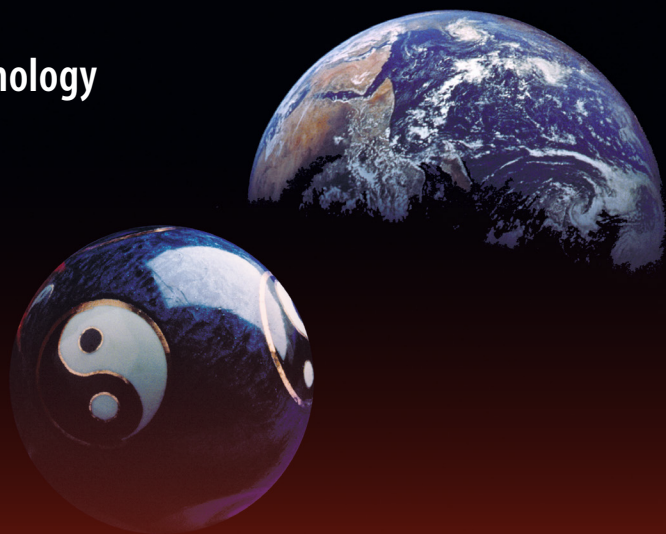


Green Energy and Technology

Sheng Wang
Hongxun Hui
Yi Ding
Yonghua Song



Hydrogen Integration in Energy Systems: Modeling, Optimization, and Reliability Evaluation

Ensuring a Reliable Net Zero Transition

 Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to “green”—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers “green” solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.


****Indexed in Scopus**.**

****Indexed in Ei Compendex**.**

Sheng Wang · Hongxun Hui · Yi Ding ·
Yonghua Song

Hydrogen Integration in Energy Systems: Modeling, Optimization, and Reliability Evaluation

Ensuring a Reliable Net Zero Transition

Sheng Wang 
School of Engineering
Newcastle University
Newcastle upon Tyne, UK

Yi Ding
College of Electrical Engineering
Zhejiang University
Hangzhou, China

Hongxun Hui
The State Key Laboratory of Internet
of Things for Smart City (SKL-IOTSC)
University of Macau
Macao, China

Yonghua Song
The State Key Laboratory of Internet
of Things for Smart City (SKL-IOTSC)
University of Macau
Macao, China

ISSN 1865-3529

Green Energy and Technology

ISBN 978-3-032-07166-8

<https://doi.org/10.1007/978-3-032-07167-5>

ISSN 1865-3537 (electronic)

ISBN 978-3-032-07167-5 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2025

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

Preface

Global warming has been witnessed in the past few decades, caused by the emission of greenhouse gases, such as carbon dioxide, which not only affects the habitat of animals but also threatens the lives of mankind in modern societies. Around the world, resulting from the excessive consumption of fossil fuels, such as natural gas, the energy sector is the culprit behind carbon dioxide emissions and climate change. To achieve net-zero ambitions, energy systems worldwide urgently call for cleaner energy sources. Green hydrogen, produced through electrolysis facilities using surplus renewable energy generation, has emerged as a promising solution. However, because hydrogen shares distinctive properties with natural gas, many fundamental questions, including how to smoothly integrate hydrogen into the existing energy systems, how to operate such a new structured energy system, and what the systematic impact will be, remain unclear.

To bridge the research gap and ensure a net-zero energy transition, this book aims to develop new modelling, optimisation, and reliability evaluation approaches that support the transition of current energy systems to hydrogen-integrated energy systems (HI-ES). This book can potentially set the theoretical foundations for developing, more advanced control strategies and application scenarios for HI-ES, and inform policymakers through bespoke advice on hydrogen integration road maps. This book is organised as follows:

Chapter 1 introduces the motivation, basic concept, political environments, and ongoing demonstration projects of HI-ES, summarises the challenges we are facing, and presents the organisation of this book.

