Analysis of the Electromechanical Characteristics of Power Transformer under Different Residual Fluxes

Wenqi Ge 1,*, Chenchen Zhang 1, Yi Xie 1, Ming Yu 2 and Youhua Wang 3

1 School of Control and Mechanical Engineering, Tianjin Chengjian University, Tianjin 300384, China; Zhangchenchen08@163.com (C.Z.); xieyi111007@163.com (Y.X.)
2 School of Computer and Information Engineering, Tianjin Chengjian University, Tianjin 300384, China; maxyuming@126.com
3 State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin 300130, China; wangyi@hebut.edu.cn
* Correspondence: gewenqi@tcu.edu.cn

Abstract: When the electromagnetic transients occur in a power transformer, an inrush current is generated in its winding. The inrush current not only affects the performance of the transformer windings, but also affects the lifetime of the transformer. Many factors affect the inrush current, the most influential ones among which are the closing phase angle and the residual flux. In this paper, a dry-type transformer simulation model is built to analyze the influence of the inrush current on the performance of transformer windings during no-load reclosing conditions. Firstly, the inrush current was generated in the transformer windings during the no-load reclosing operation under different residual fluxes. Secondly, the field-circuit coupling 3d finite element method is used to analyze the electromagnetic force at different locations of the transformer windings under the influence of different inrush currents. The results of winding structural parameter variations are obtained through electromagnetic-structural coupling simulation, and the electromagnetic forces are used as the input parameter for the structural analysis. Finally, the residual flux is generated by controlling the opening and closing angle of the transformer through the phase-controlled switch, and the winding electromechanical characteristics are tested under different residual fluxes. Finally, comparisons of the test and simulation results are drawn to verify the impact of the closing angle and residual flux on inrush current and the winding deformation during the no-load reclosing conditions.

Keywords: inrush current; residual flux; field-circuit coupling; electromechanical characteristics

1. Introduction

When a power transformer is cut out of the system, a certain amount of residual flux will be generated due to the hysteresis characteristics of the core material. The residual flux will have a large impact on the stable operation of the transformer when the transformer is reclosed. The inrush current can be 6–10 times the rated current when electromagnetic transients occur in the reclosing process of the power transformer. Therefore, accurate measurement of the residual flux of the core is of great significance for analyzing the electromechanical characteristics of the winding under the inrush current.

To detect the residual flux in the transformer core, many algorithms and models have been proposed by domestic and foreign researchers. For example, Ref. [1] used the change in the permeability of local hysteresis lines to calculate the residual flux, but its calculation method is too complicated for application in engineering practice. Ref. [2] proposed a method for calculating the residual flux considering the transient magnetization current, and derived an empirical formula for the calculation of the residual flux magnetic density, the error of which can always be less than 10%. However, this method cannot determine the direction of the residual flux. Refs. [3,4] proposed a residual flux measurement method by establishing a known relationship between the residual flux and the current of a power
transformer. They built a core detection circuit for ring transformers, processes the experiments to obtain transient measurement current signals, and substituted the results into the residual flux and current relationship equation. This method was able to obtain the residual flux in the core of power transformers more accurately.

For more results, many researchers have started their research from the perspective considering the residual flux’s direction. For example, Ref. [5] proposed a residual flux measurement method considering the residual flux direction. The transient current of the coil under different voltages and residual flux densities was analyzed by means of both the principle calculation and simulation analysis, and an empirical formula for the residual flux was obtained. Finally, the results were verified by experiments. A method for interpreting the residual flux of a single-phase transformer by sequentially applying two Direct Current (DC) voltages of opposite polarity to the transformer windings and then detecting their corresponding transient response currents was proposed in [6]. The equation between the residual flux and the transient current difference was fitted using the data analysis method. Finally, the effectiveness of the method was verified through experiment. Although the above methods are able calculate the residual flux’s value in the transformer core, they are difficult to implement in practice.

Excessive inrush current in the windings can seriously affect the electromechanical characteristics of the transformer, which may even in serious cases lead to the destruction of the transformer. Refs. [7,8] analyzed the electromagnetic forces generated by inrush currents and the impact they have on the transformer structure. Mechanical failures of the transformer usually manifest as the deformation and the displacement of the windings. When the deformation and displacement of the windings exceeds the threshold value, plastic deformation occurs, and the insulation capacity is gradually reduced. Furthermore, the failure resistance of the transformer is significantly reduced.

