A Method of Optimal Malfunction Management in Urban Natural Gas Transmission and Distribution Systems

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Abstract. Given the increasing number of urban natural gas transmission and distribution systems, it is particularly crucial to optimize the management of natural gas operations, especially when equipment failure or pipeline leakage occurs in the supply system. To meet the needs of customers for natural gas, in this paper, we considered two cases of pipeline rupture leakage and pressure regulation station failure for different supply areas. We combined natural gas supply pipelines, pressure regulating stations and a gasholder station to establish a failure optimization management model and used genetic algorithms and one-dimensional fluid dynamics models for optimization management and proposed the following two solutions: 1. Complete operation strategy: modify both the pressure of the pressure regulating station and the air supply volume of the gasholder station; 2. Partial operation strategy: modify the pressure of the pressure regulating station only, and keep the supply volume of the gasholder station constant. Finally, our model is applied to an urban natural gas transmission and distribution system. Based on the actual results, failure optimization management is proposed according to the location and the type of failure and constructive options are suggested for the operation of natural gas networks.

1. Introduction
With the emergence of China's energy transformation, demand for natural gas, the cleanest fossil fuel, is increasing. After production, purification, transmission, storage and distribution of the gas, the gas then reaches the users. If the main pipeline is broken or there is leakage or damage to a pressure regulating station during the gas transmission process, the gas supply will be limited. It is necessary to carry out scientific research and reasonable planning for these two parts of the transmission and distribution system to ensure that customer demand for natural gas can be met as completely as possible in the event of a failure. Finally, we should encourage natural gas consumption by residents and promote the process of energy transformation.

During the optimization of a natural gas pipeline network, a common method is to optimize the gas regulating system (Li et al. 2015) and to build the gas supply network into a star-shaped manifold network. Establishing mixed integer non-linear optimization model to analyze steady-state natural gas flow in multi-period, applying it to Turkey natural gas network construction and providing insights into natural gas operation (Üster and Dilaveroğlu 2014). Adopting a two-stage stochastic linear programming approach research the use of gas for power production, increase the stochasticity of practical problems, and evaluate the actual situation (Bruno et al. 2017). Combining Bayesian network, damage model and sensitivity analysis, a regression analysis model is established, and a risk-based maintenance plan optimization method is proposed to analyze the failure. (BahooToroddy et al. 2019)
With the maximum flow rate as the objective function, a genetic algorithm is used to establish a natural gas pipeline network optimization model and a heating pipe network model to ensure maximum pipe network traffic under normal and abnormal conditions. (Zhang and Liu 2017; Guelpa and Verda 2018). Most of the existing researches focus on pipe network construction optimization, prevention of pipeline leakage, pipeline leak detection and pipeline leakage repair. This paper is based on the failure of natural gas supply, in order to ensure the normal supply of gas to the end users, and to ensure the effectiveness of supply and reduction of gas leak, the fault is divided into pipeline leakage and problems with pressure regulating stations, and two optimization methods are proposed: a complete operation strategy and a partial operation strategy. Based on a model of a town-level natural gas transmission and distribution system, genetic algorithms and one-dimensional hydrodynamic models are used to optimize management of faults.

2. Malfunction and operation approaches

An urban natural gas transmission and distribution system refers to a system consisting of all facilities from the gate station to the customer. This system is generally composed of a gate station, a natural gas pipeline, a gas storage facility, a pressure regulating facility, a management facility, and a monitoring system. There are two kinds of failures in an urban natural gas transmission and distribution system (Fig. 1): the first type of failure is pipeline rupture (including the case where the degree of pipeline leakage reaches a nonnegligible level). There are two causes of pipeline rupture: 1. The rupture occurs in the loop section of the natural gas pipeline. The solution is to close the nearest valve upstream and downstream from the ruptured pipeline. This scheme isolates the ruptured pipeline while all other parts of the natural gas transmission and distribution system operate normally. The result is a decrease in supplied loops, leading to an increase in supplied resistance. 2. The rupture occurs in the one-way loop-free section; the solution is to continue to supply gas under reduced pressure. The second type of fault is the failure of a pressure regulating station. For the current transportation situation of natural gas, some of the gas supply equipment continues to provide power in the event of a failure of the pressure regulating station. As a result, the natural gas supply network remains unchanged and the total gas supply power is reduced.

