A Transformer Vibration Signal Separation Method Based on BP Neural Network

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***Abstract*—The power transformer is one of the most important power equipment in the power system, whose operation reliability is related to the safe and stable operation of the power system. Therefore, the transformer fault diagnosis has been paid much attention by the researchers. The mechanical fault diagnosis method based on the vibration signal of the tank surface has been widely studied because the measurement system has no direct electrical connection with the transformer and has a strong anti-interference ability. The traditional vibration signal analysis method generally analyzes the mixed signal on the surface of the transformer tank, and can't effectively evaluate the mechanical state of the winding and the core. Therefore, it is of great significance to carry out the research on the vibration signal separation technology of transformer. In this paper, a vibration signal separation technique for transformer oil tank surface based on BP neural network is proposed. The average value of the waveform similarity coefficient of the core vibration signal is 0.813, the average value of the waveform similarity coefficient of the winding vibration signal is 0.834, which is an ideal effect. It provides an important technical method for the effective evaluation of the mechanical state of the winding and the core.**

Keywords—transformer; BP neural network; winding; core; vibration signal separation

I. INTRODUCTION

The power transformer is one of the most important power equipment in the power system. Once it fails, it may lead to large-scale blackout which is very serious and may cause huge economic loss and even casualties. The power transformer has long overhaul period, large cost and wide influence. Therefore, it is of great significance to study the fault diagnosis and state evaluation of the power transformer to ensure the safe and reliable operation of the whole power system.

Over the years, statistics show that windings and cores are one of the components with high failure rate in transformers. According to statistics, the annual failure rate of the transformer winding and core of the 110kV and above voltage grades of State Grid Corporation of China is about 81.8%[1]. The analysis of transformer faults in Shandong province by the Shandong Electric Power Research Institute shows that the transformer winding damage caused by the external short circuit fault accounts for the 34% of the total obstacle statistical data[2]. It can be seen that the deformation of transformer winding caused by the lack of short circuit ability is one of the main causes of power transformer damage, and the defects of the transformer are mainly distributed on the parts of the core and winding.

The transformer diagnosis method based on vibration signal is widely researched due to its no direct electrical connection with the transformer and strong anti-interference capability[3]. At present, the vibration signal analysis method generally analyzes the mixed signals on the surface of transformer oil tank, and the signals contain a lot of vibration information of the core and winding. The vibration of the transformer produced from the vibration sources such as winding, core and air cooling device[4], and then interact with each other, the final mixed signals pass through fasteners, transformer oil and other transfer media to the tank surface. If the vibration signal on the surface of the tank is analyzed directly, the mechanical state of the winding and core can't be evaluated effectively. Therefore, it is of great significance to study the separation of vibration signals on the surface of the transformer oil tank for the transformer state monitoring technology based on the vibration signal analysis method. In this paper, the vibration signal separation technology of transformer oil tank surface based on BP neural network is proposed, which is based on the vibration characteristics of the winding and core, and its effectiveness is verified.

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II. VIBRATION MECHANISM OF TRANSFORMER

A. Vibration Mechanism of Core

The core of the transformer is usually made of silicon steel. As silicon steel is a magnetic material with high magnetic permeability, high magnetic induction intensity is produced in the coil. Therefore, in order to reduce eddy current losses, cores are laminated with silicon steel sheets insulated from each other.t, as shown in Fig. 1.

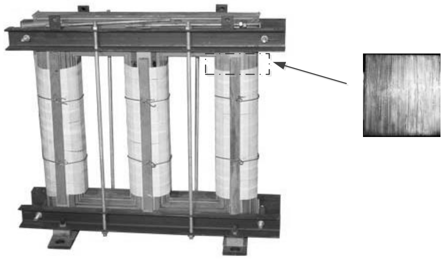

Fig. 1. Transformer core structure diagram

When the yoke is tight enough and silicon steel is tight enough, it can be considered that the vibration of the core comes mainly from the magnetostriction effect of silicon steel sheet. The period of magnetostriction is half of the supply current cycle, so the fundamental frequency of core vibration is two times the power frequency. Because of the nonlinearity of the core magnetostriction and the difference of the flux path along the inner frame and the outer frame of the core, the vibration spectrum of the core also contains the high order harmonic components except the fundamental frequency.

Under the linear condition of magnetic field intensity and magnetic induction intensity, the vibration acceleration is proportional to the voltage square. However, considering the nonlinearity of the core material and the possible saturation in the operation, the 100Hz harmonic component with a high amplitude generally exists in the vibration of the core.

