Research on Multi-frequency Ultrasonic On-Line Monitoring Technology of Transformer Oil Based on Neural Network

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***Abstract*—:The distribution network is directly oriented to terminal users, which can guarantee the reliability of residential and industrial production power supply. The distribution transformer is an important equipment of the distribution network. It has a wide distribution range and a large quantity，so the safe and reliable operation of the distribution network is the key to guaranteeing users' normal production and living. However, judging from the accidents that have occurred in recent years, many transformer accidents do not have any symptoms before they occur. This shows that the current routine test projects and test cycles still have certain limitations, and some accident precursor information cannot be captured in time. Taking into account the limitations of traditional detection methods, it is necessary to add effective monitoring methods to distribution transformers in a timely manner. This paper proposes a transformer oil condition monitoring method based on multi-frequency ultrasound. We obtained oil samples from 88 transformers that are running in the substation. First, in the laboratory, the oil samples are tested for the breakdown voltage and dielectric loss factor , micro water and acid value these four parameters. According to the multi-indicator comprehensive analysis, the status of the selected transformer oil samples is classified, and then a new type of multi-frequency ultrasonic equipment is used. Separately fired a beam of ultrasonic waves of different frequencies into each set of oil samples, and various parameters of ultrasonic waves obtained by the ultrasonic receiver module in real time. Then utilize the neural network to process ultrasonic parameters (wave speed, amplitude and phase angle of 240-dimensional data of the three-phase ultrasonic waves at 40 frequency points) and establish the relationship between ultrasonic spectrum parameters and the transformer oil state. The mapping relationship enables real-time, accurate and comprehensive monitoring of the state of transformer insulation oil.**

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I. INTRODUCTION

Power equipment is an important part of the power grid. Safe and stable operation of power equipment is an essential factor in ensuring the normal operation of the power system. The transformer is one of the most important power equipments in the power system. Monitoring the status of the transformer in a timely manner is of great significance for maintaining the reliable operation of the power system [1-3]. Since the 1950s, with the concept of "power system equipment monitoring", different monitoring methods have appeared one after another. From the 1980s to the 1990s, the development of computer technology, sensor technology, and optical fiber technology has improved the state monitoring and fault diagnosis of power equipment.

At present, the detection methods for transformers at home and abroad are mainly used for oil analysis experiments, partial discharge analysis, and ultrasonic fault location [4-7]. However, in these methods, transformer oil detection is not only complicated in the operation process, but also introduces errors in the inspection process. In addition, according to the detection cycle of oil extraction experiments, the oil samples are regularly collected every year, and the real-time information of the transformer operating status cannot be provided, and it is difficult to make a real-time and accurate judgment on the status of the transformer insulation oil. The occurrence of many transformer accidents without warning in recent years also confirms the limitations of the current routine experiment methods and experimental cycles. In order to improve the safety and stability level of smart grids and the management benefits of power grid equipment, it is necessary to strengthen and improve the monitoring ability of transformers and the continuity of prevention in the future.

Therefore, it is necessary to add effective monitoring methods for transformers in a timely manner.

The multi-frequency ultrasound on-line monitoring technology of transformer oil based on neural network can install multi-frequency ultrasonic device in transformer oil tank. Under the condition of real-time monitoring of transformer oil status level, it is not affected by the electromagnetic environment of the site, with good real-time performance and accuracy.There is no need to separately prepare the sample for full online measurement. It is a method for monitoring transformer oil status that is worth promoting.

The transformer oil online monitoring equipment based on the principle of multi-frequency ultrasonic , through the study of the material's sound velocity, density, acoustic attenuation, elastic coefficient and other macroscopic quantities, to reveal the essence of the microscopic world of substance. That is, the property and state of the transformer oil can be determined by detecting the ultrasonic parameters propagated in the transformer oil [8, 9]. Using a multi-frequency ultrasound device, the device can simultaneously send a beam of 40 different frequencies of ultrasonic waves to the liquid medium. At the same time, the ultrasonic receiver module can receive three groups of ultrasonic signals at different frequencies from three different positions of the probe. The ultrasonic amplitude and phase angle data, as well as the ultrasonic propagation velocity in the liquid, are measured. For details, see section 3.2. The transformer oil sample in practical application is selected to measure the ultrasonic parameters and oiling experimental parameters (including acid value, micro-water, dielectric loss, breakdown voltage, etc.) separately. Firstly, several laboratory measurement parameters are synthesized. The new oil value and the national standard value are the boundaries, and the transformer oil is graded. Then the BP neural network is used to correlate the data, and the correlation between the multi-frequency ultrasonic data and the oil sample grade is determined, and partial oil sample data is used for verification. This algorithm is used to establish the correlation between multi-frequency ultrasonic scan data and transformer oil status levels, and the validity of the transformer oil quality online monitoring method based on multi-frequency ultrasound is verified by the accuracy of network identification. The specific research work is summarized as follows:

