ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty

Linquan Bai [a], Fangxing Li [a,*], Hantao Cui [a], Tao Jiang [b,*], Hongbin Sun [c], Jinxiang Zhu [d]

[a] Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, USA
[b] School of Electrical Engineering, Northeast Dianli University, Jilin, China
[c] Tsinghua University, Beijing, China
[d] Grid System Consulting, ABB Inc, Raleigh, USA

HIGHLIGHTS

- The gas and electricity integrated energy system (IES) is modeled in detail.
- A multi-period coordinated operating strategy of the IES is proposed.
- Both of the electrical and gas network constraints are considered.
- The wind power uncertainty is addressed by interval optimization.
- A demand response model is incorporated into the optimization model.

ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form 15 September 2015
Accepted 19 October 2015
Available online xxxx

Keywords:
Coordinated operation
Demand response
Gas and electricity network
Integrated energy systems
Interval optimization
Wind power uncertainty

ABSTRACT

In the United States, natural gas-fired generators gained increasing popularity in recent years due to the low fuel cost and emission, as well as the proven large gas reserves. Consequently, the highly interdependency between the gas and electricity networks is needed to be considered in the system operation. To improve the overall system operation and optimize the energy flow, an interval optimization based coordinated operating strategy for the gas-electricity integrated energy system (IES) is proposed in this paper considering demand response and wind power uncertainty. In the proposed model, the gas and electricity infrastructures are modeled in detail and their operation constraints are fully considered, wherein the nonlinear characteristics are modeled including pipeline gas flow and compressors. Then a demand response program is incorporated into the optimization model and its effects on the IES operation are investigated. Based on interval mathematics, wind power uncertainty is represented as interval numbers instead of probability distributions. A case study is performed on a six-bus electricity network with a seven-node gas network to demonstrate the effectiveness of the proposed method; further, the IEEE 118-bus system coupling with a 14-node natural gas system is used to verify its applicability in practical bulk systems.

1. Introduction

In recent years, the interdependency between natural gas and electricity power energy systems are dramatically increasing with more natural gas utilized for electricity generation. In the United States, the natural gas consumption by electric power sector has increased from 32% in 2007 to 39% in 2009 [1]. Gas-fired power plants provide a linkage between natural gas and electricity networks. Compared to traditional coal-fired generators, gas-fired generators are preferred for its competitive fuel cost, lower pollutant emissions and fast response to fluctuating renewable energy [2]. In New England ISO (ISO-NE), more than 50% of electricity is now generated from natural gas, compared to only 15% in 2000, with even more growth in the use of natural gas-fired generation anticipated going forward [3]. Natural gas transmission could affect the security and the economics of power transmission. For the highly interdependency between the two energy sectors, natural gas and electricity networks are regarded as an integrated energy system (IES) [4].

* Corresponding authors.

http://dx.doi.org/10.1016/j.apenergy.2015.10.119
0306-2619/

Please cite this article in press as: Bai L et al. Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.10.119

Nomenclature

$Q_{w,t}$	production of gas well w at time t
$Q_{w,\max}$	maximum production of gas well w
$Q_{w,\min}$	minimum production of gas well w
f_{mn}	gas flow from node m to node n
π_m	pressure of gas node m
C_{mn}	flow factor of pipeline m–n
$H_{j,t}$	horsepower of compressor j at time t
$Q_{d,t}$	gas load d at time t
$Q_{f,t}$	gas consumption of gas-fired unit f at t
$P_{d,t}$	electric load d at time t
$P_{c,t}$	power consumption of compressor c
RU_g	ramp up limit of unit g
$P_{l,\max}$	power flow limit of line j
$R_{k,t}$	spinning reserve of unit k at time t
$Q_{r,t}$	responsive gas load r at time t
$C_{g,r,t}$	incentive price to gas load r at time t
$K_{g,r}$	elasticity of gas load r
φ_g	proportion of gas DR participation
$\Delta Q_{n,t}$	unserved gas load n at time t
$R_{j,\max}$	maximum compression ratio of j
$R_{j,\min}$	minimum compression ratio of j
$Q_{s,t}$	capacity of storage s at time t
$Q_{s,\max}$	maximum capacity of storage s
$Q_{s,\min}$	minimum capacity of storage s
IR_S	hourly inflow limit of storage s
OR_S	hourly outflow limit of storage s
$P_{w,t}$	wind power w at time t
$P_{g,t}$	generator g output at time t
$P_{g,\max}$	maximum output of generator g
$P_{g,\min}$	minimum output of generator g
RD_g	ramp down limit of unit g
GSF	generation shift factor
$R_{t,\min}$	required system reserve at time t
$P_{r,t}$	responsive electric demand r at time t
$K_{e,r}$	incentive price to electricity load r at t
$K_{e,r}$	elasticity of electricity load r
φ_e	proportion of electric DR participation
$\Delta P_{i,t}$	unserved electric load i at time t