Chapter 2 develops the reliability modelling and evaluation frameworks of the generic integrated electricity-gas systems, which are the predecessor of HI-ES. First, reliability network equivalents are utilised to represent reliability models of gas-fired generating units, gas sources, power-to-gas facilities, and other conventional generating units. A contingency management scheme is then developed considering the coupling between electricity and gas systems based on an integrated electricity and gas optimal power flow technique. Finally, the time-sequential Monte Carlo simulation approach is used to model the chronological characteristics of the corresponding reliability network equivalents.

Chapter 3 proposes a coordinated optimisation framework for multi-energy systems and end-users to promote operational flexibility. First, we develop a multi-level self-scheduling framework for the demand side resources to comprehensively explore the flexibility potential. The constraints of gas flow dynamics are then formulated to ensure that the linepack in the energy systems can accommodate the fluctuating gas demand. The second-order cone (SOC) relaxation is adopted to convexify the nonlinearity in the motion equation of gas flow dynamics. Moreover, to tackle the overall mixed-integer SOC programming problem, we propose an enhanced Benders decomposition strategy by embedding the lift-and-project cutting plane method, and further, devise a novel solution procedure.

Chapter 4 tries to conceptualise the unique reliability trade-off effects in integrated energy systems, considering flexibility from both the demand side and the transmission system. Firstly, the flexibility of end-users and linepacks is explored based on the Energy Hub and gas flow dynamics models. Then, the reliability models of energy system components are developed using the discretised-time Markov process to characterise the temporal state evolution in the operational horizon. A look-ahead contingency management scheme is then proposed to minimise the electricity and gas load curtailments. Taking account of all the possible system states, the operational reliabilities of the energy system are evaluated using the time-sequential Monte Carlo simulation.

Chapter 5 develops the steady-state optimal energy flow model and tractable solution techniques for HI-ES based on the mathematical models developed in previous chapters. Firstly, we develop a novel optimal energy flow model of HI-ES, where the physical characteristics (e.g., specific gravity) of the gas mixtures are modelled as variables to reflect the impacts of alternative gas injections more accurately. Security indices are introduced to restrain the variation in gas composition. Then, convex optimisation techniques are tailored to transfer the original highly nonlinear and nonconvex optimisation problem into a tractable form. An advanced sequential programming procedure is proposed with self-adaptive convergence criteria to better balance the feasibility and convergence.

Chapter 6 further extends the optimal energy flow model and tractable solution techniques for HI-ES to the transient state analysis. First, a convex hull of the gas security range is derived from the Dutton method. Then, the multi-period optimal energy flow is proposed to mitigate the impacts of alternative gas injection on gas security over the entire operational period. Both the dynamics of gas composition and gas flow are modelled, which can accurately describe the travel of alternative gas concentrations in real-time. The dynamics in the gas mixture properties (e.g., specific gravity) are modelled as variables to fully reveal the impacts of time-varying gas compositions. To tackle the high non-convexities in the multi-period optimal energy flow problem, second-order-cone relaxation is well-tailored and first used in the case of varying gas compositions, making the motion equations and advective transport equations more tractable. An advanced second-order-cone sequential programming is devised to drive the relaxation tight more efficiently.

Chapter 7 proposes the long-term reliability evaluation method for HI-ES based on Chap. 5. First, new reliability indices are proposed to evaluate both gas adequacy and

gas interchangeability under uncertainties. Then, a multi-state reliability model of the pipeline is developed to characterise the corrosion evolution and hydrogen embrittlement in the long term. A contingency management scheme is devised to minimise load curtailments and gas interchangeability deviations under component failures. Moreover, several reformulation techniques are tailored to convexify the original two-stage mixed-integer nonlinear contingency management scheme optimisation problem. An analytical reliability evaluation method embedded with a system state reduction technique is designed to evaluate the long-term reliability of the HI-ES more efficiently.

Chapter 8 proposes a short-term reliability assessment approach for HI-ES based on Chap. 6. First, the multi-performance and multi-state universal generating functions are constructed to efficiently model the short-term reliability of the power-to-gas facility and the wind farm, respectively. Then, a reliability management universal generating functions operator is proposed to minimise both load shedding and gas security violations. A set of novel reliability indices is proposed to comprehensively assess the gas security violations under uncertain gas compositions. Moreover, an analytical short-term reliability assessment approach is proposed, where the state-based sequential approximation and state-based McCormick envelope techniques are tailored and embedded. By optimising the solution ordered by the system states, the nonconvexities in the reliability management optimisation problem can be handled tractably without increasing the computation burden.

