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A chance constrained programming approach to integrated planning of distributed power generation and natural gas network

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ABSTRACT

The growing integration of distributed electric power generators means the reliability of electricity distribution system will increasingly depend on the reliability of primary energy resources such as natural gas supply for natural gas-fired distributed power generation. This, therefore, necessitates an integrated approach for planning both the electricity and natural gas distribution systems for the purpose of ensuring reliable natural gas supply for electricity generation. We propose a probabilistic planning approach based on the chance constrained programming method for planning these two systems in the presence of uncertain real and reactive power demand. The proposed model minimizes the investment cost of gas-fired generators, natural gas pipeline and the operation cost of the natural gas-fired distributed generators over a long-term planning horizon. The proposed integrated planning approach is used to develop a 10 years long-term plan for 9 and 33 bus distribution systems. The result shows that the integrated planning approach results in a cheaper and more reliable system in comparison with a traditional sequential planning approach.

1. Introduction

Natural gas (NG) fired power generators are expected to serve as a bridging technology in the energy transition from fossil fuels to renewables. This is because natural gas-fired distributed power generators (NGDG) are flexible with relatively high efficiencies and a competitive investment and operating cost [1]. In consequence to this, the rate at which NG-fired generators are installed continue to increase worldwide. This trend is further encouraged by the availability of cheap NG supply.

By 2020, 42% of new NG-fired generators are expected to be natural gas-fired distributed power generators (NGDGs) [2]. Typically, NGDGs have relatively short installation time and are usually scalable due to their modularity characteristics. In addition, recent advancements in NGDG technologies have made them competitive cost-wise making them a viable solution for bridging the gap between electricity demand and supply, especially in developing regions [2] where access to funds, weak physical infrastructure, and market inefficiencies remain a challenge [3]. Examples of NGDGs include reciprocating engines, fuel cells, gas turbines, and microturbines that are connected to the electric power distribution grid.

The efficient utilization of NGDGs depends on the reliability and availability of sufficient NG supply thereby motivating an increased interest in the adoption of integrated planning approach to planning the electric and NG distribution system. Integrated planning of the NG transportation and the electric systems can be broadly divided into operations planning [4–7] and investment planning [8–15]. The objective of operations planning is to ensure the reliability of NG supply for the purpose of meeting the varying electricity demand in the short-term. Investment planning, on the other hand, ensures the availability of adequate infrastructure for reliable long-term energy supply. Long-term planning models can be further classified into integrated transmission [4,9–11] and distribution [8,11,12] system planning.

Transmission systems' planning entails planning at higher electric voltages and NG pressure while the distribution system planning concentrates on planning for NG and electric power transportation at lower pressure and voltages respectively. From a modeling perspective, reactive power are of lesser importance in transmission system planning [4,9,11]. However, in the electric power distribution system, real and reactive power plays a significant role in maintaining the bus voltages [8]. NG distribution systems are usually void of compressors, typically resulting in pressure drop across the pipeline segments. Consequently, distribution pipelines must be planned to ensure the NG nodal pressures remain within acceptable limits.

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Nomenclature

A. Abbreviation

NG	natural gas
NGDG	natural gas-fired distributed power generator
CCP	chance constrained programming

B. Identifier

k	identifier for lateral feeders $k = 0, 1, \ldots, K$

C. Indices

b	index of electricity bus, $b = 0, 1, \ldots, B$
t	index of planning time horizon, $t = 0, 1, \ldots, T$
i, j	index of source and sink NG nodes associated with a pipeline segment
ρ	index of quantized NGDG sizes
ϱ	index of quantized capacitor bank sizes

D. Binary variables

$\lambda_{\rho,b,t}$	1 if a new NGDG size ρ is connected to bus b in time t. 0 otherwise
$\pi_{\varrho,b,t}$	1 if a new capacitor bank size ρ is connected to bus b in time t. 0 otherwise
y_{ijt}	1 if a pipeline y is installed between NG nodes i, j in time t. 0 otherwise
B_{ijt}	1 if NG flow from NG node i to j in time t. 0 otherwise

E. Random variables

ξ_1	uncertain real electric power demand forecast
ξ_2	uncertain reactive electric power demand forecast

