Infrared Technology-Based Sensor Data Analysis for Thermal Fault Identification of Electrical Equipment in Intelligent Substations

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The electrical equipment of intelligent substation cannot deal with the problem of load mutation, and the load adjustment is not timely, which leads to the poor performance of thermal fault identification of electrical equipment. Therefore, a study on thermal fault identification of the electrical equipment of intelligent substation based on infrared technology is proposed. First, under the background of infrared technology, according to the thermal fault feature extraction model of substation electrical equipment, the principle of double station cross location is proposed; combined with the sampling results of thermal fault characteristic parameters of electrical equipment in intelligent substation, the thermal fault characteristics are analyzed; through the process of thermal fault identification of electrical equipment in intelligent substation, the preliminary classification structure of thermal fault is obtained and the thermal fault identification is completed. The experimental results show that the designed method has good performance of thermal fault identification, high output stability, better identification effect after optimization, and highly sensitive identification ability.

1. Introduction

With the continuous development of intelligent substation control technology, the use of electrical equipment for intelligent control and management of substations can improve the stable and reliable operation capacity of intelligent substations [1, 2]. The stability of electrical equipment in intelligent substation is poor due to its long-term high load operation. The characteristic is that under extreme conditions, the output power and load of electrical equipment in intelligent substation increase sharply, resulting in a large difference in the fault of electrical equipment in substation. In order to improve the operation stability of electrical equipment in substation, it is necessary to optimize the fault diagnosis and detection of electrical equipment in substation and improve the working condition self-adaptability of electrical equipment in intelligent substation [3, 4]. With the rapid development of power systems in modern society, a variety of electrical equipment and technologies related to power are also being developed and improved. The electrical equipment of intelligent substation improves people’s living standards and productivity [5]. At the same time, due to its own defects and loopholes, electrical equipment is often shut down, product quality is reduced, and even people’s life safety is threatened. Therefore, identifying the operation of electrical equipment in intelligent substation, identifying the fault location and diagnosing the cause of the fault in time, and ensuring the safe operation of electrical equipment are the key areas of current research.

Relevant scholars have conducted in-depth research on this. Reference [6] designed the fusion of infrared image and visible light image technology and applied it to the thermal fault monitoring of electrical equipment in substations. Using the integrated image acquisition PTZ, the infrared
image and visible image are integrated by using the calculation method of image segmentation and fusion, and the designed monitoring system is applied to the actual scene. Reference [7] combines the technology of infrared temperature sensor and thermistor sensor and uses the data transmission characteristics of ZigBee wireless network to develop an overheating monitoring system for marine electrical equipment. The network protocol, the circuit around the control chip, and the sensor circuit of the overheating monitoring system are designed in detail to improve the temperature monitoring effect of marine electrical equipment. Reference [8] proposed the design of a distributed substation high-voltage electrical equipment online monitoring system based on image segmentation technology as an important supporting mechanism for real-time monitoring and displaying system frequency, harmonic voltage, harmonic current, three-phase voltage imbalance, voltage ripple and flicker, real power factor, and other power quality parameters specified in national standards. Based on this, this paper first analyzes the problems existing in the construction of distributed substation electrical equipment online monitoring network design system and then gives the construction strategy of high-voltage electrical equipment online monitoring system. Reference [9] designed and developed an intelligent monitoring system for 10 kV box-type substation based on the Internet of things. The box transformer integrated state sensing equipment and edge computing gateway equipment, completed multidimensional operation parameter collection and local analysis and calculation, and sent data to the IOT data collection platform through the narrow-band IOT network. The platform application software realizes real-time online monitoring, fault early warning, and operation evaluation of box transformer. The system function is verified by engineering practice.

Based on the abovementioned methods, this paper designs a thermal fault identification method of electrical equipment in intelligent substation based on infrared technology. Under the premise of infrared technology, the thermal fault feature extraction model of electrical equipment in substation is constructed; then, the principle of double station cross location is analyzed to obtain the thermal fault features, analyze the preliminary classification structure of thermal fault, and complete the thermal fault identification. The research shows that the design method has good performance of thermal fault identification.