Chapter 9 proposes a gas interchangeability resilience evaluation method for HIES. First, gas interchangeability resilience is defined by proposing several novel metrics. Then, A two-stage gas interchangeability management scheme is proposed to accommodate the hydrogen injections. The steady-state optimal electricity and hydrogen-gas energy flow technique is performed first to obtain the desired operating state of the H-IEGS. Then, the dynamic gas composition tracking is implemented to calculate the real-time travelling of hydrogen contents in the gas network and evaluate the time-varying gas interchangeability metrics. Moreover, to improve the computation efficiency, a self-adaptive linearization technique is proposed and embedded in the solution process of discretised partial derivative equations.

Chapter 10 presents the outlook for the future energy market framework for HIES considering heterogeneous gas compositions. First, we propose a joint market-clearing model, where the nonlinear physical properties of gas mixtures caused by varying gas compositions are characterised. The impacts of hydrogen blending on the carbon emission cost are also quantified. To retrieve the nodal energy price from this highly nonlinear and nonconvex optimisation problem, a successive second-order cone programming method is tailored to get the dual variables tractably. Considering the continuous market-clearing process, a warm-start technique is proposed to provide initial reference points for the successive second-order cone programming to improve the computation efficiency.

For reading this book, a basic knowledge of advanced mathematics (including linear algebra, calculus, probability theory, optimisation theory, etc.) and a basic knowledge of electricity/gas systems are required. This book focuses on the recently hot topics on net-zero energy systems. It may be of interest to those researchers,

engineers, and policymakers who are working on net-zero energy system design, planning, operation, economics, markets, and relevant policy making.

Newcastle upon Tyne, UK
November 2024

Sheng Wang

Acknowledgements Funding Information. The authors would like to acknowledge the financial support from the National Natural Science Foundation of China (52407075); the Science and Technology Development Fund, Macau SAR (File no. 001/2024/SKL and File no. 0117/2022/A3); the Guangdong Basic and Applied Basic Research Foundation (2023A1515110163), the State Key Laboratory of Power System Operation and Control (SKLD24KM11); the Chair Professor Research Grant of University of Macau (File no. CPG2025-00023-IOTSC), and Newcastle University Academic Track (NUAcT) Fellowship.

Copyrights. Parts of this book incorporate content from the following publications, all of which were authored/co-authored by the book contributors and have been reproduced with permission from the original publishers:

1. Wang, Sheng, Yi Ding, Chengjin Ye, Can Wan, and Yuchang Mo. “Reliability evaluation of integrated electricity—gas system utilizing network equivalent and integrated optimal power flow techniques.” *Journal of Modern Power Systems and Clean Energy* 7, no. 6 (2019): 1523–1535.
2. Wang, Sheng, Hongxun Hui, Yi Ding, and Junyi Zhai. “Decentralized demand response for energy hubs in integrated electricity and gas systems considering linepack flexibility.” *IEEE Internet of Things Journal* 11, no. 7 (2023): 11848–11861.
3. Wang, Sheng, Junyi Zhai, Hongxun Hui, Yi Ding, and Yonghua Song. “Operational reliability of integrated energy systems considering gas flow dynamics and demand-side flexibilities.” *IEEE Transactions on Industrial Informatics* 20, no. 2 (2023): 1360–1373.
4. Wang, Sheng, Junyi Zhai, and Hongxun Hui. “Optimal energy flow in integrated electricity and gas systems with injection of alternative gas.” *IEEE Transactions on Sustainable Energy* 14, no. 3 (2023): 1540–1557.
5. Wang, Sheng, Hongxun Hui, Tao Chen, and Junyi Zhai. “Multi-period operation of integrated electricity and gas systems with hydrogen blending considering gas composition dynamics.” *Applied Energy* 377 (2025): 124563.
6. Wang, Sheng, Hongxun Hui, Yi Ding, and Yonghua Song. “Long-term reliability evaluation of integrated electricity and gas systems considering distributed hydrogen injections.” *Applied Energy* 356 (2024): 122374.
7. Wang, Sheng, Hongxun Hui, and Junyi Zhai. “Short-term reliability assessment of integrated power-gas systems with hydrogen injections using universal generating function.” *IEEE Transactions on Industry Applications* 59, no. 5 (2023): 5760–5773.
8. Wang, Sheng, Hongxun Hui, and Pierluigi Siano. “Resilience of gas interchangeability in hydrogen-blended integrated electricity and gas systems: A transient approach with dynamic gas composition tracking.” *iEnergy* 2, no. 2 (2023): 143–154.
9. Wang, Sheng, Hongxun Hui, Junyi Zhai, and Pierluigi Siano. “Carbon-embedded nodal energy price in hydrogen-blended integrated electricity and gas systems

