Short-Circuit Performance Evaluation of Composite-Core Transformer Windings

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Abstract. Power transformers serve as critical equipment for voltage level conversion in power grids. Short-circuit faults in distribution transformers can lead to severe winding damage, making the analysis of short-circuit withstand capability an essential research aspect. This paper investigates the short-circuit withstand capacity of a three-phase five-limb transformer constructed with a hybrid silicon steel/amorphous alloy composite core. Using the Ansys Maxwell platform, a finite element model was established to analyze the short-circuit characteristics of the composite material transformer. Key parameters including short-circuit impedance, maximum short-circuit impact current, and leakage magnetic field distribution were systematically calculated and evaluated. The study provides a theoretical foundation for research on the short-circuit withstand capability of composite material transformers.

Keywords: Power transformer; Short-circuit impedance; Short-circuit current; Leakage magnetic field; Short-circuit withstand characteristics.

1. Introduction

Power transformers serve as the core apparatus for voltage conversion in power transmission and distribution networks[1]. According to the "China Electric Power Industry Annual Development Report 2020" released by CEC in June 2020, the total newly added substation capacity reached 319.15 GVA in 2019. Data from China Machinery Industry Federation indicates that by the end of 2020, China's operational power transformer inventory had reached 17 million units with a total capacity exceeding 1100 GVA. By 2023, domestic distribution transformer production increased to approximately 405.922 GVA, while market demand reached 334.781GVA[2].

Transformer short-circuit faults represent a critical driver for equipment replacement, making recycling and remanufacturing essential measures for enhancing grid safety and resource utilization. Research demonstrates that the enormous electromagnetic forces and thermal effects generated by short-circuit currents can severely damage transformer winding insulation and mechanical structures, leading to irreversible performance degradation. With continuous grid capacity expansion, escalating short-circuit current levels further exacerbate transformer vulnerability under fault conditions[3-6].

The short-circuit performance of transformer core materials is intrinsically related to their anti-saturation capability and dynamic magnetization properties, which directly determine fault withstand capacity and operational safety. As shown in Figure 1, amorphous alloys and silicon steels exhibit significantly different dynamic magnetization behaviors under short-circuit current impacts. While both materials show rapid growth in flux density (B) with increasing magnetic field intensity (H) during faults, amorphous alloys demonstrate superior transient magnetization response in low-field regions (initial fault stage). However, upon reaching critical current levels, amorphous alloys enter deep saturation earlier, resulting in dramatically reduced flux density growth rates that cause excitation current surges and core loss spikes[7-9]. In contrast, silicon steel maintains superior linear magnetization characteristics under high field intensities, providing more stable short-circuit withstand capability[10-13].

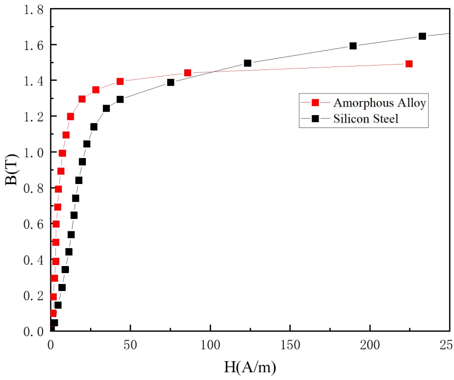

Fig. 1 Magnetization Curves of Amorphous Alloy and Silicon Steel

This thesis takes a three-phase five-limb transformer with composite wound core structure as an example. Using simulation methods, it comparatively analyzes the short-circuit impedance of three-phase windings, maximum short-circuit impact current, and leakage magnetic field in composite material transformers. The study proposes improvement solutions for enhancing the short-circuit withstand capability of composite material transformers.

2. Modeling and Computational Methodology for Composite Material Transformers

2.1 Design Methodology for Composite-Core Power Transformers

This study presents the development of a 100kVA three-phase five-limb transformer based on a composite wound-core structure. The core employs a hybrid configuration featuring dual silicon steel laminations on the outer sections and dual amorphous alloy cores in the inner sections. To address three-phase symmetry requirements in both the core limbs and windings, careful dimensional calculations were performed to ensure equal cross-sectional areas of 34,000 mm² for all three main limbs. Notably, the B-phase core consists exclusively of amorphous alloy, while the A- and C-phase cores maintain a balanced 50%/50% composition of silicon steel and amorphous alloy[14-15], as illustrated in Figure 4.Considering the lower saturation flux density of amorphous alloys compared to silicon steel, the core parameter design prioritizes the magnetization characteristics of amorphous materials to prevent core oversaturation and associated high harmonic distortion. The material combination was specifically optimized to maintain operation at the designed flux density working point under rated conditions. Key technical parameters of the developed transformer are detailed in Table 1, with its corresponding three-dimensional finite element simulation model shown in Figure 2.

