A Novel Transformer Winding Fault Diagnosis Method Based on Damped Oscillation Wave

Zhuorui Jin¹, Jian Sun², Qing Yang² and Peiyu Su³

¹ State Grid Mianyang Electric Power Supply Company, Mianyang, China, 621000
² State Key Laboratory of Power Distribution Equipment & System Security and New Technology, Chongqing University, Chongqing, China, 400030
³ Hangzhou Power Supply Company of State Grid Zhejiang Electric Power, Hangzhou, China, 310009

Abstract. Winding status is an important part of transformer fault diagnosis. In this paper, the diagnosis test platform includes a reduced-scale transformer with the connection group model of Ynyn0, and its voltage ratio is 10 kV/0.4 kV. The voltage response of single-phase windings of three-winding transformers with varying degrees of short-circuit faults is measured under a damped oscillation wave with an amplitude of 4 kV and an equivalent frequency of 20 kHz. The transfer function of high-voltage phase and its corresponding low-voltage phase in the normal and fault condition is calculated. Three characteristic criterion of the transfer function are analysed in order to diagnose short-circuit faults in single-phase windings of three-winding transformers.

1. Introduction
The safety and stability of power transformers are of great significance to guarantee the quality of power supply [1]. Winding status is an important part of transformer fault diagnosis [2]. According to statistics from the International Conference on Large Power Grids (CIGRE) on global power transformer faults, during 1996-2010, 19.4% of transformer faults were attributed to winding-related issues [3]. Therefore, how to quickly diagnose transformer faults and improve the accuracy of fault diagnosis is of great significance to power systems.

Frequency response analysis method (FRA) and transfer function method (TF) have played an important role in transformer winding fault diagnosis. Many scholars have researched transformer winding fault diagnosis based on FRA [4-6]. Hashemnia improved and verified the diagnosis of winding deformation with the aid of FRA [7-8]. FRA is the most widely used method to diagnose transformer faults at present. Through comparison of frequency response of different windings of the same transformer and that of the different time stages of the same winding [9], experienced staff can judge whether the winding had fault. However, human factors brought uncertain factors to the accuracy of winding fault diagnosis using FRA. The basic idea of the transfer function method is to evaluate the winding state of the transformer based on the transfer function and different mathematical diagnostic criteria of it [10-12]. Rahimpour conducted an in-depth analysis of the transformer winding deformation failure using the TF. The transfer function of the transformer winding was calculated under different deformations (axial and radial deformation) to realize winding fault diagnosis [13-14]. In the previous research, the transfer function of the single-phase transformer winding interlayer fault using the damped oscillation wave was obtained.
Therefore, the feasibility of using the damped oscillation wave to diagnose the transformer winding fault was verified [15].

The sweep response method, which was widely used in the field, required special equipment for a long testing time [16]. The transformer factory test includes the damped oscillatory wave test. Therefore, the use of damped oscillatory waves for transformer winding fault diagnosis does not require the addition of new equipment, and the test time was short. The frequency of damped oscillating voltage applied in the field voltage withstand test was relatively low, generally 10-1000 Hz, and the results can only be used to detect the occurrence of partial discharge fault of winding [17]. On account of the characteristics of damped oscillation wave used in this paper with broad spectrum and high amplitude, the initial fault of three-phase transformer winding can be more efficiently diagnosed.

Transformers that are used in substations are large and expensive. The destructive testing of winding short-circuit fault diagnosis will cause huge economic losses [18]. Thus, it was necessary to conduct a test with a reduced-scale transformer that had a similar structure and the same insulation mode as the actual transformer. Reduced-ratio transformer model was widely used in transformer winding fault diagnosis [19]. In this paper, the fault diagnosis method of three-phase transformer windings using damped oscillation wave was studied based on the reduced-scale three-phase transformer test platform.

