Contents

Foreword xv
Acknowledgments xvii

Part 1 Introduction

1 Introduction to cyber-physical-social systems and their applications in power systems engineering 3
Siddharth Suryanarayanan, Robin Roche, and Timothy M. Hansen

1.1 What is a cyber-physical system? 3
1.2 What is a cyber-physical-social system? 4
1.3 Applications of CPSS in power engineering 5
1.4 Organization of the book 7
References 11

Part 2 Stability and security of the grid

2 Distributed control design for damping inter-area oscillations in cyber-physical power networks 15
Meimanat Mahmoudi and Kevin Tomsovic

2.1 Introduction 15
2.2 Power system electromechanical model with distributed control input 18
2.3 Distributed control design using group sparse regularization functions 20
2.3.1 Distributed linear quadratic control design using group sparse regularization functions 22
2.4 Application I: inducing a desired communication structure for damping inter-area oscillations in power networks 24
2.4.1 Illustration on the two-area four-machine system 25
2.5 Application II: control and communication codesign for damping inter-area oscillations in power networks 29
2.6 Conclusion 33
Acknowledgment 34
References 34

3 Distributed algorithms for wide-area monitoring of power systems: a cyber-physical perspective **39**
Jianhua Zhang, Seyedbehzad Nabavi, Aranya Chakrabortty, and Yufeng Xin

3.1 Introduction 39
3.2 Problem formulation 42
3.3 Modal estimation using Prony method 43
3.4 Proposed architectures for distributed modal estimation 44
3.4.1 Architecture 1: distributed Prony using standard ADMM (S-ADMM) 45
3.4.2 Architecture 1 with asynchronous communication (A-ADMM) 47
3.4.3 Architecture 2: distributed Prony using distributed ADMM (D-ADMM) 48
3.4.4 Architecture 3: distributed Prony using hierarchical ADMM (H-ADMM) 51
3.5 Update strategies for asynchronous communication 53
3.5.1 Delay model for wide-area communication 54
3.5.2 Proposed A-ADMM strategies 55
3.6 Case studies of proposed architectures 60
3.7 Simulation results for asynchronous ADMM strategies 64
3.7.1 S-ADMM vs A-ADMM 64
3.7.2 Sensitivity of A-ADMM to delay thresholds 67
3.8 Conclusions 71
References 72

4 Cyber-physical strategies for generator coherency in the face of malicious attack **75**
Pirathayini Srikantha, Jin (Wei) Kocsis, and Deepa Kundur

4.1 Introduction 75
4.2 System settings 76
4.2.1 Cyber-physical dynamical smart grid model 77
4.2.2 Smart grid stability 78
4.3 Flocking-based control for smart grid resilience 78
4.3.1 Flocking analogy 78
4.3.2 Two-tier hierarchy for scalable control 79
4.3.3 Control laws for lead agents 82
4.3.4 Generator coherency identification 83
4.3.5 Case study 84
4.4 DER attack-mitigation framework 87
4.4.1 A pursuer-evader analogy for grid destabilization 88
4.4.2 Nonlinear attack-mitigation differential game 88
4.4.3 Construction of attack-mitigation control strategies 90
4.4.4 Case study 91

4.5 Final remarks 92
References 95

5 Dynamic contingency analysis and remedial action tools for secure electric cyber-physical systems 97
Joydeep Mitra, Mohammed Benidris, and Nga Nguyen

5.1 Introduction 98
5.2 On-line transient stability assessment 99
5.3 System model and transient stability – direct methods 100
5.4 Calculation of the controlling UEP 102
5.4.1 Characterization of the region of convergence of the controlling UEPs 103
5.4.2 BCU-based approach 103
5.4.3 Homotopy-based methods 105
5.5 Approaches for remedial actions 107
5.5.1 Energy margin and sensitivity analysis-based remedial action control 108
5.5.2 Preventive actions based on generation shifting 115
5.5.3 Preventive actions with FACTS devices 116
5.5.4 Corrective actions 119
5.6 Example 124
5.7 Conclusion 128
References 128

Part 3 New philosophies of control and economics in distribution systems

6 Customer modeling and pricing-mechanisms for demand response in smart electric distribution grids 135
Timothy M. Hansen, Robin Roche, Siddharth Suryanarayanan, Anthony A. Maciejewski, Howard Jay Siegel, and Edwin K. P. Chong

6.1 Customer modeling introduction 136
6.2 Aggregator-based residential demand response 138
6.2.1 CPSS 138
6.2.2 Aggregator 139
6.2.3 Aggregator demand response 139
6.2.4 Aggregator profit function 141
6.3 Customer models 141
6.3.1 Customer overview: Gamma parameter 141
6.3.2 Alpha model 142
6.3.3 Customer loads 144
6.4 Pricing mechanisms 144
6.5 Heuristic framework 146
6.5.1 Problem formulation 146
6.5.2 Genetic algorithm implementation 147