with heterogeneous gas compositions.” *IEEE Transactions on Sustainable Energy* (2024).

The authors gratefully acknowledge the respective publishers for granting permission to reuse these materials. These adaptations are made in accordance with the publishers’ reuse policies, and proper attribution has been maintained throughout.

Competing Interests The authors have no competing interests to declare that are relevant to the content of this manuscript.

Contents

1	Introduction	1
1.1	Role of Hydrogen in Net Zero	1
1.2	Hydrogen Integration in Energy Systems	4
1.3	Political Environment	7
1.3.1	Europe	7
1.3.2	The US	8
1.3.3	China	9
1.3.4	Other Countries or Regions	10
1.4	Demonstration Projects	10
1.4.1	Europe	10
1.4.2	The US	11
1.4.3	China	12
1.4.4	Other Countries or Regions	13
1.5	Technical Challenges	14
1.6	Literature Reviews	15
1.6.1	Modelling of Traditional Energy Systems With Uniform Gas Composition	15
1.6.2	Modelling of HI-ES	16
1.6.3	Reliability Evaluation Methods	19
1.7	Summary	21
1.8	Organisation of This Book	22
	References	23
2	Reliability Modelling Framework of Energy Systems With Uniform Gas Composition	31
2.1	Introduction	31
2.2	Framework of IEGS	32
2.3	Reliability Network Equivalents	33
2.3.1	Reliability Network Equivalents for Gas-Fired Generating Units	33

2.3.2	Reliability Network Equivalents for Conventional Fossil Generating Units	36
2.3.3	Reliability Network Equivalents for Gas Sources	37
2.3.4	Reliability Network Equivalents for Power-to-Gas Facilities	37
2.4	Contingency Management Schema	38
2.4.1	Interruption Costs Considering Energy Substitution	38
2.4.2	IOPF-Based Contingency Management Schema for IEGS	40
2.5	Reliability Evaluation Procedures	42
2.6	Case Studies	43
2.6.1	Case 1: Reliability Impacts of Random Failures of Gas Sources	43
2.6.2	Case 2: Reliability Impacts of GFUs and PTGs	47
2.6.3	Case 3: Reliability Impacts of Flexible Loads	50
2.7	Conclusions	51
	References	51
3	Optimal Operation of Energy Systems With Uniform Gas Composition Using Linepacks	53
3.1	Introduction	53
3.2	Structure of IEGS and EHs	56
3.3	Multi-level Self-scheduling Model	56
3.3.1	Optimal Scheduling of EH in Day-Ahead	59
3.3.2	Multi-level Self-scheduling of EH in Intraday	61
3.4	Linepack Flexibility Model	65
3.4.1	Optimal Scheduling of IEGS in Day-Ahead	65
3.4.2	Gas Flow Dynamics for Linepack Utilisation in Intraday	66
3.5	Coordinated Optimal Control	68
3.5.1	Formulation of Coordinated Optimal Control Problem	68
3.5.2	Decentralized Solution Methodology	69
3.6	Case Studies	72
3.6.1	Case 1: Provision of DR in a Stressed Case	72
3.6.2	Case 2: Validation of Proposed Methods	75
3.6.3	Case 3: Comparison of Various DR Requirements	78
3.7	Conclusions	79
3.8	Appendix	80
	References	81