2. Methodology

2.1. Transfer function method

The transfer function method plays an increasingly important role in transformer winding fault diagnosis. The characteristic parameters before and after the transformer winding fault will change, especially its internal resistance, inductance and capacitance parameters will change with the category and severity of the winding defect. The transfer function is related to the characteristic parameters of the winding. Therefore, a quantitative analysis of the degree and type of transformer winding faults is achieved through transfer functions. By analysing the change trend of the transfer function curve with and without the transformer winding defect and the characteristic criterion of the transfer function, the diagnosis of the winding state is realized. The transfer function of transformer winding using damped oscillation wave as shown in equation (1).

\[
TF = 20 \log\left(\frac{\text{FFT}(U_{out})}{\text{FFT}(U_{in})}\right)
\]

Where \(U_{in}\) is the injection voltage and \(U_{out}\) is the response voltage of each phase.

2.2. Characteristic criterion of transfer functions

In this paper, three characteristic criteria are used to analyse the transfer function of the winding in different situation. The three characteristic criteria are as follow.

- **Correlation coefficient \(\rho(X, Y)\).** The larger the correlation coefficient, the closer the transfer function.

\[
\rho(X, Y) = \frac{\sum_{i=1}^{n} (x_i, y_i)}{\sqrt{\sum_{i=1}^{n} x_i^2 \cdot \sum_{i=1}^{n} y_i^2}}
\]

- **Spectral deviation \(\sigma(X, Y)\).** It indicates that the transfer function curve changes similarly when the spectral deviation is small.

\[
\sigma(X, Y) = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{x_i - (x_i + y_i) / 2}{(x_i + y_i) / 2} \right)^2 + \left( \frac{y_i - (x_i + y_i) / 2}{(x_i + y_i) / 2} \right)^2 \right)^{1/2}
\]

- **Absolute logarithmic deviation \(ALSE\).** It reflects the numerical deviation of the transfer function of different states.
\[ ALSE (X, Y) = \frac{1}{n} \sum_{i=1}^{n} \left| \log_{10} y_i - \log_{10} x_i \right| \]

Where \( X = (x_1, x_2, ..., x_n) \), which is the transfer function of the windings without the fault, \( Y = (y_1, y_2, ..., y_n) \), which is the transfer function of windings with fault. \( n \) is the number of frequency response points of the transfer function. Their definitions are as shown in equation (2) - (4). By comparing the change variety of the transfer function and the numerical deviation of the characteristic criterion, the diagnosis of the state of the transformer winding can be realized.

3. Establishment of test platform
The size of the reduced-scale three-phase transformer is 1.9 m × 1 m × 1.5 m. Its inside is a three-phase three-post type. The high-voltage winding is a pie-type structure with a total of 30 pie-types. The low-voltage winding is a 6-layer layer structure winding. This transformer is a scaled-scale model of a 110 kV three-phase transformer.
The high-voltage winding cake of one phase of the three-phase transformer are attached with wires in order to imitate the short-circuit defect of high-voltage phase of winding. Figure 1 shows that the two-layer short circuit winding fault of three-phase transformer is simulated.

![Figure 1. Simulation of transformer winding two-layer short-circuit fault.](image)

The winding short-circuit defect of three-phase transformer diagnosis platform is shown in Figure 2. A damped oscillation waves with an amplitude of 4 kV and an equivalent frequency of 20 kHz is used to high-voltage phase. The oscilloscope with high sampling frequency is applied to obtain the response.

![Figure 2. Winding interlayer short-circuit fault diagnosis test platform of three-phase transformer.](image)
voltage of the winding under different situations. The transfer function of the three-phase transformer winding is counted by equation (1). The equation (2) - (4) is used to calculate the characteristic criterion of the transfer function and perform quantitative analysis. It could determine whether the damped oscillation wave can be employed to accurately diagnose the short-circuit defect of the three-phase transformer winding.

4. Results

4.1. Response voltage of winding short-circuit fault
The high-voltage phase of the three-phase transformer, like phase A, was injected by a damped oscillation wave. The short-circuit between two layers of A-phase winding of the transformer was set, and the response voltage of each phase of the transformer obtained by oscilloscope with high sampling frequency is shown in Figure 3.

![Figure 3](image_url)

Figure 3. Each phase voltage response of two-layer short-circuit fault in A-phase of transformer.

It can be seen from Figure 3 that when the A-phase winding was faulty, a damped oscillation wave was injected in the faulty phase, the amplitude of the response voltage of the high-voltage phase was significantly reduced, and the frequency of voltage was significantly increased. Therefore, the voltage of all phase of the transformer has different changes under the damped oscillation wave, which can be used to reflect the fault state of the transformer winding.

