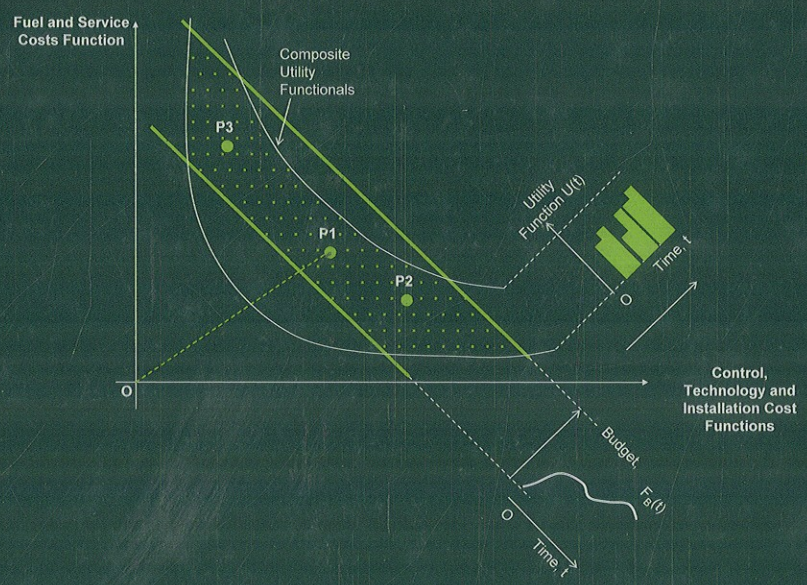
Economic Market Design and Planning *for* Electric Power Systems



JAMES MOMOH • LAMINE MILI

WILEY

IEEE
Celebrating 125 Years
of Engineering the Future

IEEE PRESS SERIES ON POWER ENGINEERING
Mohamed E. El-Hawary, *Series Editor*

CONTENTS

PREFACE xi
CONTRIBUTORS xiii

1 *A FRAMEWORK FOR INTERDISCIPLINARY RESEARCH AND EDUCATION* 1

James Momoh
1.1 Introduction 1
1.2 Power System Challenges 3
1.2.1 The Power System Modeling and Computational Challenge 4
1.2.2 Modeling and Computational Techniques 5
1.2.3 New Curriculum that Incorporates the Disciplines of Systems Theory, Economic and Environmental Science for the Electric Power Network 5
1.3 Solution of the EPNES Architecture 5
1.3.1 Modular Description of the EPNES Architecture 5
1.3.2 Some Expectations of Studies Using EPNES Benchmark Test Beds 7
1.4 Implementation Strategies for EPNES 8
1.4.1 Performance Measures 8
1.4.2 Definition of Objectives 8
1.4.3 Selected Objective Functions and Pictorial Illustrations 9
1.5 Test Beds for EPNES 13
1.5.1 Power System Model for the Navy 13
1.5.2 Civil Testbed—179-Bus WSCC Benchmark Power System 15
1.6 Examples of Funded Research Work in Response to the EPNES Solicitation 16
1.6.1 Funded Research by Topical Areas/Groups under the EPNES Award 16
1.6.2 EPNES Award Distribution 17
1.7 Future Directions of EPNES 18
1.8 Conclusions 18
Acknowledgments 19
Bibliography 19

2 *MODELING ELECTRICITY MARKETS: A BRIEF INTRODUCTION* 21

Alfredo Garcia, Lamine Mili, and James Momoh
2.1 Introduction 21
2.2 The Basic Structure of a Market for Electricity 22

2.2.1 Consumer Surplus 23
2.2.2 Congestion Rents 24
2.2.3 Market Power 24
2.2.4 Architecture of Electricity Markets 25
2.3 Modeling Strategic Behavior 26
2.3.1 Brief Literature Review 26
2.3.2 Price-Based Models 27
2.3.3 Quality-Based Models 30
2.4 The Locational Marginal Pricing System of PJM 32
2.4.1 Introduction 32
2.4.2 Congestion Charges and Financial Transmission Rights 33
2.4.3 Example of a 3-Bus System 34
2.5 LMP Calculation Using Adaptive Dynamic Programming 39
2.5.1 Overview of the Static LMP Problem 39
2.5.2 LMP in Stochastic and Dynamic Market with Uncertainty 40
2.6 Conclusions 42
Bibliography 42