B. Vibration Mechanism of Winding

The vibration of the winding is mainly caused by the periodic electromagnetic force of the wire winding passing through the current in the leakage magnetic field. Under normal circumstances, the axial force and the radial force of the winding are analyzed. The axial force causes the winding to compress to the middle. This mechanical stress produced by the electric power may affect the turn-to-turn insulation of the winding. And the radial force causes the winding to expand outward, which may lose the stability and cause the insulation damage between the phases.

The electromagnetic force of the winding is proportional to the square of the current. The vibration acceleration of the winding is proportional to the square of the current. The fundamental frequency of the winding vibration is 2 times the current frequency. In actual operation, there is a certain amount of harmonic component in the current passing through the winding, and vibration is influenced by the nonlinear material such as the insulation pad. The vibration signals of the windings contain harmonic components.

III. EXPERIMENTAL METHOD AND EXPERIMENTAL SYSTEM

A. BP Neural Network

BP neural network is a multi-layer neural network with three or more layers. There are several neurons in each layer. As shown in Fig. 2, there are no connections between the upper and lower neurons and all the neurons in the left and right layers are all connected. The BP neural network is trained by the supervised learning mode. When a pair of learning modes is provided to the network, the activation value of the neuron is propagated from the input layer to the output layer through the hidden layer, and the corresponding network response is output at each neuron in the output layer. Then, according to the principle of reducing the error between output and actual output, each weight is modified from the output layer to the input layer, which is called error back propagation algorithm. With the continuous modification of error propagation training, the accuracy of network is increasing. From the above analysis, the BP neural network is applicable to the case where the output signal has no feedback effect on the input signal, and is suitable for separating the vibration signals of the winding and the core. In general, the learning steps of BP neural network are as follows:

(1) Initialize learning parameters and network, such as setting learning factors, network initial weight matrix and so on.

(2) Provide training samples for training until the error requirements are met.

(3) Forward propagation process: For a given training input samples, the output of the network is calculated and compared with the expected result. If there is an error, the step (4) is executed, or the return step (2).

(4) Back propagation process: Calculate the error of the same layer, modify the threshold and weight, and return to step (2).

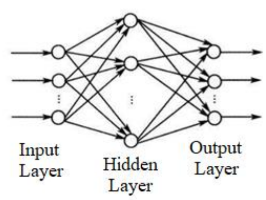

Fig. 2. BP neural network

B. Experimental System

According to the mechanism of transformer vibration, the no-load test and steady state short-circuit test of transformer are carried out respectively. In the no load test, the winding only has a very small excitation current, so the transformer vibration in the test can be considered as generated only by the core [5]. In the steady state short-circuit test, when the current is large enough, it can be considered that all the measured vibration signals come from the vibration of the winding.

The mixed signals measured on the tank surface of the transformer are used as the input layer, the vibration signal of the core and the vibration signal of the winding are used as the output layer, and the two BP neural networks are constructed at the same measuring point, and the trained network is used to separate the mixed signal. And winding vibration and core vibration are obtained. The test transformer used in this paper is a three-phase test transformer, and the layout of measuring points is shown in Fig. 3. The parameters of the transformer are SY-50/10, 50KVA and 10kV/400V.

The vibration signals under 400V no-load condition, which all are considered to come from the core, are used as the output layer. The mixed vibration signals under different load conditions are used as the input layer. The core neural network is built. And then, the vibration signals under 80A steady short circuit condition, which all are considered to come from the winding, are used as the output layer. The mixed vibration signals under different load conditions are used as the input layer. The winding neural network is built.

In order to test the separation effect of neural network, keep the condition of 400V, and different load test are carried out. The measured mixed vibration signals are used as the new input layer, and the vibration signals of the core and the winding are calculated by the learned neural network. The vibration signals of the core and the winding are compared with the corresponding operating conditions.

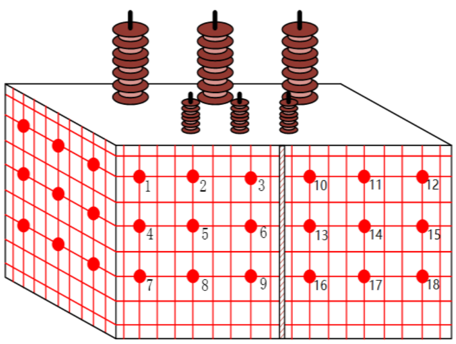

Fig. 3. Layout of measuring points on three-phase testing transformer

IV. Research on Transformer Vibration Signal Separation Technology Based on BP Neural Network

In the process of neural network training, 70% of data are used for training, as training sets; 15% of data are used as validation sets; 15% of data are used for test and as test sets. In Fig. 4, target represents the target result, and output represents the output data based on the learned neural network. R is the correlation coefficient, the range of R is [0,1], and the larger the R value, the higher the correlation coefficient. As shown in Fig. 4, the correlation coefficient of the core neural network training sets is 0.979, the correlation coefficient of the verification sets is 0.987, the correlation coefficient of the test sets is 0.978, the correlation coefficient of the total data is 0.979, which is close to 1. It is considered that the learning effect of the core neural network is good, and the mixed signals can be separated effectively.