Among them, the function of the infrared receiving optical system is to focus the infrared radiation in the target area on the detector. Its structure is similar to the usual receiving optical system, but because it works in the infrared band, its optical material and coating must be adapted to its working wavelength. The infrared sensor converts the infrared radiation of the target and background into electrical signals, which is output to the information processor in the form of video after nonuniformity correction and amplification.

The information processor is composed of hardware and software. After fast processing the video, the target is obtained, and then output through the data interface. The display device can display video signals and status information in real time. The function of the central computer is to provide timing, state, interface, internal, and external instructions and other controls for the whole system. The scanning and servo controller is used to control the work of the optical scanning mirror or servo platform, and feedback the angular position information of the optical scanning mirror or servo platform to the central computer.

The main advantage of infrared induction technology is that it meets the requirements of high concealment of stealth itself, that is, passive detection, no radiation of electromagnetic waves, and because the working wavelength is 3–4 orders of magnitude shorter than microwave radar, it can form a target image with high detail, and the target resolution is also high.

At this stage, due to the rapid development of infrared technology, the location of abnormal nodes for thermal faults of electrical equipment based on infrared technology has been widely used in the research field of intelligent substations [10, 11]. Infrared technology needs to accept the signals generated by all abnormal nodes, such as transmission errors or excessive heat inside the nodes, and then identify the approximate range of abnormal nodes according to the actual signal transmission position and transmission direction. Thus, the rough range location of abnormal thermal fault nodes of electrical equipment in intelligent substation can be realized.

2. The Principle of Abnormal Node Location for Thermal Fault of Electrical Equipment in Intelligent Substation Based on Infrared Technology

Infrared induction technology uses the hotspots or images formed by the infrared radiation difference between the target and the back to obtain the target scene information. The infrared receiving optical system is composed of optical system and detector, information processor, scanning and servo controller, information output interface, central computer, and other devices.

2.1. Double Station Cross Location. Generally, the infrared technology angle measurement and positioning system will adopt the double observation station method to realize the triangular cross positioning according to the measured angle information. However, in the process of locating the thermal fault abnormal node of the electrical equipment in the actual intelligent substation, when the abnormal node is near the 0 degree or 180 degree orientation, the measured distance will deviate from the actual situation, which is called geometric dilution in the research field [12]. On this premise, this paper analyzes the basic operation principle of the two station cross location and deeply studies the positioning accuracy and other issues. It is applied to the infrared detection system. By integrating the characteristics of the infrared technology platform, a thermal fault feature extraction model of substation electrical equipment with orthogonal multistation side angles is obtained as shown in Figure 1.
According to the thermal fault feature extraction model of substation electrical equipment in Figure 1, the principle of double-station cross location is determined. The double-station cross location is based on two uncertain observation stations [13], the distance is determined by measuring the angle of the target and other data, and the location is based on the human visual system. The distance between the targets is determined by the cross angle relationship between the observation target and the two observation stations. The positioning principle is shown in Figure 2:

Among them, Figure 2 shows various angle relationships. In order to facilitate analysis, the following assumptions are made in principle:

1. It is completely correct to assume that the lengths of \( AA' \), \( BB' \), and \( CC' \) do not have any error value in the measurement process.

2. It is assumed that the error value of the infrared detector in measuring the azimuth has been known, and it is described as \( \Delta \theta_1 \) and \( \Delta \theta_2 \).

3. Assuming that the difference between the horizontal path distance and the inclined path distance can be ignored, according to Figure 2, the vertex angle will meet the following equation:

\[
\theta_3 = \theta_2 + \theta_1. \tag{1}
\]

Based on the above assumptions, we collect and analyze the thermal fault characteristics of electrical equipment.

2.2. Collection and Analysis of Thermal Fault Characteristic Parameters of Electrical Equipment in Intelligent Substation

2.2.1. Collection of Thermal Fault Characteristic Parameters of Electrical Equipment in Intelligent Substation. In order to realize the collection of thermal fault characteristic parameters of electrical equipment in intelligent substation based on infrared technology, the multidimensional parameter identification, and node location methods of Internet of things are used to extract and locate the thermal fault characteristics of electrical equipment in intelligent substation, so as to improve the adaptability of thermal fault detection [14]. According to the abovementioned analysis, the implementation flowchart of thermal fault location and detection of electrical equipment in intelligent substation is shown in Figure 3.