There are two kinds of fault handling strategies for the fault optimization management of urban natural gas transmission and distribution systems: the first strategy is the complete operation strategy, in which the supplied pressure of the surge station \( T \) and the supplied ratio of the gas storage station \( x \) are constantly modified to obtain the minimum objective function; the second is the partial operation strategy, in which the fault optimization process can only modify the supplied pressure of the surge station \( T \) to maintain the supply of the gas storage station. The supplied ratio of the gas storage station \( x \) is constant, and the minimum of the objective function is obtained.

3. Independent variables and Limitations

Vector \( T \) represents the pressure provided by the pressure regulating station, vector \( x \) represents the fraction of natural gas flow supply at the gas storage station, and \( P \) represents the pipeline pressure in a natural gas transmission and distribution system.

\[
T = [T_1, T_2, \ldots, T_{M-1}, T_M] \quad (1)
\]

\[
x = [x_1, x_2, \ldots, x_{N-1}, x_N], \quad \sum_{k=1}^{N} x_k = 1 \quad (2)
\]

\[
P_{\min} < P < P_{\max} \quad (3)
\]

The pressure regulating station regulates and stabilizes the pipeline pressure in an urban natural gas transmission and distribution system where the number of pressure regulating stations is \( M \); \( T_j \) represents the ratio of the supplied pressure to the maximum supply pressure in the pressure regulating station at a given time, ranging from 0 (the pressure regulating station does not work) to 1 (the pressure regulating station provides its maximum pressure).

The gas storage station provides storage of natural gas. Under normal circumstances, it is used for a vehicle refueling business or as the decentralized point for user gas. Under a fault condition, it
becomes the backup gas source and guarantees the natural gas supply for at least three days. The number of gas storage stations is \( N \).

The maximum and minimum pressures of the natural gas pipeline are expressed by \( P_{\text{max}} \) and \( P_{\text{min}} \), respectively. The maximum pipeline pressure in the is the maximum allowed according to the design of the pipeline. The upper limit of the pipeline pressure allowed is 2.5MPa. The lower limit of the pressure cannot be determined only by the parameters of the pipeline but is also modified according to the actual situation and should take into account the problem of power loss in the natural gas supply process. To ensure that the supplied pressure of the user gas supply pipeline is 3KPa, the lower limit of pipeline pressure in an urban natural gas transmission and distribution system is 0.4MPa.

4. One-dimensional hydrodynamic model of pipeline pressure

It is assumed that the natural gas pipeline is a branch between two connected nodes, and a network topology map is constructed. The model applies the mass conservation law to all nodes in the natural gas transmission and distribution system, and the momentum conservation law is applied to all branches in the natural gas transmission and distribution system. The incidence matrix \( A \), is used to describe the relationship between a node and a branch. When \( A_{ij} \) is 1, it indicates that the branch enters the node; when \( A_{ij} \) is -1, it indicates that the branch exits the node; and, in other cases, \( A_{ij} \) is 0.

The velocity of fluid dynamic disturbance in the natural gas pipeline is much higher than that of the fluid, so the influence of the indefinite term on the pressure is not considered and the density remains constant, so the operating speed of the natural gas in the pipeline is unchanged. A natural gas flow balance representation of all nodes is shown in Eq. (4).

\[
\sum_i m_{\text{in}} - \sum_i m_{\text{out}} = \sum_i m_{\text{ext}} \tag{4}
\]

When a fault occurs, a gas storage station becomes a backup gas source, and it is used to increase the supplied volume of natural gas. The pressure regulating station increases the supplied pressure accordingly. The pressure rises caused by the pressure regulating station in the natural gas transmission and distribution system is expressed as Eq. (5):

\[
\Delta T = T_{\text{end}} - T_{\text{init}} = x \Delta T_{\text{max}} \tag{5}
\]

where \( T_{\text{end}} \) is the pressure value in the pipeline that is pressurized by the pressure regulating station after the fault occurs, \( T_{\text{init}} \) is the pressure value of the pressure regulating station under normal conditions, and \( \Delta T_{\text{max}} \) is the maximum pressure that can be added by the pressure regulating station.