In the same way, the correlation coefficient of the training sets of the winding neural network is 0.918, the correlation coefficient of the verification sets is 0.914, the correlation coefficient of the test sets is 0.914, the correlation coefficient of the total data is 0.917. The learning effect of the winding neural network is good, and the mixed signals can be separated by the learning network.

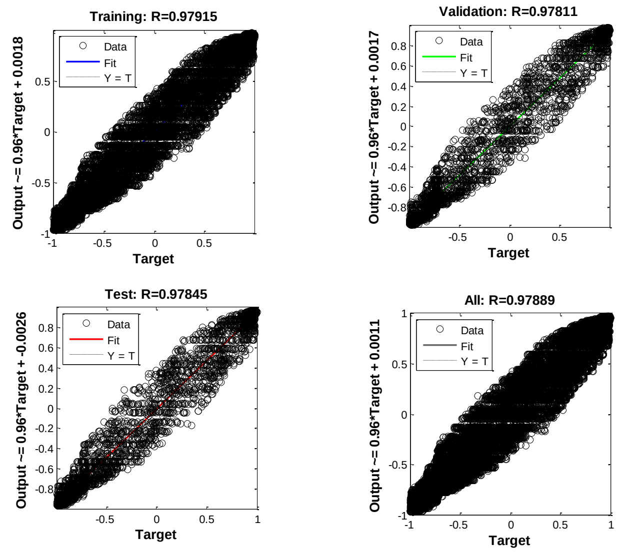

Fig. 4. The core neural network learning effectiveness

Taking the No. 1 measuring point as an example, this paper illustrates the separation effect of winding and core vibration signals based on BP neural network., as shown in Fig. 5. The blue curve is the core source signal based on the no-load test, and the red curve is the core signal separated from the BP neural network. From the time domain diagram, it can be seen that the core signals based on the no-load test is similar to the separated signals, but there is a certain phase difference. It can be seen from the frequency domain diagram that the vibration amplitude of the source signals and the separated signals at the base frequency 100Hz and the main frequency 200Hz are almost exactly the same. The effect is ideal.

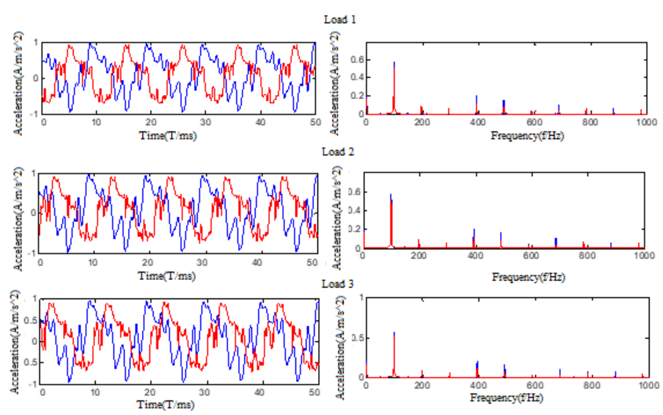

Fig. 5. The core neural network separation result

In order to quantify the separation effect of the neural network, the concept of waveform similarity coefficient is introduced [6]. The waveform similarity coefficient is defined as follows:

$$\lambda_{ij} = \lambda(y_i, s_j) = \frac{\sum_{k=1}^{M} \left| y_i(k) s_j(k) \right|}{\sqrt{\sum_{k=1}^{M} y_i^2(k) \sum_{k=1}^{M} s_j^2(k)}} \quad (1)$$

Where, M is the length of the signals, λ_{ij} indicates the degree of similarity between y_i and s_j. The range of λ value is [0,1]. When λ =1, it is considered that the two signal waveform is exactly the same.

The waveform similarity coefficient of the separation of the core neural network is almost above 0.8, and the average value of the waveform similarity coefficient is 0.813, as shown in Tab. 1. It is considered that the separation effect of the core network is generally feasible.

