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Fault Diagnosis Approach for Pneumatic Control Valves Based on Modified Expert System

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***Abstract*— This paper studies the fault diagnosis method of pneumatic control valve. Firstly, the faults characteristics of pneumatic control valves are analyzed according to the operating principle and status of pneumatic control valves; secondly, the expert experience of the fault diagnosis of pneumatic control valves is summarized, which is verified according to the operating mechanism; thirdly, a fault diagnosis approach for pneumatic control valves based on modified expert system is proposed, by combining particle swarm optimization (PSO) algorithm with expert rules. Finally, the availability and advantages of the proposed approach is verified by the designed valve experimental system platform. The results show that compared with the basic expert system-based method, the modified method improves the accuracy and reduces the false negative rate effectively.**

Keywords-pneumatic control velve; fault diagnosis; expert system; particle swarm optimization algorithm

I. INTRODUCTION

Pneumatic control valves are one of the important actuators of industrial process control systems, which are widely used in various industrial fields. However, various faults of pneumatic control valves are common because of the high-temperature, high-pressure and humid working environments, which affects the industrial production and even unexpected shutdowns and casualties. At present, periodic inspection is usually used to overhaul the pneumatic control valves in industrial sites. But there is a serious problem of 'over-maintenance' in this method, which usually causes a large amount of equipment damaged [1]. Therefore, fault diagnosis methods without disassembling valves have attracted wide attention.

The existing fault diagnosis approaches for pneumatic control valves can be sorted into three classes: analytical model-based methods, data-based methods, and expert knowledge-based methods [2]. Analytical model-based methods make full use of the mechanism of the pneumatic control valve. But the methods require accurate mechanism model, and they are hard to be used for fault diagnosis of pneumatic control valves in practice. The data-based method aims to mining the running status information of process signals for fault diagnosis. But that method has many drawbacks in the learning process, such as slow learning speed, over-fitting and difficulty to explain. Expert knowledge-based methods rely on the accumulated experience and knowledge of experts, such as expert system [3-5].

Expert knowledge-based methods are widely used in industrial sites because they do not require the accurate mathematical model and are easy to implement and understand, which make full use of experts' rich knowledge and experience [5]. But many parameters in expert knowledge-based methods are usually determined by the experience of the experts and hardly to adjust, which causes the problem of missed diagnosis. The acquisition of expert experience is a long process, which is essentially the process of mining process data manually because process data implies relevant information of various working conditions [6]. Many existing data mining methods are the potential alternatives to the manual mining process. It is a feasible method by combining the particle swarm optimization [7] algorithm with the traditional expert system to optimize the expert system parameters.

Aiming at the problems of a strong subjective with selecting parameters and difficulty to adjust parameters, a fault diagnosis approach for pneumatic control valves based on modified expert system is proposed in this paper. Firstly, faults of pneumatic control valves are analyzed to lay the foundation for fault diagnosis; Then, an expert system for fault diagnosis of pneumatic control valves is established, which is combined with particle swarm optimization algorithm to determine parameters. Finally, the performance of the fault diagnosis method based on modified expert system is verified by the designed experimental system.

II. THE OPERATING PRINCIPLE AND FAULT ANALYSIS OF PNEUMATIC CONTROL VALVES

A. The Operating Principle of Pneumatic Control Valves

The pneumatic control valve is an assembly of devices consisting of control valve, pneumatic servomotor and positioner. The typical structure is shown in Fig. 1. The electro-pneumatic positioner converts the output signal of the controller into the thrust of the valve stem of the control valve, and the thrust torque is further converted into an angle signal to control the valve opening. The

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Figure 1. Pneumatic control valve

positioner and the displacement of the stem compose the minor control loop which improves the performance of the pneumatic control valves [8].

B. Faults Analysis of Pneumatic Control Valves

The faults of the pneumatic control valves mostly occur in the valve body. The valve body contains a large number of parts. As shown in Table 1, the fault of each part is described in details. The faults of the pneumatic control valves mostly occur in the valve body. The valve body contains a large number of parts. As shown in Table 1, the fault of each part is described in details. When faults occur, valve stem stroke and air chamber pressure are abnormal. The valve stem stroke and air chamber pressure are analyzed to diagnose the valve by expert system. Take the friction increasing fault as an example to analyze and verify the expert experience in the below.

