Electromagnetic vibration analysis method of short circuit in transformer winding based on field circuit coupling

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Abstract. The short circuit fault may cause serious deformation of the transformer winding even affect the safety and stability of the equipment and the whole power system. This paper mainly studies the flux leakage, electromagnetic force and vibration characteristics of winding under short-circuit fault based on field circuit coupling model. Firstly, the 10kV power transformer is modeled as the research object to analyze the flux leakage and electromagnetic force of the transformer windings in short circuit condition based on the field-circuit coupling principle. Then, the electromagnetic excitation is extracted for harmonic response analysis to investigate the electromagnetic vibration characteristics of the windings. Finally, the short circuit experiment is designed to verify the above research. It is found in this paper that the flux leakage, electromagnetic force and vibration amplitude of the transformer windings are all strengthened sharply under short circuit fault. This conclusion provides an important basis for transformer design and condition.

1. Introduction
Transformer is one of the key equipment in power system, which undertakes the important tasks of voltage exchange, power distribution and transmission. Short circuit fault is one of the common transformer faults, especially when the transformer is short-circuited at the port, the huge electromagnetic force makes the transformer windings produce great electromagnetic vibration and even leads to the mechanical deformation of the windings [1,2]. Therefore, it is necessary to study the force and vibration characteristics of the winding under short circuit fault.

In recent years, many scholars have studied the magnetic field characteristics of electrical equipment based on field circuit coupling, and which is combined with the finite element mechanical field to study the electromagnetic vibration characteristics. Among them, reference[3] analyzed the electromagnetic harmonic response characteristics of the inductive harmonic filter transformer based on the field-circuit coupling model. Reference[4] establish finite element model coupling electromagnetic field - mechanical field for exploring the vibration increase of transformer iron core due to DC bias; Reference [5] studies the
influence of inrush current of transformer excitation on electromagnetic field and winding mechanical deformation through three-dimensional finite element model. In addition, reference [6] further studies the electromagnetic vibration noise of transformers and analyzes the sound level of vibration noise. Based on the above research, this paper mainly predicts the dynamic electromagnetic force and mechanical response of transformer winding under short circuit fault.

In this paper, we propose a numerical method based on the field-circuit coupling principle for electromagnetic vibration harmonic response analysis in three-phase transformer under short circuit fault. Firstly, the electromagnetic environment of transformer winding short circuit fault is simulated by establishing transformer finite element electromagnetic model, and we combine it with the time domain differential current model to analyze the winding flux leakage and dynamic electromagnetic force. Then, the electromagnetic vibration spectrum is calculated based on the harmonic response analysis. Finally, a physical experiment is done to demonstrate the effectiveness of the numerical method.

2. Theoretic analysis

2.1 The field circuit coupled model

Firstly, Edge finite element method and vector magnetic potential $A$ are used to establish the transformer magnetic field model, this is shown in equation (1):

$$\nabla \times \frac{1}{\mu} \nabla \times A = J$$

where, $\mu$ is the permeability, $J$ is the current density vector, and represents the magnitude and direction of the current.

The integral interpolation function of magnetic field region solved by edge finite element method is:

$$A = \sum_{n=1}^{n} M_{n}(x, y, z) A_{n}$$

By solving equation (2) with green's theorem, the galerkin weighted residual equation of the corresponding magnetic field region can be obtained as equation (3):

$$\int_{\Omega} \frac{1}{\mu} (\nabla \times M_{n}) \cdot (\nabla \times M_{m}) A_{n} dV = \int_{\Omega} M_{m} \cdot J dV$$

where, $\{M_{n}\}$ is the weight function sequence. If current $i$ is known in the magnetic field model, the weighted residual equation can be discretized into algebraic equations to obtain $A$, which is used to calculated magnetic energy.

Secondly, we combine the magnetic field and electric field model to analyze the field-circuit coupling principle, the transformer flux chain equation is:

$$S \tau t = L_{i}$$

where, $u$ is voltage excitation; $L_{D}$ is the dynamic inductance matrix. If the coil current at $t_{k}$ is $i_{k}$, and the equation established in the circuit model is solved by using the fourth-order runge-kutta method, it can be known that the current at $t_{k+1}$ is:
\[ i_{k+1} = i_k + \frac{h}{6}(\lambda_1 + 2\lambda_2 + 2\lambda_3 + \lambda_4) \]  \hspace{1cm} (6)

where, \( h \) is the step size, and \( \lambda_1 \sim \lambda_4 \) are piece wise slope in the step size.

