RESEARCH ON FAULT DIAGNOSIS OF THERMODYNAMIC SYSTEM BASED ON THE NETWORK MODEL OFINTERNET OF THINGS

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Abstract: Aiming at the problem that the traditional diagnosis model is difficult to be established accurately, a fault diagnosis algorithm based on the fault diagnosis criterion is constructed to study the fault diagnosis of thermodynamic system based on the network model of Internet of Things. By analyzing the fault parameters of the equipment system, the algorithm establishes the fault matrix, calculates the mapping relation function corresponding to the states with unknown and known matrix, and obtains the optimal solution of the objective function. It solves the problem that the traditional diagnosis scheme is difficult to accurately diagnose the unknown model. By analyzing the cause and mechanism of the system fault, the diagnosis criterion of each kind of fault is determined. The fault matrix is established by calculation and judgment. The simulation experiment of gas path fault shows that the criterion of turbine blade mechanical damage fault is that the turbine efficiency is reduced by 5%, which is consistent with the theoretical analysis. This shows that the proposed algorithm is effective and the simulated data can be used as technical support for fault diagnosis of similar thermodynamic systems.

Key words: *internet of things (IOT); Thermodynamic system; failure*

1. Introduction

With the development and application of Internet of Things (IOT)technology, it has been widely used in gas turbine fault detection and diagnosis in recent years [1]. However, traditional fault diagnosis methods generally need to determine the exact analytical model, and they are impossible to get accurate fault diagnosis results when the model is unknown or the description is not accurate [2]. In recent years, with the deepening of theoretical research, the application of fault diagnosis methods based on the IOT model is more and more extensive. IOT technology makes it possible to obtain and share massive data such as device state and information and environmental parameters [3], so that a large number of data can be used and excavated, thereby findingout the rule from it and realizing the purpose of accurate fault diagnosis [4]. Therefore, it is of great practical significance to study the fault diagnosis of thermodynamic system based on the IOT network model in this paper, in order to further improve the fault diagnosis accuracy of thermodynamic system of gas turbine and other equipment

[5].

In this paper, fault diagnosis algorithm based on IOT model is used to study the fault diagnosis of thermodynamic system. Taking gas turbine fault diagnosis as the research object and various compressor faults as the criterion of fault diagnosis, the fault diagnosis algorithm based on turbine fault mechanism analysis is used to study the fault diagnosis of thermodynamic system. There is a corresponding relationship between the state space and the feature space. When the system determines a certain state, then the characteristics of the system will be determined, that is, there is a corresponding mapping relationship. The fault diagnosis algorithm is the process in which the mapping between the state space and the feature space which constitute the whole space of fault diagnosis is calculated based on the turbine fault mechanism analysis, thereby finding the optimal diagnosis scheme.

The research in this paper has some innovation. By means of the thermodynamic equations of each component of gas turbine’s gas path, the least deviation method is used to linearize all the equations, and the unmeasurable deviation of performance parameters is connected with the deviation of measuring parameters, and the corresponding fault matrix is established. This paper introduces the technology of IOT into gas path fault detection, simulates the fault of gas path based on the calculated fault matrix, obtains the deviation of measuring parameters when all faults occur, and verifies the correctness of fault simulation. It solves the problem that the traditional diagnosis method cannot get accurate fault diagnosis results when the model is unknown or the description is not accurate.

In this paper, the fault diagnosis of thermodynamic systems based on the IOT network model is studied by using fault diagnosis algorithm, and the IOT network model is constructed. Based on the difference of gas turbine fault criteria, a turbine fault mechanism analysis algorithm is proposed, and the main principle and implementation flow of the algorithm are analyzed. Finally, the algorithm is tested, and the experimental results are analyzed and summarized.