According to the implementation flowchart of thermal fault location and detection of electrical equipment in intelligent substation shown in Figure 1, the zero sequence overcurrent protection and characteristic parameter identification method are adopted [15], and the extracted zero sequence component of thermal fault of electrical equipment in intelligent substation is taken as the constraint object parameter to obtain the frequency value of thermal fault parameter distribution of electrical equipment in intelligent substation, which is expressed as follows:

\[
U_G = \sum_{i=1}^{n} a_i(t)e. \tag{2}
\]

In formula (2), \( a_i(t) \) represents the carrier frequency of thermal fault parameter distribution of electrical equipment in intelligent substation, \( i \) represents the order of thermal fault location and detection, and \( e \) represents the amplitude of thermal fault parameter input.

At this time, according to the subspace component of the thermal fault sample information of the electrical equipment in the intelligent substation, the frequency distributed fusion results of the thermal fault parameters of the electrical equipment in the intelligent substation are obtained [16], and the closing conditions are manually traversed and changed to obtain the frequency component of the thermal fault characteristics of the electrical equipment in the intelligent substation. The calculation formula is expressed as follows:
In formula (3), $k_i$ represents the number of transformer signal pulses and $n$ represents the number of fault characteristics output by transformer no-load closing modeling. According to the $n$ fault features of the transformer no-load closing modeling output, the fault samples of the substation are collected, and the thermal fault feature fusion analysis of the electrical equipment in the intelligent substation is carried out on this basis.

2.2.2. **Fusion Analysis of Thermal Fault Characteristics of Electrical Equipment in Intelligent Substation.** In order to realize the fusion analysis of thermal fault characteristics of electrical equipment in intelligent substation, the fusion analysis model of thermal fault characteristics of electrical equipment in intelligent substation is built based on the sample results of thermal fault steady-state information collection of electrical equipment in intelligent substation [17], and the equivalent circuit diagram of thermal fault of electrical equipment in intelligent substation is obtained as shown in Figure 4.

According to the equivalent circuit diagram in Figure 4, the power spectral density of thermal fault characteristic output of electrical equipment in intelligent substation is obtained as follows:

$$ B_k = \frac{b_k}{f_i(n)} \quad (4) $$

In formula (4), $b_k$ represents the output voltage of no-load closing of the transformer, the excitation inductance, and excitation resistance are regarded as constants, and the soft threshold detection method is adopted. The threshold parameters for thermal fault location of electrical equipment in intelligent substation are as follows:

$$ W_{ZXC} = (|\ln [k_i \times n] - \alpha T_s| + B_k). \quad (5) $$

In formula (5), $T_s$ represents the flux linkage after transformer no-load closing, $\alpha$ represents the adaptive adjustment coefficient of transformer no-load closing output, and the value range is $0 \leq \alpha \leq 1$. Through the above analysis, the fusion analysis of thermal fault characteristics of electrical equipment in intelligent substation is completed.

3. **Realization of Thermal Fault Identification of Electrical Equipment in Intelligent Substation Based on Infrared Technology**

After the fusion analysis of the thermal fault characteristics of the electrical equipment in the intelligent substation, it is determined that the inertia weight $\lambda$ is directly related to the global search ability in the optimization process of the thermal fault analysis results [18]. Therefore, the optimization is implemented to form the dynamic inertia weight $\lambda'$. Its calculation formula is as follows:

$$ \lambda' = W_{ZXC} - \left[ V^2 \times \lambda_{\text{max}} - V^2 \times \lambda_{\text{min}} \right] \quad (6) $$

![Figure 4: Equivalent circuit diagram of thermal fault of electrical equipment in intelligent substation.](image-url)
In formula (6), $V$ represents the number of iterations and $\omega_{\text{max}}$ and $\omega_{\text{min}}$ both represent the weight. The former is the maximum and the latter is the minimum.