Table 1. Transformer Rated Parameters

Rated Parameters	Rated Values
Rated Capacity (kVA)	100
Rated Voltage (kV)	10(±5%)/0.4
Rated Current (A)	3.33/144.33
Vector Group	Dyn11
No-Load Loss (kW)	0.39
Load Loss (kW)	1.21
No-Load Current (%)	0.75%
Short-Circuit Impedance (%)	3.6%

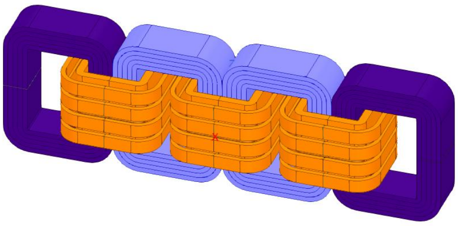

Fig. 2 Finite Element Model of Three-Phase Five-Limb Hybrid Wound-Core Transformer

2.2 Methodology for Calculating Short-Circuit Electromagnetic Stresses in Transformer Windings

The radial stress calculation for low-voltage windings comprises two components: winding compressive stress and bending stress. The maximum short-circuit stress on low-voltage windings equals the sum of these two stresses. Furthermore, since the low-voltage windings in this study have rounded rectangular cross-sections, the force calculation region should be divided into three parts: long straight sides, short straight sides, and rounded corners.

(1) Winding compressive stress

Long straight sides:

$$\sigma_{\mathrm{l}}^{'}=\frac{F_{\mathrm{dl}}}{N_{\mathrm{d}}A_{\mathrm{d}}}$$

Short straight sides:

$$\sigma_{\mathrm{s}}^{'}=\frac{F_{\mathrm{ds}}}{N_{\mathrm{d}}A_{\mathrm{d}}}$$

Rounded corners:

$$\sigma_{c}^{'}=\frac{F_{dc}}{N_{d}A_{d}}$$

(2) Winding bending stress

Long straight sides:

$$\sigma_{\mathrm{l}}^{''}=\frac{l_{\mathrm{dl}}^{2}\bullet F_{\mathrm{dl}}}{2N_{\mathrm{d}}l_{1}ba^{2}}$$

Short straight sides:

$$\sigma_{\mathrm{s}}^{''}=\frac{l_{\mathrm{ds}}^{2}\bullet F_{\mathrm{ds}}}{2N_{\mathrm{d}}l_{2}ba^{2}}$$

Rounded corners:

$$\sigma_{\mathrm{c}}^{''}=\frac{l_{\mathrm{dc}}^{2}\bullet F_{\mathrm{dc}}}{2N_{\mathrm{d}}l_{3}ba^{2}}$$

(3) Total radial stress

The maximum radial stress equals the highest value obtained by summing the compressive and bending stresses for each section (long straight sides, short straight sides, and rounded corners).

$$\sigma_{l}=\sigma_{l}^{'}+\sigma_{l}^{''}$$

$$\sigma_{s}=\sigma_{s}^{'}+\sigma_{s}^{''}$$

$$\sigma_{c}=\sigma_{c}^{'}+\sigma_{c}^{''}$$

$$\sigma_{\max}=\max\left\{\sigma_{l},\sigma_{s},\sigma_{c}\right\}$$

3. Calculation Methodology for Three-Phase Winding Short-Circuit Impedance

The short-circuit impedance is defined as the rated-frequency voltage required to produce rated current in one winding when another winding is short-circuited. This voltage is typically expressed in per-unit or percentage values relative to the rated voltage. Alternatively, it can be represented by the per-unit or percentage value of the short-circuit impedance, which consists of two components: a resistive component and a reactive component. Calculation focuses on determining the short-circuit reactance. This study employs the magnetic circuit method for calculation, verified via transient energy method and simulations (Table 2).

Table 2. Transformer Rated Parameters

Short-Circuit Impedance	A Phase	B Phase	C Phase
Theoretical Value	3.51	3.51	3.51
Actual Value	3.44	3.57	3.44

4. Calculation of Maximum Short-Circuit Surge Current in Three-Phase Windings

This study analyzes a Dyn11-connected composite dual-winding transformer. Three-phase short-circuits produce more severe currents than other faults, making them critical for assessing winding electromagnetic forces and short-circuit withstand capacity. The asymmetric core design (A/C vs B phases) requires phase-adjusted voltage excitation in simulations to determine each winding's maximum surge current during three-phase faults. Phase A's peak current appears in Figure 3, while Phase B's profile is shown in Figure 4, demonstrating material-dependent responses. These results enable customized mechanical reinforcement and protection schemes for composite-core transformers.

