CONTENTS

PREFACE xiii
CONTRIBUTORS xvii

1  FUNDAMENTALS OF ELECTRIC POWER SYSTEMS  1

Xiao-Ping Zhang
1.1 Introduction of Electric Power Systems  1
1.2 Electric Power Generation  2
  1.2.1 Conventional Power Plants  2
    1.2.1.1 Fossil Fuel Power Plants  2
    1.2.1.2 CCGT Power Plants  3
    1.2.1.3 Nuclear Power Plants  3
  1.2.2 Renewable Power Generation Technologies  4
    1.2.2.1 Wind Energy Generation  4
    1.2.2.2 Ocean Energy Generation  5
    1.2.2.3 Photovoltaic Generation Systems  6
    1.2.2.4 Bioenergy  6
    1.2.2.5 Geothermal Energy  7
    1.2.2.6 Hydrogen  7
1.3 Structure of Electric Power Systems  7
  1.3.1 Structure  7
  1.3.2 Benefits of System Interconnection  9
1.4 Ultra-High Voltage Power Transmission  11
  1.4.1 The Concept of Ultra-High Voltage Power Transmission  11
  1.4.2 Economic Comparison of Extra-High Voltage and Ultra-High Voltage Power Transmission  13
  1.4.3 Ultra-High Voltage AC Power Transmission Technology  14
  1.4.4 Ultra-High Voltage DC Technology  14
  1.4.5 Ultra-High Voltage Power Transmission in China  15
  1.4.6 Ultra-High Voltage Power Transmission in the World  17
1.5 Modeling of Electric Power Systems  17
  1.5.1 Transmission Lines  17
  1.5.2 Transformers  18
  1.5.3 Loads  19
  1.5.4 Synchronous Generators  20
  1.5.5 HVDC Systems and Flexible AC Transmission Systems (FACTS)  20
1.6 Power Flow Analysis  20
  1.6.1 Classifications of Buses for Power Flow Analysis  20
    1.6.1.1 Slack Bus  20
    1.6.1.2 PV Buses  21
    1.6.1.3 PQ Buses  21
# CONTENTS

1.6.2 Formulation of Load Flow Solution 21  
1.6.3 Power Flow Solution by Newton-Raphson Method 22  
1.6.4 Fast Decoupled Load Flow Method 24  
1.6.5 DC Load Flow Method 25  

1.7 Optimal Operation of Electric Power Systems 26  
1.7.1 Security-Constrained Economic Dispatch 26  
1.7.1.1 Classic Economic Dispatch Without Transmission Network Power Loss 26  
1.7.1.2 Security Constrained Economic Dispatch 28  
1.7.2 Optimal Power Flow Techniques 28  
1.7.2.1 Development of Optimization Techniques in OPF Solutions 28  
1.7.2.3 OPF Formulation 30  
1.7.2.4 Optimal Power Flow Solution by Nonlinear Interior Point Methods 31  

1.8 Operation and Control of Electric Power Systems—SCADA/EMS 34  
1.8.1 Introduction of SCADA/EMS 34  
1.8.2 SCADA/EMS of Conventional Energy Control Centers 36  
1.8.3 New Development Trends of SCADA/EMS of Energy Control Centers 37  
1.8.3.1 New Environments 37  
1.8.3.2 Advanced Software Technologies 38  

1.9 Active Power and Frequency Control 39  
1.9.1 Frequency Control and Active Power Reserve 39  
1.9.2 Objectives of Automatic Generation Control 40  
1.9.3 Turbine-Generator-Governor System Model 40  
1.9.4 AGC for a Single-Generator System 42  
1.9.5 AGC for Two-Area Systems 43  
1.9.6 Frequency Control and AGC in Electricity Markets 43  

1.10 Voltage Control and Reactive Power Management 44  
1.10.1 Introduction of Voltage Control and Reactive Power Management 44  
1.10.2 Reactive Power Characteristics of Power System Components 45  
1.10.3 Devices for Voltage and Reactive Power Control 45  
1.10.4 Optimal Voltage and Reactive Power Control 47  
1.10.5 Reactive Power Service Provisions in Electricity Markets 47  