To analyze the effects of excessive inrush currents on transformers, structural optimization and simulation methods for analyzing magnetic fields of transformers have emerged. One of the most widely used computational analysis methods for electromagnetic as well as the structural simulation is the finite element method. Residual flux in the core could produce an inrush current which amplitude can far exceed the rated current. For example, in [9], a numerical analysis method was proposed to accurately calculate the inrush current of a three-phase three-arm core transformer considering the nonlinear magnetization curve of the iron core. Ref. [10] used Octave software to calculate the maximum value of the inrush current generated by a single-phase transformer. Meanwhile, the magnetic density, air-gap leakage, and winding losses of the transformer core under the maximum inrush current were analyzed using finite element simulation analysis. In Ref. [11], a method for calculating the inrush current of superconducting transformers was proposed, and the accuracy of the calculation results was verified by experiments. Refs. [12–15] analyzed the transient electromagnetic forces of large power transformer windings under short-circuit currents. A three-dimensional transformer electromagnetic-structural coupling finite element model was established to analyze the dynamic electromagnetic force and winding mechanical structure interaction during short-circuit condition, and the simulation analysis results were compared with the experimental results. Ref. [16] qualitatively and quantitatively analyzed the mechanical power generated in the transformer winding under the action of inrush current by means of analytical and numerical methods. The analytical and computational results were compared and analyzed with the experimental results, which proved the validity of the method and the correctness of the conclusions. A method based on digital image processing of transformer winding deformation was proposed in Ref. [17]. Ref. [18] detected and classified different operating conditions of transformers by building a neural network classification model. The above studies focus on the deformation of transformer windings under excitation current and the ability of windings to resist fault current, with fewer studies examining the combined variation of the transformers under inrush current, with no clear conclusions being given.
Both the short-circuit current and the inrush current have a great impact on the transformer, and in some cases, the inrush current on the transformer winding can even produce a greater impact than the short-circuit current. Ref. [8] analyzed the short-circuit forces on the windings of a 50 KVA, dry-type transformer under short-circuit current using finite elements and verified the correctness of the simulation analysis by experiments. In Ref. [19], a single-phase, 50 MVA transformer model was established, and the model was analyzed using the finite element method to analyze the axial and radial forces on the transformer windings under the inrush current. In Ref. [20], the electromechanical stresses generated in the transformer windings by the inrush current and short-circuit current were studied by means of both numerical calculations and simulation analysis. In Ref. [21], the radial short-circuit forces generated on the transformer’s low-voltage (LV) winding under short-circuit were studied. The relationship between the leakage flux in the transformer windings and the short-circuit electromagnetic force was analyzed. The radial short-circuit forces were calculated, and the ability of the LV winding to withstand short-circuit currents was evaluated according to International Electrotechnical Commission (IEC) standards and short-circuit experiments. Ref. [22] used the electromagnetic-thermal-fluid coupling method to analyze the effects of inrush currents on transformer windings. Ref. [23] used the field-circuit coupling method to calculate the leakage magnetic field and the short-circuit electromagnetic force under short-circuit conditions. According to the actual parameters, the flexural of the windings was analyzed to study the axial stability of the windings. In Ref. [24], the field-circuit coupling method was used to compare the leakage and the electromagnetic forces of transformer low-voltage windings under different short-circuit conditions. In Ref. [25], a simulation model of transformer winding loosening, winding deformation and winding insulation failure was developed using a simulation model of a transformer in normal operation, and the vibration characteristics of winding faults were analyzed. The above-mentioned studies mainly focus on the analysis of the impact of short-circuit current on transformer windings from a structural perspective. Studies on the effect of the electromagnetic transients generated by the inrush current on the electromechanical characteristics of the transformer are fewer, and most of the conclusions are vague, while at the same time lacking experimental verification.

With increasing transformer capacity, the impact of the inrush current on the transformer becomes more and more significant. In particular, in the case of no-load reclosing, the impact of inrush current on the transformer is more prominent. In this case, the analysis of the inrush current during the no-load reclosing transient, as well as the electromechanical characteristics of the windings under the inrush current, are of great importance, and may extend the lifetime of the transformer and allow the diagnosis of transformer fault. Therefore, this paper provides a comprehensive analysis of the transformer magnetic field changes and leakage flux distribution at the moment of transformer reclosing. At the same time, the electromagnetic-structural field coupling method is used to analyze the impact of the inrush current by the transformer re-closing condition.

Inrush current is generated at the instant of no-load reclosing of the transformer, and is mainly a result of the closing phase angle and residual flux. Currently, most of the research on residual flux is focused on measurement and suppression, and most of the methods are difficult to implement in operating transformers. Therefore, this paper uses the phase-controlled switching technique to control and calculate the residual fluxes of the transformer core under different closing phase angles, as well as to analyze the peak excitation inrush currents and their effect on the transformer windings generated under different residual fluxes.

In summary, this paper presents a comprehensive analysis of the electromechanical characteristic of power transformer windings with different residual fluxes and reclosing angles. Firstly, a simulation circuit of the power transformer is established to analyze and obtain the inrush current under the no-load reclosing condition of the transformer with different residual fluxes. Secondly, the “field-path” coupling method and finite element method are combined to analyze the electromagnetic force of the transformer.
winding under the inrush current corresponding to different residual fluxes. After that, the power transformer electromagnetic-structural coupling analysis model is established to analyze the deformation of the winding structure. Then, based on the simulation results, the parametric relationships between residual flux and closing phase angle and electromagnetic force and winding deformation are obtained. Finally, the validity of the simulation method and the correctness of the results are verified by experiments.

2. The Generation and Calculation of Residual Flux Magnetism

2.1. Generation of Residual Flux Magnetism

Power transformer cores are mainly composed of silicon steel sheets with hysteresis characteristics, and the hysteresis characteristics exhibited by transformer cores differ depending on the core material. The hysteresis characteristics of the transformer core are mainly manifested when the external magnetization conditions are increased, i.e., after the transformer is energized, there will be a magnetization curve and a hysteresis return, i.e., the magnetization and demagnetization paths are different.

