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Multi-timescale coordinated schedule of interdependent electricity-natural gas systems considering electricity grid steady-state and gas network dynamics☆

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ABSTRACT

The tight interdependency between electricity and natural gas systems brings new operation challenges to coordinate the two systems for achieving optimized multi-energy supply. The coordinated short-term schedule and real-time dispatch of an integrated electricity-natural gas system (IEGS) with energy coupling components (i.e., P2G (power to gas) assets and gas-fired generators) are proposed. Specifically, in the short-term schedule, electricity generators and gas sources are optimized in a unified model to achieve the minimal operation cost, where prevailing operation constraints related to hourly-scale steady-state power flow and minute-scale gas transmission dynamics are satisfied and extreme wind power scenarios are also considered. In the real-time dispatch, P2G assets and gas-fired generators are optimized to smooth the wind power forecast errors, aiming at mitigating impacts of wind power uncertainties on gas pressures variations. Through real-time dispatch, extreme wind power scenarios which cause violations of gas pressures will be identified and fed back to the short-term schedule problem, seeking for new operation strategies that would mitigate potential gas pressure violations induced by wind power uncertainties in real time. An IEGS, consisting of a 15-node and 14-pipeline natural gas network and a 24-bus and 35-branch power network, is established to validate the proposed approach. Simulation results demonstrate that linepack, P2G, and gas-fired generators can be utilized to effectively enhance operational economics and robustness of IEGS against uncertainties.

1. Introduction

Among various primary energy sources, natural gas has received more attentions owing to its abundant reserves, convenience to store, high energy conversion efficiency, and low pollutant emission. To this end, the share of natural gas in electric power generation has gradually increased, which has significantly intensified the coupling between natural gas and electric power systems [1]. Indeed, researches have shown that electricity and natural gas coupled system can entail lower investment costs as compared to traditional independent systems [2]. Consequently, coordinated optimal scheduling of natural gas, electricity, and other energy resources is of great interests for improving energy utilization efficiency and ensuring energy supply reliability.

The integrated electricity-natural gas system (IEGS) has attracted wide attentions in industry and academia. In IEGS, gas-fired power plants, P2G (power to gas) technology, and linepack of natural gas pipelines can provide a great deal of flexibility to enhance economic and reliable operations [3,4]. Indeed, gas-fired generators and P2G assets can realize the large-scale interconversion of electricity energy and natural gas, and the inherit storage capacity of the natural gas network can help mitigate fluctuations of renewable energy as well as gas and electricity demands, thus forming a cost-efficient and reliable integrated energy system [5–7].

Recently, many scholars have implemented relevant research on energy flow analysis as well as optimal planning and operation of IEGS. A Newton-Raphson based approach was described in [8,9] to analyze the steady-state energy flow of IEGS. An expansion planning approach for IEGS was proposed in [10] to minimize infrastructure expansion and operation costs over the entire time horizon. A planning model for IEGS, formulated as a two-stage robust optimization problem, was proposed in [11] to enhance power grid resilience under extreme conditions. Two interval-based uncertainty analysis methods were

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presented in [12] to study the impact of wind power on steady-state operation of IEGS. A unit commitment and economic dispatch framework coupled with an energy flow model of natural gas network was developed in [13]. A security-constrained economic dispatch model for IEGS was proposed in [14], formulated as a bi-level optimization problem with day-ahead electricity economic dispatch at the upper level and optimal allocation of natural gas at the lower level. A security-constrained unit commitment model combined with natural gas network constraints was proposed in [15]. A security-constrained unit commitment formulation was proposed in [16], which was solved by Bender's decomposition through a master problem to handle power constraints and subproblems to check gas network constraints. An optimization model was developed in [17] to capture spatiotemporal interactions between gas and electricity transmission networks, in which electricity and gas dispatch were solved separately.

When analyzing the coordinate operation of IEGS, it is important to recognize that response times of electric power and natural gas systems are significantly different. Indeed, as electrical system time constant is relatively small, following a disturbance the power grid can reach a new steady state almost instantaneously; on the contrary, natural gas flow is a much slower process, with the propagation of pressure and gas flow changes around 350 m/s [18], resulting in a much longer transient time in response to fluctuations. Thus, in recognizing the effects of natural gas dynamics on generation scheduling in IEGS, the characteristics of power flow and gas transmission at different timescales need to be considered simultaneously. Gas network dynamics was analyzed in [19] by transforming spatial partial differential equations into finite difference equations. A dynamic optimal energy flow model for IEGS was proposed in [20] by combining transient gas flow and steady-state power flow, which was transformed into a single stage linear programming problem with a unified timescale. A combined quasi-dynamic simulation model was introduced in [18], including a transient hydraulic model for gas system and an AC-optimal power flow based steady-state electric power model. An optimal electricity-gas coordinated scheduling was introduced in [21] considering electricity transmission N-1 contingencies and gas dynamics, which was solved by a two-stage linearized method. Considering wind power uncertainties and dynamic security constraints of the gas network, a two-stage robust generation scheduling was proposed in [22] to explore the effect of gas flow dynamics in robust generation scheduling.

