Electric Power Systems Research 98 (2013) 1–10

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

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

Stochastic generation-expansion planning and diversification of energy transmission paths

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ARTICLE INFO

Article history:
Received 3 September 2011
Received in revised form
26 September 2012
Accepted 29 December 2012
Available online 30 January 2013

Keywords:
Benders decomposition
Electric power system
Generation expansion planning
Monte Carlo simulation
Natural gas system
Optimization

ABSTRACT

The paper addresses a stochastic generation-expansion planning model in the interdependent operation of an electric power system (EPS) and a natural gas system (NGS). The objective of the proposed optimization model is to provide consumers with a reliable electric energy supply by proper generation-expansion planning and diversification of energy transmission paths with minimal investment and operating costs. The proposed method takes into account constraints in the EPS and NGS. The Monte Carlo simulation method is applied to consider random outages of EPS and NGS elements and inaccuracies in the long-term electric load forecasting. A scenario reduction technique is used for reducing the computational burden of a large number of planning scenarios. The EPS and NGS are presented by a direct current (DC) model and a transportation model. The optimization problem is decoupled into a master problem and a subproblem using the Benders decomposition to cope with large-scale problems. The master problem deals with the optimization of investment in new generation units and energy transmission paths. The subproblem comprises a two-level optimization with a decomposed EPS reliability check as the master problem of the subproblem, and a NGS reliability check as the final subproblem. The case studies illustrate the applications of the proposed stochastic method in a coordinated generation-expansion planning problem when considering uncertainties.

1. Introduction

Today we are witnessing a growing interdependency of EPSs and NGSs with the number of gas-dependent power plants, such as gas-fired and combined-cycle power plants, increasing. The mayor economic reasons for such a development are energy deficits and rising electricity prices, which motivate investments in gas-dependent power plants. Investment incentives also come from the plants' high efficiency, low investment cost, lower environmental impact, expeditious permitting and their operation flexibility in comparison with conventional coal plants [1].

From the economic and technical aspect, the interdependent operation of EPSs and NGSs should result in a higher EPS operation reliability, higher security of energy supply and lower energy prices. However, strong interdependency of energy systems can lead to severe energy crises, such as the 2009 natural gas crisis in Europe, when natural gas transportation paths from East to West Europe were cut off. Industry and millions of homes in Europe were left without the supply of natural gas. In addition, the energy shortage was partly compensated by additional electric energy production, pushing EPSs to their reliability margins, which consequently jeopardized the EPSs' reliability and the security of supply with electric energy. This and similar experience teaches us that in order to assure reliable energy supply the expansion planning process should allow for the possibilities of diversification with respect to different energy sources and transmission paths.

Considering the reliability of electric energy supply, gas-dependent power plants, which convert the energy of natural gas to electric energy, can be located either near consumption centers or near natural gas sources, which are usually located far from consumption centers. In the first case, it is natural gas pipelines that play a major role in ensuring reliable electric energy supply, and in the second case, it is transmission lines. The research presented in this paper addresses the question of optimal generation-expansion planning and diversification of energy transmission paths in order to operate the system reliably by supplying the load economically.

It is necessary to change the traditional concept of EPS planning that considers EPSs as independent from other energy sources and transmission systems. A solution is the coordinated planning of EPSs and NGSs using integrated models of both systems. Existing literature proposes several integrated models of EPSs and NGSs, addressing different problems in the field of power system operation and planning. Reference [2] computes the maximal generation of combined-cycle power plants applying a two-phase nonlinear optimization model of the EPS and NGS, taking into account the joint reliability of the EPS and NGS. Reference [3] addresses the

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http://dx.doi.org/10.1016/j.epsr.2012.12.017

Nomenclature

Indices:

A	superscript index for accompanying energy path
b	subscript index for load block
C	superscript index for candidate unit
E	superscript index for existing unit
i	subscript index for production unit or well
j	subscript index for energy transmission path
k	subscript index for natural gas load
max	superscript index for maximal value
r	superscript index of Benders iteration
ref	subscript index for reference bus
s	subscript index for scenario
T	superscript index for matrix transposition
t	subscript index for year
z	subscript index for electric load
0	subscript index for initial state
*	superscript index for gas-fired unit consumption
ˆ	superscript index for optimal solution

