Theoretical and Simulation Study on On-line Monitoring Technology of Transformer Short-Circuit Impedance

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Abstract: Based on the equivalent circuit of transformer, this paper deduces the calculation method of short-circuit impedance of three-phase transformer based on multiple measurement data. Taking a single-phase transformer as the research object, the ‘magnetic field-circuit’ simulation model is established. The normal operation and winding deformation caused by different axial displacements are simulated and analyzed. The results show that short-circuit impedance changes when transformer winding is axially deformed, and the degree of change is related to the degree of deformation. Compared with the normal situation, the short-circuit impedance increases by 52.1% when the four transformer coils are moved 15 mm each. Therefore, on-line monitoring of the transformer short-circuit impedance can reflect the abnormal deformation of the transformer winding to a certain extent.

1 Introduction
Transformer is the most expensive and important electrical equipment in power system. It is of great significance to monitor on-line and prevent its failure[1-3]. The winding deformation fault caused by external short circuit accounts for a large proportion of transformer faults[4-5]. The off-line detection method needs to shut down the transformer, which results in the interruption of power supply, makes it difficult to recover in time, and consumes a lot of manpower and material resources[6-7]. In recent years, online monitoring methods have received more attention. At present, on-line monitoring of transformer winding deformation mainly includes short-circuit impedance method, frequency response method and sweep impedance method[8]. Both the frequency response method and the sweep impedance method inject signals of different frequencies into the transformer through the signal generating device, and judge whether the transformer winding is deformed from the result of the frequency response, both of which require the monitoring device to remain uninterrupted running. The measurement device of short circuit impedance method is relatively simple, and it is easier to realize long-term operation without fault[9-11]. At present, the research of on-line monitoring method of short-circuit impedance mainly includes two aspects: one is to use transformer equivalent circuit to deduce and calculate. The other is to use existing mature circuit software to simulate, such as Simulink toolbox in MATLAB or PSPICE[6,12].

Both theoretical derivation and circuit software simulation are based on transformer equivalent to lumped parameter elements. Circuit model simulation cannot simulate the change of magnetic field when transformer winding deformation occurs. For the development of practical devices, more refined simulation and experimental data are needed.

Paper[10] calculates the short-circuit impedance of transformer under off-line condition by using the ‘magnetic field-circuit’ coupling method. This method is applied to the on-line monitoring of short-circuit impedance. Taking a single-phase transformer as the research object, the ‘magnetic
field-circuit simulation model is established. The normal operation and winding deformation caused by different axial displacements are simulated and analyzed.

2 On-line Monitoring Principle of Transformer Short Circuit Impedance
Firstly, a simple single-phase transformer is taken as an example for analysis. The equivalent principle diagram of single-phase transformer is shown in Figure.1 below.

![Figure.1 Short-circuit impedance calculation schematic diagram of single-phase transformer](image)

In Figure.1, $Z_1$, $R_1$ and $X_1$ are high-voltage side impedance, resistance and reactance, respectively. $Z_{12}$, $R_{12}$ and $X_{12}$ are the values of low-voltage side impedance $Z_2$, resistance $R_2$ and reactance $X_2$ converted to high-voltage side respectively. $Z_{10}$, $R_{10}$ and $X_{10}$ are excitation impedance, resistance and reactance respectively. $U_1$ is the input voltage of the high voltage side of the transformer. $U_2$ is the low voltage side output voltage of the transformer. $U_{12}$ is the converted value of transformer low voltage side voltage at high voltage side.

According to Figure.1 above, the following formula is satisfied.

$$
\frac{U_1 - U_{12}}{I_I} = (R_1 + jX_1) + \frac{I_1}{I_1} (R_{12} + jX_{12})
$$

(1)

For two consecutive measurements, the measurement numbers are A and B.

$$
\begin{align*}
\frac{U^A_1 - U^A_{12}}{I^A_I} &= (R_1 + jX_1) + \frac{I^A_1}{I^A_1} (R_{12} + jX_{12}) \\

\frac{U^B_1 - U^B_{12}}{I^B_I} &= (R_1 + jX_1) + \frac{I^B_1}{I^B_1} (R_{12} + jX_{12})
\end{align*}
$$

