Research on Reliability Evaluation of Natural Gas Pipeline Network System- A Review

Yifei Wang, Chun Su
School of Mechanical Engineering
Southeast University
Nanjing 211189, China
suchun@seu.edu.cn

***Abstract*—Natural gas is a kind of clean energy, it has become an important energy form. The safety and reliability of natural gas pipeline network (NGPN) is crucial for the transportation and usage of natural gas. This paper summarizes the research progress as well as its application of NGPN system's reliability in recent years. It mainly includes two aspects, i.e. structural reliability and gas supply reliability. From the view of structural reliability, the analytical approaches and evaluation indicators are analyzed. The advantage and shortcoming of various approaches for gas supply reliability are compared. The modeling methods for gas supply's reliability are summarized from the views of natural gas supply and structural failure respectively. Finally, some feasible research directions are suggested for NGPN system's reliability .**

Keywords- natural gas pipeline network (NGPN); structural reliability; gas supply reliability; modeling; reliability evaluation

I. INTRODUCTION

Compared with coal and petroleum, natural gas is a kind of clean energy due to its less pollution and emission during the process of production and use [1]. With the increasing emphasis on environmental protection, natural gas has gradually replaced coal in various industrial and civil fields. In the last decades, the demand for natural gas increases rapidly, and natural gas has become an important form of energy with the fastest growing rate. Compared with the compressed and liquefied natural gas transportation, the cost for pipeline transportation is lower and its efficiency is high. Thus, pipeline is the best choice for natural gas' transportation of large-scale and long-distance. Taking China as an example, the total mileage of oil and gas pipelines has reached 1,164,400 kilometers by the end of 2016, among which 68,000 kilometers are natural gas pipelines [2].

In China, the demand side for natural gas comes mainly from the eastern part [3], especially along the coastal area, while the major domestic natural gas production areas are located in the western area, including Sichuan, Xinjiang, Shanxi, etc. Furthermore, the domestic natural gas supply is far from meeting the demand, a large amount of natural gas needs to be imported from abroad. After years of efforts, China has built a gas supply system, including "West-to-East Gas Transmission" and "Air-Sea Landing", and a regional natural gas pipeline network (NGPN) has been constructed.

The natural gas is flammable and explosive, during the transportation and usage, it is far more likely to cause leakage and explosion. Table I lists some of the natural gas pipeline explosion accidents happened in recent years [4]. Although the time and place of the above accidents are different, all of them have resulted in serious consequences, including huge economic loss, casualty, and environmental damage. Therefore, it is of great economic value and social significance to carry out reliability evaluation so as to ensure safe and reliable operation of NGPN system.

TABLE I. TYPICAL EXPLOSION ACCIDENTS OF NGPN IN RECENT YEARS

Time	Location	Reason	Consequence
June, 2014	Andhra Pradesh, India	Explosion of gas pipeline causes Fire	14 deaths and 15 seriously injured
August, 2014	Kaohsiung, China	Gas leak explosion	32 deaths, 321 injuries
April, 2015	California, USA	Leakage of natural gas pipeline caused by construction and explosion	More than 14 injuries, 4 of them were seriously injured
July, 2016	Enshi, China	Gas explosion caused by geological hazard	2 deaths, 7 injuries, and 5 houses damaged
October, 2016	Oregon, USA	Natural gas leakage caused by building construction damage and explosion	8 injuries

Up to now, a large number of studies have been carried out on the reliability assessment of NGPN system, while there still lacks a systematic evaluation method for NGPN system's reliability. In this study, we sort out and analyze the existing researches in this field. Furthermore, the structural reliability and gas supply reliability for NGPN are presented respectively. Finally, some directions for NGPN system's reliability evaluation are suggested.

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II. Definition of NGPN system's reliability

The reliability of NGPN system refers to its ability to complete the transportation task under the specified operating conditions and within a specified time [5]. Generally, the reliability evaluation of NGPN system includes two aspects: (1) Production safety: the safety of each component in NGPN system is in a controllable state, and it can ensure the ability to avoid chain reaction in case of accident; (2) Gas supply safety: NGPN meets the consumers' demand for gas under specified time and conditions.