(1) For the transformers with different operating conditions in the field, select 88 groups of samples and measure ultrasonic spectrum data and experimental parameter; (The ultrasound scanning experiment for each group of oil samples takes 4 hours, and the data collection requires a lot of time, so current data volume is limited)

(2) According to the multi-indicator comprehensive analysis of the oiling experimental parameters, three levels of good, common, and attentional grades are assigned to the transformer;

(3) The neural network algorithm is used to establish the correlation function of the multi-frequency ultrasonic data and transformer oil state levels, and the correctness of the correlation is verified;

(4) To summarize the rationality and effectiveness of mapping the transformer oil status with multi-frequency ultrasound.

II. Introduction to the Experimental Platform

A. Introduction to Experimental Principle

Ultrasonic detection technology is a technique for obtaining the physical and chemical properties of the measured substance through the interaction between high-frequency sound waves and substances. This technique uses ultrasonic waves to propagate in the medium and measures the propagation speed, acoustic impedance, and acoustic attenuation of the acoustic wave and other parameters related to the characteristics and state of the medium. To determine the characteristics of the media and composition changes through these acoustic measurements, and then determine the physical and chemical properties of the media [10].

Ultrasonic testing has the advantages of non-invasive, fast, real-time, and no preparation of samples. According to the existing research results at home and abroad, ultrasound can respond to information such as density, viscosity, bubble size, gas content, and impurity content in the medium [11,12]. Therefore, ultrasonic testing technology is gradually applied in the fields of medicine, materials science, oceanography and chemical engineering. In recent years, the use of liquid food detection systems has also gradually increased.

In this paper, according to these characteristics of ultrasonic testing, a multi-frequency ultrasonic testing system for transformer oil parameters is used for experiments. The device can simultaneously transmit a beam of ultrasonic waves of different frequencies to the medium to be detected, and achieve the purpose of monitoring the transformer oil through the measurement of the ultrasonic parameters. The measured multi-frequency ultrasonic data is the multi-dimensional spectrum of the “response” of the multi-frequency ultrasonic signal to the detected object (transformer oil sample). This multidimensional spectrum is closely related to the state of the transformer oil. The components that determine the state of the transformer oil include the oil aging product, the acid value of the oil, the water content, the number of particles, the surface tension, the volume resistivity, and the dielectric dissipation factor.The specific implementation ideas are shown in Figure 1.

B. Introduction of Experimental Equipment

The multi-frequency ultrasonic testing system for transformer oil parameters includes three main modules: a multi-frequency ultrasonic sensor, an ultrasonic transmitting and receiving control module, and a data processing module.

The system work overview block diagram is shown in Figure 2.

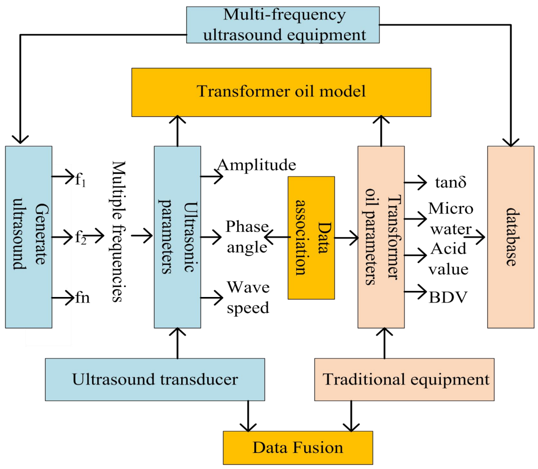

Fig.1 Project implementation idea

The ultrasonic transmitting and receiving control module is internally equipped with a multi-frequency ultrasonic generating device. The multi-frequency ultrasonic generating device cooperates with the ultrasonic transmitting module to generate an ultrasonic beam of specific frequencies required by the experiment and outputs it through the ultrasonic output interface. The transmitted ultrasonic wave propagates through the medium to be detected (transformer oil sample) and is received by the ultrasonic signal receiving module and converted into a digital signal by the signal processing circuit. These digital signals are then transmitted through the port to the data processing module. The output signal is controlled by the frequency control module and the power control module. The power control module can determine the height and width of the generated pulse. The frequency control module determines the carrier frequency, thereby ensuring that the transducer emits an appropriate ultrasonic signal.