4	Reliability Evaluation of Integrated Energy Systems Considering Gas Flow Dynamics and Demand-Side Flexibilities	85
4.1	Introduction	85
4.2	Evaluation Framework	87
4.3	Modelling of IES Flexibilities	87
4.3.1	Flexibility of End-Users on the Demand Side	87
4.3.2	Flexibility of Gas Flow Dynamics in Transmission System	89
4.4	Look-Ahead Contingency Management	91
4.4.1	Operational Reliability Model of Components	91
4.4.2	Look-Ahead Contingency Management Scheme of Integrated Energy Systems	93
4.5	Operational Reliability Evaluation Procedures	95
4.5.1	Linearization of Gas Flow Dynamic Equations With a Forward-Approximation-Based Technique	95
4.5.2	Operational Reliability Evaluation Procedures	96
4.6	Case Studies	97
4.6.1	Case 1: Impacts of Flexibilities from End-Users and Gas Flow Dynamics on the IES Operation	98
4.6.2	Case 2: Evaluation of IES Operational Reliabilities	100
4.6.3	Case 3: Long-Term Evaluation Results	103
4.7	Conclusions	106
4.8	Appendix	106
4.8.1	Specific Elements in EH Model	106
4.8.2	Calculation Procedures of State Transition Probabilities	107
4.8.3	Derivation Process of Reference Point	108
	References	109
5	Steady-State Optimal Energy Flow in Hydrogen-Integrated Energy Systems	113
5.1	Introduction	113
5.2	Framework of Security Management in H-IEGS	114
5.2.1	Wobbe Index	114
5.2.2	Weaver Flame Speed Factor	115
5.2.3	Combustion Potential	115
5.3	OEF Model of H-IEGS With Alternative Gas Injections	116
5.3.1	Steady-State Model of the Gas System	116
5.3.2	Model of the Coupling Components	120
5.3.3	Model of the Electricity System	121
5.3.4	Objective Function	122

5.4	Reformulation of OEF Model	122
5.4.1	MISOC Relaxation of Gas Flow Equations	123
5.4.2	Reformulation of Bilinear Terms Using McCormick Envelopes	124
5.4.3	Linearization of Security Indices	125
5.5	Solution Procedure Using Sequential Programming	125
5.6	Case Studies	126
5.6.1	Effectiveness of the Proposed Solution Methods	127
5.6.2	Optimisation Results of the OEF in H-IEGS	129
5.6.3	Applications of the Proposed OEF Model	130
5.6.4	Validation Using a Large-Scale Case	140
5.7	Conclusions	143
5.8	Appendix	144
5.8.1	Calculation of Compressibility Factor for Gas Mixture	144
5.8.2	Proof of Convergence of Sequential Programming	144
	References	146
6	Transient-State Optimal Energy Flow in Hydrogen-Integrated Energy Systems Considering Gas Composition Dynamics	149
6.1	Introduction	149
6.2	Convex Hull of Gas Security Range	150
6.3	Transient-State MPOEF Model	153
6.3.1	Transient-State Model of Gas System	153
6.3.2	Model of Coupling Components	158
6.3.3	Model of the Electricity System	159
6.4	Solution Method	159
6.4.1	SOC Reformulation of MPOEF Problem	159
6.4.2	Sequential SOC Programming Procedures	161
6.5	Case Studies	162
6.5.1	Validation of Proposed MPOEF	163
6.5.2	Travelling of Alternative Gas	165
6.5.3	Multi-period Operation Results	166
6.6	Conclusions	169
	References	169
7	Long-Term Reliability of Hydrogen-Integrated Energy Systems Considering Hydrogen Embrittlement	171
7.1	Introduction	171
7.2	Long-Term Reliability Indices for H-IEGS	173
7.2.1	Reliability Indices for Gas Adequacy	173
7.2.2	Reliability Indices for Gas Interchangeability	174
7.3	Reliability Models of H-IEGS Components	176

