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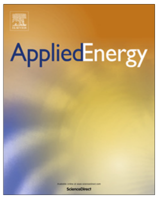

An interval gas flow analysis in natural gas and electricity coupled networks considering the uncertainty of wind power

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HIGHLIGHTS

- A comprehensive model of natural gas and electricity coupled networks is built.
- Two methods on the uncertainty analysis using interval algorithm is proposed.
- The interval solutions can provide great insights into the coupled systems.
- An accessible capacity model of wind power under gas network constraints is built.

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ABSTRACT

The wide application of renewable energy sources in power systems has a significant influence on both electrical and tightly coupled systems. The aim of this paper is to build a comprehensive system model of a natural gas and electricity coupled network. The concept of distributed stack nodes was introduced to overcome the shortcoming of adjusting active power by a single gas-fired unit to achieve power balance. On this basis, the impact of the active power output uncertainty of wind farms was studied, and the interval flow of the natural gas system was analyzed by two proposed methods. The results were compared with Monte Carlo stochastic simulation. Case studies demonstrated the effectiveness of the proposed method and led to the conclusion that the uncertainty of wind power has a significant impact on the steady-state operation of natural gas systems. Interval solutions could provide great insights into the operating and planning of coupled systems with wind power uncertainty.

1. Introduction

Natural gas has become an important choice of fuel for power systems because of its lower pollutant emission, higher energy conversion efficiency, shorter construction period, and better load characteristics. Natural gas now accounts for a significant proportion of the total generating capacity of many regions; it accounts for 40% in Britain, 39.4% in America, more than 30% in Europe, and 29% in Japan [1]. Thus, natural gas plays an increasingly influential role in electric power generation systems. Coupling between natural gas systems and power systems is increasing, which may result in a unified management as a coupled system in the future. The increasing capacity of natural gas consumption by gas turbines will contribute to the challenges of natural gas distribution and system operation. Therefore, issues associated with electricity and natural gas coupled systems require more attention and have become a practical and significant subject.

Interdependency between electrical and natural gas systems has been studied in [2–6]. An integrated formulation for the steady-state analysis of electricity and natural gas coupled systems was proposed in [2] with the consideration of a distributed slack nodes technique in the electrical network. A combined electrical and natural gas network expansion planning model is proposed in [3] to minimize the multiple system operational cost and network expansion cost simultaneously. The natural gas network was modeled in [4] using daily and hourly limits on pipelines, sub-areas, plants and generation units used for commitment of generating units, and the allocation of natural gas for the next day utilization. Measurement of the security of social services was also accomplished. An approach of the coordinated scheduling of security-constrained electrical and natural gas infrastructures is discussed in [5] taking into account the slow transient process in the natural gas distribution system. A multi-time period combined gas and electricity network optimization model was developed in

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Nomenclature

k, m	index of natural gas system nodes
c	index of compressors
l	index of gas turbines
t	index of gas supply
b	index of nodes that violate pressure limits in a natural gas system
i, j	index of electric system nodes
N_e	nodes in the electricity system
N_{PV}	PV-type nodes in the electricity system
N_g	gas turbines in the natural gas system
N_w	wind turbines in the natural gas system
GHV	1015, gross heating value (BTU/SCF)
P_τ	rated power of wind turbine
$P^i_{G,\max}$	max active power output of ith generation
v_τ	rated wind speed of wind turbine (m/s)
v_{co}	cut-off wind speed of wind turbine (m/s)
C_{km}	coefficient to indicate the physical characteristics
η_c	overall efficiency of cth compressor
α	variable coefficient
$f^{t.\min}_{gs}$	min gas flow of tth gas supply
$f^{t.\max}_{gs}$	max gas flow of tth gas supply
$f^{\min}_c$	min in-flow of cth compressor
$f^{\max}_c$	max in-flow of cth compressor
$p^{t.\max}_{gs}$	max pressure of tth gas supply
$p^{t.\min}_{gs}$	min pressure of tth gas supply
$p^{\max}_k$	max pressure at kth node
$p^{\min}_k$	min pressure at kth node
$p^o_{c.\max}$	max outlet node pressure of cth compressor
$S^{\max}_c$	max compression ratio of cth compressor
$p^{\max}_{bu}$	upper pressure limit at bth node (PSIA)
$p^{\min}_{bl}$	lower pressure limit at bth node (PSIA)
$\boldsymbol{A}$	branch-node incidence matrix
G_{ij}	conductance of the nodal admittance matrix (p.u.)
B_{ij}	susceptance of the nodal admittance matrix (p.u.)
$\alpha^l_g, \beta^l_g, \gamma^l_g$	heat rate coefficients of lth gas turbine
β_i	participation factor of the generation
$\overline{U_i}$	max magnitude of ith node (p.u.)
$\underline{U_i}$	min magnitude of ith node (p.u.)