After improving the global search capability of the infrared technology and completing the self-optimization of the infrared technology, in order to enable the infrared technology to quickly complete the search of the global intelligent substation electrical equipment thermal fault classification and identification results [19, 20], the parameters are optimized. The optimized parameters are penalty factors and nuclear parameters, which are expressed in $c$ and $g$, respectively. Then, the calculation formula of the optimized fitness $c(x)$ function is as follows:

$$c(x) = \sum_{i=1}^{n} \left[ (f - f_0)^2 \times \lambda' \right].$$  \hspace{1cm} (7)

In formula (7), $f$ and $f_0$ both represent output results. The former corresponds to the actual, and the latter corresponds to the expectation; $n$ indicates that the quantity that corresponds to the sample of the check set.

Infrared technology is used to identify the thermal faults of electrical equipment in different types of intelligent substations. The specific operation process is shown in Figure 5:

3.1. Training Phase. Through the collected thermal fault data of electrical equipment in intelligent substation, feature extraction, dimension reduction, and other operations are carried out to obtain the training sample set, and appropriate kernel functions are selected for model training [21–23].

3.2. Fault Identification Stage. Through the thermal fault data of electrical equipment in the intelligent substation in the training stage, the decision-making output value of the test sample is calculated and obtained, and the classification decision is made through the output value of the function [24, 25].

After the fault is identified, HHT is used to analyze the zero sequence voltage signal and ordered current signal within one cycle after the fault, and the preliminary classification steps of thermal faults of electrical equipment in intelligent substation are given in Figure 6.

According to the preliminary classification of thermal faults of electrical equipment in intelligent substation as shown in Figure 6, when the line fault is determined to be low resistance fault, we analyze and process the fault voltage and data to determine the fault type and phase. HHT is used to process the three-phase voltage and three-phase current signals within one cycle after the fault, and the Hilbert spectrum of the signal is obtained [26]. Because the Hilbert spectrum contains abundant transient information, fault information can be extracted. The fault eigenvector is constructed by the instantaneous amplitudes of IMF1 and IMF2. At the same time, the dimensionality of the constructed point fault eigenvector is reduced, and the principal components of the fault eigenvector are extracted.

HHT is a new kind of nonlinear analysis because the transmission line of electrical equipment in intelligent substation will produce abundant transient components when faults occur. First, the stationary signal is divided into multiple intrinsic mode components IMF step by step according to the fluctuation or trend of different scales. The IMF is Hilbert-transformed to obtain the time-frequency spectrum of the signal, which has good time-frequency resolution, can better reflect the original characteristics of the signal, detect sudden change signals, and use HHT
method to establish the distribution line fault eigenvector of electrical equipment in intelligent substation.

Transmission line fault signals of electrical equipment in intelligent substations are nonstationary signals. Extracting feature information from nonstationary signals is the key to thermal fault identification. Because the high-frequency component can intuitively and sensitively describe the signal mutation. Therefore, different IMF components are decomposed through EMD, and the mutation degree of the later components at the mutation point will become weaker, and the information containing the original signal will become less and less. Generally, 1–2 IMF components can be selected to extract the original fault information. The specific structure of thermal fault identification of electrical equipment in intelligent substation is shown in Figure 7:

The specific operation steps are as follows:

1. The parameters in the transmission line fault of the electrical equipment in the intelligent substation are initialized, the scale and motion space are set, the initial fitness is calculated respectively, and the optimal position of the individual is updated at the same time.

2. Judge whether the thermal fault meets the conditions of current update. If the conditions are met, update the level, and then update the position; on the contrary, the location is updated directly to calculate the fitness value and the optimal location of each individual.

3. We judge whether the termination conditions of the algorithm are met and output the optimal value at the same time. Otherwise, we return to step (2).

4. Output-output thermal fault identification characteristics, and we set the individual with the best fitness value as the optimal individual.

To sum up, the research on thermal fault identification of electrical equipment in intelligent substation based on infrared technology is completed.

4. Experimental Analysis

In order to verify the application performance and effect of thermal fault identification of electrical equipment in intelligent substation based on infrared technology, the electrical equipment in intelligent substation of a power enterprise is taken as the research object to obtain the relevant data of the equipment. In the process of data collection, in order to ensure the accuracy and comprehensiveness of the collected data, combined with the geographical environment and transmission line category of the electrical equipment in intelligent substation of the enterprise, the step length of the acquisition line is set as 3 km. The collection time was two months, and a total of 10 groups of data were obtained and fault 1, fault 2, and fault 3, respectively. The number of three types of hidden troubles is 10, 15, and 13, respectively. The above three hidden troubles have development characteristics, which are easy to cause insulation damage of transmission lines of electrical equipment in intelligent substations, tower tilt, leakage, and power operation faults.