6.6 Simulation study 148
6.6.1 Simulation setup 148
6.6.2 Results 149
6.7 Conclusions 156
References 157

7 Application of the agent-based technology to invoke demand flexibility under the SG-BEMS integration framework 161
Luis A. Hurtado, Phuong H. Nguyen, and Wil L. Kling

7.1 Introduction to the concept of demand flexibility 162
7.1.1 Demand side management and demand response 162
7.1.2 Operational flexibility 163
7.1.3 Demand flexibility 164
7.1.4 Emerging energy systems 166
7.2 The SG-BEMS interoperation framework 167
7.2.1 Framework domains 167
7.2.2 Roles and responsibility 168
7.2.3 Services 169
7.2.4 Operation scheme 169
7.3 New control philosophy 170
7.3.1 Agent-based control 171
7.3.2 The SG-BEMS structure 172
7.4 Application of the agent-based control architecture 173
7.4.1 The models 173
7.4.2 Optimization problem 177
7.4.3 Simulation-based case study 179
7.4.4 Simulation results 181
References 190

8 Grid integration of electric and hybrid electric vehicles in cyber-physical-social systems 193
Wencong Su, Rui Ma, and Shengyao Xu

8.1 Introduction 194
8.2 Electrified transportation system in a CPSS environment 196
8.2.1 "Physical" infrastructure 198
8.2.2 "Cyber" infrastructure 200
8.2.3 "Social" considerations 207
8.3 Future research trends 210
8.4 Conclusions 212
Acknowledgment 212
References 212

9 Increasing local renewable energy use in smart neighborhoods through coordinated trading **217**
Berk Celik, Robin Roche, David Bouquain, and Abdellatif Miraoui

9.1 Introduction 217
9.2 System model 220
9.2.1 Modeling approach 220
9.2.2 Smart home model 221
9.2.3 Neighborhood model 225
9.2.4 Electricity price model 225
9.3 Control Strategies 227
9.3.1 Baseline algorithm 227
9.3.2 Selfish energy management 228
9.3.3 Coordinated Management: distributed 229
9.3.4 Coordinated Management: centralized 238
9.4 Simulation Results 240
9.4.1 Simulation setup 241
9.4.2 Overall cost comparison 241
9.4.3 Detailed analysis 242
9.5 Discussion 247
9.5.1 Overview of Results 247
9.5.2 Next steps 249
9.6 Conclusion 250
References 250

10 Compensation of droop control in DC microgrid with multiple distributed generators **253**
Nanfang Yang, Damien Paire, Fei Gao, and Abdellatif Miraoui

10.1 Introduction 254
10.1.1 Active current sharing schemes 254
10.1.2 Droop control technique 256
10.1.3 Compensations of droop control 257
10.2 Analysis of the basic droop control 259
10.2.1 Nominal voltage reference offset 260
10.2.2 Unequal cable resistances 263
10.3 Compensation of the basic droop control 263
10.3.1 Voltage restoration methods 264
10.3.2 Load sharing compensation 266
10.3.3 Mixed methods 266
10.4 Implementation and analysis of the compensation 268
10.4.1 Voltage deviation compensation 269
10.4.2 Load sharing compensation 269
10.4.3 Stability analysis 270
10.5 Simulation 272

10.5.1 Simulation setup 272
10.5.2 Simulation results 274
10.5.3 Evaluation of the compensation methods 277
10.6 Experimental verification 279
10.6.1 Experiment setup 279
10.6.2 Load steps analysis 282
10.7 Conclusion 283
References 286

11 Co-operative responsive electric vehicles for social-economic dispatch 291
Mehdi Rahmani-andebili and Ganesh Kumar Venayagamoorthy

11.1 Introduction 294
11.2 Sustainability indictors 295
11.2.1 Social sustainability indicator 295
11.2.2 Economic sustainability indicator 295
11.3 Responsiveness model of the REVs with respect to incentive scheme 296
11.4 SED-REVs problem 296
11.4.1 Objective function of the SED-REVs problem 298
11.4.2 Constraints of the SED-REVs problem 300
11.5 Proposed optimization technique 301
11.5.1 Stochastic optimization 301
11.5.2 Forecasting uncertain states of the problem 302
11.5.3 Modeling uncertainties of the forecasted data 303
11.5.4 SA algorithm as the optimization tool 305
11.6 Numerical study and results analysis 307
11.6.1 Initial data 307
11.6.2 Studying the system with a predefined scheme of incentive 307
11.6.3 Investigating optimal scheme of incentive 310
11.7 Conclusion 313
Acknowledgment 313
References 313

Part 4 Social aspects and implementations

12 If you build it, will they come? Getting consumers on board with the future of the smart grid 319
Patricia A. Aloise-Young, Jennifer E. Cross, and Perla K. Sandoval

12.1 Introduction 319
12.2 Smart homes 320
12.2.1 Smart thermostats and smart appliances 321
12.2.2 Summary 324

12.3 Smart meters 325
12.3.1 Smart meter backlash 325
12.3.2 Shortcomings of the PG&E deployment 326
12.3.3 Summary 333
12.4 Distributed generation 333
12.4.1 Community-based social marketing 334
12.4.2 Summary 338
12.5 Conclusions 338
References 340

