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A planning approach for reducing the impact of natural gas network on electricity markets

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HIGHLIGHTS

- We present a planning approach natural gas and electricity market operation.
- We consider failure events on the natural gas network.
- We employ a simulation procedure for reliability assessment.
- We explore alternative natural gas storage locations.
- We quantify the impact of storage on the electricity market outcome.

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ABSTRACT

In this paper, we present a planning approach for reducing the impact that failure events in the natural gas (NG) network impose on the electricity market operation. For this purpose, an efficient computational methodology based on the Monte Carlo sequential simulation approach is developed, in order to realistically simulate the annual operation of the NG network and deduce the failure events at the connection nodes of the NG-fired power plants. The failure events are then fed into a mid-term scheduling model based on the day-ahead electricity market clearing algorithm, in order to quantify their impact on electricity prices, unit commitment and dispatch, and the energy mix. An appropriate methodology on the location selection of new storage capacity in the NG network is also described, and a case study based on the combined Hellenic electric power system and NG network is used as a test-bed for evaluating the alternative locations.

1. Introduction

During the last decades, the electric power sector has undergone significant changes driven by political, economic and technical reasons. An outstanding feature among the technical reasons is the development of natural gas (NG) combined-cycle power plants. These plants have several advantages with respect to traditional thermal power plants, such as lower investment costs, shorter depreciation periods, and lower environmental impact. In fact, the growth of the electricity generation sector in many countries has been mainly based on the construction of NG-fired plants [1]. As a result, the NG network is in high interdependence with the respective electric power system.

Failure events that occur in the NG network can cause interruption of NG supply to one or more electricity generation units connected to it, hence imposing a significant impact on the electricity market operation [2–6]. The traditional hydrothermal unit commitment and short-term operation planning tools do not consider such failure events, when deciding for the dispatching of NG-fired plants along with other thermal sources (coal, oil, nuclear) [7,8].

Shahidehpour et al. [9] are the first to study the short-term operation of the integrated electric and natural gas system and evaluate the consequences of gas system failures on the electricity market operation; however, the NG network is not modeled in [9].

The combined model of the NG and the electric power system is also addressed in [3,10–12], but mainly within the scope of operational and security studies. In [3], an integrated security-constrained unit commitment (SCUC) problem is presented to assess the operational effect of the interdependent infrastructures. In [10], a joint operator of NG and electric systems is proposed to minimize operation costs taking into account both systems' constraints. In [11], the NG network constraints are incorporated into the solution of the SCUC, and the feasibility of different solutions in

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a nonlinear NG network is tested by applying the Newton–Raphson method. In [12], the impact of NG limitations on medium-term hydro-thermal scheduling is studied. These reports mainly refer to the operation horizon and do not address the planning problem.

Zerriffi et al. [13] study power system disturbance situations that mainly arise during special events (e.g., primary fuel supply disruptions, conflict-induced stresses, weather-related damages) and their possible causes and impacts. Wu et al. [14] consider other system uncertainties including components outages, load forecast errors, and water inflow, for a midterm SCUC model to optimize coordinated water and natural gas supplies. The uncertainties are modeled as scenarios in the Monte Carlo simulation. Case-based simulation is employed in [15] for the simulation of the system behavior, though in a different context; however, the Monte Carlo sequential simulation approach [16–19] can be easily and effectively used for calculating the operational and reliability indices of a power system by simulating its actual behavior, without requiring past data. In [20], stochastic optimization is used to analyze the effects of network uncertainties in the short-term operation of the integrated electric and NG system. However, additional efforts are required to study the reliability of NG networks and their impact on the respective electric power systems for a midterm horizon.

Lastly, Sahin et al. [21] study the midterm scheduling payoffs and risks of a generating company (GENCO) in volatile operating conditions. The proposed algorithm considers the integration of intermittent wind units into GENCO's generation assets and coordinates the GENCO's hourly wind generation schedule with that of NG units (with volatile gas prices) and hydro units (with water inflow forecast) for maximizing GENCO's payoff.

In this paper, we present a modeling and simulation procedure for the reliability assessment of the NG network. We quantify the impact of the NG network failure events on the electricity market outcome. Our main contribution is a planning approach, implemented in this paper as the introduction of new NG storage facilities for mitigating the impact of NG failure events on the integrated NG and electric power system.