1.11 Applications of Power Electronics to Power System Control 48  
1.11.1 Flexible AC Transmission Systems (FACTS) 48  
1.11.2 Power System Control by FACTS 49  

References 50  

2 RESTRUCTURED ELECTRIC POWER SYSTEMS AND ELECTRICITY MARKETS 53  

Kwok W. Cheung, Gary W. Rosenwald, Xing Wang, and David I. Sun  

2.1 History of Electric Power Systems Restructuring 53  
2.1.1 Vertically Integrated Utilities and Power Pools 54  
2.1.2 Worldwide Movement of Power Industry Restructuring 54  
2.1.2.1 Nordic Countries 55  
2.1.2.2 Great Britain 55  
2.1.2.3 Continental Europe 55
Xiao-Ping Zhang

3.1 Game Theory and Its Applications 99

3.2 Electricity Markets and Market Power 100

3.2.1 Types of Electricity Markets 100

3.2.1.1 Bid-Based Auction Pool / PoolCo / Spot Market 100

3.2.1.2 Bilateral Agreements, Forward Contracts, and Contracts for Differences 101

3.2.2 Competition Types 102

3.2.2.1 Perfect Competition 102

3.2.2.2 Imperfect or Oligopolistic Competition 103

3.3 Market Power Monitoring, Modeling, and Analysis 103

3.3.1 The Concept of Market Power 103

3.3.2 Techniques for Measuring Market Power 104

3.3.2.1 The Price-Cost Margin Index 104

3.3.2.2 The Herfindahl-Hirschman Index 104

3.3.2.3 Estimation of Pricing Behavior Through Simulation Analysis 105

3.3.2.4 Oligopoly Equilibrium Analysis 105

3.3.3 Oligopolistic Equilibrium Models 105

3.3.3.1 Bertrand Equilibrium 106

3.3.3.2 Cournot Equilibrium 106

3.3.3.3 Supply Function Equilibrium 106

3.3.3.4 Stackelberg Equilibrium 107

3.3.3.5 Conjectured Supply Function Equilibrium 107

3.3.4 Market Power Modeling Using Equilibrium Models 107

3.4 Application of the Equilibrium Models in the Electricity Markets 109

3.4.1 Bertrand Equilibrium Model 109

3.4.2 Cournot Equilibrium Model 109

3.4.3 Supply Function Equilibrium Models in Electricity Markets 111

3.4.3.1 Application of Supply Function Equilibrium Models 111

3.4.3.2 Electricity Network Modeling 113

3.4.3.3 Modeling of Contracts 114

3.4.3.4 Choosing the Appropriate Strategic Variable 114

3.4.3.5 Conjecture Supply Function Equilibrium Model 114

3.4.4 Conjectural Variation and CSF Equilibrium Models 115

3.5 Computational Tools for Electricity Market Equilibrium Modeling and Market Power Analysis 115

3.5.1 Mathematical Programs with Equilibrium Constraints (MPEC) 116

3.5.2 Bilevel Programming 117

3.5.3 Equilibrium Problems with Equilibrium Constraints (EPEC) 117

3.5.3.1 Formulation of Single-Leader-Follower Games as an MPEC 117

3.5.3.2 Formulation of Multi-Leader-Follower Games as an EPEC 119

3.5.4 NCP Functions for MPCCs 120

3.5.4.1 The Fischer-Burmeister Function 120

3.5.4.2 The Min-Function 120
3.5.4.3 The Chen-Chen-Kanzow Function 120

3.6 Solution Techniques for MPECs 121
  3.6.1 SQP Methods 121
  3.6.2 Interior Point Methods 121
    3.6.2.1 Interior Point Methods with Relaxed Complementarity Constraints 121
    3.6.2.2 Interior Point Methods with Two-Sided Relaxation 122
    3.6.2.3 Interior Point Methods with Penalty 123
  3.6.3 Mixed-Integer Linear Program (MILP) Methods 124
  3.6.4 Artificial Intelligence Approach 124

3.7 Solution Techniques for EPECs 125
  3.7.1 Diagonalization Solution Methods 126
    3.7.1.1 Nonlinear Jacobi Method 126
    3.7.1.2 Nonlinear Gauss-Seidel Method 126
  3.7.2 Simultaneous Solution Methods 127