F. Variables

$P_{b,t}$	real electric power generation connected to bus b in time t
$P_{b,t}^{(e)}$	real power generation from existing (e) generators connected to bus b in time t
$P_{b,t}^{(n)}$	real power generation from new (n) NGDGs connected to bus b in time t
$P_{b,t}^{(ip)}$	real power imported (ip) from the transmission grid via bus b in time t
$Q_{b,t}$	reactive electric power generation connected to bus b in time t
$Q_{b,t}^{(e)}$	reactive power generation from existing (e) generators connected to bus b in time t
$Q_{b,t}^{(n)}$	reactive power generation from new (n) NGDG connected to bus b in time t
$Q_{b,t}^{(ip)}$	reactive power imported (ip) from the transmission grid via bus b in time t
$Q_{b,t}^{(c)}$	reactive power generation from capacitor bank (c) connected to bus b in time t
$\Phi_{i,j,t}$	NG flow-rate in the pipe connecting nodes i and j in time t
$\Psi_{i,j}$	the pipeline resistance of the pipe connecting NG nodes i and j
$v_{b,t}$	bus voltage in time t
$\hat{p}_{b,t}$	real power flow from sending node b between buses b and $b+1$ in time t
$\hat{q}_{b,t}$	reactive power flow from sending node b between buses b and $b+1$ in time t
$\hat{s}_{b,t}$	complex power flow between buses b and $b+1$ in time t
δ_t	annuity payment
$\Gamma_{i,t}$	NG pressure at the source NG node i in time t
$\Gamma_{j,t}$	NG pressure at the sink NG node j in time t
$\Theta_{i,t}$	square of the NG pressure at source node i in time t
$\Theta_{j,t}$	square of the nodal NG pressure at sink node j in time t

F. Parameters

$C_{\rho}^{(I)}$	present value of the overnight investment (I) cost of installing NGDG of size ρ
$C_{\varrho}^{(I)}$	present value of the overnight investment (I) cost of installing capacitor bank of size ϱ
$C^{(I)}$	present value of the overnight investment (I) cost of building a pipe of type y
$C^{(o)}$	operating (o) cost i.e. fixed and variable cost of embedded electric power generation
$C^{(ip)}$	cost of importing (ip) electricity from the electric transmission grid
$L_{i,j}$	length of existing and candidate pipe connecting NG nodes i and j
$\Delta_{i,j}$	diameter of existing and candidate pipe connecting NG nodes i and j
F_r	annual failure rates of each segment of pipeline per miles
τ	cost of repairing a segment of the pipeline
OC	outage cost of a segment of the pipeline
ς	average outage duration of a segment of the pipeline
ir	interest rate %
x_b	reactance of the feeder connecting bus b to $b+1$
r_b	resistance of the feeder connecting bus b to $b+1$
$P_{b,t}^{(L)}$	peak local real power demand at bus b in time t
$Q_{b,t}^{(L)}$	peak local reactive power demand at bus b in time t
$\underline{\hat{S}_b}$	lower limit on the complex power flow in the distribution feeder b
$\bar{\hat{S}}_b$	upper limits on the power flow in the distribution feeder b
$\underline{V_b}$	lower limit on the bus b voltage
$\bar{V}_b$	upper limit on the bus b voltage
PG_{ρ}	real power nameplate capacity of generator ρ
QG_{ρ}	reactive power nameplate capacity of generator ρ
QC_{ϱ}	nameplate capacity of capacity bank ϱ
a_i, b_i, c_i	the gas fuel rates coefficients of the NG-fired generators
$M_{1,t}$	maximum total possible NG flow-rate in any section of the pipeline in time t
M_2	maximum possible pressure difference between two nodes
$\underline{\Gamma_i}$	lower limit on the nodal pressure at source nodes i
$\bar{\Gamma}_i$	upper limit on the nodal pressure at source nodes i
$S_{i,t}$	NG supply from NG source node i in time t
$D_{i,t}$	NG demand at node i in time t

G. Chance constraint parameters

α	desired confidence level of satisfying the uncertain real electric power demand
β	desired confidence level of satisfying the uncertain reactive electric power demand

H. Sets

Ω_B	set of electricity buses, indexed by (b,r)
Ω_p	set of NG distribution pipes, indexed by (i,j)
Ω_{ρ}	set of quantized NGDG sizes
Ω_{ϱ}	set of quantized capacitor bank sizes
Ω_d	set of NG demand nodes
Ω_s	set of supply nodes