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Technical and economic evaluation of hydraulic reliability of urban high pressure gas loop network

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Abstract

Scientific analysis and providing a way to improve the reliability of high-pressure urban gas networks for sustainable and safe gas supply by suppliers is essential. A reasonable forecast for the achievable flow for each subscriber at the time of failure is the critical network hydraulic reliability in quantitative analysis and is not easy in loop networks. In this article, based on hydraulic indicators and the principles of engineering economics, the degree of reliability and availability of the city gas network has been analyzed. The proposed method relies on the data and findings of the hydraulic analysis and hydraulic regime of node flow in the network and the reliability in different situations with the utilization coefficient of the pressure drop, based on actual flow is analyzed, and provide a solution in determining the cost of the gas supplier company. The results show that the hydraulic reliability of the network has a high impact on the stability of the gas network and for improve of it, the gas companies have to pay attention to design and implementation costs as well as repair and operation costs in network service time.

Keywords: Network hydraulic reliability, utilization coefficient of the pressure drop, current value, structural reliability, network hydraulic regime

1- Introduction

The high-pressure city gas network is an essential part of the energy supply system, and its reliability is a critical factor in ensuring a stable and secure gas supply. The analysis of the reliability of gas pipeline network includes structural and hydraulic reliabilities (Jie Li, 2005). Using a loop design for a gas network is an important step in achieving structural network reliability. Kansal and Devi (2007) studied this subject. Hydraulic reliability aims to provide the required pressure and flow in all possible conditions for customers. Especially when a pipeline breaks down and consequently supplies the gas network in accordance with the needs of all domestic, industrial and commercial customers. (Gheisi & Naser, 2014) Currently, research on hydraulic reliability focuses primarily on the water supply network and to a lesser extent on the gas network (Zhuang, Lansey, & Kang, 2011). However, a loop gas network is a complex system that, if The failure of a pipeline still supplies a certain amount of gas and certainly, in addition to the uncertainty of the flow in the pipelines, obscures the issue of whether they are secret or parallel (Jun Li, Qin, Yan, Ma, & Yu, 2016).

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On the other hand, increasing the reliability of a network requires money and increasing design coefficients that make it difficult to decide on the degree of this reliability and make technical and financial analysis necessary.

2- Theory of hydraulic reliability and hydraulic specifications of the gas network

The city's high-pressure gas network includes a large number of pipelines, non-piping connections, and valves. As a network is often configured as a loop, a more reliable and stable gas supply is ensured. If any of the pipelines fail, it is necessary to disconnect and repair this component. In this case, the network must meet part or all of customers' needs, so the integrity of a network depends on its service capacity, and the theory of reliability can be used to assess ability. Customer node hydraulic reliability and network hydraulic reliability are two common indicators for measuring network service capacity (Abunada, Trifunović, Kennedy, & Babel, 2014).

$$\mathrm{R_j} = \frac{\mathrm{Q^{avl}}}{\mathrm{Q_j}} \tag{1}$$

$$\mathrm{R}_{net} = \frac{\sum_{\mathrm{n}} \mathrm{Q^{avl}}}{\sum \mathrm{Q_j}} \tag{2}$$