3 *ALTERNATIVE ECONOMIC CRITERIA AND PROACTIVE PLANNING FOR TRANSMISSION INVESTMENT IN DEREGULATED POWER SYSTEMS* 45

Enzo E. Sauma and Shmuel S. Oren
3.1 Introduction 46
3.2 Conflict Optimization Objectives for Network Expansions 49
3.2.1 A Radial-Network Example 49
3.2.2 Sensitivity Analysis in the Radial-Network Example 56
3.3 Policy Implications 57
3.4 Proactive Transmission Planning 57
3.4.1 Model Assumptions 58
3.4.2 Model Notation 60
3.4.3 Model Formulation 61
3.4.4 Transmission Investment Models Comparison 62
3.5 Illustrative Example 64
3.6 Conclusions and Future Work 67
Bibliography 68
Appendix 68

4 *PAYMENT COST MINIMIZATION WITH DEMAND BIDS AND PARTIAL CAPACITY COST COMPENSATIONS FOR DAY-AHEAD ELECTRICITY AUCTIONS* 71

Peter B. Luh, Ying Chen, Joseph H. Yan, Gary A. Stern, William E. Blankson, and Feng Zhao
4.1 Introduction 72
4.2 Literature Review 73
4.3 Problem Formulation 73
4.4 Solution Methodology 75
4.4.1 Augmented Lagrangian 76
4.4.2 Formulating and Solving Unit Subproblems 76
4.4.3 Formulating and Solving Bid Subproblems 79

4.4.4 Solve the Dual Problem 80
4.4.5 Generating Feasible Solutions 80
4.4.6 Initialization and Stopping Criteria 81
4.5 Results and Insights 81
4.6 Conclusion 84
Acknowledgment 84
Bibliography 84

5 *DYNAMIC OLIGOPOLISTIC COMPETITION IN AN ELECTRIC POWER NETWORK AND IMPACTS OF INFRASTRUCTURE DISRUPTIONS* 87

Reetabrata Mookherjee, Benjamin F. Hobbs, Terry L. Friesz, and Matthew A. Rigdon
5.1 Introduction and Motivation 87
5.2 Summary and Modeling Approach 89
5.3 Model Description 90
5.3.1 Notation 90
5.3.2 Generating Firm's Extremal Problem 92
5.3.3 ISO's Problem 94
5.4 Formulation of NCP 95
5.4.1 Complementary Conditions for Generating Firms 95
5.4.2 Complementary Conditions for the ISO 97
5.4.3 The Complete NCP Formulation 98
5.5 Numerical Example 98
5.6 Conclusions and Future Work 108
Acknowledgment 108
Appendix: Glossary of Relevant Terms form Electricity Economics 108
Bibliography 110

6 *PLANT RELIABILITY IN MONOPOLIES AND DUOPOLIES: A COMPARISON OF MARKET OUTCOMES WITH SOCIALLY OPTIMAL LEVELS* 113

George Deltas and Christoforos Hadjicostis
6.1 Introduction 114
6.2 Modeling Framework 116
6.3 Profit Maximizing Outcome of a Monopolistic Generator 118
6.4 Nash Equilibrium in a Duopolistic Market Structure 120
6.5 Social Optimum 122
6.6 Comparison of Equilibria and Discussion 123
6.7 Asymmetric Maintenance Policies 125
6.8 Conclusion 127
Acknowledgment 128
Bibliography 128

7 *BUILDING AN EFFICIENT RELIABLE AND SUSTAINABLE POWER SYSTEM: AN INTERDISCIPLINARY APPROACH* 131

James Momoh, Philip Fanara, Jr., Haydar Kurban, and L. Jide Iwarere
7.1 Introduction 131
7.1.1 Shortcoming in Current Power Systems 132
7.1.2 Our Proposed Solutions to the Above Shortcomings 132