During the experiment, the reactor is used as the experimental equipment, and the normal fluctuation state of inter-turn short-circuit interface is preset. When the input voltage meets the rated voltage, the reactor production standard and power grid conditions are checked. If it meets the grid application requirements, the input voltage is loaded to 540 V. The maximum number of iterations is 200, and the learning factors $c_1$ and $c_2$ are 1.4 and 1.6, respectively. Under different influence factors, the thermal fault of electrical equipment in intelligent substation presents different characteristic parameters and sensitivities. In order to clearly describe the fault characteristics, kurtosis, variance, phase lead, and other characteristic quantities are used to describe the time-domain characteristic parameters, which are described in Table 1.

According to the parameters in Table 1, in order to accurately obtain the thermal fault characteristic band filter signal of electrical equipment in intelligent substation, the uniform division method is adopted to divide all time-domain characteristic parameters, which is completed by wavelet decomposition, and is orthogonal wavelet. The frequency domain characteristic parameters are described by the sub-band frequency-filtered signal obtained after division, and the following can be obtained based on the Parseval identity:

$$D_F = \frac{\sum |d_K|^2 \times F_G}{R_T}. \tag{8}$$

In formula (8), $F_G$ represents frequency domain characteristic parameters; $d_K$ represents wavelet packet
coefficient; and $R_T$ indicates threat coefficient. Based on formula (8), it is concluded that $D_F$ has energy dimension, which can be used for energy feature extraction. The specific flow of the experiment is shown in Figure 8:

In order to test the feature extraction performance of hidden faults of power transmission lines in this method, the time-domain characteristic parameter results are taken as the measurement standard according to the process in Figure 8. Taking hidden faults of power transmission lines as an example, this method is used to obtain the time-domain characteristic parameters of thermal fault identification in Table 1, and the influence level of this parameter on different types of hidden faults is calculated by formula (8). The average value of the calculation results is taken as the result, which is described in Table 2.

According to the results in Table 2, there are certain differences in the results of the five time-domain characteristic parameters of the transmission line thermal fault categories of electrical equipment in the three intelligent substations, and there are certain differences in the influence of the five time-domain characteristic parameters on the three thermal faults. Among them, the average values of the three time-domain characteristic parameters of phase lead, frequency mean, and amplitude square root mean are

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Time-domain characteristic parameters</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kurtosis</td>
<td>The numerical statistic reflecting the distribution characteristics of random variables is the normalized fourth-order central moment</td>
</tr>
<tr>
<td>2</td>
<td>Variance</td>
<td>A measure of the degree of dispersion of a random variable or group of data measured in probability theory and statistical variance</td>
</tr>
<tr>
<td>3</td>
<td>Phase lead</td>
<td>During the change process of several sinusoidal AC flows with the same frequency, they reach zero first relative to the timing starting point $t = 0$</td>
</tr>
<tr>
<td>4</td>
<td>Frequency mean</td>
<td>The mean value of the sample frequency distribution, that is, the weighted mean value of the group median with the group frequency as the weight</td>
</tr>
<tr>
<td>5</td>
<td>Root mean square value of amplitude</td>
<td>The square root of the mean of the sum of squares of the amplitudes</td>
</tr>
</tbody>
</table>

**Table 1: Detailed setting table of characteristic quantity parameters.**

<table>
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</tr>
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<td>5</td>
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<td>The square root of the mean of the sum of squares of the amplitudes</td>
</tr>
</tbody>
</table>