At the end of 1970s, the Ministry of Natural Gas Industry of the former Soviet Union compiled "Reliability Calculation Method for Trunk Gas Pipeline (BTH II 2-86)" and "Code for Design of Natural Gas Trunk Pipeline (SNIP2.05.06-85)". These regulations are helpful to evaluate the reliability of pipeline for the government [6, 7]. In the United States, ANSI Pipe Standards are applied to manage the NGPN. This kind of management system covers NGPN's whole life cycle and can achieve the integrated management of production, supply and marketing of NGPN system [8]. In 2010, the Det Norske Veritas Energy Department revised the Submarine System (DNV-OS-F101-2010) standard [9,10]. This standard analyzes the possible catastrophic problems of pipeline system from three aspects of risk assessment, accident prediction and emergency treatment respectively. It can evaluate the pipeline system's reliability by taking into consideration of the impact degree, disaster scope and economic loss as the evaluation criteria. In 2015, the National Standardization Management Committee of China took the lead in formulating the National Standard for the Integrity Management of Oil and Gas Pipelines (GB32167-2025) [11]. It is the guideline and criterion for the safety management and evaluation of pipeline industry in China. Up to now, there are still some differences in reliability evaluation indicators and assessment methods among different countries, and a unified evaluation system has not been formed.

Traditional reliability assessment methods are mainly for the safety management of single pipeline or local small-scale pipeline network system, which cannot meet the demand of large-scale pipeline network. Huang [12] proposed the concept of large-scale NGPN system's reliability, and formulated a framework for reliability assessment of large-scale NGPN system. In fact, the reliability enhancement scheme of large NGPN system can be described from the following three aspects: (1) promoting the integration of management and control; (2) strengthening reliability management; (3) formulating maintenance plan scientifically.

For a single natural gas pipeline system, the reliability evaluation is mainly to evaluate whether the pipeline structure is reliable or not. As for the reliability of NGPN system, the basic objective is to ensure the safety of natural gas supply and its usage. Therefore, the reliability of gas supply should meet consumers' needs, and it is crucial to keep the pipeline network having sufficient gas supply capacity. Furthermore, the reliability evaluation methods for NGPN can be divided into structural reliability and gas supply reliability.

III. Structural reliability of NGPN

The structural reliability refers to the ability of the NGPN system to ensure its structural integrity and connectivity without failure during the logistics process and life cycle of natural gas transportation [13]. For NGPN system, its structure is mainly composed of pipeline sections, stations, equipments, valve chambers, etc. [14]. Structural reliability evaluation can comprehensively consider the connectivity and failure probability among the components of NGPN system so as to reflect the overall reliability of the pipeline network system. The following evaluation indicators are often used in the analysis of NGPN's structural reliability, including reliability, availability, average fault occurrence time, and maintainability [15]. The major reliability analysis methods include fault tree analysis (FTA), Monte Carlo method, etc.

(1) Fault tree analysis (FTA)

The FTA method needs to establish a fault tree for the research object. After that, the minimum cut set is used to obtain the failure probability according to the weight of each fault event [16]. FTA has a clear logic relationship, which can present the event composition and causality of pipeline network's failure and failure mode. However, for NGPN, the logic structure of the fault tree model is complex and the calculation is also time-consuming.

Considering that traditional FTA is difficult to accurately represent real events, Dong et al. [17] used expert heuristic and fuzzy set theory to calculate pipeline's failure probability, and the error can be reduced to some extent. Badida et al. [18] studied pipeline failure probability and risk assessment under the influence of natural disasters, and completed structural reliability calculation with expert inspiration and fuzzy FTA. Cheng et al. [19] applied FTA and fuzzy set theory to an emergency shutdown system of LNG terminal, and an algorithm is proposed to obtain the critical components and determine the weak paths in the system.

(2) Monte Carlo method

Essentially, Monte Carlo method is a stochastic simulation method which uses random number to simulate and solve various computational problems, and it has certain black box characteristics [20]. By using this method, it is easy to establish the limit state equations corresponding to the actual accident conditions. However, due to the complex structure of NGPN system as well as the changeable operation conditions, when using this method some problems will be inevitably encountered, such as establishing the limit state equation, and the demand for simulation calculation, etc [21].

Chaudry et al. [22] used Monte Carlo method to study the reliability of gas and electricity network. The research content is helpful to realize risk assessment of energy supply. Leira et al. [23] applied the enhanced Monte Carlo method to evaluate the reliability of pipeline system with multiple corrosion defects, and on this basis, the influence of correlation between different defects on failure probability was studied. Yu et al. [24] put forward a method to quantify the reliability of natural gas pipeline supply. By combining the reliability theory with hydrothermal analysis, the gas supply capacity was evaluated according to relevant indicators.

As for the evaluating of the pipeline network's structural reliability, up to now most studies follow the classical reliability theory and conventional theoretical methods. Based on historical data, Hovey et al. [25] analyzed the operation reliability of long-distance gas pipelines, three evaluation indicators are used, i.e. failure rate, reliability and availability, and the gas pipelines' reliability characteristics were obtained. Li et al. [26] compared three different methods in calculating the failure rate of gas pipeline, and completed case analysis by using the collected data, so as to determine the best scope of applications of different methods. Rimkevicius et al. [27] evaluated the reliability of oil and gas long-distance pipeline network, four indexes were used, including failure rate, average maintenance time, average interruption duration and frequency. Sun et al. [28] analyzed the historical data of pipeline failure, a probability model of pipeline's failure was established based on Weibull distribution, and the unit reliability of gas transmission network was obtained. Caleyo et al. [29] used two stochastic models, i.e. homogeneous Poisson process and power law process, to analyze pipeline historical failure data, the failure rate of pipeline system was calculated. In order to estimate the failure probability of pipelines, Dundulis et al. [30] proposed a probability analysis framework based on the integrity, where the effects of pipeline material parameters, defect data and failure data were considered.