Here, if the coil current increment is \( \Delta i \), the total power supply is related to the dynamic inductance and current as shown in equation (7):

\[ \Delta W_i = \frac{1}{2} L_{\text{eq}} \Delta i \Delta i \hspace{1cm} j, k = 1, 2 \]  \hspace{1cm} (7)

Meanwhile, the local linearization method is adopted to solve the nonlinear magnetic field inside the transformer at each moment. Under the condition of the same variation of current, the magnetic field energy increment of the transformer corresponding to the internal system is:

\[ \Delta W_i = \frac{1}{2} \Delta B \Delta H \Delta \Omega \]  \hspace{1cm} (8)

Based on the principle of energy conservation, the dynamic inductance \( L_D \) can be calculated by combining equation (7) and equation (8).

The solution process of field circuit coupling can be realized by the following steps:

Step.1: Given the coil current \( i_k \) of the magnetic field model at a certain moment, the edge finite element method was used to solve the magnetic field in the model. Than energy disturbance was used to solve the dynamic inductance \( L_D \).

Step.2: The inductance parameters \( L_D \) and voltage excitation are substituted into the time-domain differential equation (5) in the circuit model, and the fourth-order runge-kutta method is used to calculate the current \( i_{k+1} \) at the next moment.

Step.3: The magnetic field at the next moment is calculated using the coil current \( i_{k+1} \) solved in the circuit model.

2.2 Principle of harmonic response analysis

The winding of transformer is a mechanical system with multi-degrees of freedom. The electromagnetic force of transformer winding is calculated using the virtual displacement method[7] as:

\[ F (t) = \frac{\partial W_m}{\partial r} = \frac{1}{2} i \frac{\partial L_D}{\partial r} \]  \hspace{1cm} (9)

where, \( F \) is the electromagnetic force; \( W_m \) is the magnetic field energy storage of winding leakage magnetic field; \( i \) and \( L_D \) are winding current and inductance calculated based on field-circuit coupling in section 1.1.

We convert the time-domain electromagnetic force obtained in transient electromagnetic field analysis into a harmonic response component by the Fourier transform, which are used as simple harmonic excitation sources for harmonic response analysis of steady state structures. Considering the material stiffness and damping, the harmonic response analysis principle is:

\[ [M][\dot{u}] + [C][\dot{u}] + [K(u)][u] = \{F(t)\} \]  \hspace{1cm} (10)

where, \([M]\) is structure mass matrix, \([C]\) is structure damping matrix, \([K(u)]\) is structure stiffness matrix, \(\{F(t)\}\) is excitation vector, \(\{u\}\) is node displacement vector.

3. Simulation analysis

In this section, we simulate winding electromagnetic characteristics under the short circuit fault based on field-circuit coupling theory. Initially, a finite element model of transformer with 10kV three-phase three-limb core and double-winding is established. The parameters are shown in Table.1, and the geometric details of transformer are shown in Fig.1.
Table 1. The rated parameters of the transformer

| Parameters                        | HV   | LV   |
|----------------------------------|------|------|
| Number of phase winding          | 3    | 3    |
| The rated voltage (V)            | 10000| 380  |
| Number of winding turns          | 425  | 32   |
| Height of winding (mm)           | 325  | 325  |
| Winding inner diameter (mm)      | 354  | 248  |
| Winding outer diameter (mm)      | 420  | 314  |

Fig.1. Geometry details of transformer

The electromagnetic field analysis of the transformer winding is realized based on the field-circuit coupling model. The circuit model under the short circuit condition is shown in Fig.2, the excitation source is the sine voltage excitation. The material parameters are given in the magnetic field model as shown in Table. 2. The meshing adopts the sub-region division method to improve the calculation accuracy. In addition, in order to facilitate the observation of the electromagnetic field characteristics under short-circuit fault, we simulate the electromagnetic field under normal conditions as the control group.