Figure 1 shows the partitioning of the magnetization curve of the core material after the transformer is energized, where region I denotes the starting region, region II denotes the Rayleigh region, region III denotes the nonlinear steep region, and region VI denotes the converging saturation region. As can be seen from Figure 1, once the core starts to be magnetized, even if the magnetic field strength $H$ decreases to zero, the magnetic induction strength $B$ in the core does not drop to zero, and the magnetic induction strength value in the core at this time is the residual flux $B_r$.

![Transformer core magnetization curve partition diagram.](image)

Figure 1. Transformer core magnetization curve partition diagram.

Usually, the magnetic field strength $H$ when the transformer is powered off varies, the resulting hysteresis return will be different, and the residual flux $B_r$ will be different. The degree of saturation of the core during power failure will also affect the residual flux $B_r$. Therefore, it is possible to estimate the magnitude and direction of the residual flux $B_r$ in the core from the magnetic field strength $H$ and the hysteresis return at the moment of power failure of the transformer.

2.2. Calculation of Residual Flux Magnetism

The phase angle, amplitude, and direction of the residual flux at the moment of transformer closing are the main factors affecting the size of the inrush current amplitude and its duration under no-load reclosing. However, the peak of the inrush current is mainly affected by the phase angle $\theta$ and the remaining flux $\phi_r$. Under the unsaturated state of the
core flux $\phi$, the magnetization curve of the core basically conforms to the linear variation. When $\phi$ approaches the saturation flux $\phi_s$, the magnetization curve gradually becomes nonlinear, and the excitation current increases sharply as the core saturation increases, at which time the excitation current can even reach thousands of times the rated no-load current, i.e., the inrush current.

According to the full current law, it can be obtained:

$$H(t) = \frac{N i(t)}{l}$$  \hspace{1cm} (1)

where $l$ is the transformer magnetic circuit length (m); $N$ is the number of turns of the excitation winding; $H$ is the magnetic field strength (A/m); $i(t)$ is the current in the excitation winding (A).

Because the excitation winding direct current resistance $R$ is very small and the leakage resistance is very small, the calculation ignores the direct current resistance voltage drop as well as the leakage resistance voltage drop, and according to the law of electromagnetic induction, the following can be obtained:

$$B(t) = \frac{\phi}{S} = \frac{1}{NS} \int_{t_1}^{t_2} V(t) dt$$  \hspace{1cm} (2)

where $S$ is the effective cross-sectional area of the transformer (m$^2$); $B(t)$ is the average magnetic density in the core (T); $\phi$ is the main magnetic flux (Wb).

Based on the voltage and current data at the moment of the controller control break, the corresponding $B$ and $H$ values are calculated to obtain the $B$-$H$ curve corresponding to the iron core. Additionally, the ratio of the maximum magnetic density $B_m$ formed by the hysteresis return to the residual flux magnetic density $B_r$ is determined according to the different operating voltages, and then $B_r$ is obtained from the measured $B_m$.

3. Generation and Calculation of Excitation Inrush Current

The transformer needs to go through a transient process after reclosing before it can reach a steady state, i.e., the decay process of the excitation current. Equation (3) shows the relationship between voltage, current and flux in a transformer.

$$V_m \sin(\omega_1 t + \theta) = i_0(t)R + N \frac{d\phi_m(t)}{dt}$$  \hspace{1cm} (3)

where $V_m$ is the peak voltage (V), $\theta$ is the voltage switching angle when the transformer is closed ($^\circ$), $i_0(t)$ is the instantaneous current generated at the time of reclosing (A), $\phi_m(t)$ is the instantaneous flux which contains the main flux and the leakage flux (Wb), $R$ is the resistance of the windings in the transformer ($\Omega$).

Equation (4) is the value of the instantaneous flux when the transformer is energized instantaneously.

$$\phi_m(t) = (\phi_p \cos \theta \pm \phi_r) e^{-\frac{R}{L} t} - \phi_p \cos(\omega_1 t + \theta)$$  \hspace{1cm} (4)

where the peak value of the steady-state flux of $\phi_p$ (Wb), $\phi_r$ is the value of the residual flux (Wb), $L$ is the inductance of the excitation coil (H).

When $\theta = 0^\circ$ and the $\phi_r$ of the residual flux is positive, the flux waveform is shown in Figure 2.

From Figure 2, the magnetic flux $\phi$ in the transformer core is kept at a low level when the residual flux equals to zero. When residual flux is present, the initial value of the magnetic flux in the core will be increased, which makes it easier to saturate the core.

Figure 3 shows a typical inrush current waveform at the moment of transformer energization.
Figure 2. Flux waveforms of $\phi$ start with the residual flux $\phi_r$, and $\phi_0 = 0$.

From Figure 2, the magnetic flux $\phi$ in the transformer core is kept at a low level when the residual flux equals to zero. When residual flux is present, the initial value of the magnetic flux in the core will be increased, which makes it easier to saturate the core.

Figure 3 shows a typical inrush current waveform at the moment of transformer energization.

When calculating the peak inrush current, it is first necessary to determine the saturation flux in the core, which can be determined by Equation (5).

$$\phi_s = \int_S B \cdot dS$$  \hspace{1cm} (5)

where $S$ is the cross-sectional area of the iron core (cm$^2$).