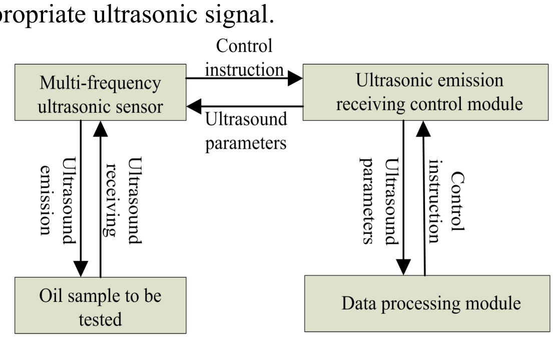

Fig.2 Principle of system

III. Experimental oil sample status classification

At present, the assessment method of the state of transformer oil is not the same, and there has not been a uniform division standard and division method. Since the main task of this paper is to train the correlation between ultrasonic parameters and transformer oil laboratory parameters, state division should be based on the characteristics of current data. The data sample of this paper is extracted from the substation transformers . The oil samples are basically normal. Therefore, the breakdown voltage, acid value, dielectric loss angle factor, and micro water are selected. The four important indexes are calculated and analyzed by using the corresponding values of the new oil for each index and the specified value of the national standard. The transformer oil is divided into three levels: good, common, and pay attention.Due to the majority of transformer 110kV and 220kV voltage levels in substations of Guangdong Power Grid, the voltage ratings of all sampling transformers in this paper are 110kV and 220kV.

This article divides the transformer oil into three states S1, S2, and S3, namely, good state, normal state, and attention state. Each state is synthesized by the above four indicators, each of which has its own rating. The four indexes of the new oil were measured in advance under normal experimental conditions as initial values, and the corresponding national standard values were also introduced for calculation. When the test data value is better than the new oil measurement value, the index is good, marked as 2 (before the new oil is injected into the transformer, it needs to be filtered, purified, kerosene dehydration and other operations, so the transformer oil index may be better than the new oil in the laboratory). When the experimental data is inferior to the new oil value but better than the national standard value, the indicator is normal and is in the normal state, and is recorded as 1; when the experimental data is inferior to the national standard value, the transformer oil needs to pay attention at this time, that is attention status, denoted as 0. The initial value and national standard value of each index are shown in Table 1.

TABLE I
INITIAL VALUES OF FOUR INDICATORS (NEW OIL MEASURED VALUES) AND NATIONAL STANDARD VALUE

	Initial values	national standard value
BDV（kV)	57.2	≧40
Micro water content(μL/L)	6	≦25
Acid value(mgKOH/g)	0.007	≦0.03
Tanδ (90℃)%	0.071	≦1

Here, the relative degradation degree is introduced in the operates on the state index, and the state level of the index is determined based on the calculation result. Assume that Xr is the experimental measurement value of the state indicator, X_0 is the measured value of this indicator of the new oil, and X_g is the national standard value of the indicator.

For the micro-water, acid value and dielectric dissipation factor, the smaller the three values are, the better the condition is. According to equation (1), the single state level Xn of the oil sample is calculated. When Xs is less than 0, the indicator is good, and the state value Xn is denoted as 2; when 0<Xs<1, the index of the oil sample is normal, and Xn is 1; and when Xs>1, the oil sample is in the attention state and Xn is 0.

$$X_s = \frac{X_r - X_0}{X_g - X_0} \tag{1}$$

For the index that the larger the breakdown voltage is, the better the condition is, and the correlation between the range of the calculation result and the index state level is the same as above.

