ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

An integrated systemic method for supply reliability assessment of natural gas pipeline networks

Huai Su[a], Jinjun Zhang[a,*], Enrico Zio[b,c], Nan Yang[a], Xueyi Li[a], Zongjie Zhang[a,d]

[a] National Engineering Laboratory for Pipeline Safety/MOE Key Laboratory of Petroleum Engineering/Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum-Beijing, 102249 Beijing, China

[b] Dipartimento di Energia, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy

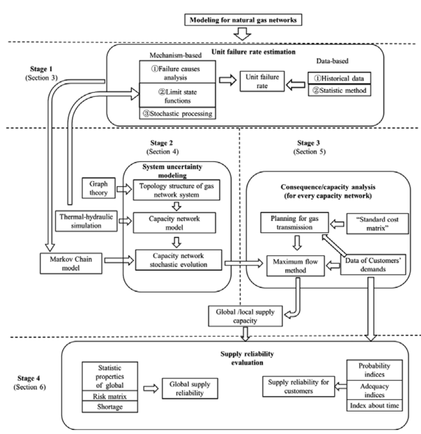
[c] Chair System Science and the Energy Challenge, Fondation Electricité de France (EDF), CentraleSupélec, Université Paris Saclay, Grande Voie des Vignes, 92290 Chatenay-Malabry, France

[d] Petrochina West East Gas Pipeline, Dongfushan Road 458, Pudong District 200122, Shanghai, China

HIGHLIGHTS

- A method is developed to analyze reliability of supply of gas pipeline networks.
- Uncertainty, complexity and physical constraint are considered in the method.
- Indices are developed with respect to global system and individual customer.
- The application of the method is studied in a complex natural gas pipeline network.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Natural gas network
Reliability of supply
Failure analysis
Uncertainty analysis
Consequence analysis
Graph theory

ABSTRACT

A systematic method is developed for supply reliability assessment of natural gas pipeline networks. In the developed method, the integration of stochastic processes, graph theory and thermal-hydraulic simulation is performed accounting for uncertainty and complexity. The supply capacity of a pipeline network depends on the unit states and the network structure, both of which change stochastically because of stochastic failures of the units. To describe this, in this work a capacity network stochastic model is developed, based on Markov modeling and graph theory. The model is embedded in an optimization algorithm to compute the capacities of the pipeline network under different scenarios and analyze the consequences of failures of units in the system. Indices of supply reliability and risk are developed with respect to two aspects: global system and individual customers. In the case study, a gas pipeline network is considered and the results are analyzed in detail.

* Corresponding author at: College of Mechanical and Transportation Engineering, China University of Petroleum, Fuxue Road 18, Changping District 102249, Beijing, China.
E-mail address: zhangjj@cup.edu.cn (J. Zhang).

https://doi.org/10.1016/j.apenergy.2017.10.108
Received 19 May 2017; Received in revised form 14 October 2017; Accepted 29 October 2017

Please cite this article as: Su, H., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.10.108

1. Introduction

Natural gas pipeline networks are important critical infrastructures connecting natural gas resources and demands. Several unexpected natural gas supply interruptions have occurred in the last decade with severe consequences on economy and society stability around the world [1]. Realizing the importance of natural gas pipeline networks for energy security, reliable and continuous supply of natural gas has become a serious and worldwide concern for economic, political and technical reasons.

Recently, reliability, risk and vulnerability perspectives have been embraced for natural gas supply security [2,3]. Reliability has been applied to engineering systems for > 60 years. The most widely accepted qualitative definition of reliability is in terms of the probability of a component, sub-system or system "to perform a required function in set conditions and for a stated period of time" [4]. However, for the supply function of natural gas pipeline networks, we take the definition of reliability for critical infrastructure systems. The supply reliability of a natural gas pipeline network is defined as the probability of successfully providing the service required to satisfy the customers' demand of gas. Supply reliability indices are, then, calculated considering both supply capacity and demands.

Many efforts have been devoted to research in the field of reliability of infrastructure networks, as above defined. System reliability analysis methods, such as logic modeling and system decomposition, have also been classically used to estimate system reliability [3,5,6]. Statistics is used to calculate the reliability indices when relevant historical data are available [7–9].

However, conventional reliability theory cannot capture the complexities (structure and dynamic) of large infrastructures extending on large geographic scales, operating under variable conditions and consisting of large number of components with heterogeneity [10,11]. Specifically for natural gas supply reliability assessment, a comprehensive model is needed to describe the uncertainty, function, operation and capacity of the system and the consequences of specific events.

