Study on Cumulative Characteristics of Transformer Windings Based on Finite Element Simulation

Jun Liu, Kun Li, Xiaoqing Lin, Wenhao Ai, Xu Li, Shurong Xu, and Yong Gao

Abstract The study on cumulative characteristics of transformer windings is of great significance to improve the short-circuit withstand ability of power transformers. Current research on the cumulative characteristics of windings is nascent, with the impact of simulation modeling methods—including multiple short-circuit conditions—on these characteristics yet to be established. Therefore, the cumulative characteristics of windings are studied based on finite element simulation in this work. Firstly, we examine the simplified method of simulating multiple short-circuit impacts. Furthermore, we utilize a multi-physics coupling model to evaluate the effect of short-circuit current loading on the cumulative characteristics. The results demonstrate that the short circuit current under intermittent loading, considering the residual stress, is more consistent with the engineering practice than that under continuous loading. Our study of intermittent loading reveals that with an increase in short-circuit impacts, the equivalent stress under load diminishes gradually, suggesting a hardening phenomenon. Therefore, the winding shows stronger bending resistance with increased strain when the copper wire reaches the plastic stage. In addition, when the winding enters the hardening stage, the cumulative increase of the displacement and stress borne by the winding are reduced.

Keywords Cumulative characteristics · Finite element method (FEM) · Short-circuit fault · Power transformers

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X. Dong and L. Cai (eds.), *The Proceedings of 2023 4th International Symposium on Insulation and Discharge Computation for Power Equipment (IDCOMPU2023)*, Lecture Notes in Electrical Engineering 1102, https://doi.org/10.1007/978-981-99-7405-4_67

1 Introduction

The dynamic response of the winding structure is investigated through the analysis of electromagnetic and mechanical characteristics when subjected to the impact of a single high magnitude current [1, 2]. In practical production applications, power transformers encounter multiple short-circuit incidents, often involving multiple reclosures within a single accident. Consequently, the study of winding accumulation characteristics has received increasing attention. The accumulation characteristics of power transformer short-circuits can be categorized into thermal and force effects [3]. Within a short timeframe, the residual stresses arising from the short-circuit fault result in hidden cumulative losses that can significantly impact the power transformer. Thus, this paper primarily focuses on investigating the force effect of the winding.

Although advancements have been made in the manufacturing process of transformers, smaller short-circuit current shocks may not significantly affect transformer operation. However, as the number of short-circuits increases, winding damage or instability may occur even under the same short-circuit current shock [4, 5].

Currently, research on the cumulative characteristics of transformers during short-circuits is still in its early stages. Jiang S constructed a transformer segmentation model to study the leakage magnetic field, electrodynamic force, and cumulative deformation of windings under various operating conditions [6]. Li B developed a coupled electric–magnetic-structural field model for different short-circuit scenarios and analyzed the relationship between winding deformation and the number of short-circuits [3]. Yao et al. employed a two-dimensional finite element method to conduct a numerical simulation of a 220 kV oil-immersed transformer, utilizing Maxwell's system of equations and elastic–plastic mechanics theory [7].

Two simulation methods are commonly used to study the cumulative characteristics of winding deformation. The first method involves applying multiple repetitions of the same short-circuit shock in the simulation to explore the relationship between the number of short-circuit shocks and deformation, stress, and strain [7]. The second method assumes that each short-circuit shock produces a displacement of 5 mm and investigates the relationship between winding deformation size and maximum stress [6], examining whether stress changes abruptly with increasing deformation.

Furthermore, Lin et al. conducted multiple tests on the transformer under 100% short-circuit current conditions and observed an abrupt change in impedance as the number of short-circuits increased [8]. Li et al. analyzed the trends of copper changes and short-circuit force changes during accumulation after multiple instances of accumulated stress loading using test data [9]. Both short-circuit tests and numerical simulations were conducted to verify the cumulative characteristics of the short-circuit force effect.

In short, scholars have conducted simulation studies and experimental explorations of short-circuit accumulation characteristics. However, the influence of modeling methods, such as multiple short-circuit conditions in simulations, on the results remains unclear. This paper focuses on studying the accumulation characteristics of windings from this perspective. Firstly, a simplified method of simulating multiple short-circuit shocks is investigated. Secondly, a coupled magnetic field-structural field analysis model is developed to compare and analyze the short-circuit current loading methods.