TABLE I. WAVEFORM SIMILARITY COEFFICIENT OF CORE NEURAL NETWORK

Load	**Measuring Point**					
	1	2	3	4	5	6
Load 1	0.932	0.913	0.923	0.956	0.519	0.60
Load 2	0.934	0.908	0.926	0.958	0.536	0.610
Load 3	0.946	0.916	0.938	0.968	0.580	0.642
Load	**Measuring Point**					
	7	8	9	10	11	12
Load 1	0.872	0.760	0.779	0.769	0.841	0.900
Load 2	0.732	0.643	0.465	0.776	0.832	0.902
Load 3	0.818	0.758	0.653	0.740	0.844	0.890
Load	**Measuring Point**					
	13	14	15	16	17	18
Load 1	0.789	0.650	0.766	0.949	0.851	0.95
Load 2	0.780	0.623	0.767	0.952	0.857	0.953
Load 3	0.805	0.605	0.746	0.952	0.859	0.955

Using the learned winding neural network to separate the mixed signals under different loads, as shown in Fig. 6. The blue curve is the source signal of the winding under different load conditions, and the red curve is the separated winding signal based on the BP neural network. There is a certain phase difference between the winding source signal and the winding signal separated by the neural network. In the frequency domain diagram, the vibration amplitude of the source signals and the separated signals is almost exactly the same, and the separation effect is generally ideal.

The waveform similarity coefficients of the winding neural network are shown in Tab. 2. It's found that when the load is low, that is the current is small, the separation effect is not ideal. With the increase of current, the waveform similarity coefficient is improved. This is because the lower the load, the smaller the current, the smaller the amplitude of the winding vibration, the smaller the signal-to-noise ratio, and the smaller correlation coefficient of the neural network. In actual operation, because of large current, the transformer has a high signal-to-noise ratio, so the separation effect can be ideal.

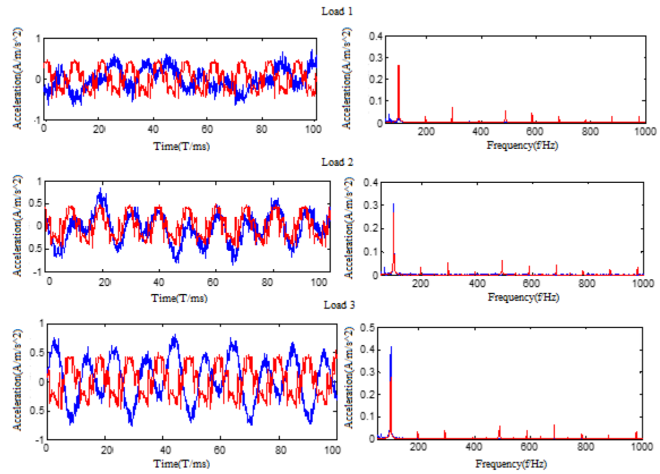

Fig. 6. The winding neural network separation result

TABLE II. WAVEFORM SIMILARITY COEFFICIENT OF WINDING NEURAL NETWORK

Load	**Measuring Point**					
	1	2	3	4	5	6
Load 1	0.435	0.378	0.373	0.422	0.412	0.485
Load 2	0.689	0.572	0.602	0.653	0.617	0.572
Load 3	0.826	0.793	0.853	0.825	0.782	0.795
Load	**Measuring Point**					
	7	8	9	10	11	12
Load 1	0.451	0.340	0.422	0.504	0.537	0.421
Load 2	0.616	0.625	0.609	0.621	0.681	0.652
Load 3	0.890	0.829	0.840	0.782	0.813	0.857
Load	**Measuring Point**					
	13	14	15	16	17	18
Load 1	0.465	0.49	0.463	0.664	0.462	0.749
Load 2	0.602	0.610	0.580	0.831	0.649	0.888
Load 3	0.796	0.825	0.795	0.918	0.840	0.950

V. CONCLUSION

This paper analyzes the vibration mechanism of transformer winding and core, and introduces the principle of BP neural network algorithm. Based on the BP neural network, the mixed vibration signal separation neural networks are obtained, and the vibration signals of the tank surface are separated effectively, and the following conclusions are obtained:

(1) The BP neural network is suitable for the output signal without feedback on the input signal, and is suitable for the separation of the vibration signal of the transformer winding and core.

(2) According to the vibration mechanism of the transformer, in the no-load test, the winding has a very small excitation current, and the vibration of the transformer can be considered to be produced only by the core, and the vibration signal can be used as the output layer of the core neural network. In the steady short-circuit test, when the short circuit current is large, the transformer vibration can be considered to

be produced only by the winding, and the vibration signal can be used as the output layer of the winding neural network.

(3) When the vibration signals of the core are separated, the core source signal is similar to the separated core signal waveform. The amplitude of the vibration is almost the same at the fundamental frequency 100Hz and the main frequency 200Hz. And the waveform similarity coefficient is introduced to evaluate the separation effect, the average value is 0.813. The separation effect of core neural network is good.

(4) When the vibration signals of the winding are separated, the separation effect is not ideal if the load is low. With the increase of current, the waveform similarity coefficient is improved.

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