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Review

Integrated planning of natural gas and electric power systems

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ABSTRACT

Global electricity generation from natural gas is expected to continue in an upward trend in the coming years thereby increasing the interdependency between the electricity and the Natural gas transportation system. The reliability concerns associated with this interdependency has necessitated an integrated approach to planning both systems to achieve an overall system reliability. This paper proposes a planning approach that minimizes the capital and operational cost of the electricity and natural gas transmission system subject to probabilistic constraints such that a desired confidence level of supply is attained. A Chance constrained and reliability programming optimization model was proposed for solving the long-term integrated planning problem and their performance was compared by illustrating them on the standard IEEE 30 bus test system superimposed on the Belgian high-calorific gas network.

1. Introduction

The worldwide electricity generation capacity is expected to grow by 69% from 21.6 trillion kilowatt-hours (kWh) in 2012 to 36.5 trillion kWh in 2040 [1]. In the same time period, electricity generation from Natural Gas (NG) is expected to increase from 22% to 28% of global generation capacity [1]. To put this in perspective, NG-fired generation accounted for 40% of the 81,621 GWh of net electricity generation in the Alberta Canada in comparison to 51% from coal in 2015, NG is expected to account for 70% of net electricity generation by 2030 [2].

A number of factors have stimulated this growth amongst which are the availability of relatively cheap natural gas supply, and comparatively clean nature of NG fuel [3–6]. This growth, however, implies an increasing dependency of the electric system on the natural gas transportation systems. This cascaded dependency between the NG and the power systems presents reliability concerns because of the ease with which reliability concerns on one system can be propagated to the other. For instance, during 2013/2014 polar vortex in the northeast of USA, increased NG demand for heating led to a shortage of NG supply for electricity generation, thereby raising serious reliability concerns in the electricity system [7]. Addressing these reliability concerns necessitates an integrated approach to planning electric power and NG systems.

The integrated planning of the electricity and NG transmission system has been approached from an operational [8–11] and/or long-term investment [12–16] perspective. In most of these proposed approaches, the integrated planning problem is a nonlinear, non-convex optimization problem which is very difficult to solve [5]. Some of the proposed solution approaches include, sequential [17,10], analytical [5,18], decomposition [4,10,9,13], and heuristic [4]. In most of these models, the objective of the planning model is the minimization of the capital and operational costs of ensuring the electric power and NG demand are reliably met. In most cases, these costs increases exponentially with the size of the interconnected systems and the level of interdependencies. The reliability of the electricity system, however, tends to reduce with increasing complexities and dependence on the NG systems. This is because from reliability theory, the reliability of a system made up of two or more systems connected in series is a product of the reliabilities of the constituent systems [19]. The exponential relationship between investment cost and upper-reliability percentiles tends to reduce the financial viability of NG-fired Generators (NGGs), especially in a least-cost dispatch system. This can be managed by utilizing Probabilistic planning models [20] that ensures that the uncertain electricity and NG demand are met with an average desired confidence level at a minimum cost.

A probabilistic modeling approach [20] such as Chance Constraint Programming (CCP) [21–23], and Reliability Programing (RP) [24] are reliability-based optimization approach where the objective and/or constraint are modeled with probability measures of the extent to which they can be violated. In the CCP models, the desired reliability level(s) of the probabilistic constraints are set a priori while in the RP model the objective of the planning model is optimized without fixing the desired confidence level, rather a cost called the loss function is associated with the violation of the reliability criteria [25,26].

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Nomenclature

A. Abbreviation

NG	Natural Gas
NGG	Natural Gas-fired power Generator
CCP	Chance Constraint Programming
RP	Reliability Programming

B. Indices

b	Index of source electric power bus
r	Index of sink electric power bus
i	Index of source NG node associated with an NG pipeline
j	Index of sink NG node associated with an NG pipeline
t	Index of planning time horizon, t = 0,1,…T
ϱ	Index of NG-fired generator sizes
p	Index of NG pipeline
c	Index of compressor stations

C. Binary Variables

$\lambda_{\varrho,b,t}$	1 if a new NG fired generator type ϱ is installed on b in year t. 0 otherwise
$y_{i,j,t}$	1 if a pipeline is installed between NG nodes i, j in year t. 0 otherwise
$\psi_{i,j,t}$	1 if a compressor is installed between NG nodes i, j in year t. 0 otherwise
$z_{i,j,t}$	1 when there NG flows from node i to j and 0 otherwise.
$\phi_{i,t}$	1 when the upper limit of NG source is increased by 5 Mm^3 from previous year