2. Related Work

In recent years, the IOT technology has been widely used in the fault detection of various devices. Many scholars have carried out related research on it. Yang J J has proposed a multi-classification method of printing machine fault diagnosis based on support vector machine, optimized model parameters based on LibSVM library, and carried out MATLAB simulation. The result shows that this method has higher classification accuracy [6]. According to the process of printing machine fault diagnosis, Yi W adopts IOT and Java Web technology todevelop a remote diagnosis system of printing press based on the IOT is developed by using software platforms such as MySQL5.5 and Netbeans. The on-line detection and remote diagnosis of printing press are realized, and the problem of wide distribution and difficult maintenance of printing press issolved [7]. Leng K proposes a fault diagnosis model based on neural network and finds that the fault diagnosis system can not only reduce the communication burden, but also have a high diagnosis rateand can be well used in the fault diagnosis system of aquaculture IOT [8]. Wei D analyzes the advantages and disadvantages of the traditional aiNet network model for mechanical fault diagnosis. Based on this, he introduces the clonal mutation algorithm and K-nearest neighbor theory, designs a multi-layer immune network model. This model can achieve the effective identification of new faults through the cooperation of self-diagnosis layer and adaptive diagnosis layer [9]. Qin L. designs a fault diagnosis system for air conditioning based on IOT and data fusion and finds that this system can monitor the running state of the air conditioning equipment and realize the purpose of fault diagnosis of air-conditioning equipment in the IOT of building electric equipment [10]. Chang F constructs the fault diagnosis model of belt conveyor based on IOT and data fusion technology. The results show that this technique can accurately diagnose the fault type of belt conveyor [11].

Fei C establishes a set of professional and technical diagnostic model including equipment and parameters, which realizes the timely early warning of mechanical failure and improves the processing and management level of mechanical equipment [12]. Su Y F sets up an integrated information fusion fault diagnosis model based on fuzzy theory and evidence theory. Through the example analysis of power transformer, it is proved that the fault diagnosis based on the total state information from the IOT can get more accurate diagnosis results than partial information [13].

Generally speaking, most of the studies of domestic and foreign scholars focus on the establishment of fault system, the construction of fault diagnosis model and the verification of the model. Many scholars have verified by examples that the establishment of the IOT network model can effectively diagnose the failure of various equipment thermodynamic systems. However, domestic and foreign scholars lack of specific research on the application of the IOT model in fault diagnosis. Therefore, on the basis of previous studies, it is of great significance to study the fault diagnosis of thermodynamic systems based on the IOT model.

3. Establishment of the Fault diagnosis Criterion for the Thermodynamic System

3.1. Judgment criteria for compressor failures

Compressor blade fouling: Compressor blade fouling is the most common and most difficult to detect in the operation of gas turbine. It causes little change in performance at first. However, with the increase of running time, its effect on performance is also increasing [14]. During the operation of the gas turbine, every kilowatt of gas turbine will inhale nearly 500kg air within 24 hours [15]. At present, the most commonly used air filters on the market can only isolate dust and soil with larger size, but for particles less than 5 mm, they cannot play a role. Compressors in the course of work will gradually form fouling on the blade. And when the compressor inlet bearing seal fails, the entry of lubricating oil fog will accelerate the formation of dirt. The cause ofblade fouling is usually divided into internal and external aspects. Some foreign scholars have established the model of gas turbine to simulate the fault in recent years. The criterion of the simulation is that the compression efficiency of compressor is reduced by 2% and the flow rate is reduced by 7%. Therefore, combined with the literature, the compression efficiency being reduced by 2% and the flow rate being reduced by 7% are used as the judgment criterion of faults in fouling simulation of compressors.

The tip clearance of the compressor blade increases: During the compressor operation, the blade tip of the compressor will be worn out by the shear force of the air flow or the friction of the tiny particles during the flow process if the operation time is long. This leads to the increase of the tip clearance of the compressor blade. In addition, when the rotor is uneven, it will cause friction between the blade and the casing, which will result in the increase of the tip clearance. This is also the result of bearing damage. For an axial compressor, when the tip clearance of the blade increases by 0.5 mm compared with the normal condition, the experimental results show that the reduced flow rate will decrease by 4%, but the efficiency will not change. Therefore, when simulating compressor tip gap increasing fault, the criterion adopted is that the flow rate is reduced by 4%.

