Green Energy and Technology

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

Ensuring a Reliable Net Zero Transition

Springer

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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, newreliability 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-termreliability 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.

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