7.2 Overview of Concepts 133
7.2.1 Reliability 133
7.2.2 Bulk Power System Reliability Requirements 134
7.2.3 Public Perception 135
7.2.4 Power System / New Technology 135
7.3 Theoretical Foundations: Theoretical Support for Handling Contingencies 140
7.3.1 Contingency Issues 140
7.3.2 Foundation of Public Perception 141
7.3.3 Available Transmission Capability (ATC) 142
7.3.4 Reliability Measures/Indices 143
7.3.5 Expected Socially Unserved Energy (ESUE) and Load Loss 145
7.3.6 System Performance Index 147
7.3.7 Computation of Weighted Probability Index (WPI) 148
7.4 Design Methodologies 149
7.5 Implementation Approach 150
7.5.1 Load Flow Analysis with FACTS Devices (TCSC) for WSCC System 150
7.5.2 Performance Evaluation Studies on IEEE 30-Bus and WSCC Systems 151
7.6 Implementation Results 151
7.6.1 Load Flow Analysis with FACTS Devices (TCSC) for WSCC System 151
7.6.2 Performance Evaluation Studies on IEEE 30-Bus System 153
7.6.3 Performance Evaluation Studies on the WSCC System 155
7.7 Conclusion 157
Acknowledgments 158
Bibliography 158

8 *RISK-BASED POWER SYSTEM PLANNING INTEGRATING SOCIAL AND ECONOMIC DIRECT AND INDIRECT COSTS* 161

Lamine Mili and Kevin Dooley
8.1 Introduction 162
8.2 The Partitioned Multiobjective Risk Method 164
8.3 Partitioned Mutiobjective Risk Method Applied to Power System Planning 166
8.4 Integrating the Social and Economic Impacts in Power System Planning 169
8.5 Energy Crises and Public Crises 170
8.5.1 Describing the Methodology for Economic and Social Cost Assessment 170
8.5.2 The CRA Method 172
8.5.3 Data Analysis of the California Crises and of the 2003 U.S. Blackout 173
8.6 Conclusions and Future Work 176
Bibliography 177

9 *MODELS FOR TRANSMISSION EXPANSION PLANNING BASED ON RECONFIGURABLE CAPACITOR SWITCHING* 181

James McCalley, Ratnesh Kumar, Venkataramana Ajjarapu, Oscar Volij, Haifeng Liu, Licheng Jin, and Wenzhuo Shang
9.1 Introduction 181

9.2 Planning Processes 184
9.2.1 Engineering Analyses and Cost Responsibilities 185
9.2.2 Cost Recovery for Transmission Owners 187
9.2.3 Economically Motivated Expansion 188
9.2.4 Further Reading 189
9.3 Transmission Limits 189
9.4 Decision Support Models 191
9.4.1 Optimization Formulation 192
9.4.2 Planning Transmission Circuits 195
9.4.3 Planning Transmission Control 199
9.4.4 Dynamic Analysis 213
9.5 Market Efficiency and Transmission Investment 219
9.6 Summary 232
Acknowledgments 232
Bibliography 232

10 *NEXT GENERATION OPTIMIZATION FOR ELECTRIC POWER SYSTEMS* 237

James Momoh
10.1 Introduction 237
10.2 Structure of the Next Generation Optimization 239
10.2.1 Overview of Modules 239
10.2.2 Organization 241
10.3 Foundations of the Next Generation Optimization 242
10.3.1 Overview 242
10.3.2 Decision Analysis Tools 243
10.3.3 Selected Methods in Classical Optimization 248
10.3.4 Optimal Control 250
10.3.5 Dynamic Programming (DP) 252
10.3.6 Adaptive Dynamic Programming (ADP) 253
10.3.7 Variants of Adaptive Dynamic Programming 255
10.3.8 Comparison of ADP Variants 258
10.4 Application of Next Generation Optimization to Power Systems 260
10.4.1 Overview 260
10.4.2 Framework for Implementation of DSOPF 261
10.4.3 Applications of DSOPF to Power Systems Problems 262
10.5 Grant Challenges in Next Generation Optimization and Research Needs 272
10.6 Concluding Remarks and Benchmark Problems 273
Acknowledgments 273
Bibliography 274

INDEX 277