

Application of neural network in heating network leakage fault diagnosis

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Abstract: In order to investigate the leak detection strategy of a heating network, a space-based simulation mathematical model for the heating network under leakage conditions is built by graph theory. The pressure changes of all the nodes in the heating network are obtained from node leak and pipe leak conditions. Then, a leakage diagnosis system based on the back propagation (BP) neural network is established. This diagnosis system can predict the leakage pipe by collecting the pressure change data of the monitoring points, which can preliminarily estimate the leak location. The usefulness of this system is proved by an example. The experimental results show that the forecast accuracy by this diagnosis system can reach 100%.

Key words: heating network; fault; diagnosis; artificial neural network

With the rapid growth of centralized heating systems, the application of heating networks becomes more and more widespread. Because of the effects of various factors, such as materials of pipes and components, laying methods, environment, construction and management, the failures of heating networks in different areas occur. Water leakage is the most common fault. Water in the heating system is softened or heated up, so the leakage may lead to a waste of energy, a waste of water resources and heavy economic loss^[1]. This paper aims to find the leaking position as soon as possible and to improve the reliability of the heating network, and then to increase the economic and social benefit of heating companies.

Previous researches show that the water recharge rates in well-managed heating networks are less than 0.5%. For other heating networks, the water recharge rates are 2% to 3%, and in a special case, the rate is even over 5%^[2]. And the rate becomes greater in failure conditions. In view of leakage, many heating companies employ many safeguards and technologies to be aware of this situation, and some achievements have been made. The measurements usually adopted are as follows. First, special groups are organized to patrol along the pipeline, and a big leakage can be found according to the ground moisture. Secondly, the return water temperature is observed. If the temperature is too low, a leakage may occur. Thirdly, the leakage apparatus is located in the inspection well or on the pipeline, and then the leakage can be diagnosed by the professionals. These measurements are popular in China at present. However, they are also easily affect-

ed by human and external factors, and the leakage rate cannot be reduced to a good level.

Herein, a method of leakage fault diagnosis based on artificial neural network technology is investigated by monitoring the pressure changes of the monitoring points in real time. And it is verified by an example.

1 Fault Diagnosis Method for Heating Network

The application of the artificial neural network technology in leakage fault diagnosis for water-supply networks and gas networks increases gradually^[3-4], but it does not exist in heating networks. Compared with water-supply networks and gas networks, heating networks are enclosed systems under normal conditions and have stable hydraulic characteristics in a certain period. Therefore, using the artificial neural network technology to diagnose the leakage faults in heating networks is specific and effective.

For a given heating network, any failure of a pipeline or a node can affect the water pressure of other nodes. Different levels of faults result in different effects. Besides, a same failure has different effects on the node pressure at different positions. Li^[5] simulated the leakage conditions for various types of heating networks and summarized the variations of the node pressure and the pipeline flow. When a pipe and all the components in this pipe are considered as a unit, the heating network can be seen as a system composed of pipe units. As for the fault diagnosis of a heating network system, the leakage pipe should be first identified. The accuracy of the identification of the leakage pipe directly affects the fault diagnosis. Herein, a leakage detection and location model based on the BP neural network is established by taking the water pressure as the parameter.

The BP neural network is a hierarchical class-type forward mapping network with a multilayer structure. It has a strong nonlinear mapping ability, an intelligent adaptive learning ability and a good fault tolerance ability. The BP neural network consists of an input layer, an output layer and one or more hidden layers. Neurons in the same layer are not related to each other, while the neurons in adjacent layers are connected by the weight and the threshold. The BP algorithm establishes the mapping relationship between the input and output vectors by repeatedly training one group of training samples and regulating the weight and the threshold to minimize the mean-square deviation between the practical and the expected output values.

The method of using the BP neural network to locate the leak fault of the heating network is used to learn the relationship between the fault positions and the pressure changes of the monitoring points under different fault conditions. It means that once a leakage of the heating network occurs, it can be diagnosed by inputting the pressure changes of the

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monitoring points. The input layer of the BP network model in this paper is the pressure changes of the monitoring points, and the number of the neurons equal to the number of the monitoring points. In order to correct the influence of different input neurons on the learning process and prevent the saturation of the response function, the input data are normalized in a range of from 0.1 to 0.9. The output layer uses the Sigmoid response function, and its neurons correspond to the nodes of the heating network. We assume that the values of the neurons at the two ends of the leakage pipeline are 1 while the others are 0. One or two hidden layers are chosen based on the actual situation, and in the normal case one hidden layer can meet the learning requirements.