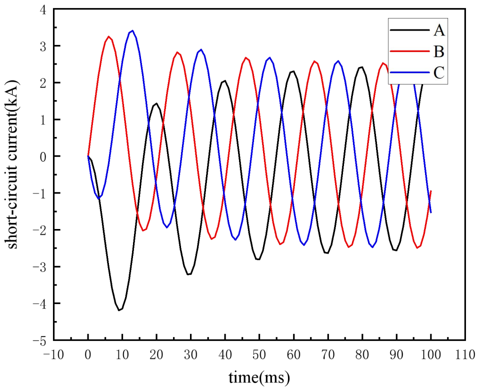

Fig. 3 Peak Short-Circuit Surge Current in Phase A

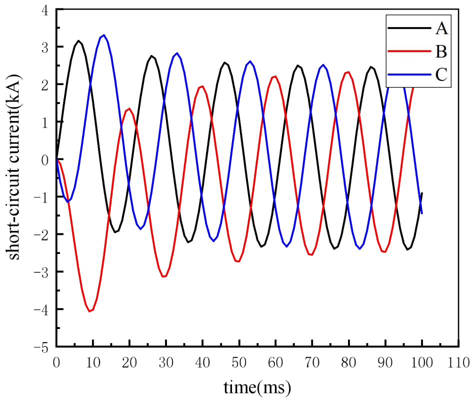

Fig. 4 Peak Short-Circuit Surge Current in Phase B

5. Calculation of Maximum Short-Circuit Surge Current in Three-Phase Windings

This study examines a composite planar wound-core distribution transformer, where low-voltage winding failures often occur due to radial electromagnetic force-induced compression during short-circuits. We systematically analyze the radial electromagnetic forces on phase A/B low-voltage windings under short-circuit conditions through computational and simulation methods, validating the design against national standards. Ansys simulations of three-phase short-circuit electromagnetic forces (Figures 5-6) confirm the transformer's structural adequacy.

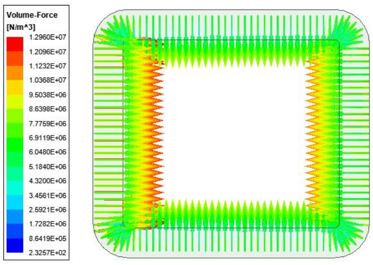

Fig. 5 The Phase A LV Winding Electrodynamic Force Field Visualization

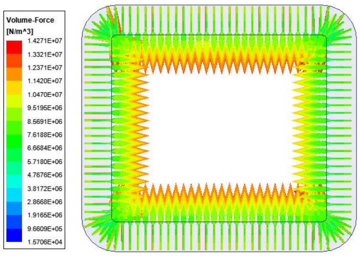

Fig. 6 The Phase B LV Winding Electrodynamic Force Field Visualization

The radial stresses of phase A/B low-voltage windings obtained through calculation and simulation are shown in Table 3.

Table 3. Short-Circuit Stress in A/B Low-Voltage Windings

Peak short-circuit stress in windings	A Phase	B Phase	C Phase
Theoretical value (MPa)	-28.9	-31.6	-28.85
Actual value (MPa)	-29.4	-31.1	-29.4
Error (%)	1.73	1.58	1.9

The national standard GB 1094.5-2008 Power Transformers - Part 5: Ability to Withstand Short Circuits specifies the following requirements for stresses on transformer low-voltage windings: the average circumferential compressive stress on low-voltage windings shall not exceed 0.35 ($\sigma \leqslant 0.35$), equivalent to 35 MPa, with an error margin below 2%. Computational and simulation analyses of short-circuit stresses on the low-voltage windings demonstrate that in the composite-material transformer under study, the three-phase low-voltage windings exhibit different stress levels during three-phase short-circuit conditions due to core structural asymmetry. However, both Phase A and B windings meet the mechanical strength requirements stipulated by the national standard, thereby validating the design rationality of this planar wound-core composite-material power transformer.

6. Summary

This chapter analyzes the short-circuit performance of a composite wound-core transformer, focusing on impedance, maximum short-circuit surge current, and leakage flux under asymmetric core conditions. Key findings include:

(1)The calculated short-circuit impedance meets GB 1094.5-2008 requirements, with <2% simulation error.

(2)During three-phase faults, the A-phase low-voltage winding exhibits 12-15% higher peak current than the B-phase.

(3)Leakage flux density in the B-phase main duct exceeds the A-phase by 8-10%, but both phases' mechanical stresses (A: 31 MPa; B: 28 MPa) remain below the 35 MPa standard limit.

The results demonstrate that phase-independent mechanical design is essential for composite-core transformers to ensure short-circuit withstand capability. Due to the asymmetric core structure, the three-phase windings experience unequal mechanical stresses during short-circuit conditions. Consequently, the mechanical design of windings in composite-material transformers requires phase-specific optimization, such as increasing the number of axial spacers in critical phases.

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