Extensive research has been conducted to address the coordinated planning and operation in the gas and electricity network. In [5], a combined gas and electricity network expansion planning model is proposed to minimize gas and electricity operational cost and network expansion cost simultaneously. A co-optimization planning model is proposed in [6] considering the long-term interdependency of natural gas and electricity infrastructures under security constraints. A long-term multi-area, multi-stage model integrated expansion planning of electricity and natural gas systems are presented in [7]. As for short term economic dispatch, an operating strategy is proposed in [8] to coordinate the electricity and natural gas in Great Britain. The impact of gas network on power security and economic dispatch are investigated in [9–11]. In [9,10], integrated optimization model is proposed to incorporate the natural gas network constraints into the optimal solution of security-constrained unit commitment. [11] proposes a security constrained optimal power and natural gas flow under N-1 contingencies.

With the integration of variable and uncertain renewable energy, the coordination of IES is facing new challenges. The uncertainties are not considered in the above model so that a small perturbation in the wind power data may lead to non-optimality or even infeasibility. Stochastic programming [8,12,13] and robust optimization [14–17] are usually used to deal with wind uncertainties. Several works have investigated the impact of wind power uncertainty on system operation. In [8], stochastic optimization is adopted in the optimization model to deal with wind power uncertainty, in which a large number of wind forecast scenarios are generated and a scenario reduction algorithm is applied. [12,13] applied stochastic optimization to the unit commitment problem with a number of wind power scenarios. However, stochastic optimization requires the probability distribution of wind power, which is not easy to be accurately obtained in practice. In addition, it is time consuming to generate a large number of scenarios [14]. A robust optimization approach is proposed in [15] to analyze the interdependency of the IES considering wind power uncertainty. In this work, the wind power uncertainty is actually addressed based on scenario analysis with introducing a penalty coefficient for reducing variance. [14,16] apply robust optimization to unit commitment problem considering wind power uncertainty. [17] proposes a look-ahead robust scheduling model for wind-thermal system considering natural gas congestion, but the constraints of the gas pipelines are considered in a simplified manner. Actually, robust optimization is usually considered to be too conservative due to the fact it always tries to find the worst-case scenario solutions which happen at a very low probability. In addition, due to the non-convex constraints of the pipeline and compressor model in the gas network, the robust optimization model for IES becomes difficult to solve.

In this paper, interval optimization [18,19] is introduced to address wind power uncertainty, wherein the wind power is represented as interval numbers. In the interval mathematics, all the uncertain information will be maintained in the solving process, which is also easy to implement in engineering applications. The interval optimization minimizes the operating cost interval rather than the worst case scenarios in robust optimization [18]. Also, it has better computational performance than stochastic optimization [19]. Furthermore, demand response has been recognized as an effective means to enhance power system operation [20,21], but few literatures considered demand response in the IES.

Therefore, this paper proposes an interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. With the objective of operating cost minimization, the multi-period power and gas flow are optimally determined. The gas and electricity networks are modeled in detail and security operation constraints are imposed. Then an incentive-based demand response program is incorporated into the proposed model and its effects on IES operation are analyzed. With the consideration of wind power uncertainty, the proposed model is solved by interval optimization. Finally, a multi-scenario case study verifies the proposed method.

The rest of this paper is organized as follows. Section 2 introduces the detailed models of the gas and electricity networks. Section 3 presents the interval optimization based operating strategy for the integrated energy system. Section 4 presents case studies to demonstrate the effectiveness of the proposed method. Finally, Section 5 concludes the paper.

2. Gas-electricity integrated energy system modeling

2.1. Natural gas network model

The natural gas network is composed of gas well, gas pipeline, compressor, gas storage and gas loads. Natural gas is produced at