Reviewing the above existing research, the work on coordinated operation of P2G, gas-fired generators, and linepack to achieve economic operation of IEGS while effectively mitigating wind energy uncertainties is rather limited. Specially, since linepack can only be accurately quantified by the description of gas transmission dynamics at a short timescale, a unified co-optimization model, integrating electricity transmission and gas delivering at different timescales, is in urgent need.

This paper focuses on a multi-timescale optimization framework of IEGS, in which short-term schedule and real-time dispatch are coordinated to achieve operational economics and robustness against wind power uncertainties. In short-term schedule of IEGS, a unified optimization model is developed in which the hourly-scale steady-state electricity transmission and minute-scale dynamical gas delivery are integrated to achieve economic operation, while considering the forecasted and extreme scenarios of wind power. Specifically, the minute-scale mass flow rates at P2G and gas-fired generator nodes are coupled with their corresponding hourly-scale electric power consumption and generation. In real-time dispatch, operation of P2G assets and gas-fired generators are optimized to smooth out wind power forecasting errors, i.e., their outputs are adaptively adjusted to ensure that gas pressures deviate from their short-term scheduled values as small as possible. In both short-term schedule and real-time dispatch, owing to gas compressibility, linepack will offer flexibility to enhance economic operation and mitigate wind energy uncertainty. The coordination between short-term schedule and real-time dispatch is realized by the closed-loop iterative framework, i.e. real-time dispatch takes short-term schedule results as input, while extreme wind power scenarios identified from real-time dispatch are fed back to short-term schedule to design new economic scheduling results that are robust against extreme wind power scenarios. The iterative procedure terminates when no new extreme scenario is identified in the real-time dispatch problem.

The remainder of this paper is organized as follows. Section 2 illustrates multi-timescale coordinated scheduling of IEGS from two aspects. Section 3 describes the optimization models of short-term scheduling and real-time dispatch for IEGS, while considering prevailing unit commitment constraints, steady-state DC power flow constraints, and transient gas transmission constraints. Simulation results are presented in Section 4. Section 5 draws the conclusions.

2. Multi-timescale coordinated schedule of IEGS

Multi-timescale coordination of IEGS scheduling can be illustrated via the following two aspects.

(i) The short-term schedule and the real-time dispatch are coordinated by identifying extreme scenarios of wind power from real-time dispatch and adding into short-term scheduling optimization iteratively, until no new extreme scenarios arise, as shown in Fig. 1. Specifically, the objective of the short-term schedule is to achieve economic operation while considering forecasted values and the extreme scenarios of wind power as well as operation constraints of steady-state electricity transmission network and gas delivering dynamics. In real-time dispatch, P2G assets and gas-fired generators are utilized to smooth the minute-scale fluctuations of wind power, aiming to minimize the deviation of pressure in gas network from the scheduled one. In summary, wind power uncertain is mitigated via two ways, i.e. considering hourly-scale extreme scenarios in short-term schedule and smoothing minute-scale fluctuation by utilizing P2G, gas-fired generators, and linepack in real-time dispatch.

(ii) In the short-term schedule, the steady-state power flow and the transient gas flow of different timescales are combined in a single optimization model. With hourly forecasts on wind power generation as well as natural gas and electricity demands, the integrated coordination schedule is implemented to determine hourly optimal electricity generation, P2G operation, and gas source mass flow rates, which minimize the total operation costs while satisfying constraints of steady-state electricity power flow and natural gas transmission dynamics. The reasons for combining the steady-state power flow and transient gas flow at different timescales into a single optimization model can be understood from two aspects: (a) When electricity demands or generations change, the transition process in the electricity system can be completed in milliseconds; however, the resulted operational changes of the corresponding

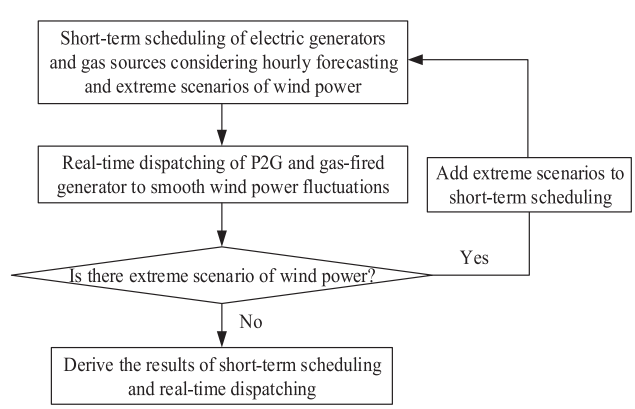

Fig. 1. Coordinated short-term schedule and real-time dispatch of an IEGS.