers.....	527
17.5.3	Dynamic Simulation on Four-Machine System	528
17.6	Nonlinear Control of Wind Generation Systems.....	529
17.6.1	Nonlinear Control.....	529
17.6.2	Third-Order Model of WT with DFIG	530
17.6.3	Nonlinear Control Design for the WT with DFIG.....	531
17.6.3.1	Model Exact Linearization of the WT with DFIG	531
17.6.3.2	Nonlinear Control Design for the WT with DFIG	534
17.6.5	Dynamic Simulations	535
17.6.5.1	CCT Analysis.....	535
17.6.5.2	Dynamic Performance.....	536
17.7	Modelling of Large Wind Farms Using System Dynamic Equivalence.....	536
17.7.1	Identification of Coherency Groups	537
17.7.2	Network Reduction	537
17.7.3	Aggregation of Dynamic Parameters	538
17.7.4	Dynamic Simulations	538
17.8	Interconnection of Large Wind Farms with Power Grid via HVDC Link.....	540
17.8.1	Development in VSC HVDC Technologies	540
17.8.2	VSC HVDC Control for Wind Farm Interconnection.....	542
17.8.3	Dynamic Simulations	543
	References	543
	Index	547