(2)

It can be solved by formula (2):

$$
Z_1 = R_1 + jX_1 = \frac{U^A_1 I^B_{12} - U^A_{12} I^B_I}{I^A_{12} I^B_{12}} = \frac{I^A_I I^B_{12} - I^B_I I^A_{12}}{I^A_{12} I^B_{12}}
$$

(3)

$$
Z_{12} = R_{12} + jX_{12} = \frac{U^B_1 I^A_{12} - U^B_{12} I^A_I}{I^B_{12} I^A_{12}} = \frac{I^B_I I^A_{12} - I^A_I I^B_{12}}{I^B_{12} I^A_{12}}
$$

(4)

$|Z_1 + Z_{12}|$ is the value of the short-circuit impedance value.

For common three-phase transformers, in order to solve the short-circuit impedance, each phase input and output voltage and current must be obtained, which can be obtained by PT and CT. For YN or Y wiring, the voltage and current of each phase winding can be directly measured, and the short-circuit impedance can be calculated directly into the above formula. If it is the $\triangle$ connection mode, the phase windings are connected in series and cannot be directly solved. At this time, it satisfies:
\[
\frac{U_1 - U_{12}}{I_i} = (R_i + X_{12} + jX_{1}) - \frac{I_{10}}{I_i} (R_{12} + jX_{12})
\]  \hspace{1cm} (5)

\(I_{10}\) is the excitation current and cannot be directly measured. In the two measurements, if the interval time is small, the load is considered to remain unchanged, and the excitation currents measured twice are equal, that is, \(I_{10} = I_{10}^A = I_{10}^B\), at this time, it can be calculated by formula (6):

\[
\begin{align*}
U_1^A - U_{12}^A &= I_1^A (R_i + R_{12} + j(X_1 + X_{12})) - I_{10}^A (R_{12} + X_{12}) \\
U_1^B - U_{12}^B &= I_1^B (R_i + R_{12} + j(X_1 + X_{12})) - I_{10}^B (R_{12} + X_{12})
\end{align*}
\]  \hspace{1cm} (6)

Formula (7) can be derived from simultaneous solution of equation group (6):

\[
R_i + R_{12} + j(X_1 + X_{12}) = \frac{(U_1^B - kU_2^B) - (U_1^A - kU_2^A)}{I_1^B - I_1^A}
\]  \hspace{1cm} (7)

Formula (7) shows that on-line calculation of short-circuit impedance requires voltage and current values at both high and low voltage sides, including RMS and phase angle. For large power transformers, the resistance value can be neglected.

3. Simulation Analysis of ‘Magnetic Field-Circuit’

In recent years, the magnetic field-circuit method has been widely used in the analysis of electromagnetic characteristics of electric equipment, such as motors, transformers, reactors and so on. Because the magnetic field-circuit coupling method can directly obtain the corresponding relationship between input and output characteristics, it can be directly solved according to the definition of ‘short-circuit impedance’. On this basis, this paper applies it to the simulation study of on-line monitoring of short-circuit impedance. A lot of research has been done on the simulation and modeling method of magnetic field-circuit. In this paper, the method described in paper [7]-[9] is used to build the model.

3.1 Simulation Model

The model of magnetic field-circuit coupling method is divided into two parts: one is the finite element model of transformer core winding, as shown in Figure 2; the other is the circuit model of equivalent winding in circuit, as shown in Figure 3.

**Figure 2** Finite element model of transformer’s magnetic field-circuit method
The model in Figure 2 corresponds to the actual transformer in Figure.1, where the low-voltage winding is on the inside and the high-voltage winding is on the outside. The finite element model of transformer is established by Maxwell software, and the partial differential equation (8) including vector magnetic potential $A$ is solved.

$$\nabla^2 \vec{A} = \mu \vec{J}$$  \hspace{1cm} (8)

In formula (8), $\vec{J}$ is the current density. The boundary conditions are natural boundary conditions, namely

$$\nabla \times \vec{A} = 0$$  \hspace{1cm} (9)

In Figure.3, a voltage regulator is connected to the input end of the transformer. The output end of the transformer is loaded in series with a resistance and an inductance, in which the resistance is 25.2 $\Omega$ and the inductance is 3.18 mH. 400-1 and 400-2 correspond to the low-voltage winding in the finite element model and 800-1~800-4 correspond to the high-voltage winding in the finite element model. According to equation (7), two different input voltages are applied for each calculation of the short-circuit impedance.

