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Impact of compressor failures on gas transmission network capability

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ABSTRACT

National Grid, the gas operator in the United Kingdom, has experienced challenges in evaluating the capability of its gas transmission network to maintain function in the event of risks particularly to withstand the impact of compressor failures. We propose a mathematical programming model to support the operator in dealing with the problem. Several solution techniques are developed to solve the various versions of the problem efficiently. In the case of little data on compressor failure, an uncertainty theory is applied to solve this problem if the compressor failures are independent; while a robust optimisation technique is developed to solve it when they are not. Otherwise, when there are data on compressor failure, Monte Carlo simulation is applied to find the expected capability of the gas transmission network. Computational experiments, carried out on a case study at National Grid, demonstrate the efficiency of the proposed model and solution techniques. A further analysis is performed to determine the impact of compressor failures and suggest efficient maintenance policies for National Grid.

1. Introduction

Gas currently plays an essential role in natural energy sources because of its low carbon dioxide emission and abundant reserves. It has a primary role in electricity generation. According to the International Energy Outlook 2016, world demand for energy will grow by 48% between 2012 and 2040, and fossil fuels are expected to account for more than three-quarters of this. Natural gas is the fastest-growing fossil fuel with global consumption increasing by 1.9% per year. Hence, efficient and effective gas transportation networks are a critical requirement for gas operators. Gas transportation networks involve three major subsystems: namely, the gathering system (from oil-shores to terminals), the transmission system (from terminals to off-takes), and the distribution system (from off-takes to customers). Unlike the gathering system and the distribution system which are characterised by low pressure, small diameter pipelines, the transmission system is characterised by long, large diameter pipelines operated at high pressures. The efficient performance of the gas transmission system thus poses a challenge in maintaining the safe regulation of pressure such that gas demands at off-takes are satisfied. Controlling pressure and flow in the gas transmission system depends on a number of compressor stations at which several compressors operate in serial and/or parallel. Compressor station/unit failures are extremely challenging for gas transmission. Evaluation of the impact of failures on gas transmission capability is a significant issue for gas operators.

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The maximum flow problem can be used to evaluate network capability. It is one of the classic optimisation problems with many real applications in electrical power systems, computer networks, communication networks, logistic networks and transportation networks [1–3]. However, the uncertain maximum flow problem has not received as much attention by researchers. The few relevant works in the literature may be categorised into two approaches: uncertainty theory and robust optimisation. Uncertainty theory, as we use it, was first introduced by Liu [4] for solving project scheduling problem with uncertain duration times. Using the framework of Liu's uncertainty theory, Han et al. [5] investigate the maximum flow problem in an uncertain network. They introduce the concept of maximum flow function of network, and then use the so-called 99-method to give the uncertainty distribution and the expected value of the maximum flow of uncertain network. Ding [6] formulates an α-maximum flow model to find the distribution of the maximum flow for the problem with uncertain capacity on any arc, proving an equivalence relationship between the α-maximum flow model and the classic maximum flow model. A polynomial algorithm is developed based on properties of α-maximum flow model. Shi et al. [7] investigate two maximum flow models of an uncertain random network under the framework of chance theory. They consist of the expected value constrained maximum flow and the chance constrained maximum flow with uncertain random arc capacities. The authors propose two algorithms to solve these models, and prove that there exists an equivalence relationship between the models and the deterministic ones. Alipour and Mirnia [8] formulate uncertain dynamic network flow problems in which arc capacities are uncertain (may vary with time or not), and flow varies over time in each arc. They build an algorithm to solve the problems with independent uncertainties. The algorithm cannot be applied for the problems with correlated uncertain factors or time-dependent distribution functions. Models built within the framework of uncertain or chance theory focus mainly on maximum flow problems with uncertain capacities on arcs. Models are lacking for the maximum flow problem with uncertain capacity on nodes. For uncertain maximum flow problems solved by robust optimisation, readers can refer to [9–10]. Bertsimas and Sim [9] propose an approach to address data uncertainty (e.g., both the cost coefficients and the data in the constraints) for network flow problems that allows control of the degree of conservatism of the solution. In [10], the authors investigate uncertainty in the network structure (e.g, nodes and arcs) and assume that the network parameters (e.g., capacities) are known and deterministic. In particular, they study the robust and adaptive versions of the maximum flow problem in networks with node and arc failures. In general, the approaches have not considered the impact of degeneration of node's capacity on maximum flow in network.

For literature reviews of optimisation problems related to gas networks, we refer to [11–12]. Zheng et al. [11] focus on three specific aspects, production, transportation and marketing, and consider six general problems: production scheduling, maximal recovery, network design, fuel cost minimisation, and regulated and deregulated market problems. Their survey discusses mathematical formulations and existing optimisation methods. Rios-Mercado and Borraz-Sanchez [12] present the relevant research works in the natural gas transport industry, studying short-term storage, pipeline resistance and gas quality satisfaction, and fuel cost minimisation. For the theoretical foundations and the applications of long-term basis storage, readers can refer to [13–16]. Studies on pipeline resistance and gas quality satisfaction can be found in [17–20]. Fuel cost minimisation is discussed in [21–24]. Studies on flow model for natural gas transmission in pipes under transient and steady states can be found in [25] and [26], respectively. For the procedure to design the mainline system in natural gas networks, readers can refer to [27]. The authors introduce a comprehensive mathematical model to determine the optimal pipeline-investment decisions for the gas network design, such as pipe diameter, thickness, pressure, length, compression ratio, etc. Recently, Ghaithan et al. [28] have developed a multi-objective optimisation model for the integrated downstream oil and gas supply chain. The objectives consist of minimising the total cost, maximising the total revenue and maximising the service level. In the model, multi-period and multi-product inputs are included. The authors use an improved augmented ϵ-constraint algorithm to find Pareto optimal solutions. A case study from a Saudi Arabian oil and gas supply chain is solved to evaluate the performance of the model and the algorithm. This model can support managers in medium-term tactical decision making. Although these works address applications of optimisation theory to the gas transmission and storage to satisfy contractual demands and physical network constraints, there is a limited literature on uncertain maximum flow problems in gas transmission networks. Koch et al. [29] propose many mathematical programming models and algorithms to evaluate the gas network capability, but their models and algorithms can only solve deterministic problems. Recently, Praks and Kopustinskas [30–31], Praks et al. [32] have developed models for determining the maximum network capability under uncertainty. Praks and Kopustinskas [30] build a reliability model based using Monte Carlo methods to test various "what-if" scenarios. Their methods can be used not only for evaluating the current situation of security of supply, but also for testing the effects of new network components (e.g., new pipelines) in various development strategies of the gas transmission network. Praks and Kopustinskas [31] and Praks et al. [32] develop a probabilistic gas network simulator (ProGasNet) software tool to estimate supply reliability, effect of time-dependent storage discharge, quantitative effects of new infrastructure, security of supply under different disruption scenarios. The tool is useful to compare and evaluate different supply options, new network development plans and analyse potential crisis situations. However, none of this work has considered the effects of compressor station reliability on gas network capability. Praks et al. [33] develop a Monte Carlo simulation-based approach to analyse disruptions of components (e.g., pipelines, terminals and compressor stations) in the European gas transmission network. They construct a vulnerability identification algorithm for determining a combination of component failures leading to the most significant security of supply disruptions. In the simulation, they do not consider the operational configuration of compressor units in stations (i.e., serial, parallel, or both). In addition, the Monte Carlo simulation-based approach becomes time-consuming as the number of components in the gas transmission network becomes significant.