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An integrated simulation model for analysing electricity and gas systems

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ABSTRACT

This paper aims at analysing the impacts of interdependencies between electricity and natural gas systems in terms of security of energy supply. When analysing both systems several interdependencies can be observed, however, the most significant interdependencies are as follows: (1) gas dependency of gas fired power plants in electricity system and (2) electric dependency of electric-driven compressors in gas system. Since both systems depend on each other, it is of major interest from an energy security perspective to investigate how failures triggered in either of the systems propagate from one system to the other. We proposed an integrated simulation model that aims at reflecting the dynamics of the systems in case of disruptions and takes the cascading effects of these disruptions into account. While developing the integrated model, first electricity and gas systems are modelled separately and then linked by an (MATLAB-based) interface. The effectiveness of the proposed model is investigated using characteristic disruption scenarios. Computational results demonstrate that the integrated simulation model is very user-friendly and quite effective and efficient in analysing the interactions between electricity and gas systems.

Introduction

Critical energy infrastructures (CEIs) including electricity, natural gas and oil systems, provide fuel that is essential for the continuous and reliable functioning of national or regional security, economic operations, public health and safety. The disruption or loss of functionality of these infrastructures would have weakening impact on the defense and economic security and quality of life. CEI systems are not isolated but increasingly interconnected and interdependent with the development of modern technology. For instance reliable electricity supply is a necessity throughout the natural gas system in order to maintain the normal operation while natural gas delivery is a requirement to generate electricity in gas fired power plants (GFPPs). Higher interdependencies between CEI systems make the entire energy system more vulnerable than ever since a disruption occurring in one system (e.g. an unexpected failure) has consequences on the other dependent systems and possibly even back to the system where the disruption originated. These tight relations are increasing the potential risk for catastrophic events, triggered by cascading effects of intentional and unintentional types of disruptions. The growing importance of this risk is also realized by the governments and they focused on strengthening the national energy policy framework to provide sustainable energy supply with affordable services [1]. Several organizations have published reports providing key inputs into the development of energy policies [2–5]. The main aim of National Energy Security Assessment (NESA) analysis is to identify the key energy security issues. This takes the main factors challenging the adequate, reliable and competitive delivery of energy in each of the liquid fuels, natural gas and electricity sectors into consideration. European commission initiatives such as "Green Paper on A European Programme for Critical Infrastructure Protection/2005" [3] and "Council Directive 114/2008 on the Identification and Designation of European Critical Infrastructures and the Assessment of the Need to Improve Their Protection" [5] issued the identification of CEIs, analysing their interdependencies and improving the protection policies. Moreover recent studies in the energy security literature focused on introducing new approaches and trends on energy security to deal with its increased complex and multi-dimensioned nature [6–9]. In [6], the authors highlighted the need for focusing the entire energy system and developing an integrated approach in solving energy security challenges. The knowledge required for

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energy security is presented through three distinct perspectives derived from political and natural science, engineering, economics, and systems analysis. The first perspective, sovereignty mainly deals with strategic security, international relations and political science while the second perspective robustness, deals with physical vulnerabilities of dynamic, integrated energy systems and includes the concepts of engineering and natural science. The last perspective resilience, which originated from economics and complexity science, is based on increasing the withstanding ability of the energy system from various disruptions and protecting the system against threats by long term investments and technologies.

Electricity and gas are two important CEI systems and they both rely on networks operating at transmission (high current electricity grids or high pressure gas networks, respectively) and distribution level (low current electricity grids or low pressure gas networks, respectively) to deliver energy from generation points (electric power plants/gas wells) to end consumers. Traditionally, the operations and evaluation of both systems are handled separately; however electricity and gas systems are interdependent and each system has significant impacts on the performance and efficiency of each other. Gas system network consists of different components that depend on electrical power in order to operate the network (electric driven compressors, underground gas storage facilities, key valves, regulators, drilling rigs, etc.). Moreover, the usage of electric driven compressors is increasing due to lower installation and maintenance costs. In addition many regions require emission standards that oblige the use of electric driven compressors [10]. On the other hand electricity networks utilize gas as a safe and secure fossil fuel mainly due to its environmental friendliness and global occurrence. Shale gas production has already had a significant impact on the deployment of new infrastructures, especially in USA, where the installed capacity of GFPP has dramatically increased during the last years and is expected to continue increasing in the coming years, which has obviously increased the dependency of the electricity system on the gas system [11]. This could also be the case in other regions of the world, including Europe, especially under scenarios of abundant cheap shale gas and low carbon policies. Moreover, modern GFPPs can be also used flexibly, in most cases as a backup for intermittent renewable energy sources, mainly wind and solar energy. Current plans for an increased installation of renewable energy sources will further increase the role of gas as a backup for electricity generation. Because of the close interactions between electricity and gas systems, analysing the systems independently may not provide adequate information to ensure the proper functioning of the energy supply system. Besides, it is a quite insufficient approach in today's world since the continuity of energy supply has become a major concern for most of the countries.