Variables

f_{km}	pipeline's natural gas flow (SCFD)
$\boldsymbol{f}$	vector of gas flow
f^{in}_c	inlet gas flow of cth compressor
f^t_{gs}	gas flow of tth gas supply
p_k	pressure at kth node (PSIA)
p_{bu}	upper bound of pressure at bth node (PSIA)
p_{bl}	lower bound of pressure at bth node (PSIA)
p^o_c	outlet node pressure of cth compressor
p^{in}_c	inlet node pressure of cth compressor
p^t_{gs}	node pressure of tth gas supply
BHP_c	energy consumption of cth compressor
$\boldsymbol{L}$	vector of gas load
S_c	compression ratio of cth compressor $S_c = p^o_c/p^{in}_c$
ΔP_i	active power mismatch at ith node (p.u.)
ΔP_Σ	whole active power imbalance in the electricity system (p.u.)
P_{Loss}	whole active power loss in the electricity system (p.u.)
P^i_G	active power injection at ith node (p.u.)
P^i_D	active power demand at ith node (p.u.)
P^i_{cal}	calculated active power injected at ith node (p.u.)
ΔQ_i	reactive power mismatch at ith node (p.u.)
Q^i_G	reactive power injection at ith node (p.u.)
Q^i_D	reactive power demand at ith node (p.u.)
Q^i_{cal}	calculated reactive power injected at ith node (p.u.)
U_i	voltage magnitude at ith node (p.u.)
θ_i	voltage phase angle at ith node (p.u.)
L^l_g	gas flow required of lth gas turbine
$\lim_{up}\%$	percentage of over up pressure limit
$\lim_{low}\%$	percentage of over low pressure limit

[6] considering the varying nature of gas flow, network support facilities, and the power ramping characteristics of electric power generation units.

On the other hand, because energy shortages and environmental pollution have become significant problems, wind power has become competitive thanks to its environmentally friendliness, mature technologies, and sustainability. A survey by the Global Wind Energy Council (GWEC) showed that the total installed capacity of global wind power was 318,596 MW in 2013 and rose 15.99% within two years to 369,553 MW in 2014. However, a wind turbine is unable to provide continuous and stable active power because it is limited by real-time changes in the wind. Wind power is an inherently unreliable power supply with characteristics of volatility, randomness, and intermittency.

Thus, the uncertainty of wind power strongly influences the security and stability of power systems, which has been well studied by many researchers in the past [7–9]. A stochastic security-constrained unit commitment model for reconfigurable transmission networks was adopted in [7] to facilitate wind power integration. The proposed model utilized network reconfiguration to minimize the entire costs while accommodating transmission constraints. A multi-state model for wind farms is established and applied to power system reliability assessment in [8] as well as solving a series of reliability-centered decision-making problems of power systems. A stochastic cost model is presented in [9] considering the demand and wind generation uncertainties, and this solution would help power system operators in optimal day-ahead planning.

In today's trend of coupled network's unified operation mode, the massive introduction of intermittent wind power introduces serious reliability challenges for both electric and natural gas systems. Study of the impact uncertainty of wind power has on the operation of natural gas systems tightly coupled with electric systems is required. A limited amount of previous literature has reported the impact of wind power on the existing interdependency between energy infrastructures [10–12]. An interval optimization based coordinated operation strategy for the gas-electric integrated energy system is proposed in [10] considering demand response and wind power uncertainty. The potential impact of a large amount of wind generation on the Great Britain gas network was investigated for a multi-time period analysis in [11] using a combined gas and electric network model. A robust optimization model for analyzing the interdependency between natural gas, coal, and electric power infrastructures was proposed

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