Here j is any customer nodes and $\mathrm{R_j}$ is the hydraulic reliability of the node. $\mathrm{Q^{avl}}$ is the actual amount of gas consumed in nm j in units of $\mathrm{N\frac{m^3}{h}}$. $\mathrm{Q_j}$ is the required amount of node j, and n is the number of network nodes. $\mathrm{R_{net}}$ is the hydraulic reliability of the network. In the usual case, when none of the pipelines are damaged, it is assumed that the network provides the rated current required by all customers. In this case, the pressure and required flow by all customers and the reliability of the node are provided, and the values of $\mathrm{R_j}$ and $\mathrm{R_{net}}$ are equal to one. In the event of a breakdown, each pipeline has its own breakdown rate and follows a lifetime curve known as the "bathtub" during service life (Majid, Mohsin, & Yusof, 2012). Suppose a pipeline breaks down due to corrosion, wear or collision with a third party, etc. In this case, the pipe is disconnected from the network for repair and in this case the service capacity is affected. As a result, not all nodes may be able to provide nominal current for customer nodes, and therefore the actual current of nodes is less than the nominal current. The complexity of the loop network also makes it more difficult to identify which node is affected. Therefore, in analyzing the hydraulic reliability of the network, it is necessary to determine the actual current of each node in any failure situation, which of course is not an easy task. In a city gas network, each node is in fact a pressure reducing station that is connected to a high pressure network and supplies gas to domestic, commercial or industrial customers, so each station can be considered as a consumer in Considered. The high pressure gas network was also considered as a system with node flow and not torque flow. In some nodes, the pressure affects the flow of the pressure reducing station. If the inlet pressure of the station is less, the regulator will have a performance problem and will not be able to supply enough gas to the design level, and therefore $\mathrm{R_j}$ and $\mathrm{R_{net}}$will be less than one (Jun Li et al., 2016).

Uncertainty about the flow direction is the distinguishing feature for distinguishing a tree network from a loop network. When each pipe breaks down, it needs to be disconnected from the network, and the amount of natural gas in some of the pipes changes. Also, by making changes in the direction of flow, ambiguity in the series or parallel relationships between pipelines remains and, consequently, increases the complexity of network computing. As the number of loops increases, the network's hydraulic reliability analysis increases, and the principle of balance between parallel pipelines becomes difficult. In addition, due to the relationship between node pressure and node current, it is more difficult to calculate the actual node current in a loop network than in a tree network. Given that for hydraulic analysis of the network, it is necessary to calculate the node flow. Because only concerning the node's current, the pressure of the unknown node can be extracted and vice versa. Jun Li et al., (2016) proposed several methods; however, due to their weaknesses and non-compliance with the experimental results, a new, more consistent approach with the findings and engineering experiences is required. In this method, with the help of the equilibrium equation of nodes, the actual flow and pressure of each node is determined and based on it, the hydraulic reliability of the network and nodes is calculated.

3- Hydraulic reliability of the network system

Network hydraulic reliability is related to the overall service capacity of the network to meet the needs of all consumers. It is a crucial issue for gas supply companies to consider. During network operation, the network design and pipeline parameters are difficult to modify with design-time methods. The main reason for the decrease in the hydraulic reliability of the network during breakdowns lies in the index of "the utilization coefficient of the pressure drop" The pressure drop in the network is due to the reduction of "designed pressure storage." In a high-pressure gas network, the "pressure drop utilization coefficient" can be expressed by equation (3) (Jun Li et al., 2016).

$$\varphi = \frac{\Delta P_s}{\Delta P_r} \tag{3}$$

φ is the coefficient of use in the pressure drop, ΔP_r is the pressure drop in the normal state in terms of Mpa, and ΔP_s is the available pressure drop in terms of Mpa2. The lower the index, the higher the "designed pressure reserve" of the network, which requires design modification, increased pipe diameter, etc. It requires a higher cost, and gas companies need to decide on a cost-effective price.

4- Example

Applying the proposed approach for a simple two-loop network demonstrates the capability of the method. The method is suitable for problem-solving and can also be used for more complex networks. Figure (1) shows a high-pressure gas network. Seven branches (1) to (7) are high-pressure pipelines. The pipeline branches are equipped with two valves at both ends to disconnect them from the leading network if required. Circles 1 to 5 indicate the consumer nodes; five pressure relief stations (strong-medium) supply gas to domestic, commercial, or industrial subscribers. Node 6 is the central gas supply station.

The directions in the grid indicate the flow of gas in the normal state. In the normal condition, the pressure of node six is kept constant at 4 MPa, and the current value of each node is 1000 Nm^3/h, and the minimum pressure in the network is 2.5 MPa.