Compressor blade wear and corrosion: blade wear is due to the fact that when the gas turbine is in operation, the air flow will inevitably contain solid particles which will cause erosion and cutting wear to the components. Especially when the air filter is destroyed, the large particles will enter the gas turbine to wash the blade continuously and increase the roughness of the blade. When there is more water and salt in the air, the corrosion and wear of the blade will be aggravated. The wear of the blade will affect the fluidity of the passage, reduce the efficiency, and even cause the gas turbine to work unsteadily. Specifically, when the blade wear fault occurs, on the one hand, the contact area between the blade and the airflow will increase, and the flow rate will also increase; on the other hand, the blade resistance coefficient to the airflow will increase because of the blade wear. The roughness of compressor blade surface will reduce the compression efficiency. Therefore, considering the effect of compressor fouling on compression efficiency, the compression efficiency being reduced by 2% used as the judgment criterion in the performance simulation of compressor blade wear and corrosion.

Mechanical damage of the compressor blade: When the compressor is impacted by foreign materials and suffers the blade mechanical damage, it will change the shape of the blade, so that the blade is in a twisted state or notched, which will also lead to spoiler, resulting in secondary losses. It will also reduce the airflow performance in the air channel, and the compression efficiency of the compressor will decrease. If the damage brought by foreign materials is great, even the blade will break, and then the machine may be shut down, or even the body will be seriously damaged. In the experiment of three-shaft steam turbine, foreign scholars take the reduction of compressibility by 5% as the criterion of damage to compressor blade by foreign materials. Hence, in this article, the reduction of compressibility by 5% is adopted as the judgment criterion of mechanical damage of compressors.

3.2 Turbine failure mechanism analysis

Turbine blade fouling: the cause of turbine blade fouling is similar to that of compressor blade. The turbine will use liquid fuel in the process of operation. If heavy fuel is used, the turbine blade will slowly accumulate the residue of heavy fuel liquid combustion because of the insufficient combustion. After the turbine blade is fouled, the flow resistance becomes larger and the flow channel area becomes smaller, which greatly reduces the efficiency. Referring to the fouling of compressor blade, it is considered that the criterion of turbine blade fouling can be the reduction of the turbine flow rate by 6% and that of the expansion efficiency by 2%.

Turbine blade wear and corrosion: Turbine blade wear and corrosion will reduce the performance of the turbine and also reduce its life and safety and reliability. Turbine blade corrosion and wear are mainly caused by solid particles entering the turbine. When the turbine is working, the solid particles will continuously impact on the blade, which will cause the blade wear and reduce the air flow resistance of the passage. As a result, the reduced flow rate of the turbine increases and the efficiency decreases. Therefore, in this paper, the turbine blade wear and corrosion failure criteria are that the turbine flow increases by 6% and efficiency decreases by 2%.

Mechanical damage of turbine blade: Foreign materials entering the compressor may also enter the turbine through the passage, thus causing great damage to the turbine blade, resulting in deformation, bending and wear of the turbine blade. Hence, the performance of the unit is reduced. In foreign countries, some scholars have simulated the turbine blade mechanical damage, and the criterion used is that the turbine expansion efficiency is reduced by 5%. Consequently, the turbine expansion efficiency being reduced by 5% is used as the failure criterion of the turbine blade's mechanical damage.

