# Contents

Foreword xix  
Preface xxi  
Acknowledgments xxvii

1 Grid-connected Renewable Energy Sources 1  
1.1 Introduction 1  
1.2 Renewable Power Generation 3  
1.2.1 Renewable Energy Development 5  
1.3 Grid-connected Wind Power 6  
1.3.1 Wind Power Generator Without Power Electronic Converters 7  
1.3.2 Wind Power Generator Using Partial-Scale Power Electronic Converters 7  
1.3.3 Wind Power Generator Using Full-Scale Power Electronic Converters 7  
1.3.3.1 Wind Energy Conversion System: Modeling, Control, and Analysis 9  
1.3.3.2 Hierarchical Control Structure 14  
1.3.3.3 Simulation and Experimental Examination 27  
1.3.3.4 Wind Power Generators with Embedded Energy Storage Units in Hybrid Power Systems 35  
1.4 Grid-Connected PV Power 35  
1.4.1 Solar Power Generators with Embedded Energy Storage Systems 36  
1.4.2 Solar Energy Conversion System: Modeling, Control, and Analysis 38  
1.4.2.1 PV Power Conversion System 41  
1.4.2.2 Energy Storage System 42  
1.4.2.3 Grid Connection 43  
1.4.2.4 DC Bus 44  
1.4.2.5 Modeling of the Entire PV Energy Conversion System 45  
1.4.2.6 Hierarchical Control Structure 45
## Contents

1.4.3 Experimental Results 55  
1.4.4 Control of Grid-Connected Solar Power Inverters: A Review 59  
1.5 Summary 66  
References 66  

2 Renewable Power for Control Support 69  
2.1 Introduction 69  
2.2 Wind-Energy-based Control Support 73  
2.2.1 Wind Turbines Inertial Response 73  
2.2.2 Study on a Real Isolated Power System 77  
2.2.2.1 Simulated Scenarios 77  
2.2.2.2 Impacts of the Controller Gain 78  
2.2.2.3 Influence of the Rate of Change of Power Limit 80  
2.2.3 Primary Frequency and Inertial Controls 81  
2.2.3.1 Principles of the Primary Frequency Control 81  
2.2.4 Using Secondary Control 89  
2.3 Renewable Primary Power Reserve 89  
2.3.1 Instantaneous Wind Power Reserve 89  
2.3.2 An Evaluation on the Real Case Study 92  
2.3.3 Comparison of the Reserve Allocation Strategies 96  
2.3.3.1 Reserve Quantification Over an Operating Period 96  
2.3.3.2 Reserve Potential with Wind Reserve Participation 97  
2.4 PV-Energy-Based Control Support 102  
2.5 Integration of Renewable Energy Systems Through Microgrids 105  
2.5.1 A Solution for Renewable Power Penetration 105  
2.5.2 Microgrids in Future Smart Grids 108  
2.6 Summary 112  
References 113  

3 Microgrids: Concept, Structure, and Operation Modes 119  
3.1 Introduction 119  
3.2 Microgrid Concept and Structure 125  
3.3 Operation Modes 129  
3.4 Control Mechanism of the Connected Distributed Generators in a Microgrid 130  
3.4.1 Speed Control of Classical Distributed Generators 130  
3.4.2 Control of Inverter-based Distributed Generators 131  
3.4.2.1 Control Structure in Grid-connected Mode 132  
3.4.2.2 Control Structure in Islanded Mode 135  
3.5 Contribution in the Upstream Grid Ancillary Services: Frequency Control Support Example 137  
3.5.1 Participation in the Frequency Regulation 138
3.5.2 Power Dispatching 142
3.5.2.1 Power Management 143
3.5.2.2 Storage Level Protection 144
3.5.2.3 Regulation of Operating Points 145
3.5.3 Simulation Results 147
3.6 Microgrids Laboratory Technologies 147
3.6.1 Hardware-in-the-loop-based Microgrid Laboratory 152
3.6.1.1 Hardware-in-the-loop Simulation 152
3.6.1.2 The Hardware-in-the-loop-based Microgrid Laboratory 155
3.6.2 Participant Laboratories to Provide the Present Book 157
3.6.2.1 Smart/Micro Grids Research Center 157
3.6.2.2 Laboratory of Electrical Engineering and Power Electronics 158
3.6.2.3 Power Electronics and Electrical Energy Laboratory 159
3.7 Summary 160