The leakage flux $\phi_{air}$ in the air gap can be calculated by Equation (6) (Wb).

$$\phi_{air} = \mu_0 H S_m = 2\phi_p + \phi_r - \phi_s$$  \hspace{1cm} (6)

where $H$ is the magnetic field strength (A/m).

Equation (7) is the average cross-sectional area of the coil winding $S_m$.

$$S_m = \left(\frac{\pi D_m^2}{4}\right)$$  \hspace{1cm} (7)

where $D_m$ average winding diameter (m).

In the case of magnetic saturation of the iron core, the system reactance value $X_s$ can be calculated by Equation (8).

$$X_s = \frac{\mu_0 \cdot N^2 \cdot S_m}{h} \times 2 \cdot \pi \cdot f$$  \hspace{1cm} (8)
where $\mu_0$ is the air magnetic permeability (H/m). $f$ is the power supply frequency (Hz). Equation (9) represents the switching angle.

$$\theta = K_1 \cdot \cos^{-1}\left\{ \frac{B_s - B_{mp} - B_r}{B_{mp}} \right\}$$

Equation (9) represents the switching angle.

where $K_1$ is the saturation angle correction factor. $B_s$ is the saturation magnetic flux density (T). $B_r$ is the residual flux magnetic flux density (T). $K_1$, $B_s$, and $B_r$ are equal to 0.9, 1.25 $B_{mp}$, and 0.8 $B_{mp}$.

The peak value of magnetic induction ($B_{mp}$) in the transformer core can be calculated by Equation (10).

$$B_{mp} = \frac{V}{4.44 \cdot f \cdot N \cdot S_{core}}$$

where $V$ is the voltage value when the transformer is operating (V). $S_{core}$ is the cross-sectional area of the iron core.

According to the formula derived from our previous study [26], Equation (11) is used for calculating the peak inrush current.

$$i_{0\text{max}} = \frac{K_2 \cdot V \cdot \sqrt{2}}{X_S} \cdot (1 - \cos \theta)$$

where $i_{0\text{max}}$ is the peak inrush current generated by the single-phase transformer (A). $K_2$ is the peak inrush current correction factor, whose value is 1.15.

4. Calculation of Winding Electromagnetic Force

The moment the transformer is energized, the inrush current and the leakage field interact to produce a large instantaneous electromagnetic force, and Equation (12) is the formula for calculating the electromagnetic force.

$$\vec{F} = \vec{J} \times \vec{B}$$

where $F$ is the bulk density vector of electromagnetic force (N/m$^3$), $J$ is the current density vector (A/m$^2$), $B$ is the leakage flux density (T).

To analyze the impact of electromagnetic force on the transformer winding more accurately, the electromagnetic force is usually decomposed into radial force $F_r$ and axial force $F_a$ to analyze its impact on the transformer winding in detail.

4.1. Radial Force Analysis and Calculation

The radial force $F_r$ generated by the inrush current is a major source of mechanical stress in transformer high-voltage winding during excitation. The main reason for this situation is that the electromagnetic force generated by the inrush current is not generated in the primary side winding and secondary side winding at the same time as the short-circuit current, but rather is mostly concentrated in the high-voltage winding. Therefore, the analysis of the electromechanical characteristics of the transformer winding under no-load reclosing is mainly focused on high-voltage winding. Figure 4 shows the radial electromagnetic force generated on the windings of the transformer.

Formula (13) is the formula for calculating the radial force $F_r$ on the transformer winding.

$$F_r = \frac{2\pi^2 (N \cdot I_{imr})^2 D_m}{h} \cdot 10^{-7}$$
Equation (14) shows the average value of the electromagnetic force on the winding.

\[
F_{\text{rmed}} = \frac{F_r}{\pi} = \frac{2\pi (N \cdot I_{\text{irr}})^2 D_m}{h} \cdot 10^{-7}
\]  

(14)

where \(F_r\) is the radial electromagnetic force (N). \(F_{\text{rmed}}\) is the radial average electromagnetic force (N). \(I_{\text{irr}}\) is the peak inrush current (A). \(h\) is the winding height (m). \(D_m\) is the average diameter of the winding (m). \(N\) is the number of turns of the winding coil.

Figure 5 shows two forms of deformation—forced and free flexion—when the transformer winding is subjected to excessive radial forces. The transformer winding is subjected to inward pressure under the influence of radial force. When the pressure value exceeds the mechanical strength of the low-voltage winding support structure, the winding will produce two different forms of deformation: free flexion and forced flexion. Forced flexion refers to the deformation of transformer windings along the direction of electromagnetic force under the influence of two electromagnetic forces with an angle. Free flexion means that the transformer winding has a deformation along the direction of the non-electromagnetic force under the influence of two electromagnetic forces with an angle. Factors such as the strength of the electromagnetic force, the angle of the two electromagnetic forces and the structure of the support bar may have an effect on the free flexion.

\[
\begin{align*}
\text{Radial force} & = \frac{2\pi (N \cdot I_{\text{irr}})^2 D_m}{h} \\
\text{Average electromagnetic force} & = \frac{2\pi (N \cdot I_{\text{irr}})^2 D_m}{h} \cdot 10^{-7}
\end{align*}
\]  