Xn subscripts n=1, 2, 3, 4 represent four indicators of breakdown voltage, acid value, dielectric loss angle factor, and micro-water respectively. After the indicator status levels are determined, the status values of the transformer oils are multiplied to determine the overall status of the transformer oil. The formula for calculating the overall status level X is Equation (2). If an indicator status value is 0, the product of the status value is 0. That is, if one of the four indexes of the oil sample is in an abnormal state, the status value is 0, and the transformer oil is in the attention state as a whole. If all four indicators are normal (the state value is 1), the oil sample is in the normal state, and on the basis of satisfying the normality of each indicator, any indicator is good, ie, if the state value is greater than 1, the transformer oil status is good. And in order to use the status level as the output of the neural network, the three status levels are each binary-marked.

$$X = X_1 * X_2 * X_3 * X_4 \tag{2}$$

We obtain the correlations between the state values and the state levels of the oil samples and the status flags by using the boundary division and prescribed formulas. The results is shown in Table 2.

TABLE II

CORRELATION BETWEEN STATUS VALUES AND STATUS LEVELS

Status Value	Oil Sample Status	Status tag
X>1	good	100
X=1	normal	010
X=0	attention	001

IV. BP NEURAL NETWORK ESTABLISHES CORRELATION MODEL BETWEEN ULTRASONIC PARAMETERS AND OILING EXPERIMENTAL PARAMETERS

A. Introduction to BP Neural Network Model

BP neural network (also referred to as error back propagation network) is one of the most representative and widely used artificial neural network modes at present, and has the characteristics of being able to approximate arbitrary functions with arbitrary precision. BP neural network is a multi-layer feed forward neural network. Its internal structure consists of input layer, hidden layer, and output layer. The number of hidden layers can vary with the characteristics and scale of data. It can be a single layer or multiple layers. The internal calculation process of the network is that the input layer constitutes the input layer and is calculated layer by layer through the hidden layer until reaching the output layer. In this process, the state of each neuron can only affect the state of the next neuron. If after this calculation process the output obtained does not match the expected value, the error will be returned along this calculated path, the thresholds and weights of each layer are adjusted layer by layer until the input layer is repeated and the above process is repeated. When the output layer error is less than the set accuracy, the network learning process ends [13].

Based on the above introduction to the network structure and the existing data structure, the neural network designed in this paper uses the feature values such as amplitude, phase, and wave velocity at each frequency point as the input layer to evaluate the results of the oil sample state evaluation. The sample level is the output layer. Through neural network learning, two sets of data are matched to establish the correlation between the two. Therefore, the real-time monitoring of the transformer oil ultrasound data achieves the purpose of predicting the status of the oil sample. In the process of modeling existing data, the number of internal network layers, the number of neuron nodes at each layer, the type of transfer function, and the training algorithm are required to determine.

B. Introduction of Transformer Oil Condition Evaluation Network Model

The amount of data involved in this network is large, and the form and actual meaning of the ultrasound data are described here. The signals collected by the multi-frequency ultrasonic instrument include the amplitude and phase of the three-dimensional 20 main frequency points and 20 offset frequency points of each oil sample and a total of 240-dimensional data(3×(20+20)×2=240) and the speed of ultrasonic wave propagation in this oil sample. Frequency difference between each offset frequency point and main frequency deviation is 1 kHz. It is mainly used to differentiate differential frequency points. We can only study primary frequency points . The three-phase signals L1, L2, and L3 are the ultrasonic signals detected by the probes at different installation positions, respectively. Among them, the sensor probe device structure: sensor T1 - medium - measuring room -

sensor T2. T1 sends an ultrasonic signal through the medium to the measurement room and T2. The ultrasonic waves passing through the medium are divided into two parts. One part is reflected back to T1, and the other part is transmitted to T2, the parameter returning to T1 is L1, the part transmitted in the measuring chamber medium reaches T2, and the measured parameter is L2; the signal reaching the T2 part is reflected back again and passes through the measurement room and the medium to reach T1 again, and the parameter is L3. According to its practical significance, only the L1 phase signal is completely reflected by the catadioptric reflection of the transformer oil medium, and the ultrasonic signal is not affected by the material of the measuring chamber. Therefore, when we study the characteristics of the transformer oil, L1 phase is the best signal of reducibility. In summary, the amplitude, phase, and wave velocity signals at each main frequency point of the L1 phase can best represent the data characteristics of the ultrasound spectrum.

However, due to the large scale of data at this time, in order to eliminate redundant information on the basis of retaining the main information of the data and achieve the purpose of effectively characterizing high-dimensional data with low-dimensional data, principal component analysis (PCA) is used before data input. To reduce the dimension of ultrasound data[14]. The PCA results show that the cumulative contribution rate of the first 12 principal components after dimension reduction is 95.54%, and the cumulative contribution rate of the first 23 principal components is 99.11%. Therefore, this 23-dimensional principal component eigenvalue of PCA is imported into the network as the input layer of the BP neural network.