References 160

4 Microgrid Dynamics and Modeling 165
4.1 Introduction 165
4.2 Distribution Network (Main Grid) and Connection Modeling 168
4.2.1 Distribution Network Modeling 168
4.2.1.1 Mechanical Part and Frequency Regulation Loop 170
4.2.1.2 Voltage Regulation 172
4.2.1.3 Coupling Between the Mentioned Two Parts 173
4.2.1.4 Adaptation Between the Per Units and SI Units 173
4.2.2 Modeling of Connection Between the Main Grid and the Microgrid 174
4.2.2.1 Modeling of the Medium Voltage Transmission Lines 174
4.2.2.2 Modeling of the Three-Phase Transformer 175
4.2.2.3 Modeling of Passive Loads 175
4.2.2.4 Modeling of Relevant Buses 176
4.3 Overall Representation of the Grid-Connected Microgrid 178
4.3.1 Microgrid Bus 178
4.3.2 Global Architecture Representation 178
4.3.3 Microgrid Representation in the Islanded Operation Mode 179
4.4 Microgrid Components Dynamics and Modeling 182
4.4.1 PV Model 182
4.4.1.1 PV Panels 182
4.4.2 Energy Storage Systems Modeling 186
4.4.2.1 Lead-acid Battery 186
4.4.2.2 Supercapacitor 189
4.4.3 Power Electronic Converters 193
4.5 Simplified Microgrid Frequency Response Model 198
4.5.1 Example 1 199
4.5.2 Example 2  201
4.6 A Detailed State-Space Dynamic Model  203
4.6.1 Mathematical Modeling  203
4.6.2 Simulation Example  207
4.6.3 Closed-Loop State-Space Model  210
4.7 Microgrid Dynamic Modeling and Analysis as a Multivariable System  211
4.7.1 State-space Modeling  212
4.7.2 Dynamic Analysis  215
4.8 Summary  217
References  217

5 Hierarchical Microgrid Control  221
5.1 Introduction  221
5.2 Microgrid Control Hierarchy  225
5.2.1 Local Control  227
5.2.2 Secondary Control  228
5.2.3 Central/Emergency Control  229
5.2.4 Global Control  231
5.3 Droop Control  233
5.3.1 Droop Characteristic in Conventional Power Systems  233
5.3.2 Droop Control in Inverter-based Distributed Generators  235
5.3.2.1 Inductive Grid  237
5.3.2.2 Resistive Grid  238
5.3.2.3 General Case  239
5.3.2.4 General Case-based Voltage and Frequency Control  240
5.3.3 Virtual Impedance Control  241
5.4 Hierarchical Power Management and Control  243
5.4.1 Operation Layers and Control Functions  244
5.4.2 Timescale Analyzing and Implementation Constraints  245
5.4.2.1 Power Management Using Local Measurements  247
5.4.2.2 Power Management Using Communication Network  249
5.5 Design Example  252
5.5.1 Power Dispatching  253
5.5.2 Hardware-In-the-Loop Test Results  254
5.5.3 Test Procedure  257
5.5.3.1 Test of the Micro-turbine Unit: Zone 1 (MT)  257
5.5.3.2 Impact of the PV Unit: Zone 2 (MT + PV)  258
5.5.3.3 Contribution of Supercapacitor: Zone 3 (MT + PV + SC)  258
5.5.3.4 Operating During the Night: Zone 4 (MT + SC)  258
5.6 Summary  262
References  263
7.3.3.2 The Proposed Damping Approach 338
7.3.4 Experimental Results 341
7.4 A Virtual Synchronous Generator Scheme with Emulating More Synchronous Generator Characteristics 344
7.4.1 Emulating Synchronous Generator Characteristics 345
7.4.1.1 Impedance 345
7.4.1.2 Governor and Automatic Voltage Regulator 347
7.4.1.3 Rotor 348
7.4.1.4 Synchronizing Power 348
7.4.1.5 Damping 349
7.4.2 Stability Analysis and Parameters Design 351
7.4.2.1 Islanded Operation 351
7.4.2.2 Grid-connected Operation 352
7.5 Active Power Performance Analysis in a Microgrid with Multiple Virtual Synchronous Generators 353
7.5.1 Closed-Loop State-Space Model 353
7.5.2 Oscillation Damping 355
7.5.3 Transient Active Power Sharing 356
7.6 Summary 358