(14)

4.2. Analysis and Calculation of Axial Forces

At the moment of no-load reclosing of the transformer, there will be both radial electromagnetic force component \(F_r\) and axial electromagnetic force component \(F_a\) in the winding. Figure 6 shows the axial electromagnetic force component \(F_a\) generated on high-voltage winding under the inrush current.
5.1. Matlab/Simulink Circuit Simulation Analysis

5. Transformer Modeling and Simulation Analysis

4.2. Analysis and Calculation of Axial Forces

At the moment of no-load reclosing of the transformer, there will be both radial electromagnetic force component and axial electromagnetic force component generated on high-voltage sides of the winding under the inrush current. Figure 6 shows the axial force generated in the winding under the inrush current.

The radial leakage generated at the end of the winding interacts with the inrush current to generate axial forces. The total axial force generated at the center of the winding can be found by Equation (15) [19–21].

\[ F_a = \frac{2\pi^2 \cdot (NI_{inr})^2 D_m \cdot 10^{-7} \cdot d}{h^3} \cdot \frac{d}{3} \]  

(15)

where \( F_a \) is the axial compression force (F/m). \( d \) is the radial thickness of the energized coil (m).

5. Transformer Modeling and Simulation Analysis

5.1. Matlab/Simulink Circuit Simulation Analysis

In this paper, a single-phase transformer circuit model is built, as shown in Figure 8. The research presented in this paper is a continuation of our previous work [26]. The parameters of the test transformer are shown in Table 1. To ensure that the simulation results are as close as possible to the actual values, the parameters of the prototype need to be transformed into those of the specific module, and the hysteresis characteristics of the core material, i.e., the \( i-\phi \) curve, must be taken into account.
Figure 8. The circuit simulation model of a single-phase transformer with no-load closing.

Figure 9. Magnetization curve of the transformer.

Table 1. Transformer test prototype main parameters.

| Parameters                              | Value         |
|-----------------------------------------|---------------|
| Rated capacity $S_N$/KVA               | 66.7          |
| Impedance percentage $r$/%             | 10.56         |
| Frequency $f$/Hz                        | 50            |
| Primary side and secondary side rated voltage $U_N$/KV | 219.4/219.4 |
| High and low current rating $I_N$/A     | 151.92/151.92 |
| Number of primary and secondary side turns $N$ | 232/232      |
| Rated voltage $U_N$/V                   | 219.4         |
| Rated current $I_N$/A                   | 151.92        |
| Rated magnetic density $B_m$/T           | 1.559         |
| Rated no-load current $I_{n}$/A         | 1             |
| Rated no-load current peak $I_{n}$/A    | 2.2           |
| System resistance $R$/Ω                 | 0.00748       |
| System inductance $L$/mH                | 0.0888        |

To consider the hysteresis characteristics of the core, the magnetization curve of the transformer core needs to be set. In this paper, the hysteresis design function of the Powergui module is used to design and modify the hysteresis return of the core material to complete the setting of the hysteresis characteristics of the transformer core. Figure 9 shows the magnetization curve of the transformer core after modifying the setting parameters.

Figure 10 shows the waveforms of the inrush current under two different residual fluxes conditions obtained by using the simulation software when the closing angle $\theta = 0^\circ$. 

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Figure 10. Waveform of inrush current under different residual flux when switching angle \( \theta \): (a) \( B_r = 0.68 \text{T} \); (b) \( B_r = 1.13 \text{T} \).

Figure 11 shows the corresponding inrush current amplitude under different residual fluxes and closing angles.

Figure 11. Peak inrush current under different residual flux and closing angle.

Figure 11 shows that the residual flux in the transformer core as well as the angle during no-load reclosing have an effect on the inrush current. The maximum amplitude of the inrush current can be obtained when other factors remain constant and the closing phase angle \( \theta = 0^\circ \). When the closing angle is \( \theta = 90^\circ \), the minimum amplitude of the inrush current is generated. While the reclosing angles are the same, with the increase of residual flux, the amplitude of the inrush current generated in the transformer winding is also gradually increasing, and its amplitude can reach up to 5165 A. Therefore, the inrush current in the windings is generated by the combined effect of residual flux and closing angle during transformer operation.

5.2. Simulation Analysis of Electromechanical Characteristics of Transformer Windings

5.2.1. Windings Electromagnetic Simulation Analysis

A single-phase transformer is used in order to analyze its leakage, electromagnetic force and winding deformation. Simulation analysis shows that under the combined effect of inrush current and leakage, a large electromagnetic force is generated on the winding. Therefore, the accurate measurement of magnetic leakage is very important. To ensure the accuracy of the simulation results, the measurement points of magnetic leakage are selected as comprehensively as possible. Figure 12 shows a schematic diagram of the location of the measurement point selection for air gap leakage of the transformer winding.
selected as comprehensively as possible. Figure 12 shows a schematic diagram of the location of the measurement point selection for air gap leakage of the transformer winding.

Figure 12. Leakage measurement points are selected from A–F.

Figure 13 shows the leakage curves of the measured points between the air gaps of the primary and secondary side windings at the residual flux $B_r = 1.24 \, \text{T}$ and the switching angle $\theta = 0^\circ$.