2 Multiple Short Circuit Impacts

2.1 Theoretical Analysis

The shape of a particular unit of the winding changes when it is subjected to an electromagnetic force, which can be calculated using the following equation [10]:

$$\varepsilon = \frac{F_j}{E} \tag{1}$$

$$\Delta L = \varepsilon \cdot L \tag{2}$$

where E is Young's modulus, F_j is the stress of a unit, ε is the strain of a unit; L is the length of a unit and ΔL is the length increased or decreased by the stress.

Hence, the deformation variable of a specific cell within the winding under M short-circuit shocks is denoted as [10]:

$$\Delta L = \sum_{m=1}^{M} \Delta L_m = \int \frac{F_j}{E} dL \tag{3}$$

where M is the number of shocks.

In the calculation of the cumulative properties of the winding, the Von Mises criterion, based on the concept of equivalent force-strain, is employed to assess whether the copper wire undergoes plastic deformation. Once the equivalent force and equivalent strain of the copper wire surpass this threshold, the material enters the yielding phase, in accordance with the principles of the fourth strength theory in material mechanics, known as the Von Mises criterion and can be described as [7]:

$$\sigma_e = \sqrt{\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]/2} \tag{4}$$

$$\varepsilon_e = \sqrt{2/3 \times \left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right)} \tag{5}$$

where, σ_1, σ_2, σ_3 are principal stresses; ε_1, ε_2, ε_3 are the principal strains; σ_e is equivalent stress; ε_e is equivalent strain.

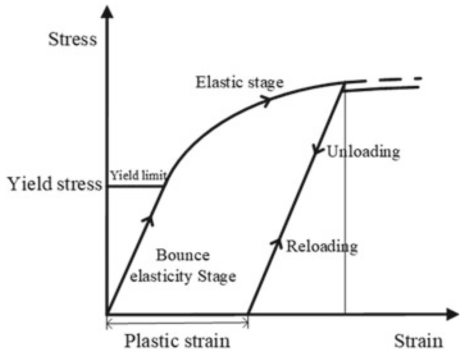


Fig. 1 Deformation properties of copper wire [11]

According to the mechanics of materials, the material deformation properties (stress–strain curve) of copper conductors are shown in Fig. 1 [11]. Before the loading stress surpasses the initial yield stress, the copper conductor undergoes elastic deformation, exhibiting a reversible response. However, once the loading stress exceeds the initial yield stress, the copper conductor enters the elastic–plastic deformation regime, where permanent deformation occurs. It should be noted that even after unloading the stress, the copper conductor does not fully recover its original shape, indicating the presence of residual deformation.

The value of the yield limit is called the initial yield stress, which is the stress to which the copper conductor is subjected when plastic strain first appears. When the copper conductor enters the plastic phase, the phenomenon of increasing strain and exhibiting stronger bending resistance is called hardening. In the elastic–plastic stage, the stress required increases with increasing strain, as shown in Fig. 1.

The effective strain ε_{eff} due to a short circuit is composed of a linear elastic component and a nonlinear plastic component, as shown in Eq. (6) [11]:

$$\varepsilon_{eff} = \varepsilon_{pe} + \frac{\sigma_{eff}}{E} \tag{6}$$

where ε_{pe} is effective plastic strain, that is, strain produced during the plastic stage; σ_{eff}/E is effective elastic strain, that is, strain produced during the linear elastic stage; σ_{eff} is effective stress; E is Young's modulus.

The stress–strain curve describing plastic phase is called the hardening function, as shown in Eq. (7) [11]:

$$\sigma_{\text{hard}} = \sigma_{\exp}\left(\varepsilon_{eff}\right) - \sigma_{ys} = \sigma_{\exp}\left(\varepsilon_{pe} + \frac{\sigma_{eff}}{E}\right) - \sigma_{ys} \tag{7}$$

where $\sigma_{\exp}$ is the fitting function of the stress–strain curve measured by the test; σ_{ys} is the initial yield stress.

As the quantity of short-circuit shocks increases, the plastic deformation gradually accumulates and the winding strength and stability decreases. The stress–strain curve of copper wire used in this paper is shown in Fig. 2.