The SIMPLE (semi-implicit method for pressure linked equation) algorithm is used to solve the variable set \([P_j, m_j]\). This SIMPLE algorithm is a guess and correction method: the pressure vector is assumed in the first iteration, and then the pressure vector and the flow vector are modified in successive iterations. The SIMPLE algorithm can be effectively applied to multiloop supply networks and multiquantity pressure regulating station systems. Based on the characteristics of the SIMPLE algorithm, the fluid flow is comprehensively analyzed without solving the dynamic equation. First assume that \( P_j = P_j^j \) to get the initial \( m_j^j \), the solution process is shown in Eq. (6):

\[
m_j^j = Y^j \cdot A^j \cdot P_j^j + Y^j \cdot \Delta T \tag{6}
\]

We use the genetic algorithm to solve the objective function. The objective function is shown in Eq. (7):

\[
\max(G_s) = \sum m_{\text{ext}} = -A \cdot m_j \tag{7}
\]

where \( G_s \) is the maximum supply of natural gas in the event of a fault and is equal to the sum of natural gas flows in all nodes in the urban natural gas transmission and distribution system.

5. Optimization solution

As shown in Eq., there is a nonlinear relationship between natural gas flow and pressure. The various items \( Y \) are related to natural gas flow. At the same time, the urban natural gas transmission and distribution system needs to connect new users or to change the supply plan of natural gas. The factors leading to the optimization problem are nonlinear, and we cannot use linear programming or convex programming. A genetic algorithm is able to find the optimal solution in the local minimum and is
used to solve the problem. Based on the principle of natural selection, the genetic algorithm simulates the optimization problem as the process of biological evolution and generates new populations through genetics, natural selection, crossover, and mutation operations. The notion of survival of the fittest influences the population to evolve to an optimal result. The mutation rate of the genetic algorithm decreases with the number of iterations. The variation distribution of the algorithm is a Gaussian distribution. To improve the performance of the algorithm, the population cross ratio is 0.8 (excluding the elite ratio in the group), and the population size is 40 to 60 generations to keep computational costs at acceptable levels. The algorithm calculates the cost to be within an acceptable range. The main steps for solution of the problem are:

Step 1: The genetic algorithm determines the total amount of natural gas required by end users for the condition of zero faults, and the demand for natural gas is different for different time periods. Thus, the maximum demand for natural gas needs to be determined. The temperature has a significant impact on the demand for natural gas, but the relationship between temperature and gas consumption is not linear because gas from the natural gas industry is supplied throughout the year and the natural gas is supplied using central heating for half of the year. In general, the demand for natural gas shows an upward trend as temperature decreases. The increase in natural gas flow in the pipeline leads to an increase in pipeline pressure, and the optimization of faults becomes more complicated. The temperature factor is significant for determining the maximum demand for natural gas.

Step 2: Using the genetic algorithm to find a set of variables \([P, m]\) that meet the constraint condition, meaning that the pressure in the pipeline still satisfies formula (3) after the pressure regulating station changes the supply pressure. The supplied pressure of a supply station and the share of a gas storage station are determined by the one-dimensional fluid dynamic model and the SIMPLE algorithm. If this step finds a set of variables \([P, m]\) that meet the constraints, we proceed to step 4. Otherwise, we proceed to step 3.

Step 3: If the set of variables \([P, m]\) that meet the constraint is not found, the total amount of natural gas supply is reduced by the iterative method and returned to step 2. The total amount of gas supply is continuously iterated by the logarithm \(y\). The mathematical expression is as shown in Eq. (8):

\[
G_i = G_{\text{init}}(1 - y^i) \quad (8)
\]

where \(G_{\text{init}}\) is the initial value of the end user natural gas demand, \(y\) is an iterative increase of the natural gas, \(i\) is the number of iterations, and \(G_i\) is the total gas supply after the iteration.

Step 4: If a set of variables \([P, m]\) that meet the constraint is found, the algorithm terminates. The total amount of natural gas \(G_{\text{end}}\) is the optimal solution of the objective function at this time, meaning that \(G_{\text{end}}\) is the maximum natural gas supply when the urban natural gas transmission and distribution system fails.

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