13 Risks, threats and mitigation strategies for SCADA systems 345
Helge Janicke, Allan Cook, Andrew Nicholson, and Kevin Jones

13.1 Introduction 345
13.1.1 Components of industrial control systems 347
13.2 Security technologies and their role in ICS protection 351
13.2.1 Level 5 351
13.2.2 Level 4 352
13.2.3 Level 3 352
13.2.4 Level 2 353
13.2.5 Level 1 and Level 0 354
13.3 Managing threats to ICS/SCADA 355
13.3.1 Attribution of attacks against ICS/SCADA 355
13.3.2 Traceback techniques 356
13.3.3 Honeypots 359
13.3.4 Malware analysis 361
13.3.5 An intelligence-led attribution approach 362
13.4 Post-incident forensics in ICS/SCADA 363
13.5 Conclusion 365
References 366

14 Occupant-engaged fast demand response for commercial buildings 371
Zhen Song, Xianjun Sam Zheng, and Sanjeev Srivastava

14.1 Introduction 372
14.1.1 Introduction to demand response 372
14.1.2 Commercial buildings as cyber-physical-social systems 373
14.1.3 Occupant-engaged DR 378
14.2 Collaborative, occupant-engaged fast demand responses 380
14.2.1 The software architecture of cEMC 380
14.2.2 Design for engaging human–machine interface: Occupants' Dashboard and FM's HMI 381
14.2.3 Temperature and ventilation arbitrations using convex optimization 387
14.2.4 Collaboration for DR scenarios 392
14.2.5 Energy split algorithm for energy games 393

14.3 Experimental study 396
14.3.1 Deployment site 396
14.3.2 Baseline setup 396
14.3.3 Field experiment 397
14.4 Conclusions and future work 400
Acknowledgments 401
References 401

Part 5 Testbeds for validation of the research concepts

15 A testbed for closed-loop cyber-physical-social system simulation and security analysis 407
Ren Liu, Ryan Goodfellow, and Anurag K. Srivastava

15.1 Introduction 408
15.1.1 Smart grid: cyber-physical-social system 408
15.1.2 Need and challenges for cyber-physical-social testbeds 408
15.1.3 Types of power grid cyber-physical testbeds 410
15.1.4 Existing cyber-physical testbed 413
15.2 Developed cyber-physical testbed 414
15.2.1 Power system layer 415
15.2.2 Monitoring layer 416
15.2.3 Communication layer 417
15.2.4 Control and application layer 423
15.3 Summary 430
Acknowledgments 430
References 431

16 Cyber-physical-social system security testbeds for an attack-resilient smart grid 433
Aditya Ashok, Pengyuan Wang, and Manimaran Govindarasu

16.1 Need for testbeds 433
16.2 Testbed design objectives and challenges 434
16.3 Conceptual testbed architecture 435
16.4 State-of-the-art – literature review 436
16.5 Testbed research areas 437
16.6 Testbed Federation 438
16.6.1 Proof-of-concept federation architecture – Smart America challenge 439
16.7 Case study application – Coordinated cyber attacks on WAMPAC 440
16.7.1 Coordinated attack vector 443
16.7.2 Impact analysis 444
16.8 Educational and outreach aspects 447
16.9 Conclusion 447
References 448

17 Distributed real-time simulations for electric power engineering 451
Manish Mohanpurkar, Mayank Panwar, Sayonsom Chanda, Marija Stevic, Rob Hovsapian, Vahan Gevorgian, Siddharth Suryanarayanan, and Antonello Monti

17.1 Introduction 452
17.2 Distributed real-time simulations 452
17.2.1 Philosophy of distributed real-time simulation 453
17.2.2 Transmission-distribution-communication co-simulation 455
17.3 Historical efforts in distributed RTS 457
17.3.1 Remote testing and distributed simulation based on the virtual test-bed 457
17.3.2 Multiple university research initiative 458
17.3.3 Cyber-security test-bed and testing 458
17.3.4 Geographically distributed thermo-electric co-simulation 459
17.3.5 A modular architecture for virtually interconnected laboratories 459
17.3.6 Automotive engineering application 460
17.4 Systematic approach toward distributed real-time simulations 460
17.4.1 Objectives and assumptions 460
17.4.2 Impacts of data latency 463
17.5 Distributed RTS between INL and NREL 464
17.5.1 Experimental setup 464
17.5.2 Latency analysis between INL and NREL 466
17.5.3 Simulation results 467
17.6 Modular architecture for interconnected laboratories 469
17.6.1 Generic design approach 469
17.6.2 Hybrid interface design 471
17.7 Applications of distributed real-time simulations 476
17.7.1 Wind and hydropower research 476
17.7.2 Hydrogen applications in power systems research 479
17.8 Concluding remarks and future work 480
References 481

Index 487