The output layer data is composed of the results of oil sample status classification. From the calculation and analysis of the second section, all state levels of the 88 oil samples of the subject were obtained. One set of oil sample data was incomplete and was removed. Of the remaining 87 groups, 68 were in good condition, 4 groups were in normal state, and 15 groups were in a state of attention.

Select 70% of the data as training data, 15% of the data as verification data, and 15% of the data as test data. Establish a BP neural network with back propagation algorithm. The number of hidden layers is determined by the formula $n = \sqrt{a+b}$ [15] (a and b are the number of input nodes and the number of output nodes, respectively). After each parameter is determined, the MATLAB pattern recognition toolbox is used to select the NARX data type to train, verify and test the network. From the output of the Confusion Matrix, it can be known that the correct rate and error rate of the training sample and the verification sample are shown in Fig. 3, and the corresponding MSE curve is shown in Fig. 4.

The test data identification result of the selected 15% sample shows that: in the test set sample, the identified good state oil sample 8 groups, the common state oil sample 2 group, and the attention state oil sample 2 group. The accuracy of the test set was 92.3%.

From the output results, it can be seen that after 12 iterations of the neural network, the network convergence is smooth and less oscillating, and the error is stable in a small value range. At this time, the overall accuracy of the network output by the Confusion Matrix is 95.4%. And the MSE value is close to 0. In summary, the pattern recognition accuracy of this network can reach 95% or more, and it can effectively classify the transformer's state level through ultrasound parameters.

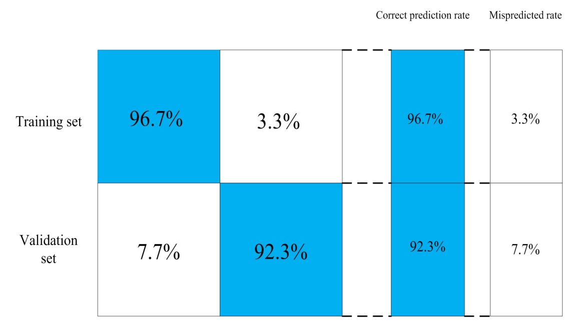

Fig.3 Predictive rate of training samples and validation samples

Using neural network and its pattern recognition toolbox, the state of transformer oil can be effectively identified. If the input data scale is larger and the status of oil samples is more widely distributed, the data separability will be enhanced, and the number of output nodes of the classification network will also increase, that is, the types of transformer oil status assessment levels will increase accordingly.

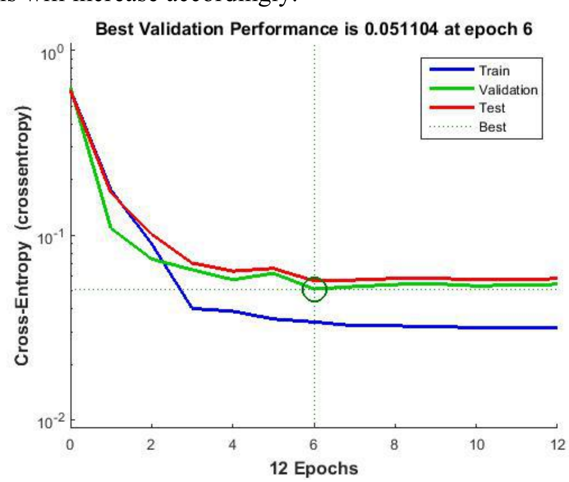

Fig.4 MSE curve of Neural network output

V. CONCLUSION

The measurement method based on multi-frequency ultrasonic technology is used in the experiment process of this paper. The ultrasonic spectrum scanning parameter and the oiling parameter measurement of the transformer oil are separately performed, Then we obtain the correlation between the two databases. From the confusion matrix, mean square error, and regression curve output by BP neural network, it can be seen that the accuracy of associating ultrasonic data with transformer oil state level data using BP neural network is high, and it is an effective method for on-line monitoring of transformer oil quality. .

The number of samples and type of the samples still have a lot of room for promoting, and the application of the new algorithm in building correlations remains to be explored [16]. In the application of transformer oil quality online monitoring technology based on multi-frequency ultrasound, the database and various algorithms can be further improved.

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