References 358

8 Virtual Inertia-based Stability and Regulation Support 361
8.1 Introduction 361
8.2 An Enhanced Virtual Synchronous Generator Control Scheme 363
8.2.1 Proposed Virtual Synchronous Generator Control Scheme 364
8.2.2 Simulation Results 367
8.2.3 Experimental Results 373
8.3 Virtual Synchronous Generator Control in Parallel Operation with Synchronous Generator 376
8.3.1 System Description 377
8.3.2 The Proposed Modified Virtual Synchronous Generator Control Scheme 378
8.3.3 Parameter Tuning Methods 382
8.3.3.1 Swing Equation Parameters 382
8.3.3.2 Governor Delay 383
8.3.3.3 Constant Virtual Stator Reactance 384
8.3.3.4 Transient Virtual Stator Impedance for Current Limiting 387
8.3.4 Simulation Results 388
8.4 Alternating Inertia-based Virtual Synchronous Generator Control 393
8.4.1 Control Strategy 393
8.4.2 Stability Analysis 397
8.4.3 Effect of Alternating Inertia on Dissipated Energy 401
8.4.4 Grid Stability Improvement 401
8.4.4.1 Virtual Synchronous Generator in Parallel with Synchronous Generator 401
8.4.4.2 Virtual Synchronous Generator as an Interface between the Synchronous Generator and the Grid 402
8.4.5 Experimental Results 405
8.5 Voltage Sag Ride-through Enhancement Using Virtual Synchronous Generator 406
8.5.1 Virtual Synchronous Generator Subjected to Voltage Sags 406
8.5.2 State Variable Analysis in Phase Plane 407
8.5.3 Voltage Sag Ride-through Enhancement 409
8.5.4 Simulation Results 411
8.5.5 Experimental Results 415
8.6 Performance Evaluation of the Virtual Synchronous Generator with More Synchronous Generator Characteristics 421
8.6.1 System Configuration and Parameters 422
8.6.2 Simulation Results 423
8.6.2.1 Grid-connected Operation 423
8.6.2.2 Islanded Operation 425
8.6.3 Experimental System 425
8.6.3.1 Grid-connected Operation 427
8.6.3.2 Islanded Operation 428
8.7 Summary 430
References 432