The use of the artificial neural network technology in establishing the fault diagnosis model of the heating network is valid only when a large number of sample data is collected. For a given network, the data can be the real monitoring data, the theoretical simulation data or a combination of these two. For the fault problem, it is very difficult to collect the real monitoring data which is distributed uniformly and ranged broadly. As an exploratory research, this paper only uses the theoretical simulation data.

2 Mathematical Model of Leakage Condition

In general, it is only necessary to calculate the hydraulic status for a supply network or a return network. The supply network and the return network are considered to be symmetric in the design situation. A mathematical model based on a plane network can be applied to the situations when the flows of the heat sources and the heat users are given. However, this method still has some limitations.

The leakage of the heating network can occur at any point in the supply network or the return network. When a leakage occurs, although the topologies of the supply network and the return network are still symmetric, the parameters of the heating network become asymmetric because of different discharges. When the leakage occurs in the pipeline of the supply network or the return network, which means that the leakage pipe is divided into two sections at the leakage point, the topology of the supply network or the return network is no longer symmetric after reconstruction. In addition, the flows of the supply pipes, the return pipes, the heat sources and the heat users are changed and the flows of the heat sources and the heat users are unknown after leakage. It is impossible to simulate and analyze the hydraulic cases by using the traditional methods based on the plane network. A new method is necessary to calculate the hydraulic status.

2.1 Model assumption

According to the design code of a district heating network, "the rate of the make-up water should be less than 1% of the circulation pump capacity and the flow of the emergency pump is four times as much as the make-up water rate under normal conditions"^[6]. Therefore, the leakage rate of the network in this paper is 1% to 5% of the total circulation pump capacity. Furthermore, assume that the emergency pump can make up water in time and the rate of the make-up water is always equal to that of the leakage. The pressure of the pressurization point is assumed to be a constant.

2.2 Mathematical model

The node numbers of the supply network and the return network are n_1 and n_2 , respectively. The pipe numbers of the supply network and the return network are b_1 and b_2 , respectively. The numbers of the heat sources and the heat users are p and q , respectively. Thus, the number of the basic circuits of the supply network is $f_1 = b_1 - n_1 + 1$ and that of the return network is $f_2 = b_2 - n_2 + 1$. The node number of the spatial networks is $N = n_1 + n_2$, and the number of the pipes is $B = b_1 + b_2 + p + q$.

The node continuity equation and the circuit energy conservation equation are still satisfied when the heating network is under leakage conditions. The mathematical equations are given by^[7-9]

$$\mathbf{A}\mathbf{G} = \mathbf{Q} \quad (1)$$

$$\mathbf{B}_f \Delta \mathbf{H} = \mathbf{0} \quad (2)$$

$$\Delta \mathbf{H} = \mathbf{S} |\mathbf{G}| \mathbf{G} - \mathbf{D} \quad (3)$$

where $\mathbf{A} = (a_{ij})_{(N-1) \times B}$ is the fundamental interconnection matrix of the spatial heating network; $\mathbf{B}_f = (b_{ij})_{(B-N+1) \times B}$ is the fundamental circuit matrix of the spatial heating network; $\mathbf{G} = \{g_1, g_2, \dots, g_B\}^T$ is the column vector of the pipe flows; $\mathbf{Q} = \{q_1, q_2, \dots, q_{N-1}\}^T$ is the column vector of the node discharges; $\Delta \mathbf{H} = \{\Delta h_1, \Delta h_2, \dots, \Delta h_B\}^T$ is the column vector of the pipe pressure drops; $\mathbf{S} = \text{diag}(s_1, s_2, \dots, s_B)$ is the diagonal matrix of the pipe resistance coefficients, which can be obtained by hydraulic calculation or parameter identification; $|\mathbf{G}| = \text{diag}(|g_1|, |g_2|, \dots, |g_B|)$ is the diagonal matrix of the absolute values of the pipe flows; $\mathbf{D} = \{dh_1, dh_2, \dots, dh_B\}^T$ is the column vector of the delivery lifts of the pumps, and if there is no pump in the i -th pipe, then $dh_i = 0$.

Unlike the normal hydraulic condition, the column vector of the node discharge \mathbf{Q} in Eq. (1) is not equal to $\mathbf{0}$ because of the leakage. There are two non-zero elements in this vector, which correspond to the leakage point and the make-up water point, respectively. Suppose that the discharge value of the leakage point is q . Then, the discharge value of the make-up water pressurization point is $-q$. From Eqs. (1) to (3), the flow and the pressure of a certain heating network can be simulated.

3 Example

There are 10 pipes in the heating network, as shown in Fig. 1. The lengths of all pipes are 500 m; the design flows of all heat-users are 100 m³/h; the design head losses of the source and all users are 150 kPa. A circulation pump (350s75A) is chosen, whose design flow is 1 000 m³/h and the design lift is 686.6 kPa.