4.2. Transfer function on high and its homologous low voltage side of winding short-circuit
The response voltage of each phase of the transformer when short-circuit faults occur in phase A with different degrees was obtained when the damped oscillation wave was injected. The transfer function of the high-voltage phase and its homologous low-voltage phase can be calculated after Fourier transform, as shown in Figure 4.

![Figure 4](image_url)

Figure 4. Transfer function of high-voltage phase and its homologous low-voltage phase of phase A short-circuit.
In the Figure 4 and Table 1, ‘normal’ refers to the transfer function that the winding of transformer without fault. ‘2-layer’ represents the transfer function whose winding with two-layers short circuit fault. ‘b-B’ means the transfer function that the wave was used to the high-voltage phase B and the response voltage was measured from the homologous low-voltage phase b.

Figure 4 shows that using the damped oscillation wave, the transfer function in the case of A-phase fault has changed significantly compared to its normal case. All resonance points of the voltage transfer function disappear except 2 kHz, which becomes smoother. And as the level of interlayer short-circuit defect of the transformer winding increases, the transfer function moves down. The non-faulty phase transfer function changes significantly at higher frequencies. Table 1 is the characteristic parameters of transfer function of high-voltage phase and its homologous low-voltage phase.

| Fault phase | Short circuit fault degree | Transfer function | \( \rho(X, Y) \) | \( \sigma(X, Y) \) | ALSE |
|-------------|-----------------------------|-------------------|----------------|----------------|------|
| Phase A     |                             |                   |                |                |      |
| 1-layer     | a-A                         | 0.99746           | 0.04745        | 1.80631        |
| winding     | b-B                         | 0.98694           | 0.07901        | 3.00812        |
|             | c-C                         | 0.9862            | 0.07547        | 2.86881        |
| 2-layer     | a-A                         | 0.99639           | 0.06939        | 2.56366        |
| winding     | b-B                         | 0.98682           | 0.07965        | 3.1076         |
|             | c-C                         | 0.98706           | 0.08124        | 3.19103        |
| 3-layer     | a-A                         | 0.99513           | 0.15932        | 3.41399        |
| winding     | b-B                         | 0.98937           | 0.06988        | 2.65149        |
|             | c-C                         | 0.98832           | 0.07175        | 2.77649        |
| 4-layer     | a-A                         | 0.99538           | 0.41252        | 4.86691        |
| winding     | b-B                         | 0.98697           | 0.07605        | 2.90224        |
|             | c-C                         | 0.98586           | 0.08239        | 3.14901        |
| 5-layer     | a-A                         | 0.99317           | 0.1833         | 5.92793        |
| winding     | b-B                         | 0.991             | 0.06497        | 2.48837        |
|             | c-C                         | 0.98957           | 0.06888        | 2.69494        |

As can be seen from Table 1, the correlation coefficient \( \rho(X, Y) \) of the faulty phase a-A is the highest comparing to the non-faulty phase, and it is all more than 0.993. It shows that when the damped oscillating wave is injected into the fault winding, the transfer function curve distribution of the homologous phase is similar. The spectral deviation \( \sigma(X, Y) \) and the absolute logarithmic deviation ALSE of the non-faulty phase is stable. The \( \sigma(X, Y) \) of that is about 0.07, and the ALSE is around 3. However, the \( \sigma(X, Y) \) and the ALSE of the faulty phase increases with the increase of the fault degree. Therefore, it is possible to realize the initial diagnosis of winding faults by comparing the changes of transfer function curve with and without the winding faults, and through the comparison of the transfer function characteristic parameters, it is possible to diagnose the degree of winding failure.

5. Conclusion
In this paper, a fault diagnosis platform for winding interlayer short circuit based on three-phase transformer with reduced-scale was established. The interlayer short circuit winding fault of three-phase transformer was simulated. High-voltage bushing of the transformer was injected by a damped oscillation wave, and the response voltage of all phase of transformer was obtained. The transfer function of the corresponding phase of the transformer and its three characteristic parameters was calculated. The method based on damped oscillation wave injection realize to diagnose the short-circuit fault of three-phase transformer winding by comparing the changes of the transfer function trend and its characteristic parameters in normal and fault condition.
6. References

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