9 Robust Microgrid Control Synthesis 435
9.1 Introduction 435
9.2 Case Study and State-Space Model 438
9.3 $H_{\infty}$ and Structured Singular Value ($\mu$) Control Theorems 442
9.3.1 $H_{\infty}$ Control Theory 442
9.3.2 Structured Singular Value ($\mu$) Control Theory 442
9.4 $H_{\infty}$-Based Control Design 444
9.4.1 Uncertainty Modeling 444
9.4.2 $H_{\infty}$ Optimal Controller 446
9.4.3 Closed-Loop Nominal Stability and Performance 446
9.4.4 Closed-Loop Robust Stability and Performance 446
9.5 $\mu$-Based Control Design 447
9.5.1 Uncertainty Modeling in $\mu$-Synthesis 448
9.5.2 D–K Iteration 449
9.5.3 Closed-Loop Nominal and Robust Performance 451
9.5.4 Robust Stability 451
9.6 Order Reduction and Application Results 453
9.6.1 Controller Order Reduction 453
9.6.2 Application Results 455
9.6.3 Comparison with Well-Tuned Proportional-Integral (PI) Controllers 458
9.6.3.1 MATLAB-Based Tuning Algorithm 460
9.6.3.2 Internal Model Control-Based PI Tuning Method 461
9.6.3.3 Comparison of Results 461
9.6.3.4 Discussion 462
9.7 Robust Multivariable Microgrid Control Design 465
9.7.1 Uncertainty Determination 465
9.7.1.1 Unstructured Uncertainty Modeling 465
9.7.1.2 Parametric Uncertainty Modeling 466
9.7.2 Robust Stability and Performance 468
9.7.2.1 Robust Stability Requirement 468
9.7.2.2 Nominal and Robust Performance Requirement 468
9.7.2.3 Robust $H_\infty$ Controller 470
9.7.2.4 Robust $H_2$ Controller 472
9.8 Robust Tuning of VSG Parameters 473
9.8.1 The Extended VSG Dynamics 474
9.8.2 Case Study and $H_\infty$ Control Synthesis 475
9.8.2.1 Case Study 475
9.8.2.2 $H_\infty$ Control Synthesis 476
9.8.3 Robust Tuning of Extended VSG Parameters 478
9.8.4 Simulation Results 481
9.9 Summary 483
References 483

10 Intelligent Microgrid Operation and Control 487
10.1 Introduction 488
10.2 Intelligent Control Technologies 491
10.2.1 Fuzzy Logic Control 491
10.2.1.1 Fuzzy Logic System as Main Controller 492
10.2.1.2 Fuzzy Logic for Controller Tuning 496
10.2.1.3 Fuzzy Logic System as a Supplementary Controller 499
10.2.2 Artificial Neural Networks 501
10.2.3 Genetic Algorithm and Particle Swarm Optimization 504
10.2.3.1 Genetic Algorithm 504
10.2.3.2 Particle Swarm Optimization 507
10.2.4 Multiagent System 508
10.2.4.1 Multiagent System Concept 508
10.2.4.2 Multiagent System Applications in Microgrid Power Management 511
10.3 ANN-based Power and Load Forecasting in Microgrids 512
10.3.1 PV Power Prediction 514
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3.2</td>
<td>Load Forecasting</td>
<td>515</td>
</tr>
<tr>
<td>10.3.3</td>
<td>Forecasting Error</td>
<td>517</td>
</tr>
<tr>
<td>10.3.3.1</td>
<td>PV Power and Load Forecasting Error Estimation</td>
<td>517</td>
</tr>
<tr>
<td>10.3.3.2</td>
<td>Errors Estimation Analysis</td>
<td>519</td>
</tr>
<tr>
<td>10.4</td>
<td>Intelligent Frequency and Voltage Control in Microgrids</td>
<td>520</td>
</tr>
<tr>
<td>10.4.1</td>
<td>Fuzzy-logic-based Supervisory Frequency Control</td>
<td>521</td>
</tr>
<tr>
<td>10.4.1.1</td>
<td>Case Study</td>
<td>522</td>
</tr>
<tr>
<td>10.4.1.2</td>
<td>Proposed Fuzzy-logic-based Control Strategy</td>
<td>523</td>
</tr>
<tr>
<td>10.4.1.3</td>
<td>Simulation Results</td>
<td>526</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Fuzzy-based Distribution Voltage Control in DC Microgrids</td>
<td>528</td>
</tr>
<tr>
<td>10.4.2.1</td>
<td>Proposed Control Strategy</td>
<td>528</td>
</tr>
<tr>
<td>10.4.2.2</td>
<td>Simulation Results</td>
<td>533</td>
</tr>
<tr>
<td>10.4.2.3</td>
<td>Experimental Results</td>
<td>537</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Particle Swarm Optimization (PSO)-based Stability Enhancement in a Microgrid with Virtual Synchronous Generators</td>
<td>538</td>
</tr>
<tr>
<td>10.4.3.1</td>
<td>Microgrid with Multiple Virtual Synchronous Generators Units</td>
<td>541</td>
</tr>
<tr>
<td>10.4.3.2</td>
<td>Particle Swarm Optimization-based Virtual Synchronous Generators Optimization</td>
<td>544</td>
</tr>
<tr>
<td>10.4.4</td>
<td>Multiagent-based Secondary Frequency Control</td>
<td>547</td>
</tr>
<tr>
<td>10.5</td>
<td>Summary</td>
<td>554</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>554</td>
</tr>
</tbody>
</table>