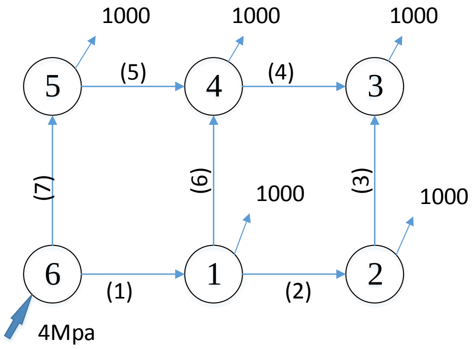

Fig. 1. High-pressure city gas loop network

Table (1) presents the results of breaking pipeline (2). Failure leads to a decrease in flow in node two and remains the same in other nodes. If the network pressure storage cannot compensate for the pressure drop, the pressure drop due to line failure (2) due to the mechanical property of the station reduces the flow of station number 2. Finally, both the hydraulic reliability of Consumer Node 2 and the hydraulic reliability of the network are reduced to less than one. The hydraulic reliability of the network using the proposed method is only 0.879, which is consistent with engineering results and experiences.

Table 1. Hydraulic reliability of the network in case of failure of line number (2)

Node number	①	②	③	④	⑤
Actual current of node Q^{avl} in terms of $N\frac{m^3}{h}$	1000	393	1000	1000	1000
Actual pressure of node P in terms of Mpa	3220	2507	2542	2951	2220
Hydraulic reliability of R_j	1.0	0.39	1.0	1.0	1.0
R_{net}network hydraulic reliability	**0.879**				

It is convenient to use this method to analyze the hydraulic reliability of the grid system while each pipeline is damaged. As shown in figure (2), different pipeline failures have different effects on network hydraulic reliability. With pipe failure (1), the greatest impact is made on network reliability and reaches less than 0.496. Pipeline (3) shows different behavior and network reliability in case of failure of this pipeline decreases to 0.998. The following results are extracted. 1. A failure in a node may lead to a reduction in current throughout the network, but the degree of reduction varies. Lines (1) and (7) may cause further reductions because they are directly connected to node 6, which is the main gas supply station. 2- The amount of gas flow of the lines in normal conditions has an effect on the overall flow of the network at the time of failure of that line and has the greatest impact on the hydraulic reliability of the network. However, the flow reduction due to the failure of each pipeline is not equal to the amount of current flowing through it under normal conditions. This result provides a simple qualitative tool for qualitative analysis of network hydraulic reliability.

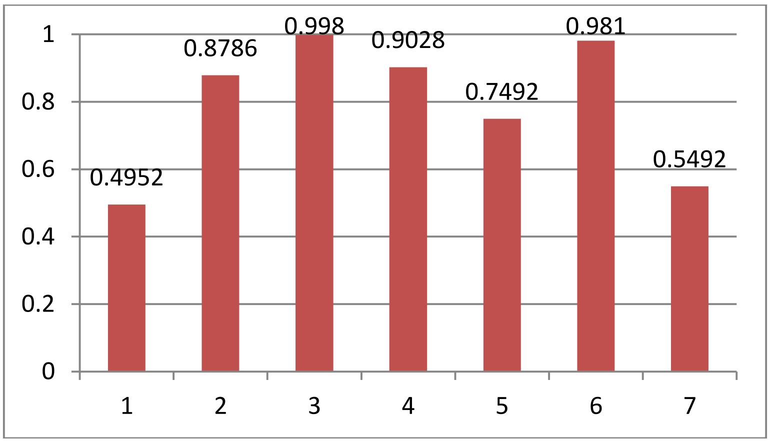

Fig.2. Hydraulic reliability of the network in the event of failure of each of the pipelines 1-7

Now, using equation (3) and the data of the above example, the "pressure drop utilization coefficient" is calculated:

$$\boldsymbol{\varphi} = \frac{\Delta \boldsymbol{P_s}}{\Delta \boldsymbol{P_r}} = \frac{\mathbf{4^2 - 2.543^2}}{\mathbf{4^2 - 2.5^2}} = \mathbf{97.8}\%$$

The utilization coefficient indicates that the available pressure drop is used normally and can help reduce the level of investment in the network. However, as with some lines, the total current resistance increases and the network is unable to pass the amount of gas required for the consumer nodes. Providing more real current resistance will cause more available pressure drop. As in the previous example, the hydraulic reliability of the network reached 0.496 with line failure (1). Assume that the pressure drop utilization coefficient in the previous example is 0.5 in the network design. So network reliability when line (1) breaks down is shown in figure (3). Compared to figure (2), the hydraulic reliability of the network has clearly improved from 0.496 to 0.655. Especially with the failure of lines 2, 3 and 4, the hydraulic reliability of the network remains the same.