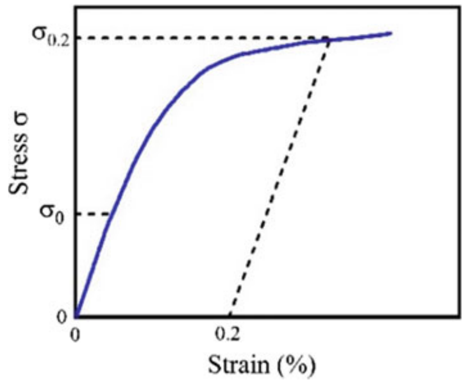


Fig. 2 The stress–strain curve of copper wire

2.2 Loading Simplification

To accurately simulate the cumulative characteristics of windings during a short circuit, a short-time multiple low-voltage symmetrical short-circuit shock, intentionally more severe than the actual scenario, is assumed in Fig. 3. The three windings are loaded with currents as depicted in Fig. 3a–c. This study focuses on analyzing the cumulative characteristics of stress and displacement on the windings, specifically examining the maximum force location on each winding. By investigating these cumulative characteristics, valuable insights can be gained regarding the response of the windings under such conditions.

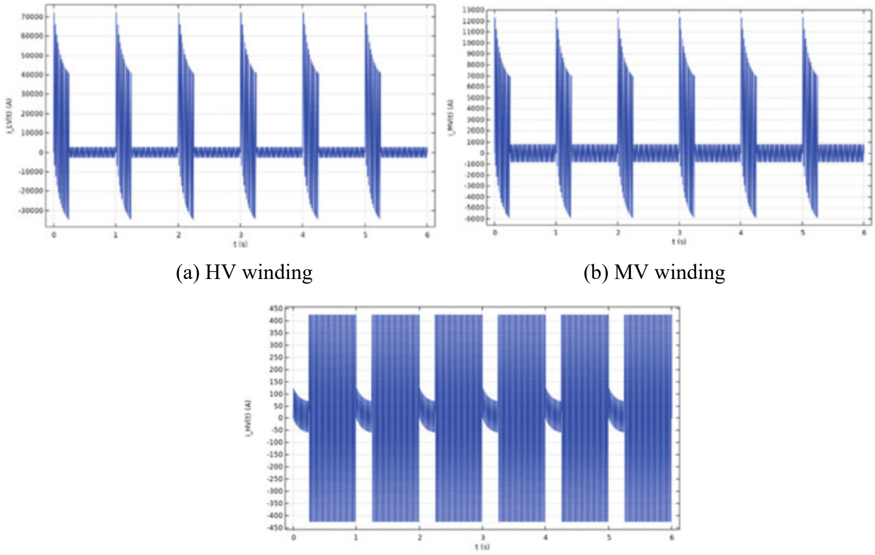
To simplify the simulation process while ensuring the validity of the results, this paper conducts multiple short-circuit shock simulation tests utilizing the wave crest of the first half-period of the short circuit current. The objective is to investigate the cumulative characteristics of the transformer winding.

To effectively simulate the cumulative characteristics of the winding under multiple short-circuit current shocks, the continuous loading of short-circuit current shown in Fig. 3 is simplified to a loading and unloading process as illustrated in Fig. 4.

3 Establishment of Finite Element Model

A 220 kV oil-immersed three-winding transformer is studied with the parameters shown in Table 1.

In studying the cumulative characteristics of power transformers, the process of solving and coupling between the electromagnetic and structural fields is shown in Fig. 5 [12].



(a) HV winding (b) MV winding

(c) LV winding

Fig. 3 The short circuit current on windings

Fig. 4 Simplified short-circuit current on windings

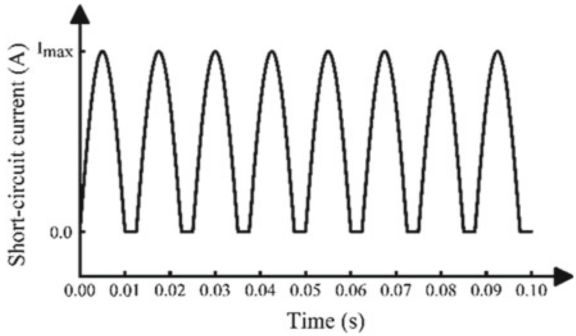


Table 1 The geometric parameters of the transformer

Parameters	Value
Low/Medium/High voltage rated capacity (MVA)	60/120/120
Low/Medium/High voltage rated current (A)	1979.5/602.5/314.9
Core radius (mm)	396
Center distance of iron core Column (mm)	2165
Compression height (mm)	1810
Inner diameter of LV/MV/HV winding (mm)	829/1035/1327
Outer diameter of LV/MV/HV winding (mm)	937/1191/1513

