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Coupled optimization of electricity and natural gas systems using augmented Lagrangian and an alternating minimization method

P.N. Biskas [a],*, N.G. Kanelakis [a], A. Papamatthaiou [b], I. Alexandridis [b]

[a] Department of Electrical Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
[b] Hellenic Gas Transmission System Operator (DESFA), Patima Magoulas, Attica, Greece

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ABSTRACT

A coupled optimization of the electricity and gas systems is presented in this paper. The electricity problem involves a unit commitment with co-optimization of energy and reserves under a power pool, considering all system operational and unit technical constraints. The gas problem involves a medium-scale highly non-convex and non-linear problem structure, which is modeled as a Mixed Integer Non-Linear Programming model. The decomposition of the overall problem is based on the Augmented Lagrangian method. An iterative process is implemented, coordinating the two interdependent systems using an alternating minimization method, in which the Lagrange multipliers are updated using the subgradient method. The gas problem is solved in two phases in order to avoid numerical instabilities; first, the direction of flow is defined, and then the gas flow is derived in the second phase. The solution algorithm is evaluated using the Greek power and gas system, comprising thirteen gas-fired units and fifty-three gas network nodes. The test results indicate the strong interdependence of the two systems, and demonstrate the efficiency of the presented algorithm in coordinating them.

Introduction

During the last years, gas units (mainly Combined Cycle Gas Turbines, CCGTs) became highly attractive due to their short construction lead time, low investment cost, shorter depreciation period, increased efficiency, small environmental footprint (namely, lower carbon emission rate), low NOx and SOx emissions, high flexibility under normal and AGC operation (critical aspect, in view of the forthcoming increased RES penetration, given the RES injection intermittency and variability). This short-term volatility needs flexible reserves as back up, for which gas-fired technology is the prime candidate. The popularity of CCGTs, along with the provided flexibility of gas storage, gave birth to common energy infrastructure considerations by regulators, system analysts and designers, identifying the strong interdependence between the electricity and gas systems in technical, economical and operational terms [1]. Despite their common nature as energy transmission systems, the operation of the natural gas system is extremely complex, employing a large-scale, highly non-convex and non-linear problem structure (comprising a group of non-linear algebraic equations), which can be modeled as a Mixed Integer Non-Linear Programming (MINLP) problem. The coordination of the well-known electricity operation scheduling with such MINLP problem, considering their integrated dynamics, constitutes a mathematical challenge and has attracted the interest of the research community within the last ten years [2–22].

A review of the developed models for combined consideration of the electricity and gas systems is given in [2]. Table 1 summarizes the main features of the models presented in the literature [3–22]. In most cases, the steady-state gas flow configuration is modeled, as compared to the transient flow modeling that takes into account the gas stored in the pipelines (linepack). In many cases, a single-period (snapshot) is studied, disregarding the inter-temporal constraints of both the electricity and gas systems. Moreover, in most cases the electricity problem is defined simply with elementary constraints (power balance equation, unit limits and possibly ramp-rates), disregarding the full unit commitment model of a power pool. Further, in most cases the non-linear gas problem is simulated and solved using mathematical programming, evolutionary programming or heuristic methods, whereas in some cases (e.g. [7,10,11,15]) a simplified linearized model is presented. Refs. [16–18] constitute the most thorough methods in terms of accurate modeling of the electricity and gas problems, employing decomposition techniques (Benders decomposition and

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* Corresponding author at: Power Systems Laboratory, Division of Electrical Energy, Department of Electrical Engineering, Aristotle University of Thessaloniki, AUTh Campus, 54124 Thessaloniki, Greece. Tel.: +30 2310 994352; fax: +30 2310 996302.

E-mail address: pbiskas@auth.gr (P.N. Biskas).

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Nomenclature

Indices and sets

$c \in \mathcal{C}_{mn}$	set of compressors in the branch connecting gas nodes m and n, whose gas consumption is tapped from gas node $m; \mathcal{C}_{mn} \subseteq \mathcal{C}$
$i \in \mathcal{G}_{gle}$	set of gas-fired generating units associated with gas load gle; $\mathcal{G}_{gle} \subseteq G$
$gl \in \mathcal{GL}_m$	set of gas loads connected to gas node m; $\mathcal{GL}_m = \mathcal{GLR}_m \cup \mathcal{GLE}_m$
$gle \in \mathcal{GLE}_m$	set of gas loads of gas-fired power units connected to gas node m; $\mathcal{GLE}_m \subseteq \mathcal{GL}_m \subseteq \mathcal{GL}$
$glr \in \mathcal{GLR}_m$	set of residential and industrial gas loads connected to gas node m; $\mathcal{GLR}_m \subseteq \mathcal{GL}_m \subseteq \mathcal{GL}$
$k \in \mathcal{K}$	set of iterations of the solution process
$m, n \in \mathcal{N}$	set of gas nodes
$mn \in BR_p$	set of passive branches (without compressor or regulator); $BR_p \subseteq BR$
N_m	set of gas nodes connected through a gas branch to gas node m; $N_m \subseteq N$
$r \in \mathcal{R}_{mn}$	set of regulators in the branch connecting gas nodes m and n, which regulate the pressure of node n; $\mathcal{R}_{mn} \subseteq \mathcal{R}$
$s \in \mathcal{S}_m$	set of gas supplies connected to gas node m; $S_m \subseteq S$
$st \in \mathcal{ST}_m$	set of LNG storages connected to gas node m; $\mathcal{ST}_m \subseteq \mathcal{ST}$
$t \in \mathcal{T}$	set of dispatch periods within the dispatch day (typically, the dispatch period is one hour)