From Figure 13, the amplitude of radial leakage at measurement points A and D, B and E, C and F are the same, but in opposite directions, while the direction and amplitude of axial leakage remain the same. The maximum value of axial leakage occurs in the middle of the winding, while the maximum value of radial leakage occurs at two ends of the
winding. The maximum axial magnetic density $B_a = 0.1157$ T and the maximum radiation magnetic density $B_r = 0.0623$ T.

5.2.2. Simulation Analysis of Winding Structure

When the external conditions are basically the same, the inrush current amplitude generated during no-load reclosing is higher than the inrush current amplitude generated under other circumstances. Meanwhile, most of the inrush current generated by no-load reclosing is concentrated in the high-voltage winding. Therefore, the paper focuses on the structural characteristics of transformer primary windings under different residual fluxes no-load reclosing conditions.

Under normal operating conditions, the electromagnetic forces and leakage fields generated in the transformer windings are relatively small, so the winding support structure is fully capable of withstanding electromagnetic stresses. However, under the transient phenomenon of a sudden increase in inrush current, the leakage field due to high currents also reaches considerable values, so that the transformer is damaged when the electromagnetic force is greater than the stress that the winding can withstand.

When the winding height is the same, the magneto-motive force in the transformer is uniformly distributed, and the radial leakage at both ends interacts with the energized winding to produce axial force, with the maximum value at both ends of the winding, squeezing the winding. The radial force is generated by the interaction between the axial leakage and the energized winding, with the maximum value in the middle of the winding and decreasing toward the ends of the winding, stretching the winding, and usually generating a circumferential stress on the primary side windings.

Figure 14 shows a schematic diagram of the positions of the primary windings in the transformer model.

![Figure 14. Positions 1–4 of the transformer primary windings simulation model.](image)

Figure 15 shows the volume force density vector diagram of the primary windings when the residual flux magnetization $B_r = 1.24$ T and the closing angle $\theta = 0^\circ$.

![Figure 15. Volumetric force density vector map.](image)
From Figure 15, it can be obtained that the electromagnetic force at both ends of the winding is greater than that at the middle, and the maximum value of the electromagnetic force reaches $2.5707 \times 10^6 \text{ N/m}^3$.

Figure 16 shows the stress and displacement clouds of the primary windings when the residual flux magnetization $B_r = 1.24 \text{ T}$ and the closing angle $\theta = 0^\circ$.

![Primary windings cloud map: (a) stress cloud map; (b) displacement cloud map.](image)

The axial force is due to the radial magnetic field. The maximum stress of the winding reaches up to $1.7334 \times 10^7 \text{ Pa}$ under the excitation of the inrush current, as can be seen from Figure 16a. Figure 16b shows that the most significant deformation is in the middle of the winding, with a maximum deformation of $4.6187 \times 10^{-2} \text{ mm}$. Based on Figure 7, the analysis of the impact of the axial force $F_a$ on the deformation of the winding, combined with Figure 16, that the axial electromagnetic force generated under the influence of the excitation surge will squeeze the winding, result in an intensification of the winding amp-turn imbalance, which will lead to the collapse of the transformer.

To ensure the accuracy of the winding structure analysis as much as possible, the transformer windings are partitioned as shown in Figure 17. In addition, the electromagnetic force at the selected measurement points on each partition winding is measured under the conditions of residual flux $B_r = 1.24 \text{ T}$ and closing angle $\theta = 0^\circ$.

![Diagram of winding division.](image)

Figure 17 uniformly divides the primary windings of the transformer model into ten intervals, and selects suitable measurement points in each interval, and simulates and analyzes the radial force $F_r$ and axial force $F_a$ on the primary windings at the measurement points under the inrush current shock.
Figure 18 shows the radial force $F_r$ and axial force $F_a$ distribution at the measurement point under the inrush current shock.

![Graphs showing force distribution](image1)

Figure 18. The primary side winding electromagnetic force: (a) primary winding 1 radial and axial forces; (b) primary winding 2 radial and axial forces; (c) primary winding 3 radial and axial forces; (d) primary winding 4 radial and axial forces.

Figure 18 shows that the value of the radial electromagnetic force is significantly higher in the middle of the primary windings than both ends, and the maximum value of the axial electromagnetic force at both ends is higher than the middle position of the primary windings, under inrush current excitation. The primary side winding is subjected to excessive radial electromagnetic force, $F_r$, which will not only lead to an increase in the air gap between the primary side and secondary side windings, but may also damage the insulation of the primary side winding, resulting in a short circuit between turns of the transformer. At the same time, the radial electromagnetic force in the middle of the winding is greater than that at the ends, thus making the structure of the primary windings of a transformer operating for a long time close to an ellipsoidal shape. Under the influence of the inrush current, the axial electromagnetic force generated at both ends of the primary windings will squeeze the winding to the middle of the winding, making the unbalance between the turns of the winding intensify, thus increasing the electromagnetic force on the winding and reducing the transformer life. In general, the axial electromagnetic force $F_a$ generally has a more pronounced effect on the end of the winding, and the middle of the winding is more influenced by the radial electromagnetic force $F_r$.