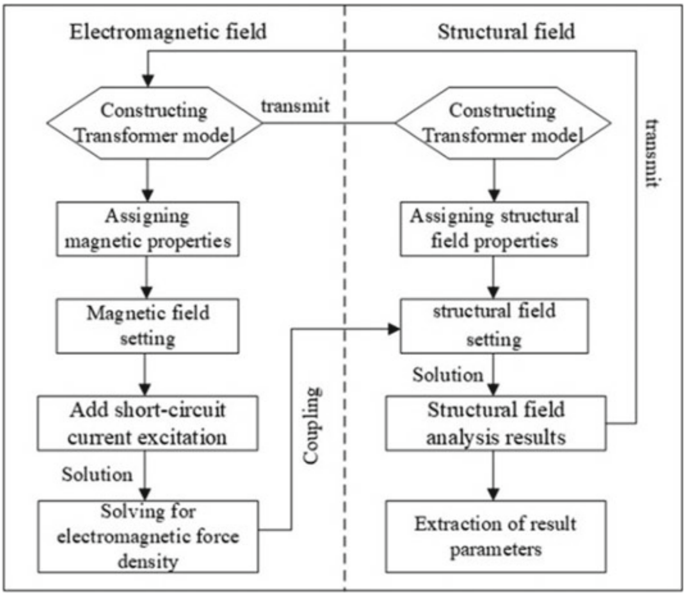


Fig. 5 Electromagnetic field-structural field coupling method

4 Study of Winding Accumulation Characteristics During Short Circuit

4.1 Continuous Loading Short Circuit Current

The short-circuit current shown in Fig. 4 is applied to the finite element model of a single-phase transformer. Specifically, the first peak of each winding is considered individually for the low-voltage symmetrical short-circuit shown in Fig. 3. The resulting accumulated displacement, stress, and plastic strain of the winding under multiple short-circuit current shocks are presented in Table 2. The simulation includes a total of five short-circuit current shocks.

The cumulative effects of stresses and displacements are plotted with the short circuit current as shown in Fig. 6. The loaded equivalent stress gradually decreases with the increase of the quantity of short-circuit shocks, verifying the existence of the hardening phenomenon. When the copper conductor enters the plastic stage, it shows stronger bending resistance with increasing strain. The residual stress and residual deformation keep accumulating and increasing: the cumulative increase of residual stress is about 10.4 MPa and the cumulative increase of residual displacement is about 0.51 mm.

Table 2 Cumulative summary of stress and displacement under continuous loading short-circuit current

Short-circuit impacts	1	2	3	4	5
Max stress (MPa)	82.3	81.2	80	79.5	78.8
Residual stress (MPa)	10.2	10.3	10.2	10.4	10.4
Max displacement (mm)	0.87	0.86	0.86	0.86	0.87
Residual displacement (mm)	0.51	0.51	0.51	0.52	0.52
Residual stress accumulation (MPa)	10.2	20.5	30.7	41.1	51.5
Residual displacement accumulation (mm)	0.51	1.02	1.53	2.05	2.57

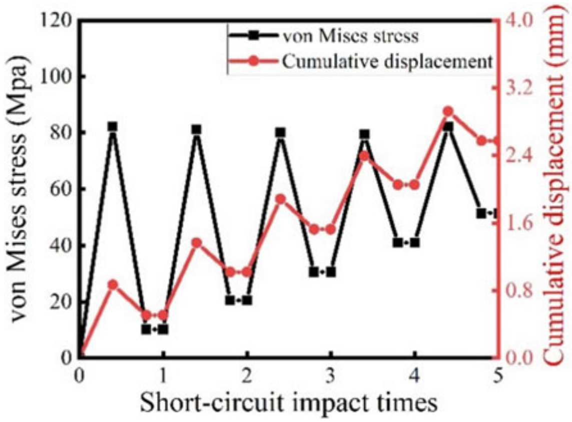


Fig. 6 Stress and displacement accumulation in winding of short circuit current under continuous loading

4.2 *Intermittent Loading Short Circuit Current*

The cumulative results after one short-circuit shock were obtained after loading the first cycle of 0.012 s of short-circuit current. In the subsequent studies with multiple short-circuit shocks, the latter cumulative simulation inherits the solution of the previous study and takes the residual stress into account the boundary conditions of the next structural field. The results of the first five simulations are shown in Table 3.