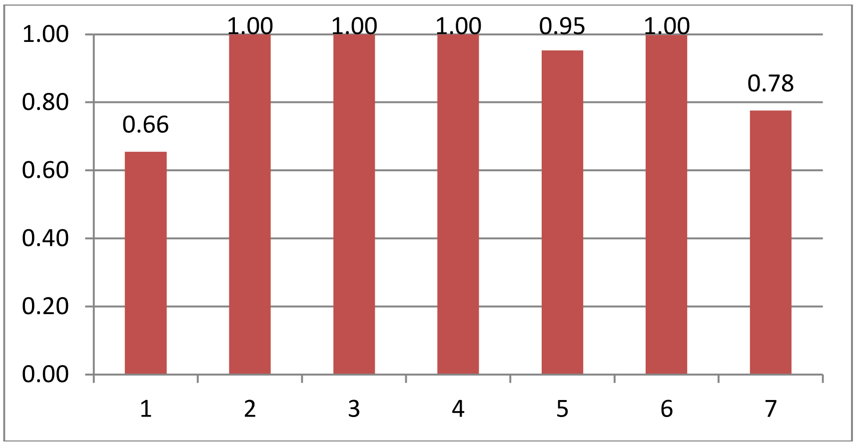

Fig 3. Hydraulic reliability of the network with a coefficient of "use 0.5" in case of failure of lines 1-7

In general, to improve the hydraulic reliability of the network to meet the needs of consumers in different conditions, the pressure drop utilization coefficient should be small enough to increase the pressure storage, which is expanded by adjusting the network design. Pipe diameter and other measures can be taken. The improved reliability is comparable to the network's reliability in the first case. It is essential to consider the level of "utilization coefficient" due to changes in pipeline design and network design. It has a lot. In the next section, the technical and economic evaluations of the two plans have been calculated and compared.

5- Technical-financial analysis to select the appropriate “utilization coefficient of the pressure drop" in the design of the gas network

As mentioned in the previous sections, any change in network design to improve and increase network capacity requires a higher cost, which will undoubtedly make it challenging to decide on the price. It means that the gas supplier company selects the appropriate the utilization coefficient of the pressure drop, according to the "cost-benefit" principle. In this section, an attempt has been made to examine the cost due to the improved capacity level in a line failure (1). To compare the two cases, the average annual failure rate of the lines should be calculated. According to the reference results (Jun Li, Yan, & Yu, 2018), the failure rate (Km.a) is 0.000214, and if the total length of the lines is 200 Kilometers to be considered. The failure rate during the network and per year is 0.0428. The costs of pressure drop and gas cut-off are varied and include direct and indirect costs. Direct prices include the cost of repairing a damaged pipeline, the cost of restarting, and indirect costs include a wide range of expenses that are difficult to calculate. The company must consider the cost of lost sales, cost of penalties for non-supply of gas that the consumer may have considered in the sales contract, cost of company credit and environmental consequences, safety costs, etc. Another influential factor is the duration of the pipeline repair. It is the time required from failure detection to returning the pipeline to its regular operation, which includes failure detection time, failure location, Reworking and repairing, restarting the channel, etc. This time depends on the level of management of the company, maintenance equipment, and maintenance capability in each company. Therefore, the repair rate of all pipelines in a particular company is the same for different lines. Because other gas companies have different levels of management, repair equipment, and repair capabilities, the repair rate of each company's pipeline is obtained according to the average failure rate of that company. In general, the pipeline repair rate is a specific ratio of the average failure rate of that company and is in the form of the following function (Jun Li et al., 2018):