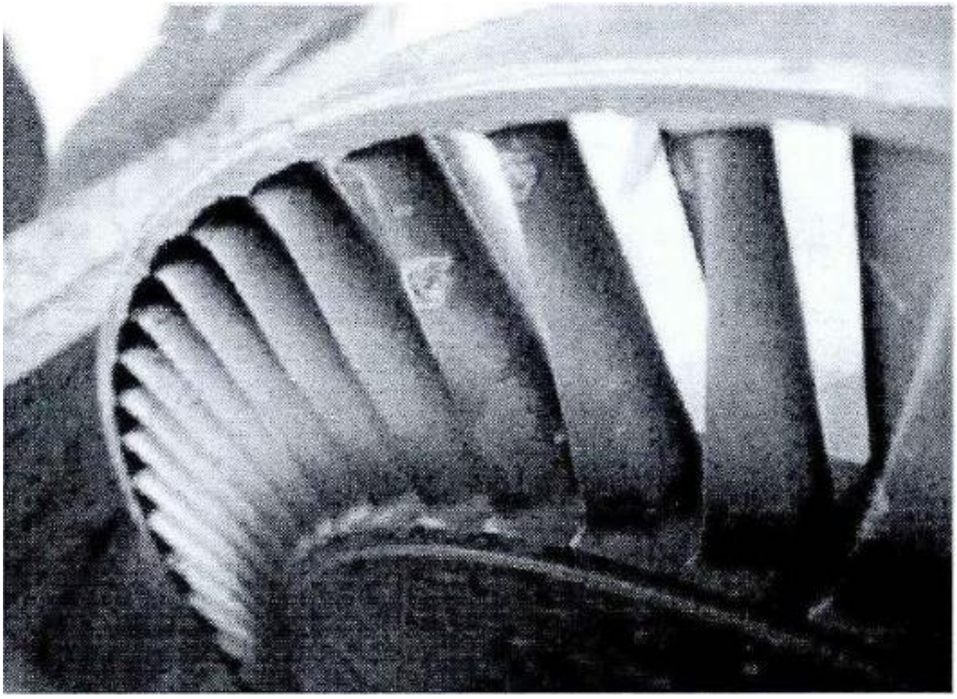

Figure 1 Mechanical damage of the turbine blade

Hot corrosion of the turbine blade: Hot corrosion is different from general corrosion. It refers to the phenomenon that in the high-speed operation of the turbine blade, because of friction with the air, produce high temperature is produced which burns the blade, leading to corrosion. This condition can also be called high temperature corrosion. In the high temperature corrosion environment, the damage to the blade is not related to the strength of the material, but to its heat and high temperature resistance. The hot corrosion will make the small grain which is not important on the blade become more and more serious because of oxygen absorption, and also make the crack expand continuously, and accelerate the mechanical fatigue and thermal fatigue. This failure will greatly reduce turbine efficiency and shorten turbine service life. For this reason, the researchers studied turbine hot corrosion, and pointed out that the factors affecting turbine hot corrosion are: (1) blade material (2) gas flow rate (3) blade surface temperature (4) sulfur and cement (5) salt content in gas. In this paper, the judgmentcriterion of turbine blade hot corrosion is the increase of turbine flow rate by 6%.

Table 1 Criterion Table

No.	Fault type	Fault basis
1	Compressor blade fouling	Compressor flow rate reduced by 7% and compressor efficiency reduced by 2%
2	Compressor tip clearance increase	Compressor reduced flow rate reduced by 4%
3	Compressor blade wear	Compressor efficiency reduced by 2%
4	Compressor blade mechanical damage	Compressor efficiency reduced by 5%
5	Turbine blade hot corrosion	Turbine flow scene increased by 6%
6	Turbine blade fouling	Turbine flow reduced by 6% and turbine efficiency

		reduced by 2%
7	Turbine blade wear	Turbine flow increased by 6% and turbine efficiency reduced by 2%
8	Turbine blade mechanical damage	The turbine efficiency reduced by 5%

4. Experimental Design and Analysis

4.1 Compressor blade fouling failure

Through table 1, one can know that the compressor blade fouling fault criterion is that the compressor's flow rate is reduced by 7 percent, and the compressor efficiency is decreased by 2 percent. Because the actual situation is too complicated, in order to simplify the calculation, this paper only studies the case of single fault, that is to say, the independent variation of other performance parameters is zero. However, as an independent variable, it is not equal to zero. Therefore, the fault model matrix can be simplified to:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta\pi_{LC} \\ \delta\pi_{HC} \\ \delta n_3 \\ \delta wf \end{bmatrix} = \begin{bmatrix} -0.3239 & -0.6791 & 0.1951 \\ 0.0231 & 0.0909 & 0.6214 \\ 0.5140 & -0.5787 & 0.0910 \\ 0.1336 & 0.2959 & 0.2251 \\ 0.4388 & -0.4137 & 1.1552 \\ -0.3239 & -0.6791 & 0.1951 \end{bmatrix} \begin{bmatrix} \delta\overline{G_{LC0}} \\ \delta\overline{\eta_{LC}} \\ \delta T_4 \end{bmatrix} = \begin{bmatrix} -0.3239 & -0.6791 & 0.1951 \\ 0.0231 & 0.0909 & 0.6214 \\ 0.5140 & -0.5787 & 0.0910 \\ 0.1336 & 0.2959 & 0.2251 \\ 0.4388 & -0.4137 & 1.1552 \\ -0.3239 & -0.6791 & 0.1951 \end{bmatrix} \begin{bmatrix} -0.07 \\ -0.02 \\ \delta T_4 \end{bmatrix} \quad (1)$$