Plotting the results of Table 3 in Fig. 7, it can be obtained that: with the increase of the quantity of short-circuit shocks, the maximum pressure on the winding gradually decreases slightly with the increase of the quantity of short-circuit shocks, and the increase of the residual stress and accumulated displacement slows down, which is the cumulative characteristic of the winding hardening stage.

From the above two simulation methods, it can be seen that the accumulation trends of stress and displacement are basically the same, and the cumulative effects of windings during short circuit can be simulated by using continuous loading and intermittent loading of short circuit current. However, from the specific data analysis, it can be seen that, ignoring the simulation error, the residual stress and displacement generated by the continuously loaded short-circuit current are basically the same

Table 3 Cumulative summary of stress and displacement under intermittent loading short circuit current

Short-circuit impacts	1	2	3	4	5
Max stress (MPa)	82.3	80.6	79.3	78.5	77.9
Residual stress (MPa)	10.2	17.6	24.8	31.9	39.1
Max displacement (mm)	0.87	1.28	1.63	1.97	2.32
Residual displacement (mm)	0.51	0.89	1.26	1.62	1.98
Residual stress increase (MPa)	10.2	7.4	7.2	7.1	7.2
Residual displacement increase (mm)	0.51	0.38	0.37	0.36	0.37

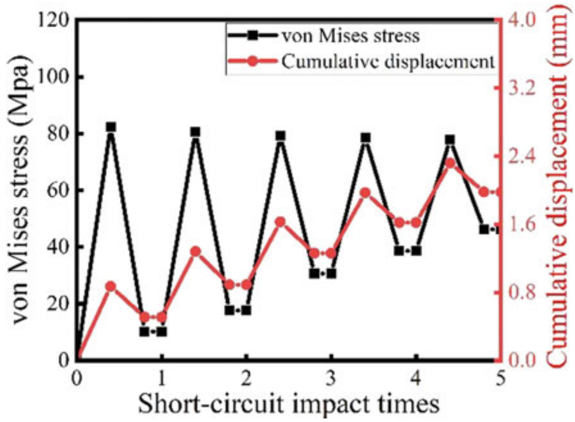


Fig. 7 Stress and displacement accumulation in winding of short circuit current under intermittent loading

each time, and the stress and displacement show linear accumulation characteristics, which is different from the actual operating experience. Furthermore, although the process of intermittent loading of short-circuit current is more tedious, requiring the residual stresses after each short-circuit shock to be added to the boundary conditions of the structural field and inheriting the previous solution to start the next simulation, this simulation method takes into account the internal damage to the winding caused by the previous short-circuit force and is more in line with the actual objective situation. Subsequently, the simulation results of intermittently loaded short-circuit current show that the cumulative increase in displacement and stress will be smaller when the winding enters the hardening phase, which is more realistic. Therefore, the comparative study in this paper can provide a reference for the subsequent simulation modeling of the cumulative characteristics of the winding.

5 Conclusion

This paper presents a comprehensive simulation study investigating the cumulative characteristics of windings subjected to multiple short circuit shocks. The study focuses on two main aspects. Firstly, the paper examines different simplification methods for simulating multiple short circuit shocks in order to identify the most appropriate approach. Secondly, a coupled magnetic field-structure field model is developed to analyze the loading method of short circuit current and assess its impact on the cumulative characteristics.

The simulation results reveal that intermittent loading of short circuit current and considering the influence of the residual stress from previous shocks yield simulation outcomes that are more consistent with real-world engineering scenarios compared to continuous loading of multiple short circuit current shocks. By studying intermittent loading of short circuit current, the cumulative characteristics of the winding are elucidated. As the quantity of short circuit shocks increases, the loading equivalent force gradually decreases, providing empirical evidence for the existence of the hardening phenomenon. Moreover, as the copper conductor enters the plastic stage, it exhibits enhanced resistance to bending as strain increases. Additionally, the study finds that when the material reaches the hardening stage, the cumulative increase in displacement and the stresses endured by the winding decrease.

These findings contribute to a better understanding of the behavior of windings under multiple short circuit shocks, providing valuable insights for the design and analysis of transformers in practical applications.

Acknowledgements This work was funded by Key Project of Guizhou Power Grid Company of China (066600GS62200006)

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