Parameters

CC_{mn}	constant corresponding to diameter, length and gas properties of branch connecting nodes m and n
D_{glr}^t	hourly gas demand forecast for the residential and/or industrial gas load glr at dispatch period t, in MW h_{th}
$D_{gle}^{\max}, D_{gle}^{\min}$	max/min gas consumption of electric gas load gle, depending on the gas-fired units associated with gle
F_c	gas consumption rate of compressor c, in MW h_{th}/kW
G_s^{max}	maximum hourly injection from supply s to the gas system, in MW h_{th}
GR	gas conversion ratio, in Nm^3/MW h_{th}
HHV	gas higher heating value, in GJ/Nm^3
HP_c^{max}, HP_c^{min}	max/min horsepower of compressor c, in kW
$I_{st}^{max}, I_{st}^{min}$	max/min hourly injection to the LNG storage st, in MW h_{th}
PR_c^{max}, PR_c^{min}	max/min pressure ratio of compressor c
RR_r^{max}, RR_r^{min}	max/min gas expansion ratio of regulator r
SC_{glr}	shedding cost of gas load glr, in €/MW h_{th}
$V_{st}^{max}, V_{st}^{min}$	max/min gas energy volume of LNG storage st, in MW h_{th}
V_{st}^0	initial gas energy volume of LNG storage st at dispatch period $t = 0$, in MW h_{th}
$W_{st}^{max}, W_{st}^{min}$	max/min hourly withdrawal from the LNG storage st to the gas system, in MW h_{th}
π_m^{max}, π_m^{min}	max/min node pressure of node m, in bar
Π_m^{max}, Π_m^{min}	max/min squared node pressure of node m, in bar^2; $\Pi_m^{max} = (\pi_m^{max})^2$, $\Pi_m^{min} = (\pi_m^{min})^2$

Variables

d_c^t	amount of gas tapped to the compressor c for energy conversion at dispatch period t, in MW h_{th}
d_{gle}^t	hourly gas consumption of electric gas load gle at dispatch period t, in MW h_{th}; each gle corresponds to one or more gas-fired units i
d_{glr}^t	cleared hourly gas consumption of non-electric (residential/industrial) gas load glr at dispatch period t, in MW h_{th}
ds_{glr}^t	gas shedding of non-electric (residential/industrial) gas load glr at dispatch period t, in MW h_{th}
fl_{mn}^t	gas flow through branch connecting gas nodes m and n at dispatch period t, in MW h_{th}
g_s^t	gas output from supply s to the natural gas system at dispatch period t, in MW h_{th}
hp_c^t	horsepower of compressor c at dispatch period t, in kW
i_{st}^t	gas injection to LNG storage st at dispatch period t, in MW h_{th}
ib_{st}^t	binary variable, equal to 1 when gas is injected to the LNG storage st at dispatch period t
p_{Gi}^t	electricity production of unit i at dispatch period t, in MW h_e
u_i^t	binary variable expressing the commitment status of gas-fired unit i at dispatch period t
ug_{gle}^t	binary variable, equal to 1 when at least one gas-fired unit that corresponds to the gas load gle is dispatched at dispatch period t
v_{st}^t	gas energy volume stored in LNG storage st at dispatch period t, in MW h_{th}
w_{st}^t	gas withdrawal from LNG storage st to the gas system at dispatch period t, in MW h_{th}
wb_{st}^t	binary variable, equal to 1 when gas is withdrawn from the LNG storage st (to the gas system) at dispatch period t
z_{mn}^t	binary variable, equal to 1 when the direction of the gas flow in branch connecting gas nodes m (start node) and n (end node) is from m to n
π_m^t	node pressure in node m at dispatch period t, in bar
Π_m^t	squared node pressure in node m at dispatch period t, in $bar^2; \Pi_m^t = (\pi_m^t)^2$

Augmented Lagrangian method) for handling the coordinated optimization problems; however, these models are applied to a test system (IEEE 118-bus system) with a 14-node test gas network. Nevertheless, in all models there is a coupling constraint linking the two systems. This is the gas consumption of gas-fired generating units, which is explicitly represented as a variable in the gas system, while in the electricity system it is computed as a function of the unit's heat rate (either taken simplified as a linear function [8,9] or as a quadratic function [3–7,10–18]). Refs. [19,20] utilize a piecewise linearization for the natural gas flow to expand the research on the combined optimization of the two transmission systems examining adequacy assessment and contingency analyses. A comprehensive study for the day-ahead scheduling that includes the variability of wind is presented in [21]. Finally, in [22] an iterative procedure is presented for the long-term transmission planning of the two systems. Finally, the modeling of the regulator is not presented in the literature.

In this paper, a coupled optimization of the electricity and natural gas systems is implemented using the Augmented Lagrangian method. The original problem consists of two respective subproblems. The objective of the overall problem is to minimize the operating costs of the two independent systems, while satisfying the respective constraints. Analytical modeling of both subproblems is implemented in this paper. The electricity problem involves a unit commitment with co-optimization of energy and reserves under a power pool, with all system operational and unit technical constraints. The gas problem involves a medium-scale highly non-convex and non-linear problem structure, which is modeled as a