Nodes 1, 6, 11 are chosen as the monitoring points. Note that these points are not optimized but randomly selected.

The data of the model are obtained from the hydraulic simulation under leakage conditions. First, the pressures of all the nodes in the heating network can be obtained from the normal hydraulic simulation. Then, the leakage conditions at different points in each pipeline are simulated. In this paper, the points which are located at a distance of 100,

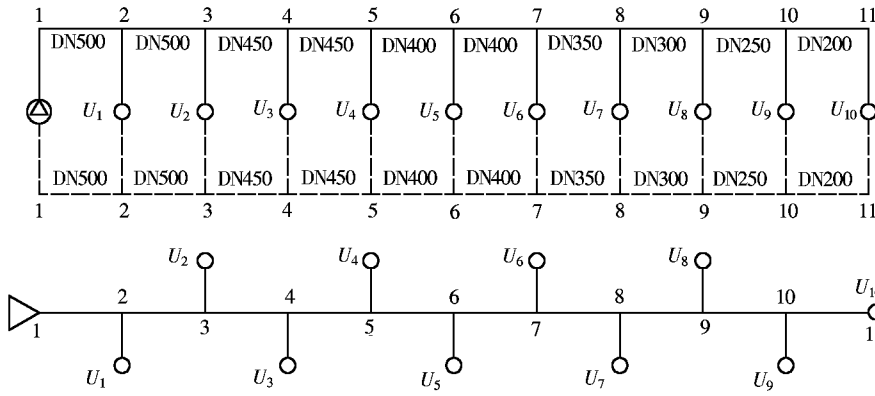


Fig. 1 Sketch map of heating network

200, 300, 400 m from the starting point of the pipeline are chosen as the leakage points, and the leakage volumes are 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, 3.5%, 4%, 4.5%, 5% of the total circulating volume, respectively, so 800 groups of data are obtained for twenty pipes. The detail data are not presented due to limited space. 10% of these data are randomly selected as testing data, and the remaining 90% are used as training data.

The topology of the BP neural network is as follows. The number of the input layer nodes is 6, which means that the pressures of 6 monitoring points change. The number of the output layer nodes is 22, corresponding to all the nodes in the heating network. A hidden layer is used and its node number is 16. The mean-square deviation between the practical and the expected output values is 0.001.

Because the training process allows for the existence of errors, fully accurate results cannot be achieved. The output data should be handled as follows. When the output value is not less than 0.5, the node is considered as the endpoint of the leakage pipeline. On the contrary, the pipeline has no leakage. Then, the predicted result is quantified. When the predicted result is accurate, the quantized value is 1; when the predicted result is wrong, the quantized value is 0; when two or more pipelines are predicted simultaneously, the quantized value is 0.5.

The training is completed after 75 times of learning, and the mean-square deviation is 9.63×10^{-4} . The accuracy of the quantized value is 100%. The output values in a range from 0.5 to 0.7 account for 1.25% of all the output ones; the output values in a range from 0.7 to 0.9 account for 6.25%; the output values in a range from 0.9 to 1 account for 92.5%. The prediction results are satisfactory.

4 Conclusion

In this paper, a model for the leakage detection and location of a heating network based on the BP neural network is established, which can approximately locate the leakage pipeline according to the pressure changes of the monitoring points. The prediction results of the model are satisfactory.

The reliability of the fault diagnosis system can be greatly improved with the increase in the number of the monitoring

points. For a given network, we can make full use of the existing monitoring points. The ability of coping with sudden accidents for city heating systems can be greatly improved by the optimal layout and adjustment of these monitoring points.

Under the normal condition, the heating network is a closed system which has steady hydraulic characteristics in a certain period. Therefore, it is easier to diagnose the leakage faults of the heating network than those of other city pipe networks. For the leakage fault diagnosis of the heating network, the method introduced in this paper is significant in theory and practice.

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神经网络在供热管网泄漏故障诊断中的应用

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摘要: 为了研究供热管网泄漏检测策略, 利用图论理论构建了一个基于空间管网的泄漏工况水力计算数学模型, 得出节点泄漏和管段泄漏工况下管网各点的压力变化情况. 然后, 采用人工神经网络方法建立了一个基于 BP 神经网络的供热管网泄漏诊断系统. 该诊断系统可根据管网中压力监测点的压力变化定位泄漏管段, 实现对泄漏点位置的初步估计. 最后, 通过实例验证了该方法的有效性. 实验结果表明, 这种诊断系统对泄漏管段的预测准确率达到 100%.

关键词: 供热管网; 故障; 诊断; 人工神经网络

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