**Table 2: Time-domain characteristic calculation results of thermal fault identification.**

<table>
<thead>
<tr>
<th>Time domain characteristic parameters</th>
<th>Thermal fault 1</th>
<th>Thermal fault 2</th>
<th>Thermal fault 3</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurtosis</td>
<td>0.781</td>
<td>0.657</td>
<td>0.695</td>
<td>0.711</td>
</tr>
<tr>
<td>Variance</td>
<td>0.802</td>
<td>0.788</td>
<td>0.813</td>
<td>0.801</td>
</tr>
<tr>
<td>Phase lead</td>
<td>0.286</td>
<td>0.298</td>
<td>0.277</td>
<td>0.287</td>
</tr>
<tr>
<td>Frequency mean</td>
<td>0.218</td>
<td>0.265</td>
<td>0.222</td>
<td>0.235</td>
</tr>
<tr>
<td>Root mean square value of amplitude</td>
<td>0.013</td>
<td>0.022</td>
<td>0.022</td>
<td>0.019</td>
</tr>
</tbody>
</table>
relatively low, indicating that they have a low degree of influence on the thermal fault. Among them, the mean results of kurtosis and variance are the highest, indicating that these two parameters have a high degree of influence on the thermal fault. Therefore, this method has good performance of thermal fault feature identification.

The thermal fault features of electrical equipment of substation are extracted. The thermal fault includes high-frequency fault and low-frequency fault. The thermal fault identification results are shown in Figure 9.

According to the analysis of Figure 3, the output stability of this method for thermal fault identification of substation electrical equipment is high. In order to test the advantages of thermal fault identification after optimization of this method and obtain the error results of thermal fault identification of power transmission lines of substation electrical equipment before and after optimization under different iteration times, so as to measure the optimization advantages of this method. The results are described in Figure 10.

It can be seen from the results in Figure 10 that before the optimization of this method, with the gradual increase of iteration times, the error result of thermal fault identification for power transmission lines of substation electrical equipment gradually decreases. When the iteration times of the method before the optimization are 40, the error result reaches a stable state; after optimization, the error results of this method reach a stable state when it is about 20 times. The results show that the identification effect of this method is better after optimization.

With the reactor load of the fixed smart substation unchanged, we test the identification ability of the thermal fault location of the methods in this paper, reference [8] and reference [9]. The identification performance of the identification model for the thermal fault location of electrical equipment is shown in Figure 11.

It can be seen from Figure 11 that the early warning data count of this method at any thermal fault location is higher than 65 times, indicating that this method has high identification accuracy for thermal fault location and can receive early warning signals in a large range and accurately identify
the thermal fault location. The count of early warning data of thermal fault sites in the reference [8] method shall not exceed 40 times, and the count of early warning data of thermal fault sites in reference [9] method shall not exceed 35 times. Through the above comparison, it can be seen that this method is more detailed and clear for the identification of thermal fault signals, indicating that this method is highly sensitive to the location of thermal fault of electrical equipment.

5. Conclusion and Prospect

5.1. Conclusion.

(1) The five time-domain characteristic parameters have different influence on the three thermal faults. Among them, the average values of the three time-domain characteristic parameters of phase lead, frequency mean, and amplitude square root mean are relatively low, and the mean results of kurtosis and variance are the highest. This method has good thermal fault characteristic identification performance.

(2) The thermal fault identification method of electrical equipment in intelligent substation based on infrared technology has high output stability.

(3) Before the optimization of this method, with the gradual increase of iteration times, the error results of thermal fault identification for substation electrical equipment and power transmission lines are gradually reduced and the identification effect is better after optimization.

(4) The early warning data counts of this method at any thermal fault location are higher than 65 times, which shows that this method has high accuracy in identifying the thermal fault location, can receive early warning signals in a large range, accurately identify the thermal fault location, and has highly sensitive identification ability.

5.2. Prospect. With the continuous development of science and technology and power system, electrical equipment has been widely used in many fields, such as intelligent video monitoring equipment, large-scale automatic operation devices in factories and cable line insulator monitoring equipment. While the electrical equipment of intelligent substation brings convenience to people’s life, the potential safety hazards of electrical equipment caused by long-term high-intensity operation environment must also be paid attention to. Once equipment failure occurs, the operation of power system in the whole country will be seriously affected. The fault identification of electrical equipment in intelligent substation by manual operators has the disadvantages of heavy operator workload, increasing human eye fatigue, and strong subjective participation in manual judgment. Therefore, eliminating manual operators to detect equipment faults and substituting intelligent fault identification model are the focus of safety maintenance of intelligent substation. The challenge of how to improve the selection of experimental data and make the experimental data empirical is the key content of the next research work.

Data Availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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