$$\mu = (10\sim1000)\bar{\lambda} \tag{4}$$

μ In the above equation, the pipeline repair rate is a company. Depending on the management level, the repair technology, and the repair capacity in the pipeline repair. $\bar{\lambda}$ is the average failure rate of network pipelines. In this example, this index is considered 1 day. If the costs are as follows, we solve the problem: Direct cost: Repair each breakdown in one day (including human resources, equipment, and machinery costs, gas wastage and restart ($ 10,000 per repair breakdown) Indirect cost: Indirect cost is usually considered to be two to three times the cost, although in some cases prices are considered more or less (here lost per cubic meter of flow It is estimated at $ 40 due to network failure. Breakdown cost in a year includes the sum of direct and indirect costs that are multiplied by the breakdown rate.

$$\bar{\lambda} * (D + I * RF) \tag{5}$$

Here $\bar{\lambda}$ is pipes averge failure rate, and D is direct cost of pipeline repair. I is indirect cost due to reduced flow and RF is reduced flow rate (cubic meters). By increasing the "utilization factor," only the hydraulic reliability of the network decreases. But the failure rate due to the structural reliability of the network does not change (Jun Li et al., 2018). On the other hand, the flow rate Missing is different in two scenarios and with a usage factor of one, on average, so the total annual cost of repairs in one year in two scenarios is as follows:

Table 4. Calculation of the average annual cost due to failure in networks with different utilization coefficients

Coefficient of use	Average lost current (cubic meters)	The average network failure rate	Direct repair cost (dollars)	Indirect cost per cubic meter of lost current (dollars)	The total annual cost of failure
1	1032.85	0.0428	10000	150	7058.9
0.5	425	0.0428	10000	150	3156.5

If we consider the service life to be 50 years, and to simplify the problem, we think the average rate of network failure, which does not change much during this period (Jun Li et al., 2018), to be constant. Then we can calculate the cost difference between the two scenarios from the current value. To calculate the flow value, we consider the annual interest rate to be 10%. Then the difference in the cost of repairs according to the current value is equal to $ 71,242, which means that if the reduction of the "utilization rate" is less than this amount, it is a good option for the company.

6- Sensitivity analysis of decision parameters:

Increase in indirect costs: If the cost doubles to $ 300 per cubic meter of lost current, then the present value of the difference between the costs of repairing faults in two networks with different utilization rates will be $ 142,458. It shows that the increase in these costs, mostly related to customers, directly affects the total cost of repairs. Whereas if the direct cost of repairs changes from $ 10,000 to $ 20,000, the current average value of the difference in repair costs will not change significantly. Also, consider the average failure rate that has reached about 0.08 in recent years (Jun Li et al., 2018). The current value surpasses about $ 133,163, almost twice the original value, indicating that this parameter also significantly impacts decision-making. The assumption that the breakdown rate is constant in different years is incorrect. According to the results, another interesting point can be extracted: if the indirect costs of repairs resulting from company credit, penalties for non-service, environmental costs, and customer satisfaction are more tangible for the company. , The company will be more willing to spend to reduce the utilization rate in pressure drop and consequently increase the hydraulic capacity of the network, which means that the company is more inclined to maintain gas stability.

7- Results

The hydraulic reliability of the network here is related to the stable supply of gas and the regular operation by suppliers. A quantitative analysis of the hydraulic reliability of the network in different conditions provides essential information for design engineers, emergency plan preparation, line updates, and maintenance plans and repairs. Considering that the calculation of the actual flow rate of the node is a critical factor in the analysis of hydraulic reliability, a method is used to determine the actual flow rate in the high-pressure looped gas network and the hydraulic reliability of the loop gas network. In different cases, the failure was calculated, and its efficiency was confirmed in the example. Also, due to the importance of reliability and based on the index of "coefficient of utilization in pressure drop," the technical and economic evaluation of the network was reviewed, and a tool was used to decide on the amount of this key index.

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