To sum up, most studies on the structural reliability of NGPN focused on the failure mechanism of pipeline, predicting the remaining useful life or calculating the failure rate of pipeline. In fact, considering only the structural reliability cannot guarantee the NGPN system's reliability. Furthermore, there are still various problems with it. To improve the structural reliability, the reliability of gas supply needs also to be considered.

IV. GAS SUPPLY RELIABILITY OF NGPN

For pipeline network's reliability analysis, the ultimate goal is to evaluate and enhance the reliability of gas supply, and so as to meet consumers' demand. Gas supply reliability refers to the ability that the pipeline network system fulfills the task of gas supply under the specified conditions and within a certain time [31]. Up to now, the researches on gas supply reliability of NGPN are still limited, and it lacks a systematic theoretical approach. Here, we introduce two major methods for evaluating gas supply reliability, i.e. Monte Carlo simulation and thermal-hydraulic simulation.

Casoetto et al. [32] established a simplified model of NGPN, and simulation software was used to calculate the gas supply capacity of NGPN under various situations, the gas supply safety of the pipeline network was obtained with enumeration method. Fu et al. [33, 34] used the central moment method and a second-order reliability method respectively to study the reliability and uncertainty of natural gas supply in energy system. The effectiveness of the proposed method was verified with a case study. However, the dynamic characteristics during the natural gas transportation has not been considered. By combining probability, thermal-hydraulic and structural integrity model, Rimkevicius et al. [27] established a set of reliability evaluation methods, which are suitable for water supply heating network as well as oil and gas pipeline network. Pavel et al. [35, 36] used Monte Carlo simulation and graph theory to simplify the complex pipe network system into node diagram, and the gas supply reliability of an European local pipe network was calculated.

In practice, the failure of natural gas supply can be caused by various factors, including pipeline corrosion, third-party damage, incorrect operation, etc. Some scholars studied NGPN's reliability by considering the influence of multiple factors. Based on cloud inference theory, Guo et al. [37] proposed a multi-factor risk assessment method to evaluate the reliability of natural gas pipelines. The results show that by using the method, the risk level of the natural gas pipeline can be clearly displayed. In order to better evaluate the safety problems in the natural gas supply, Shaikh et al. [38, 39] studied the safety level of natural gas supply in China by using the ecological network analysis (ENA) method. Wu et al. [40] obtained the probability of NGPN's accidents by using Bayesian network (BN), and expert knowledge was applied to determine the conditional probability of each BN node, where the belief function theory was used to weigh the nodes and estimated the failure probability of the pipeline network. Fan et al. [41] simplified the NGPN topology structure on the basis of graph theory, and Monte Carlo method was used to evaluate the market demand and calculate the reliability of pipeline network. By combining the unsteady flow hydraulic analysis with state transition process, Yu et al. [42, 43] calculated the gas supply capacity of NGPN. Meanwhile, by using load duration curve (LDC) approach, the demand of natural gas market was predicted. By integrated graph theory, stochastic process and thermal-hydraulic simulation, Su et al. [44] proposed a comprehensive method to evaluate gas supply reliability of NGPN system. In their work, the reliability of pipeline network was evaluated from the perspectives of environment, functional constraints, topology structure as well as dynamics. Compared with the traditional reliability methods, this method has a strong ability to describe the complexity and uncertainty of NGPN.

Table II summarizes the methods and their limitations for the gas supply reliability assessment of NGPN.

TABLE II. COMPARISON OF RELIABILITY ASSESSMENT METHODS

Reference	Methods	Limitations
Rimkevicius [27]	Gas supply reliability of NGPN was evaluated by probability, thermal-hydraulic and structural integrity model.	The uncertainty of market demand was ignored.
Pavel [35, 36]	Monte Carlo simulation and graph theory were used to study the security of gas supply.	The maintainability, hydraulic characteristics and uncertainty of demand were neglected.
Guo [37]	NGPN's reliability was evaluated with cloud reasoning, and multiple factors were considered.	The stochastic process in pipe network system was ignored.
Shaikh [38, 39]	The safety of natural gas supply was assessed.	The risk factors such as transport routes and price fluctuations were ignored.
Fan [41]	The topological structure analysis and hydraulic calculation were used to quantify the gas supply reliability.	The dynamic behavior of gas pipeline system was neglected.