6. No-Load Reclosing Test under Different Residual Flux Magnetism

6.1. Phase Control Switch Principle

To analyze the electromechanical characteristics of the windings under different residual fluxes, the transformer is controlled by a compound switch composed of thyristors to turn on and off. Figure 19 shows a schematic diagram of the phase-controlled switch.
Figure 19. Schematic diagram of the phase-controlled switch composed of thyristors.

The voltage signals of the circuit are obtained by the multi-channel data acquisition function of the hardware. After the Alternating Current (AC) excitation voltage crosses zero, the hardware controls the forward thyristor trigger angle to generate different phase signals, controls the reverse thyristor renewal, and turns on the AC contactor connecting circuit. Thus, the hardware realizes the communication between the master chip and the Personal Computer (PC) and sets the closing phase angle. Then the PC sends out the specified values to control the loading excitation to form different residual fluxes.

6.2. Windings Electromagnetic Characteristics Test

The test process (Figure 20) uses the recorder DL850 (Yokogawa, Tokyo, Japan) to record and store the final current and voltage signals, and uses the oscilloscope TEK DPO3054 (Tektronix, Beaverton, America) to display the voltage and current signals. Using the laser Doppler vibrometer LV-S01 (Sunny Optical Technology (Group) Co., LTD, Zhejiang, China), the winding deformation displacement is measured under different residual fluxes of magnetic influence. The simultaneous recording of data using a recorder and an oscilloscope can mutually verify the correctness of experimental waveforms and experimental data. The leakage density between the winding air gaps is measured using a measuring coil and the leakage waveform is displayed by a wave recorder DL850. Figure 21 shows the peak inrush current under different residual fluxes.

Figure 20. Test measurement site.
Figure 21. Maximum inrush current under different residual flux: (a) switching angle $\theta = 0^\circ$; (b) switching angle $\theta = 170^\circ$.

From the above Figure 21, it can be seen that when the transformer is closed at no-load, the inrush current generated is related to the residual flux. As the residual flux increases, the peak of the inrush current gradually increases. The main reason is that the larger the residual flux magnetic density $B_r$ in the core, the faster the core reaches saturation, the higher the degree of saturation, and the greater the value of the resulting inrush current.

Figure 22 shows that when the direction of the residual flux magnetism changes, the direction of the leakage magnetism will also change, but the size of the residual flux magnetism has little effect on the leakage magnetism. The trend of air gap leakage at both ends of the winding is basically the same, and the difference is not significant.

![Air gap leakage curve under different residual flux](image)

**Figure 22.** Air gap leakage curve under different residual flux.

### 6.3. Windings Mechanical Characteristics Test

To measure the mechanical characteristics of the transformer prototype winding under different residual flux magnetism, an acceleration sensor is used to measure the acceleration response, and a laser vibrometer is used to measure the winding displacement. By analyzing the acceleration frequency response during the winding vibration, important parameters such as the system intrinsic frequency, damping ratio and modal vibration pattern are obtained. Data acquisition of vibration signals is performed using the DH5902 (Donghua Test Technology Co., Jingjiang, Jiangsu, China) vibration test system. A general flow chart of the experiment is shown in Figure 23.
The overall flow chart of the experiment.

The test focused on measuring the vibration information of the winding biscuit at the moment of transformer reclosing, based on the structural characteristics of the transformer winding biscuit and combined with the finite element simulation analysis results, the specific measurement acquisition points are shown in Figure 24 below. The arrangement of measurement points mainly follows the principle of avoiding the omission of the main location but also as convenient as possible, each transformer winding line cake on a total of seven points of measurement.

The specific measurement points of the transformer winding vibration test.

The data of the seven vibration measurement points shown in Figure 24 above were collected at the residual flux $B_r = 0.349$ and the closing angle $\theta = 0^\circ$ and analyzed by spectrum. Figure 25 shows the peak winding acceleration for measurement points 1–7.

Peak acceleration at measurement points 1–7.

Figure 25 shows that the amplitudes of vibration acceleration are almost the same for each measurement point at symmetrical positions. The highest acceleration amplitude, of up to 4.8 mm/s$^2$, is located near measurement point No. 4.

Figure 26 shows the peak winding acceleration at measurement points 1–7 with residual flux $B_r = 0.349$ and closing angle $\theta = 0^\circ$. 

Figure 23. The overall flow chart of the experiment.
From Figure 26, it can be seen that the vibration characteristics are different for different measurement points at different frequencies. Among them, measurement point 3 has the most serious vibration and the largest vibration acceleration at the frequency of 97.7 Hz.

Figure 27 shows the deformation of Line 1 cake and Line 5 cake under different residual fluxes.

From Figure 27, it can be seen that the winding deformation gradually increases with the increase of residual flux magnetic $B_r$. The main reason is that when the residual flux magnetization $B_r$ in the core is larger, the peak of the inrush current will increase and the air gap leakage will also increase, which in turn leads to an increase in winding deformation. In the middle of the winding, due to the increase of radial force, there will be more serious deformation, making the overall structure of the transformer an oval ball shape.

7. Discussion

Table 2 shows the comparison of the simulated value $I_{\text{max}1}$ and the experimental value $I_{\text{max}2}$ of the peak inrush current generated by the transformer under different residual fluxes $B_r$ when the closing phase angle $\theta = 0^\circ$. 