11 Emergency Control and Load Shedding in Microgrids 561
11.1 Introduction 561
11.2 Load Shedding as a Well-known Emergency Control Strategy 564
11.3 Load Shedding Algorithm: Example 1 567
11.3.1 Proposed Algorithm 567
11.3.2 Case Study 569
11.3.3 Simulation Results 571
11.4 Load Shedding Algorithm: Example 2 572
11.4.1 Proposed Algorithm 572
11.4.2 Case Study 574
11.4.3 Simulation Results 576
11.5 Undervoltage–frequency Load Shedding 578
11.5.1 $\Delta v$–$\Delta f$ Plane 579
11.5.2 Voltage and Frequency Performances 581
11.6 Summary 583
|         | References                                                          | 584  |

12 Microgrid Planning and Energy Management 589
12.1 Introduction 589
12.2 Microgrid Planning: An Example 594
## Contents

12.2.1 Description of Input Parameters 595  
12.2.2 System Description and Specification 597  
12.2.3 Numerical Results and Discussion 598  
12.3 Forecasting Techniques 601  
12.3.1 PV Power Prediction 601  
12.3.2 Load Forecasting 602  
12.3.3 Energy Estimation 604  
12.3.3.1 Estimation of the Available PV Power 604  
12.4 Energy Management 605  
12.4.1 Daily Power Management and Setting of Power References 605  
12.4.1.1 Constraints 606  
12.4.1.2 Determinist Algorithm 606  
12.4.1.3 Practical Applications 608  
12.4.2 Medium-term Energy Management 609  
12.4.2.1 Reduction of the Uncertainty 609  
12.4.2.2 Energy Management of Batteries 611  
12.4.3 Short-term Power Management 612  
12.4.3.1 Primary Frequency Regulation 612  
12.4.3.2 Power Balancing Strategies for the AG 612  
12.4.4 Experimental Tests 613  
12.4.4.1 Experimental Platform 613  
12.4.4.2 Analysis of the Self-consumption of One House 615  
12.4.4.3 Increasing the Penetration Ratio 618  
12.5 Emission Reduction and Economical Optimization 624  
12.5.1 Micro-Gas Turbine (MGT) Fuel Consumption and Emissions 625  
12.5.2 Day-ahead Optimal Operational Planning 626  
12.5.2.1 Unit Commitment Problem Formulation 626  
12.5.2.2 Objective Functions and Nonlinear Constraints 626  
12.5.2.3 Application of the Dynamic Programming 628  
12.5.2.4 Maximization of Renewable Penetration and Online Adjustment 629  
12.5.3 Experimental Results 632  
12.6 Day-ahead Optimal Operation and Power Reserve Dispatching 635  
12.6.1 Scenario 1: Power Reserve Provided by MGTs 637  
12.6.1.1 Daytime 637  
12.6.1.2 Nighttime (Discharge the Battery) 638  
12.6.2 Scenario 2: Power Reserve Provided by Micro Gas Turbines and PV-based Active Generator 638  
12.6.2.1 Daytime 639  
12.6.2.2 Nighttime 639  
12.6.3 Optimal Reserve Power Dispatching Application for Unit Commitment Problem 642  
12.6.3.1 Dynamic Programing Application Scenarios 642
12.6.3.2 Comparison of Power Reserve Dispatching  643
12.6.3.3 Security Level Analysis  645
12.7 Robust Energy Consumption Scheduling in Interconnected Microgrids  645
12.7.1 Cost Minimization Formulation  648
12.7.2 Peak-to-Average Ratio Minimization Formulation  650
12.7.3 Simulation Results  652
12.8 Summary  658
  References  659

A Appendix  663

Index  665