According to the complete fault matrix model, one can know that $\delta n_3 = 0$ .Therefore, $\delta T_4 = 0.0349$ can be obtained, and thus:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta\pi_{LC} \\ \delta\pi_{HC} \\ \delta wf \end{bmatrix} = \begin{bmatrix} 0.0429 \\ 0.0186 \\ -0.0210 \\ -0.0071 \\ 0.0181 \end{bmatrix} \quad (2)$$

According to the working characteristic curve of gas turbine, theoretical analysis is carried out. When the turbine has a fault due to the fouling of the blade, the compressor's working characteristic line will move down, soboth the efficiency and the pressure ratio decrease accordingly. Since this paper simulates a situation where the power output of a gas turbine is constant, when the compressor efficiency drops, it is necessary to increase the fuel flow rate and increase the work capacity of the gas in the turbine with more heat consumption to compensate for the compression power consumed on the compressor. The results obtained from the upper formula are in agreement with the theoretical analysis.

4.2 Failure of compressor tip clearance increase

As can be seen in Table 1, the criterion for increasing the gap at the top of the compressor is a reduction of the compressor flow rate by 4%, so the fault model matrix can be simplified as follows:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta n_3 \\ \delta wf \end{bmatrix} = \begin{bmatrix} -0.3239 & 0.1951 \\ 0.0231 & 0.6214 \\ 0.5140 & 0.0910 \\ 0.1336 & 0.2251 \\ 0.3474 & 0.7584 \\ 0.4333 & 1.1553 \end{bmatrix} \begin{bmatrix} \delta \overline{G_{LC0}} \\ \delta T_4 \end{bmatrix} = \begin{bmatrix} -0.3239 & 0.1951 \\ 0.0231 & 0.6214 \\ 0.5140 & 0.0910 \\ 0.1336 & 0.2251 \\ 0.3474 & 0.7584 \\ 0.4333 & 1.1553 \end{bmatrix} \begin{bmatrix} -0.04 \\ \delta T_4 \end{bmatrix} \tag{3}$$

According to the complete fault matrix model, one can know that $\delta n_3 = 0$ .Therefore, $\delta T_4 = 0.0184$ can be obtained, and thus:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta wf \end{bmatrix} = \begin{bmatrix} 0.0158 \\ 0.0111 \\ -0.0193 \\ -0.0021 \\ 0.0031 \end{bmatrix} \tag{4}$$

When the compressor has the fault of tip clearance increase, it will lead to the decrease of the reduced flow rate in the compressor airflow channel, and the pressure ratio will decrease as well. Because of the increase of the tip clearance, the flow does not pass through the channel completely, resulting in the reduction of efficiency. But because the power is constant, it increases the input of fuel flow. The results obtained from the upper formula are in agreement with the theoretical analysis.

4.3 Compressor Blade Wear

As can be seen in Table 1, the compressor blade wear fault criterion is that the compressor efficiency is reduced by 2%, so the fault model matrix can be simplified as:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta n_3 \\ \delta wf \end{bmatrix} = \begin{bmatrix} -0.6791 & 0.1951 \\ 0.0909 & 0.6214 \\ -0.5787 & 0.0910 \\ 0.2959 & 0.2251 \\ 0.1029 & 0.7584 \\ -0.4144 & 1.1553 \end{bmatrix} \begin{bmatrix} \delta \overline{\eta_{LC}} \\ \delta T_4 \end{bmatrix} = \begin{bmatrix} -0.6791 & 0.1951 \\ 0.0909 & 0.6214 \\ -0.5787 & 0.0910 \\ 0.2959 & 0.2251 \\ 0.1029 & 0.7584 \\ -0.4144 & 1.1553 \end{bmatrix} \begin{bmatrix} -0.02 \\ \delta T_4 \end{bmatrix} \tag{5}$$

According to the complete fault matrix model, one can know that $\delta n_3 = 0$ .Therefore, $\delta T_4 = 0.0027$ can be obtained, and thus:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta wf \end{bmatrix} = \begin{bmatrix} 0.0139 \\ -0.0003 \\ 0.0121 \\ -0.0049 \\ 0.0109 \end{bmatrix} \tag{6}$$

