

Contents

	Preface and Acknowledgments Notation		
	Notation	xiii	
Part I Fui	ndamentals	1	
1	Introduction	3	
	1.1 Empowering Smart and Connected Communities through Microgrids		
	and Networked Microgrids	3	
	1.2 Challenges in Networked Microgrids	4	
	1.3 Overview of Topics	7	
	References	8	
2	Basics of Microgrid Control	11	
	2.1 Microgrid Operation	11	
	2.2 Microgrid Control	13	
	2.2.1 Hierarchical Control Principle	13	
	2.2.2 Droop Control for Microgrids	15	
	2.2.3 Master–Slave Control	18	
	2.2.4 Tertiary Control and Remedial Action Schemes	20	
	2.3 Virtual Synchronous Generator	20	
	2.4 A Note about DER Modeling	22	
	References	23	
Part II Ne	etworked Microgrids	27	
3	Compositional Networked Microgrid Power Flow	29	
	3.1 Challenges of Networked Microgrid Power Flow	29	
	3.2 Compositional Power Flow	29	
	3.2.1 ADPF for Individual Islanded Microgrids	30	
	3.2.2 ASPF for Networked Microgrids	31	
	3.2.3 ComPF Algorithm	34	
	3.3 Test and Validation of Compositional Power Flow	34	
	References	42	



viii Contents

4	Resi	ilient Networked Microgrids through Software-Defined Networking	43
	4.1	Networking Microgrids	43
	4.2	Software-Defined Networking	44
		4.2.1 Why SDN	44
		4.2.2 SDN Architecture	44
		4.2.3 OpenFlow	46
		4.2.4 SDN-Based Microgrid Communication Architecture	48
	4.3	Distributed Power Sharing for Networked Microgrids	51
		4.3.1 Droop Control and DAPI Control	51
		4.3.2 The Global Layer of Active Power Sharing for	
		Networked Microgrids	54
	4.4	SDN-Enabled Event-Triggered Communication	57
		4.4.1 Sharing Power with the Nearest Neighbors	57
		4.4.2 Event-Triggered Communication and Control through SDN	57
	4.5	The Cyberphysical Networked Microgrids Testbed	61
		4.5.1 Architecture of the Cyberphysical Networked	
		Microgrids Testbed	61
		4.5.2 The Cyberphysical Simulator and Networked	
		Microgrids Model	63
		4.5.3 Inside the Networked Microgrid Model	63
		4.5.4 Event-Triggered Communication through SDN	70
	4.6	Testing and Validation	74
		4.6.1 Study I: The Single-Event Scenario	76
		4.6.2 Study II: Multiple-Contingency Cases	83
	4.7	Conclusion and Guide for Future Applications	85
	Refe	erences	87
5	Forn	nal Analysis of Networked Microgrids Dynamics	91
	5.1	Formal Methods	91
	5.2	Formal Analysis of Microgrid Dynamics	93
		5.2.1 Impact of Disturbances on the State Matrix	94
		5.2.2 Modeling Disturbances in Networked Microgrids	95
	5.3	Stability Margin Analysis on NMs	96
		5.3.1 Quasi diagonalized Geršgorin Theorem	96
		5.3.2 Stability Margin Calculation	98
	5.4	Distributed Formal Analysis (DFA)	104
	5.5	Partitioning a Large Networked Microgrids System	105
		5.5.1 $N+M$ Decomposition	105
		5.5.2 Partitioning a Large NM System	107
		5.5.3 Modeling of Each Subsystem	108
	5.6	Implementation of DFA for Networked Microgrids Analysis	109
		5.6.1 Procedure of Calculation	109
		5.6.2 Distributed Algorithm and Data Exchange in DFA	110



		Contents	ix
		5.6.3 Implementation of DQG	112
		5.6.4 Stability Margin Assessment	112
	5.7	ε	112
		5.7.1 Reachable Set Calculation in FA	114
		5.7.2 Assessment of Stability Margin through FA Enhanced	119
		the Quasi diagonalized Geršgorin Technique 5.7.3 DFA with System Decomposition	119
		5.7.4 DFA for Calculating Reachable Set	125
		5.7.5 DQG-Based DFA Approach to Probing the Stability Margin	130
	Refe	erences	132
6	Activ	ve Fault Management for Networked Microgrids	134
	6.1	Introduction	134
	6.2	Multifunctional AFM to Enable Microgrid Survivability	135
	6.3	č	137
	6.4	Problem Formulation	137
	6.5		139
		6.5.1 Basics of Lagrangian Relaxation	139
		6.5.2 Solving AFM Using Distributed and Asynchronous SLR	141
		6.5.3 Implementation of Distributed AFM on Multiple	1.40
		Computation Cores	143
	6.6	E .	145
		6.6.1 Single-Line-to-Ground Fault6.6.2 Double-Line-to-Ground Fault	147
			150 151
	6.7	6.6.3 Three-Phase-to-Ground Fault Conclusion	151
		erences	156
7	Cube	erattack-Resilient Networked Microgrids	158
′	•	·	
	7.1	Motivation	158
	7.2	Architecture of Software-Defined Active Synchronous Detection	159
	7.3	Defense against Cyberattacks on an SDN Network	161
		7.3.1 Update of the Host Tracking Service in an SDN Controller	161
	7.4	7.3.2 Defending Strategies	162
	7.4	Active Synchronous Detection in DER Controllers of NMs	163
		7.4.1 Probe Signals for Active Synchronous Detection	163 163
		7.4.2 Active Synchronous Detection on DER Controllers7.4.3 Detection Rules	
	7.5		164 166
	1.3	Test and Validation of Software-Defined Active Synchronous Detection 7.5.1 SDASD Performance Verification on Cyberattacks Defense	166
		7.5.1 SDASD Performance verification on Cyberattacks Defense 7.5.2 Effectiveness of Active Synchronous Detection on	100
		Power Bot Attacks	172
	Refe	erences	178



Contents

8	Netv	worked DC Microgrids	180
	8.1	Overview of DC Microgrids	180
	8.2	Bipolar DC Microgrids	181
	8.3	Networked DC Microgrids	183
	8.4	Dynamic Modeling of DC Microgrids	183
		8.4.1 Implementation	186
		8.4.2 MIMO Tools for Stability and Interaction Analysis	191
	8.5		192
		8.5.1 Local Interactions	192
		8.5.2 Mutual Interactions	194
	Ref	erences	197
Part III Pi	rospe	ct	199
9	Soft	ware-Defined Distribution Network and Software-Defined Microgrids	201
	9.1	Motivation	201
	9.2	Software-Defined Distribution Network and Software-Defined	
		Networked Microgrids	203
	9.3	Scalable and Resilient Network Management	206
		9.3.1 SDN-Enabled Communication Infrastructure	206
		9.3.2 Scalable and Distributed Real-Time Data Analytics	
		Platform for SD ² N	207
	9.4	&,,,,,	208
		9.4.1 SD ² N-Enabled Distributed Distribution System State Estimation	209
		9.4.2 SD ² N-Enabled Distribution Optimal Power Flow	209
		9.4.3 Resilience Engineering for Future Power Networks	209
	Ref	erences	211
10	Futu	re Perspectives: Programmable Microgrids	215
		Smart Programmable Microgrids	216
		2 Evaluation of Programmable Microgrids	217
		Beyond Resilience	218
	Ref	erences	219
	Inde	2X	222