3.8 Technical Challenges for Solving MPECs and EPECs 128

3.9 Software Resources for Large-Scale Nonlinear Optimization 129

References 132

4 COMPUTING THE ELECTRICITY MARKET EQUILIBRIUM: USES OF MARKET EQUILIBRIUM MODELS 139

Ross Baldick

4.1 Introduction 139

4.2 Model Formulation 140
  4.2.1 Transmission Network Model 141
    4.2.1.1 Physical Model 141
    4.2.1.2 Commercial Network Model 142
    4.2.1.3 Economic Model 145
  4.2.2 Generator Cost Function and Operating Characteristics 146
    4.2.2.1 Physical Model 146
    4.2.2.2 Economic Model 147
  4.2.3 Offer Function 147
    4.2.3.1 Commercial Model 147
    4.2.3.2 Economic Model 148
  4.2.4 Demand 149
    4.2.4.1 Physical Model 149
    4.2.4.2 Commercial Model 149
    4.2.4.3 Economic Model 149
  4.2.5 Uncertainty 150
    4.2.5.1 Physical Model 150
    4.2.5.2 Commercial Model 150
    4.2.5.3 Economic Model 150

4.3 Market Operation and Price Formation 151
  4.3.1 Physical Model 151
  4.3.2 Commercial Model 151
  4.3.3 Economic Model 152

4.4 Equilibrium Definition 152

4.5 Computation 154
  4.5.1 Analytical Models 154
6.3.1.5 Modeling of Loads 198
6.3.1.6 Bus Voltage Constraints 199
6.3.2 Electricity Market Analysis 199
6.4 Electricity Market Equilibrium Analysis 202
6.4.1 Nash Supply Function Equilibrium Model 202
6.4.2 Assumptions for the Supply Function Equilibrium Electricity Market Analysis 202
6.4.3 Parameterization Methods for Linear Supply Functions in Electricity Market Equilibrium Analysis 204
6.4.3.1 Intercept Parameterization 204
6.4.3.2 Slope Parameterization 205
6.4.3.3 Slope-Intercept Parameterization 205
6.4.3.4 Linear Slope-Intercept Parameterization 205
6.5 Computing the Electricity Market Equilibrium with AC Network Model 205
6.5.1 Objective Function for the Social Welfare for Imperfect Competition 205
6.5.2 Objective Function for the Maximization of Profit of the Generating Firm 206
6.5.3 Formulation of Market Equilibrium Model 206
6.5.3.1 ISO’s Optimization Problem 206
6.5.3.2 Nonlinear Complementarity Constraints 208
6.5.4 Formulation of the Optimization Market Equilibrium Problem as EPEC 208
6.5.5 Lagrange Function for the EPEC Optimization Problem 209
6.5.6 Newton Equation for the EPEC Problem 211
6.5.7 Modeling of Reactive Power and Voltage Control 215
6.6 Implementation Issues of Electricity Market Equilibrium Analysis with AC Network Model 216
6.6.1 Initialization of the Optimization Solution 216
6.6.2 Updating the Optimization Solution 217
6.6.3 Solution Procedure 217
6.7 Numerical Examples 218
6.7.1 Reactive Power and Voltage Control 218
6.7.1.1 Description of the Test Systems 218
6.7.1.2 Test Results of the 3-Bus System 218
6.7.1.3 The IEEE 14-Bus System 220
6.7.1.4 Discussions 221
6.7.2 Transformer Control 222
6.7.2.1 Description of the Test Systems 222
6.7.2.2 Test Results on the 5-Bus System 222
6.7.2.3 Test Results on the IEEE 30-Bus System 225
6.7.3 Computational Performance 227
6.8 Conclusions 228
6.9 Appendix 229
6.9.1 Second Derivatives for Power Mismatches in Rectangular Coordinates 229
6.9.2 Second Derivatives for Transmission Line Constraints in Rectangular Coordinates 229
6.9.3 Second Derivatives in Rectangular Coordinates 230
6.9.4 Second Derivatives of Transmission Line Constraints in Rectangular Coordinates 234