Variables:

GC	natural gas flow through compressor
GD	nodal natural gas load
GL	natural gas flow through pipeline
PG	production of generation unit
PL	power flow on transmission line
Q	installation status of natural gas pipeline
X	installation status of generation unit
Y	installation status of transmission line
Z	installation status of natural gas compressor
γ	phase-shifting transformers angle
θ	bus angle
λ, μ	dual variables

Parameters and constants:

a, b	coefficients of linear load transformation
AC	number of accompanying compressors
AL	number of accompanying transmission lines
AP	number of accompanying pipelines
CG	number of candidate generation units
CIC	investment cost of compressor
D	load distribution factor
d	discount rate
DT	duration of load block
E	yearly electric energy demand
EG	number of existing generation units
ERE	random component of peak electric load growth
ERP	random component of energy demand growth
GIC	investment cost of pipeline
GW	objective function of NGS feasibility check
IC	total investment cost
L	load at each load block
$LOEP$	target LOEP, reliability criterion
M	constant with high value
NB	number of load blocks
NN	number of nodes
NS	number of scenarios
NT	number of planning years
P	yearly peak electric load
p, q, r	gas consumption coefficients of gas-fired unit
PD	bus electric load
PIC	investment cost of generating unit
PO	operation cost of generation unit
RE	average energy demand growth rate
RP	average peak electric load growth rate
TIC	investment cost of transmission line
UQ	outage status of pipeline
UW	outage status of natural gas well
UX	outage status of generation unit
UY	outage status of transmission line
UZ	outage status of compressor
W	objective function of EPS reliability check
x	reactance of transmission line

Matrices and vectors:

$\mathbf{A}$	bus – generation unit incidence matrix
$\mathbf{B}$	bus – electric load incidence matrix
$\mathbf{C}$	node – natural gas well incidence matrix
$\mathbf{D}$	node – natural gas load incidence matrix
$\mathbf{E}$	node – pipeline incidence matrix
$\mathbf{F}$	node – compressor incidence matrix
$\mathbf{GC}$	matrix of gas flows through compressors
$\mathbf{GD}$	matrix of nodal natural gas consumptions
$\mathbf{GG}$	matrix of natural gas well productions
$\mathbf{GL}$	matrix of gas flows through pipelines
$\mathbf{K}$	bus – transmission line incidence matrix
$\mathbf{PD}$	matrix of bus electric loads
$\mathbf{PG}$	matrix of unit productions
$\mathbf{PL}$	matrix of power flows
$\mathbf{S}_1, \mathbf{S}_2$	matrices of slack variables in EPS
$\mathbf{S}_3, \mathbf{S}_4$	matrices of slack variables in NGS
$\mathbf{S}_1$	vector of ones
$\mathbf{0}$	vector of zeros

Abbreviations:

DC	direct current
EPS	electric power system
EUE	expected unserved energy
FOR	forced outage rate
ISO	independent system operator
LOEP	loss of energy probability
MILP	mixed integer linear programming
NGS	natural gas system
NPV	net present value
O&M	operation and maintenance

integrated production and dispatch in EPSs and NGSs, taking into account gas pipelines and capacities constraints. References [4] and [5] propose an integrated EPS and NGS model for optimal power flow calculation with constraints in both systems. A non-linear energy transformation between natural gas consumption and gas-fired unit production is introduced as the linkage between the EPS and NGS. Similarly, Ref. [6] addresses the optimal power flow of multiple energy carriers, introducing the energy hub concept. Applying Lagrangian relaxation and dynamic programming [7], considers the short-term scheduling of integrated natural gas transmission and hydrothermal power systems. A piecewise linear approximation of nonlinear flow-pressure relations is modeled in the unit-commitment problem [8]. References [9] and [10] address security-constrained unit commitment with NGS constraints. Reference [9] applies the Benders decomposition to separate the natural gas transmission feasibility-check subproblem from the master unit-commitment problem and the power transmission feasibility-check subproblem. The NGS is presented by a nonlinear model and iteratively solved by the Newton–Raphson method. Reference [10] presents the application of fuel diversity as an effective