### 3.2 Calculation result when transformer winding is normal

For the model described in Figure 3, the effective values of the applied voltage are set to 395V and 405V respectively, and the voltage and current waveforms of the high-voltage side and low-voltage side of the transformer when the applied voltage is 395V are shown in Figure.4 below:

The simulation waveform data is exported, and the waveform is analyzed by using Matlab software. The effective value is calculated by compound trapezoid method [4], and the phase of waveform is
calculated by Fourier series method [6]. The calculation results of voltage and current at high and low voltage side are shown in Table 1 below.

**Table.1 Calculation result when transformer winding is normal**

| $U_1$ (V) | $I_1$ (A) | $U_2$ (V) | $I_2$ (A) | $|Z|$ (Ω) |
|-----------|-----------|-----------|-----------|----------|
| 395.00    | 63.19     | 756.90    | 31.39     |          |
| 0.00°     | -9.01°    | -2.36°    | -4.19°    | 0.2319   |
| 405.00    | 62.22     | 799.66    | 29.98     |          |
| 0.00°     | -9.32°    | -1.96°    | -5.01°    |          |

In Table 1, the first and third rows are the RMS of voltage or current, and the second and fourth rows are phase angles. The short-circuit impedance of transformer winding under normal condition is calculated to be 0.2319Ω.

### 3.3 Calculation results when the winding has axial displacement

Axial displacement fault of transformer winding caused by transportation and external short circuit is one of the important causes of Transformer Damage accident.

In order to study the magnitude of the short-circuit impedance when the axial displacement is deformed, the 1~4 coils in the model are sequentially moved, and the moving distance of each coil is kept at 15 mm. Figure 5 is a schematic diagram of the transformer model after moving a coil.

![Figure 5 Schematic diagram of the model after moving a coil](image)

Each time the model is modified, both two voltages are applied to the model. The calculation results are shown in Table 2. The relationship between the short-circuit impedance and the number of coils moving is shown in Figure 6.

**Table.2 Calculation results after moving coils**

| $N$ | $U_1$ (V) | $I_1$ (A) | $U_2$ (V) | $I_2$ (A) | $|Z|$ (Ω) |
|-----|-----------|-----------|-----------|-----------|----------|
| 1   | 398.18    | 63.23     | 765.69    | 30.53     | 0.2862   |
|     | 0.00      | -8.70     | -2.10     | -4.42     |          |
|     | 402.84    | 63.77     | 774.44    | 30.68     |          |
|     | 0.00      | -9.06     | -2.14     | -4.21     |          |
| 2   | 398.47    | 63.05     | 765.98    | 30.43     | 0.2931   |
|     | 0.00      | -9.14     | -2.04     | -4.17     |          |
|     | 407.98    | 64.53     | 784.00    | 31.11     |          |
|     | 0.00      | -9.44     | -2.07     | -4.00     |          |
| 3   | 393.16    | 62.30     | 756.88    | 30.08     | 0.3152   |
|     | 0.00      | -8.34     | -2.14     | -4.35     |          |
In Table 2 and Figure 6, $N$ is the number of coils that are moved. As can be seen from Figure 6, as the number of coils moved increases, the transformer short-circuit impedance increases. The calculation results show that the online monitoring short-circuit impedance method can monitor the axial displacement deformation of the transformer winding and can reflect the leakage flux change caused by the winding deformation.

4 Conclusions
1) Based on the equivalent principle of transformer, the on-line monitoring method of transformer short-circuit impedance is deduced. Theoretical analysis shows that the calculation of transformer short-circuit impedance can be realized by two consecutive transformer voltage and current measurement data;
2) When the transformer winding undergoes axial deformation, its short-circuit impedance changes, and the degree of change is related to the degree of deformation. Therefore, monitoring the short-circuit impedance of the transformer on-line can reflect the abnormal deformation of the transformer winding.

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