Under the condition that there is no fluid in the valve body and the air pressure is atmospheric pressure, the air chamber pressure rises instantaneously, if the starting current signal is given. When the air chamber pressure is greater than the maximum static friction, the valve stem starts to move. After the valve stem moves, the volume of the air chamber becomes larger, the air pressure decreases. When valve stem moves to a given opening, the pressure of the air chamber pressure and the spring force are balanced, the valve stem is stationary, and the dynamic friction changes into static friction. The difference between the peak pressure in this process and the stable pressure of this gear is called the air pressure overshoot. The air pressure overshoot is larger than no fault according to the expert experience. The pressure and displacement of friction increasing fault are shown in Fig. 2.

Force equation of valve stem of pneumatic control valve is as follows:

$$p \cdot A_e - m \cdot g - K_s \cdot (X + X_0) - F_f = m \cdot \ddot{x} \qquad (1)$$

where p is air pressure, A_e is the area of diaphragm, $K_s(X+X_0)$ is the spring force. F_f is the friction. The increment of the air chamber pressure and the increment of the static friction force have the same value and opposite directions. Therefore, the pressure of the gas chamber reaches the peak at the moment when the valve stem moves, and the static friction F_f reaches at the maximum value, which can be described as follows:

$$\Delta p \cdot A_e = \Delta F_f \qquad (2)$$

Table 1 Fault analysis of various components of pneumatic control valve

Fault Part	Fault Type	Fault Trend
Spring	Rigidity decreasing	slowly developing
Diaphragm	Air leakage	slowly developing
Packing box assembly	Friction increasing	slowly developing
Valve plug	Erosion	slowly developing
Seat ring	Sedimentation	abrupt
Valve body	Medium leakage	slowly developing

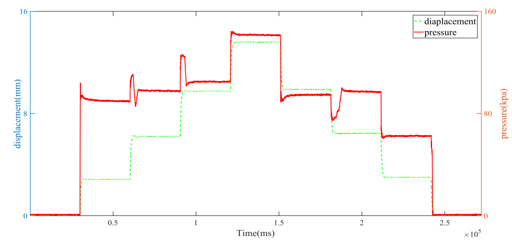

Figure 2. Pressure and displacement of friction increasing fault

Therefore, the overshoot of the air chamber pressure can reflect friction increasing fault.

III. TRADITIONAL EXPERT SYSTEM-BASED FAULT DIAGNOSIS METHOD OF PNEUMATIC CONTROL VALVES

A. Expert System

Expert system is a computer model that simulates the process of human experts processing problems. It is used to deal with complex problems that require experts to deal with in the real world, and draw the same conclusions as experts [9]. Expert systems are divided into five categories: rule-based, frame-based, case-based, model-based, and Web-based. Rule-based expert systems are most widely used in in the industrial application. The rule-based expert system is composed of six modules: knowledge base module, inference machine module, human-machine interface module, interpreter module, database module, and knowledge acquisition module.

The judgment approach for the five common faults of pneumatic control valves is summarized according to the experience of a large number of engineers and the rule-based expert system method proposed in this article.

The rules of expert system are summarized as follows:

1) *Rule 1:* If the valve stem displacement is greater than the set threshold value a_1 under the zero-opening, a valve seat sedimentation fault occurs.

2) *Rule 2:* If the difference $P_2 - P_1$ between the air chamber pressure P_2 and the pressure of no-fault P_1 at full-opening is greater than the set threshold a_2, a spring rigidity decreasing fault occurs.

3) *Rule 3:* If the peak-to-peak of air pressure under the valve opening changing is less than the set threshold a_3, and the the overshoot of the chamber pressure is greater than the set threshold a_4, friction increasing occurs.

4) *Rule 4:* If the peak-to-peak value of the chamber pressure is greater than the threshold value a_3, a diaphragm leakage fault occurs.

5) Rule 5: If the valve stem displacement is less than the set threshold value a_5 under the zero-opening, a Valve plug erosion fault occurs.

B. Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) was proposed in [7] based on artificial life and evolutionary computing theory, which can find the global optimal solution of the problem. PSO algorithm is used widely due to its simplicity and fast convergence speed.

The PSO algorithm simulates the foraging behavior of a group of birds, which aims to find the optimal solution. In PSO algorithm, the solution of each optimization problem is a particle. Each particle has an initial speed and position, and a fitness value determined by the fitness function. In addition, the flying direction and distance of each particle are determined by their speed, which guarantees that the particle can search in the optimal solution space [7, 10].

At every iteration of the PSO, the speed and position of each particle can be updated according to (3) and (4)

$$v_{id} = \omega v_{id} + c_1 r_1 \left(p_{id}^{best} - y_{id}\right) + c_2 r_2 \left(p_{gd}^{best} - y_{id}\right) \tag{3}$$

$$y_{id} = y_{id} + v_{id} \tag{4}$$

where ω is the inertia coefficient, c_1 and c_2 are the learning rates, r_1 and r_2 are generated randomly in [0,1], The second term is self-learning term which makes the particles move to the historical optimal position according to the difference between their historical optimal position and the current position. The third term is global communication term which makes the particles move to the global optimal position according to the difference between the current position and the global optimal position.

C. The Modified Expert System Based Fault Diagnosis Method

The threshold parameters of the expert system are optimized according to the process data by PSO algorithm to improve the performance of the traditional expert system.

In this issue, the fitness function is $f(x_1, x_2, \cdots$, which means the accuracy of the fault diagnosis. Specifically, the accuracy of fault diagnosis is improved by adjusting the above five threshold parameters. The five threshold parameters are mentioned above a_1, a_2, a_3, a_4, a_5 . Construct a function $f_e(x)$ for faults judgment and classification based on expert experience. The inputs of this function are air pressure and displacement, and the fault diagnosis results are obtained according to the expert experience rules. During the iteration process of particle swarm optimization, different parameters are assigned to $f_e(x)$. First, record the set of parameters with the highest accuracy after each iteration. Then, update parameters according to (3) and (4), and perform the next iteration until the convergence condition is met. Finally, the set of parameters with the highest accuracy is as the optimal value. The structure of the fault diagnosis approach for pneumatic control valves based on modified expert system is shown in Fig. 3.

Remark 1 A At each iteration, n particles are explored once near the previous position. If the new position is better, the individual historical optimal position of the particle is updated, otherwise it is not updated. Compared with the historical global optimal position, it is updated if it is better, otherwise it is not updated. Continue to iterate until meeting the condition of convergence. The global optimal value at the time the algorithm stops is the optimal solution.

Remark 2 Compared with the basic expert system, the rich operating status information contained in the process data is made full use of to select the threshold parameters using the method based on the modified expert system, which can improve the fault diagnosis performance of pneumatic control valves effectively.

IV. Experiment and Analysis

A. Introduction of Experimental System Platform

To verify the performance of the method based on the modified expert system, a set of experimental system platform is designed in this paper, which is used to collect the air pressure and valve stem displacement of the valve during the operating process of the valve under a given signal. As shown in Fig. 4, the system is mainly composed of five parts: valve body, positioner, data acquisition device, air compressor and host computer, and the type of each part is as follows:

1) *Pneumatic control valve*： DN20-101-P1.
2) *Positioner:* Siemens PS2 6DR5010-0EN00-0AA0.

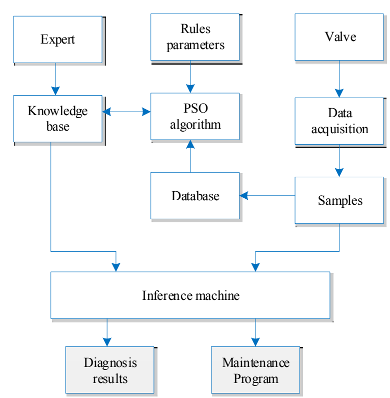

Figure 3. The structure of the fault diagnosis approach for pneumatic control valves based on modified expert system