TABLE II. COMPARISON OF RELIABILITY ASSESSMENT METHODS

Reference	Methods	Limitations
Yu [42, 43]	Monte Carlo simulation was used to predict the dynamic characteristics, and the LDC method was used to predict the market demand with uncertainty.	The impact of component's preventive maintenance and environmental variables on gas supply demand were not included.
Su [44]	A method integrating stochastic processes, graph theory, and thermal-hydraulic simulation was proposed to assess the supply reliability.	The dynamic behavior of gas pipeline system, the uncertainty of demand and duration of each operating state were neglected.

In addition, some companies have also carried out studies on reliability assessment of natural gas pipeline network. For example, cooperated with Det Norske Veritas, the National Petroleum Corporation of Brazil completed reliability evaluation for Brazilian domestic NGPN. In that project, the software of TGNET®, natural gas distribution optimization software of PLANAGE® and reliability evaluation software of TARO® were applied synthetically [45, 46].

Currently, two factors are frequently considered in the reliability model of gas supply in pipeline network. One factor is whether the supply and demand of natural gas are balanced or not, and the other factor is the influence of the structural failure on the gas supply capacity of pipeline network [47]. The problem with the former factor is that the interference model of gas supply reliability cannot reflect the influence of the pipeline structure's change to the NGPN gas supply capacity. The problem with the latter factor is that it is often failed to consider fully the changing law of consumers' demand. In addition, the classification method for the pipeline's failure mechanism is not so clear up to now. Therefore, when establishing the reliability model of gas supply network, it is of significance to improve the evaluation index system of gas supply reliability.

Based on existed studies on NGPN system's reliability, we present a framework for the reliability evaluation of NGPN, as shown in Fig. 1.

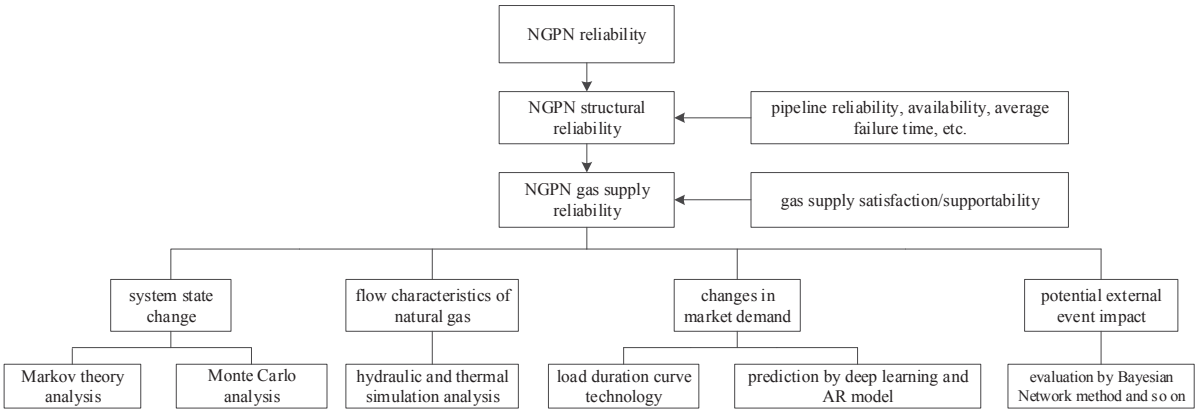

Figure 1. Framework for reliability assessment of NGPN system

In fact, the reliability of gas supply is influenced by various factors, such as system state, natural gas flow characteristics, market demand, and potential external events, etc. Therefore, it is difficult to comprehensively describe the reliability characteristics of NGPN system depending only on structural reliability or gas supply reliability. To some extent, the reliability of gas supply can be further studied only after the structural reliability of the pipeline network is guaranteed. In addition, considering the correlation of the above factors as far as possible, a more accurate assessment result of the NGPN's reliability can be obtained.

V. CONCLUSIONS AND PROSPECTS

By now, some regulations have been formulated for the management of natural gas pipelines as well as the NGPN system's reliability evaluation, a variety of reliability evaluation methods have been proposed and applied to evaluate NGPN system's reliability. However, due to the complex topology of large-scale NGPN, the complexity and uncertainty in NGPN system's failure analysis, there are still various kinds of problems needing to be solved.

In the future, the reliability evaluation of NGPN system can be further studied in the following directions. (1) It is necessary to establish a unified evaluation approach and assessment criteria, so as to facilitate an accurate evaluation of system reliability; (2) When calculating the reliability of gas supply under given time and conditions, the reliability of upstream gas source can also be combined with the acceptability of downstream consumers; (3) To conduct a more comprehensive reliability assessment, it is necessary to take into account of the third-party damage and natural disasters on NGPN systems .

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