Fig.2. Short circuit external circuit diagram
Table 2. Main material properties

| Material    | Elasticity modulus (N/m²) | Poisson ratios | Density (kg/m³) |
|-------------|---------------------------|---------------|-----------------|
| Copper      | 1.15×10¹¹                | 0.32          | 8890            |
| Spacer      | 2.5×10¹¹                 | 0.35          | 1200            |
| Iron core   | 2.0×10¹¹                 | 0.3           | 7850            |

The distribution of transformer transient magnetic flux leakage is shown in Fig.3. The cloud diagram shows that the transformer magnetic flux leakage is mainly concentrated in the position of the winding. At t=0.324s, the maximum magnetic induction intensity of the winding under normal conditions is only 1.0555×10⁻¹T, while in the condition of short circuit, the maximum magnetic induction intensity of the winding is 8.3948×10⁻¹T, it is almost 8 times than that of normal conditions. It reveals that the magnetic leakage of winding increases sharply under the short-circuit fault.

![Winding flux leakage distribution cloud diagram](image)

The main reason of the winding vibration is that the energized winding is subject to alternating electromagnetic force in the leakage magnetic field, which leads to mechanical deformation. Therefore, the electromagnetic force of the transformer winding is further studied, which is calculated in the transient solver in Maxwell. The waveform is shown in the Fig.4(a) and (b), it shows that the winding electromagnetic force period is 0.01s, which is half of the current period, it is caused by the synchronous change of current and leakage magnetic field. In addition, by comparing electromagnetic force under short circuit fault with that of normal conditions, it reveals that the peak value of short circuit electromagnetic force is about 6 times of that the normal condition, which indicate that short circuit fault will generate great mechanical stress and easily lead to the deformation of the winding. Then, frequency spectrum of electromagnetic force is obtained through Fourier transform, as shown in the Fig.4(c), the frequency components under normal condition is focused on the fundamental frequency octave band in the range of 100-300Hz, while it is concentrated in 100-500Hz under short circuit fault. Therefore, the widening of frequency band is the obvious characteristic of short circuit fault.
We extract the transformer winding harmonic electromagnetic force as electromagnetic vibration excitation for vibration harmonic response analysis. As shown in Fig.5, the main components of the vibration included 100, 200, and 300Hz under normal condition. Under short circuit fault condition, the harmonic vibration components are mainly focused on the frequency 100-500Hz. In addition, the amplitude corresponding to each frequency increases sharply, which poses a great threat to the mechanical properties of winding.

4. Experiment and verification

In order to verify the validity of the field circuit coupling model and its calculation results, A test system was used in the vibration analysis of transformer winding as shown in the Fig.6, we do two sets of experiments in normal and short-circuit conditions. In the short circuit experiment, LV winding of 10kV three-phase transformer is short-circuited, and the HV winding is injected into the three-phase voltage until the rated current is reached. The acceleration sensor is placed in the up-disc of winding to test the vibration signal, measured signal is stored in the vibration test system and analyzed by the industrial personal computer.

Fig.4. Electromagnetic force waves and spectrum of A-phase low voltage winding

Fig.5. Vibration acceleration spectrum
The dynamic waves and spectrum are shown in the Fig. 7. It can be observed that the maximum value of the vibration signal under the short-circuit fault is 0.17, and the maximum value under normal conditions is 0.0015. The vibration amplitude of the former is almost 100 times that of the latter. In addition, the spectrum of normal conditions is concentrated in 100-300Hz, while in short circuit fault, the vibration spectrum is concentrated in 100-500Hz. These results are consistent with the simulation results, which proves that the field circuit coupling harmonic response analysis method is effective in analyzing the vibration characteristics of winding.

5. Conclusion
Based on the field-circuit coupling model, this paper analyzes the magnetic flux leakage, winding stress and electromagnetic vibration harmonic response characteristics of the transformer winding under the condition of short circuit. It is found that the winding flux leakage and electromagnetic force increase sharply under short circuit fault. At the same time the winding occurs violent vibration, electromagnetic vibration signals have a wider spectrum and more complex frequency components. These characteristics provide an important basis for the mechanical design of transformer winding.

6. References
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