![Figure 26. Vibration acceleration spectrum analysis of measurement points 1–7.](image1)

![Figure 27. Windings deformation under different residual flux. (a) Line 1 pie winding deformation under different residual fluxes. (b) Line 5 pie winding deformation under different residual fluxes.](image2)
Table 2. The peak inrush current $I_{\text{max}}$ under different residual flux $B_r$ when the closing angle $\theta = 0^\circ$.

| Residual Flux Density $B_r/T$ | Peak Excitation in Rush Current $I_{\text{max}}/A$ | Simulation Value $I_{\text{max}}$ | Test Value $I_{\text{max}}$ | $I_{\text{max}}^2/I_{\text{max}1}$ |
|-------------------------------|-----------------------------------------------|-------------------------------|-----------------------------|----------------------------------|
| 0                             | 1999                                          | 1993                          | 0.9970                      |
| 0.24                          | 2101                                          | 2051                          | 0.9767                      |
| 0.41                          | 3195                                          | 3130                          | 0.9797                      |
| 0.65                          | 3367                                          | 3328                          | 0.9884                      |
| 1.24                          | 5165                                          | 5075                          | 0.9826                      |

From Table 2, it can be seen that the maximum error between the simulated value and the experimental value obtained by simulation is less than 0.3%, and the minimum error is less than 0.1%, demonstrating the effectiveness of the simulation analysis method. At the same time, with the increase of the residual flux $B_r$, the amplitude of the inrush current gradually increases, compared with zero residual flux, the residual flux $B_r$ increases to 1.24 T when the inrush current amplitude $I_{\text{max}}$ increases by about 2.5 times.

Table 3 shows the comparison between the simulated value $\Delta x_1$ and the tested value $\Delta x_2$ under different residual fluxes $B_r$ of line 5 cake.

| Residual Flux Density $B_r/T$ | Winding Deformation $\Delta x/mm$ | $\Delta x_2/\Delta x_1$ |
|-------------------------------|-----------------------------------|-------------------------|
|                               | Simulation Value $\Delta x_1$ | Test Value $\Delta x_2$ |                     |
| 0                             | 0.2436                            | 0.2206                  | 0.9056                |
| 0.24                          | 0.3391                            | 0.3291                  | 0.9705                |
| 0.41                          | 0.3497                            | 0.3467                  | 0.9914                |
| 0.65                          | 0.4364                            | 0.4164                  | 0.9542                |
| 1.24                          | 0.6926                            | 0.6636                  | 0.9581                |

From Table 3, it can be seen that the maximum error between the simulated value $\Delta x_1$ and the experimental value $\Delta x_2$ obtained by simulation is less than 1%, and the minimum error is less than 0.1%, demonstrating the effectiveness of the simulation. Meanwhile, as the residual flux $B_r$ increases, the winding deformation gradually increases. Compared with zero residual flux, the winding deformation $\Delta x$ increases about 3 times when the residual flux $B_r$ increases to 1.24 T.

Comparison and analysis of the experimental results and the simulation results proved that the different residual fluxes could lead to differences in the peak magnitude of the inrush current, the leakage magnetic field, the winding electromagnetic force, and the deformation of the winding. As the residual flux of the transformer core increases, the inrush current, as well as the winding deformation, increases significantly.

8. Conclusions

In this paper, the electromechanical characteristics of the no-load reclosing winding of a dry-type transformer under different residual fluxes are comprehensively analyzed. First, a simulation circuit was built to obtain the peak inrush current generated during no-load reclosing under different residual fluxes of the transformer core. At the same time, these current peaks are loaded as the excitation into the transformer model. Moreover, the electromechanical characteristics of the transformer winding under the influence of the inrush current generated during no-load reclosing are analyzed using the field-circuit coupling and the finite element method. Finally, for the verification tests, the closing operation of the transformer is controlled by the phase-controlled switch, and the residual flux at the closing moment is calculated based on the analysis of the breaking angle. The laser Doppler vibrometer and the measuring coil were used to measure the winding deformation and air gap leakage. On the basis of a comparative analysis of the experimental and simulation results, it can be seen that as the residual flux in the core increases, under the combined
effect of the inrush current and the air gap leakage field, a large electromagnetic force is generated on the transformer winding. According to the simulation and experimental results, the axial electromagnetic force generally affects the winding end more obviously, and the middle position of the winding is more affected by the radial electromagnetic force.

The validity and reliability of the simulation method and the principle analysis are proved in this paper by their comparison. The comprehensive analysis and experimental verification of the electromechanical characteristics of the transformer windings in the case of no-load reclosing were performed in this paper, making it possible to effectively assess the performance of transformer winding parameters under the influence of inrush current. This research can be applied to the simulation analysis of different power transformers, and is a guide for extending the service life of transformers and the in-depth study of transformer fault analysis. With the increase of grid capacity, it is of great significance to the power system to ensure the safe and stable operation of transformers.

However, when transformers are subjected to multiple inrush current shocks in a relatively short period, their electromechanical characteristics are bound to be greatly affected. Therefore, in the next step, it is necessary to analyze the electromechanical characteristics of a transformer when it experiences multiple inrush currents.

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