D. Random Variables

ξ_1	Electricity demand forecast uncertainty
ξ_2	NG demand uncertainty

E. Variables

$P_{b,t}^{(e)}$	Power generation from existing(e) generators
$P_{b,t}^{(n)}$	Power generation from new(n) NGG's
$fl_{b,r,t}$	Power flow from bus b to r in time t
$\Theta_{j,t}$	Square of the NG pressure at sink NG nodes j in time t
$\Theta_{i,t}$	Square of the NG pressure at source NG nodes i in time t
$\Gamma_{i,t}$	NG pressure at source NG nodes i in time t
$\Phi_{i,j,t}$	NG flowrate between nodes i, j in time t

F. Chance constraint variable/parameters

α	Desired confidence-level for the electricity system
β	Desired confidence-level for the NG system
γ	Desired confidence level for the entire system

G Parameters

$C_{\varrho}^{(I)}$	The overnight investment cost (I) of NG-fired generator size ϱ
$C_p^{(I)}$	The overnight investment cost (I) of NG pipeline p
$C_c^{(I)}$	The overnight investment cost (I) cost of compressor station c
$C_{\varrho}^{(o)}$	Operating cost (o) of NG -fired generator size ϱ
$C_c^{(o)}$	Operating cost (o) of NG compressor c
$X_{b,r,t}$	Reactance of the transmission lines connecting buses b, r in time t
$\theta_{b,t}$	Angle of the voltage phasor at bus b in time t
$P_{b,t}^{(L)}$	Local electricity demand at bus b in time t
$\overline{P_b}$	Unforced capacity of NGG connected to bus b
$\underline{P_b}$	Minimum operating capacity of NGG connected to bus b
$\overline{fl}$	Upper limit on capacity of the power transmission line
$\underline{fl}$	lower limit on capacity of the power transmission line
$L_{i,j}$	Length of existing and candidate pipelines connecting NG nodes i and j
$\Delta_{i,j}$	Diameter of existing and candidate pipeline connecting nodes i and j
a_i, b_i, c_i	Fuel rates coefficients of the NG-fired generators
$M_{1,t}$	Large number set to maximum possible NG flow in a pipeline in time t
M_2	Large number used to limit the square of the nodal pressure
M_3	A large value greater or equal to the maximum acceptable pressure
$\underline{\Gamma_{i,t}}$	Lower limit on the square of the nodal pressure at source node i in time t
$\overline{\Gamma_{i,t}}$	Upper limit on the square of the nodal pressure at source node i in time t
κ	Maximum pressure increase multiplier at a compressor station
$s_{i,t}$	NG supply at node i in time t
$d_{i,t}^{(e)}$	NG demand for existing (e) electric power generation at node i in time t
$d_{i,t}^{(n)}$	NG demand for new (n) power generation at node i in time t
$d_{i,t}^{(h)}$	NG demand for non-electric power generation at node i in time t
$\underline{s_{i,t}}$	Lower limit on NG supply at node i in time t
$\overline{s_{i,t}}$	Upper limit on NG supply at node i in time t
ir	Interest rate on capital
δ	Annuity

H. Sets

Ω_b	Set of electricity buses (indexed by (b,r))
Ω_p	Set of NG pipeline types by size
Ω_n	Set of all NG pipeline nodes
Ω_{ϱ}	Set of new NG- fired generator sizes
Ω_d	Set of NG demand nodes
Ω_s	Set of NG supply nodes
Ω_c	Sets of NG compressor nodes associated with active arcs

In this paper, we extend ours and other earlier research [3,17,5,12,10,27,28,13,29,23] on the integrated planning of electricity and natural gas systems. As opposed to the CCP model for the long-term planning of power and NG distribution systems presented in [3,29], the CCP and RP model in this paper, extends the tools for the integrated planning of NG and electric power transmission systems. The proposed model extends the model presented in [17,5,12,28] to include the dynamics of NG compressor and the interactions of the reliabilities of constituent systems in the long-term planning of NG and electric power transmission systems. In addition, the CCP and RP models presented in this paper co-optimize the long-term investment plan for both NG and Power system simultaneously as opposed to the sequential approach employed in [17,10,29]. Finally, the proposed CCP and the RP are analytical solution approaches to solving the integrated planning problem and differs from the heuristic solution approaches presented in [27,13].