7.3.1	Multi-state Reliability Model of Pipeline Considering Corrosion Effect	176
7.3.2	Multi-state Reliability Models of Other Components	178
7.4	Contingency Management Scheme of H-IEGS	178
7.4.1	Change of Gas Network Topology Considering Different Pipeline Failure Modes	179
7.4.2	Gas Network Model With Alternative Gas Injections and Pipeline Failures	180
7.4.3	Contingency Management Scheme of IEGS Considering Gas System Securities	182
7.5	Long-Term Reliability Evaluation Procedures	184
7.5.1	Solution Methods for Contingency Management Scheme	184
7.5.2	Analytical Long-Term Reliability Evaluation Procedures With System State Reduction Techniques	186
7.6	Case Studies	187
7.6.1	Case 1: Validation of Proposed CMS in the Representative System States	188
7.6.2	Case 2: Long-Term Reliability Indices of IEGS	191
7.7	Conclusions	195
7.8	Appendix	195
7.8.1	Calculation of Burst Pressure and Rupture Pressure	195
7.8.2	Gas Flow Direction Identification Problem	196
	References	197
8	Short-Term Reliability of Hydrogen-Integrated Energy Systems Using Universal Generating Function	199
8.1	Introduction	199
8.2	Short-Term Reliability Models of Components	200
8.2.1	Multi-performance Short-Term Reliability Model of PTG	200
8.2.2	Multi-state Short-Term Reliability Model of Wind Farm	204
8.3	Short-Term Reliability Management for H-IEGS	205
8.4	Short-Term Reliability Indices	207
8.5	Short-Term Reliability Evaluation Method	210
8.5.1	Solution Method for Reliability Management Problem	210
8.5.2	Short-Term Reliability Evaluation Procedures	211
8.6	Case Studies	213
8.6.1	Validation of Proposed Reliability Management Scheme in Representative System States	213
8.6.2	Operational Reliability Indices	217

8.7	Conclusions	218
8.8	Appendix	219
8.8.1	Feasible Region of PTG in Different States	219
8.8.2	Mathematical Formulation for Reliability Management Problem	221
8.8.3	Gas Security Indices	224
	References	225
9	Resilience Definition and Evaluation of Gas Interchangeability in Hydrogen-Integrated Energy Systems	227
9.1	Introduction	227
9.2	Gas Interchangeability Resilience	228
9.2.1	Gas Interchangeability	228
9.2.2	Resilience of Gas Interchangeability	230
9.3	Two-Stage Gas Interchangeability Management Scheme	232
9.3.1	First Stage: Steady-State Optimal Electricity and Hydrogen-Gas Flow Problem	233
9.3.2	Second Stage: Dynamic Gas Composition Tracking	236
9.4	Solution Method	238
9.4.1	Adaptive Linearizations Method	239
9.4.2	Solution Procedure	240
9.5	Case Studies	240
9.5.1	Validation of Proposed Method	240
9.5.2	Gas Interchangeability Resilience of Different Gas Buses	242
9.5.3	Gas Interchangeability Resilience During Daily Operation	245
9.5.4	Validation of Proposed Metrics	245
9.6	Conclusions	249
9.7	Appendix	249
	References	249
10	Nodal Energy Price and Market Clearing in Carbon Emission-Embedded Hydrogen-Integrated Energy Systems	251
10.1	Introduction	251
10.2	Illustration of Nodal Energy Price in H-IEGS	252
10.3	Joint Market Clearing Model of H-IEGS	254
10.3.1	Gas System Constraints	255
10.3.2	Electricity System Constraints	259
10.3.3	Coupling Constraints	259
10.4	Solution Method	260
10.4.1	Solution Method for Nodal Energy Price	260
10.4.2	Warm-Start for Continuous Market Clearing	262

10.5	Case Studies	264
10.5.1	Validation of Proposed Methods	264
10.5.2	Continuous Operation and Impact Factor Analysis of Nodal Energy Price	267
10.5.3	Validation Using a Large Case	271
10.6	Conclusions	272
	References	272