The paper is structured as follows. In Section 2, we introduce an efficient methodology based on the Monte Carlo sequential simulation approach to simulate the annual operation of the NG network and deduce the failure events of the connection nodes for the NG-fired power plants. We also describe the main market processes of an electricity pool market, and present a mid-term scheduling model based on the day-ahead market-clearing algorithm, which is used to quantify the impact of the failure events. In Section 3, we provide the details of a realistic test case, based on the Hellenic NG network and electric power system. We also list and discuss the numerical results obtained from the annual analysis of the combined Hellenic NG network and the electric power system with respect to the impact of the failure events on electricity prices, unit commitment and dispatch, and the energy mix. Finally, in Section 4 we draw conclusions and provide directions for further research.

2. Methodology

This section describes the methodology of the planning approach. In Section 2.1, we present the modeling and simulation procedure for the NG network operation. In Section 2.2, we describe the electricity market processes and operation, and the mid-term scheduling model.

2.1. Modeling and simulation of the NG network operation

The NG network can be modeled by considering nodes and branches that connect the nodes. Each branch contains one or more components, such as pipelines and equipment for control and operation. In this respect, the entire topology of even a large NG network is represented using a two-dimensional matrix **A**, where the lines indicate the number of the branch, and the columns indicate the components of the branch. Assuming the simplest topology, the components of a branch can be a sending end node, a receiving end node, and a pipe which connects these two nodes [22].

The availability state (operation, repair) of all network components is determined by applying the Monte Carlo simulation approach, for any time period of the year (one hour step) [23]. When a network component is not in operation due to a failure event, the network is divided into two or more subsystems. For the identification of subsystems, the modeling process generates a vector of nodes (**nsub**) indicating the subsystem that each node of the original network belongs to. A subsystem is considered to be in safe operation if it includes at least one supply node and one consumer (customer).

Lastly, the NG supply indices to all customers of the network included in the individual subsystems are calculated as follows:

(a) Forced Outage Rate λ (occ./year): It is defined as the ratio of the total number of observed failures events to the total operational time of a system customer for the period of one year.
(b) Unavailability **U** (h/year): It is defined as the summation of hours of the year that the system customer had no NG supply due to a failure event.

It is noted that there are two cases that a failure event occurs to a customer. Firstly, the case that the failure event happens to the same customer and, secondly, the case that the customer belongs to a subsystem which is not in safe operation (as described above). The detailed modeling algorithm is presented in Fig. 1.

Fig. 2 details the process of subsystems identification.

Firstly, vector **nsub** is initialized for all nodes (nn nodes) to the subsystem 0. The availability state for each branch (nb branches) is examined using vector **fbran**. If the branch does not contain any failure (fbran = 0), then the sending end node of this branch is assigned to the scalar *sd* and the receiving end node to the scalar *rc*. Then, a check is performed to determine if both end nodes of the specific branch are not yet assigned to a subsystem (they are still assigned to the initial subsystem 0). If yes, a new subsystem is created and both nodes are assigned to it. If no, a check is performed to determine if there is an end node of this branch that is still assigned to the initial subsystem 0. In this case, this end node is assigned to the same subsystem of the other end node. When the above procedure is repeated for all the branches of the network, the vector **nsub** is found. In case that a node after the end of this procedure is still assigned to the initial subsystem 0, this node is considered as out of operation.

The reliability modeling and simulation procedure for the NG network (Fig. 1) and particularly the process of the subsystems identification is one of the main contributions of this paper. By employing this procedure, alternative planning scenarios (e.g., the introduction of a new NG storage unit) can be assessed, in order to increase the total level of the NG network reliability, and reduce its impact on the respective electric power system.

This paper proposes the introduction of a new NG storage unit, and examines several candidate locations. A candidate location can be practically every node of the NG network except for supply nodes and customers nodes. For the selection of the best location for the installation of a new storage unit, an appropriate criterion is required. One would consider as a simple criterion the sum of unavailability hours for all customers; however, this criterion does not take into consideration the maximum capacity of each cus-