When the compressor blade is worn, this fault will change the aerodynamic performance of the compressor, which is shown by the increase of the drag coefficient, so that the pressure ratio of the low pressure compressor is increased. According to the balance of pressure ratio between low pressure compressor and high pressure compressor, and the flow rate remains constant, the pressure ratio of high pressure compressor will decrease. The wear of the blade increases the extra energy consumption, which leads to the decrease of the power. In order to keep the power constant, the fuel flow rate will increase. The results obtained from the upper formula are in agreement with the theoretical analysis.

4.4 Mechanical Damage of Compressor Blades

Table 1 shows that the criterion of compressor blade mechanical damage is that the compressor efficiency is reduced by 5%, so the fault model matrix can be simplified as follows:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta n_3 \\ \delta wf \end{bmatrix} = \begin{bmatrix} -0.6791 & 0.1951 \\ 0.0909 & 0.6214 \\ -0.5787 & 0.0910 \\ 0.2959 & 0.2251 \\ 0.1029 & 0.7584 \\ -0.4144 & 1.1553 \end{bmatrix} \begin{bmatrix} \delta \overline{\eta_{LC}} \\ \delta T_4 \end{bmatrix} = \begin{bmatrix} -0.6791 & 0.1951 \\ 0.0909 & 0.6214 \\ -0.5787 & 0.0910 \\ 0.2959 & 0.2251 \\ 0.1029 & 0.7584 \\ -0.4144 & 1.1553 \end{bmatrix} \begin{bmatrix} -0.05 \\ \delta T_4 \end{bmatrix} \tag{7}$$

According to the complete fault matrix model, one can know that $\delta n_3 = 0$ .Therefore, $\delta T_4 = 0.0068$ can be obtained, and thus:

$$\begin{bmatrix} \delta n_1 \\ \delta n_2 \\ \delta \pi_{LC} \\ \delta \pi_{HC} \\ \delta wf \end{bmatrix} = \begin{bmatrix} 0.0355 \\ -0.0009 \\ 0.0288 \\ -0.0129 \\ 0.0292 \end{bmatrix} \tag{8}$$

Similar to the compressor blade wear fault, when the compressor is impacted by foreign materials, the aerodynamic performance in the channel will become worse, and the pressure ratio in the low pressure compressor will increase because the flow rate does not change. However, the flow capacity from low pressure compressor to high pressure compressor becomes weak, which makes the pressure ratio of high pressure compressor decrease. The damage of the blade results in the incomplete work of the airflow, which makes the output power of the unit fail to meet the requirements, and the fuel flow rate must be increased to make up for the insufficient power. The results obtained from the upper formula are in agreement with the theoretical analysis.

All the above failures and changes in their measurement parameters are unified into a single table:

Table 2 Fault measurement parameter deviation

	δn_1 %	δn_2 %	$\delta \pi_{LC}$ %	$\delta \pi_{HC}$ %	δwf %
Compressor blade fouling	4.16	1.77	-2.09	-0.71	1.70
Compressor tip clearance increase	1.66	1.05	-1.89	-0.12	0.36
Compressor blade wear	1.41	-0.01	1.18	-0.53	1.14
Compressor blade mechanical damage	3.53	-0.03	2.96	-1.32	2.86
Turbine blade hot corrosion	1.15	-0.36	1.01	-0.04	0.14
Turbine blade fouling	0.16	-0.25	-0.27	-0.79	0.06
Turbine blade wear	2.35	-0.88	1.72	-0.71	0.32
Turbine blade mechanical damage	3.00	-1.32	1.81	-1.67	0.45

5. Conclusion

In this paper, the typical gas path faults of turbines are summarized with reference to domestic and foreign literature. Through the analysis of these faults from different angles, the causes and mechanism of these faults are expounded, and the diagnosis criteria of each kind of faults are determined. Based on the fault matrix, the simulation of typical faults of gas path is realized. Finally, the simulation results are analyzed based on the theoretical basis, and the results show that the simulated data can be used as the data support of the fault diagnosis algorithm.

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