In this paper we aim at analysing the interdependent electricity and gas system network behaviours in terms of cascading failure effects from one system into another in the context of energy security. The consequences are investigated when the electricity or gas system has just experienced a disruption, like failure of a pipeline or a transmission line. According to the classifications in [6], this paper deals with robustness and resilience perspectives of energy security since it considers the technical failures of the components and evaluates the resilience of the entire system under these failure scenarios. An efficient and flexible modelling tool which considers bi-directional interactions is introduced and as far as the known literature, there is no work published on analysing the two systems in such a detail and aspects. Two types of basic dependencies are considered; (a) dependency of gas fired power plants (GFPP) in electricity network system on natural gas supply, and (b) dependency of electric driven compressors in gas network system on electricity supply. The modelling of interdependencies and their effects on failure propagation is carried out within the simulation framework of a failure cascade process. The developed integrated simulation model incorporates AC power flow model and a complete hydraulic gas model to represent real world applications accurately. Moreover, since the dynamics in a gas system network is slower than that observed in the electricity, the simulation time steps are considered to be different. Later on, the effectiveness of the proposed model is investigated under different disruption scenarios. The results of the simulations are used to identify the system's contributions to cascading failures and feedback mechanisms among the systems. The results proof that analysing systems in an integrated manner provide a good knowledge on the vulnerabilities of the interdependent electricity and gas system, which could not be detected by analysing the systems individually.

The paper proceeds as follows: literature review is given in Section 'Literature review', the proposed integrated simulation model for the gas and electricity systems is described in Section 'Proposed integrated simulation model'; computational analysis on test problems are discussed in Section 'Computational results' and conclusions are given in Section 'Conclusions'.

Literature review

While extensive research that considers the systems individually can be found in literature, an integrated analysis of electricity and gas systems is rare. Identifying the limitations of one system as a result of changes in the other has recently become an active research area, since it is the responsibility of the decision makers to ensure the system operability and resilience in case of disruptions in the systems. The research in integrated analysis of electricity and gas systems can be classified in terms of technical, economic and security aspects. Comprehensive reviews of the approaches can be found in [12–14].

In [13], authors classify the research on integrated electricity and gas systems in terms of various economic and technical perspectives. The first approach is essentially based on economic evaluations aiming at exploring the interactions between the mechanisms of pricing of each carrier. This can be achieved by means of economic models, where the influence of technical constraints is often ignored or taken into account in a simplified way. In this field, an important effort has been devoted to clearing price mechanisms for coupled gas and electricity markets, especially at a trans-national level [15–18]. Other works are related to the developing of procedures for optimizing different time scales of natural gas portfolio of an electric generation company owning gas-fired power plants under stochastic price scenarios [19–21]. Additionally in [22,23] market models have been proposed for analysing the behaviour that a single subject would take as a player in the two markets, where it may be a buyer of gas and an electricity producer. Network pricing of gas and electricity is defined as a key element for placing new generation plants in [24].

The technical analysis of integrated electricity and gas systems generally focuses on operational planning and the models can be classified according to the considered time horizons as; medium-term, short-term and snapshot models. While medium-term scales range from one month to a year and short-term applications deal with hours and days, snapshot models consider a single system configuration for operation planning. A generalized network flow model is proposed in [25] for integrated analysis of electricity, gas and coal systems for a multi-period analysis. The simulation studies of the network flow model in [25] are given in [26] for a configuration of the U.S.A. energy system with medium term operational optimization. A complete gas model and a DC power flow model are used for integrated analysis in [27] where gas storage is also considered. The methodology links the two systems through gas fired power plants and aims at minimizing the total operating