Many approaches exist for modeling the stochastic properties of complex infrastructures, e.g., natural gas pipeline networks, power grids, or rail systems. Stochastic simulation methods, e.g., Monte Carlo based methods [12–16], Markov process based methods [17,18] and others [19–22], are widely used to model a complex system with uncertainties. Probabilistic dynamic modeling is applied to describe interdependences among critical infrastructures and global effects of specific scenarios [23].

Graph theory for vulnerability and reliability analysis is an effective approach that has been proposed recently to model transport infrastructure systems as graphs to analyze their connectivity properties [24,25]. In particular to analyze the vulnerability and reliability of a transmission network, there are methods based on topological properties [2,26–30], flow-based methods [31–36] and hybrid methods [13,37–39]. Further, structural-function modeling, based on graph theory and system engineering, are also used [40]. A structural-function model consists of two parts: a structure model and a function model. Physical objects in the systems are represented in terms of edges and nodes in the structure model and the system behaviors are represented in the function model. The function model can be engineering-oriented e.g. thermal-hydraulic models for natural gas networks [41], the function model for gas-grid coupling [42], or simplified and abstracted, e.g. flow-based methods [39,2,43].

Also, the importance of considering operation, function, capacity and limitation of a gas supply system is emphasized in some works, such as GEMFLOW [44] and MC-GENGERCIS [14].

The aim of this paper is to present an original methodology to evaluate supply reliability in natural gas pipeline networks. A method to describe uncertainty and complexity of pipeline network systems has been developed. The method consists of a unit analysis module, a system analysis module and a reliability calculation module. The function of the unit analysis module is to analyze complex and uncertain causal relationships between causes and failures modes. The system analysis module is developed to depict the structure and capacity of pipeline networks and simulate the response to stochastic failures. Uncertainty, system structure complexity and system dynamic complexity are considered in the model. The calculation of supply reliability in natural gas networks includes two parts: the global part and the customer part. The global part mainly aims to calculate supply capacity from the point of view of the global system. The customer part accounts for the customer demand. For a detailed assessment, indices of the customer part are divided into three aspects: probability, adequacy and time.

The developed framework integrates methods for addressing the problems from different perspectives — environmental, functional constraint, topology and dynamic. Comparing with the traditional reliability methods, it has the advantage of addressing the reliability assessment problem considering these different perspectives for holistically capturing the high complexity of the natural gas pipeline network and the related uncertainties, which cannot be easily treated with classical methods of logic modeling and system decomposition. From a practical point of view, the methodology can aid engineers and managers estimating safety margins to serve costumers reliably.

2. Methodology

For a clear illustration, the developed methodology is divided into three parts: unit failure analysis, system modeling and reliability assessment. The framework is shown in Fig. 1 and the following paper is organized as follows.

In Section 3, two methods are adopted in unit failure analysis, i.e., the failure-mechanism-based method and the historical-data-based method. Natural gas pipelines have large geographical extension and can be affected by multiple factors: then, the failure probability of pipelines changes in space and time. On the contrary, failure probabilities of the others are stable because of the limited variability of the surroundings they operate in.

To simulate the consequences of stochastic failures of units in natural gas supply systems, several methods have been developed [41,2]. In this paper, methods including stochastic processes, graph theory and thermal-hydraulic simulation are combined to simulate stochastic changes of pipeline network system (Section 4) and estimate the consequences (Section 5), accounting for uncertainty and complexity.

Then, supply reliability in natural gas pipeline networks is determined in terms of the amount of gas that the pipeline network can support and the degree to which customer demands are satisfied (Section 6).

3. Unit failure probability estimation

3.1. Pipeline failure analysis

Several factors can lead to the failure of natural gas pipelines. According to the data from European Gas Pipeline Incident Data Group (EGIG), material failure and corrosion are responsible for 30–40% of all pipeline failures; the rest is due to external factors, such as maintenance works, wrong operations and third party interference [45]. According to this, corrosion analysis is considered as a critical part in pipeline failure analysis. On account of the diverse conditions and non-linear factors affecting the structure integrity, utilizing statistical failure data can give a global estimate of pipeline reliability but may not be accurate for the specific pipelines in diverse conditions. The failure probability of a specific pipeline should be calculated with consideration of its particular factors of operation such as pipeline parameters and failure mechanisms.

The data source for pipelines failure analysis comes from pipeline internal detections. Number, location and geometric parameters of