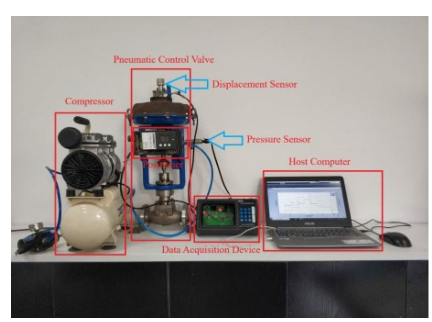

Figure 4 Experimental system

3) *Data acquisition device:* The data acquisition device is designed by our team, which includes

microcontroller unit (STM32F407IGT6), power module, serial communications module, pressure transducer (YS-250，250kpa L. ± 1.5% F.S) and displacement sensor (SFCP22R-8795 L. ±0.5% F.S).

4) Air compressor: Outstanding OTS-550.

5) Host computer: ASUS-X555L1 (Windows 7, CPU i5-5200U@2.20GHz, RAM 4G, Hard Disk 240G).

B. The Analysis of Experimental Results

The data is collected by the experimental system, and each fault is introduced under the direction of an engineer. The total number of the collected sample is 390, which contain 65 normal patterns and 325 fault patterns including various faults. The obtained expert experience is designed into an expert system with 'if-then' rules, and the threshold parameters are set by engineers. The confusion matrix of the diagnosis results using expert system is shown in Fig. 5.

In Fig. 5, the vertical axis represents the prediction label by the expert system, and the horizontal axis represents the actual label of the sample. 1-6 represent different states respectively: no-fault, diaphragm leakage, valve seat sedimentation, valve plug erosion, friction increasing and spring rigidity decreasing. Taking the first row and the second column of the table as an example, it shows that 6 samples of diaphragm leakage faults have been diagnosed as no-fault by the expert system.

PSO algorithm is introduced to optimize the threshold parameters of expert system. The parameters of the particle swarm optimization are set as follows: the particle population number n is 20, c1 and c2 are both 2, and the evolutionary generation is 1000 generations.

It can be seen from Fig. 6 that the diagnostic accuracy has increased from 76.68% to 94.7%. It can be seen from the Tabel 2 that the fault diagnosis accuracy rate has reaches at 94.7% and the total false negative rate is 3.0%.

Compared with the traditional expert system, the modified expert system-based method can improve the diagnosis accuracy and reduce the false negative rate effectively.

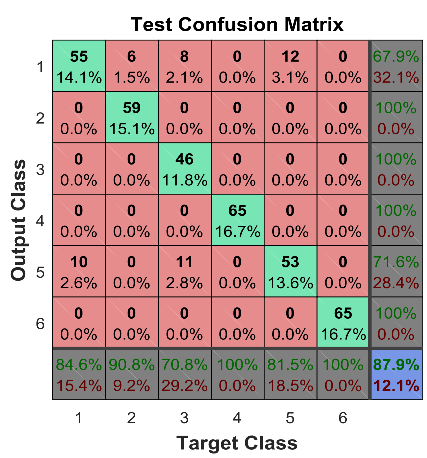

Figure 5. Diagnosis results of traditional expert system

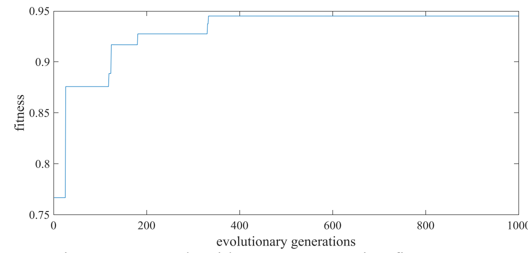

Figure 6 PSO algorithm 1000 generation fitness curve

Table 2 Diagnosis results of different methods

Method	Accuracy	FNR
Expert System	87.9%	6.6%
Modified Expert System	94.7%	3.0%

V. CONCLUSION

A fault diagnosis method of pneumatic control valves based on the modified expert system is proposed in this paper. The process data is used to optimize the threshold parameters of the traditional expert system by using PSO, which improves the performance of the traditional expert system. Experimental results show that the modified expert system-based method improves the accuracy and reduces the false negative rate, which is of great significance for the valve detection on the industrial site.

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