Research on Cumulative Effects of Power Transformer Winding Deformation Under Multiple Short-Circuit Condition

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The winding damaged caused by the impact of short circuit impact is one of the most important reasons of transformer accidents, but the studies on the multiple short-circuit conidtion caused the winding cumulative deformation is rarely seen. According to the above problem, this paper presents a math model to calculate the winding cumulative deformation, adopts the method of magnetic - structure field coupling, numerical calculates and analyzes the mechanical properties under the multiple short-circuit condition of windings, considering the influence of cumulative effects. The results show that the cumulative effect has a negative effect on transformer winding short-circuit strength, this paper presents the mathematical model can effectively calculate the winding deformation under multiple short-circuit condition, for transformer winding short-circuit strength design provides a theoretical basis.

***Index Terms*—Electromagnetic forces, finite element analysis, power transformers, short-circuit currents**

I. INTRODUCTION

IT is inevitable for power transformer to suffer short circuit in the power system operation. When the short-circuit occurs, the short-circuit current will be several times of rate current, which can produce strong magnetic field in the transformer winding, under the interaction of short-circuit current and magnetic field above, the winding will suffer huge short-circuit force [1], [2]. If transformer winding mechanical strength is insufficient, in such a big electrodynamic force, it is likely to happen winding deformation and even extend into inter-turns short circuit or bread, high and low voltage winding short circuit, and body collapse [3]-[5].

Most transformers are not damaged under once short-circuit fault, but multiple short-circuit cumulative effect causes the permanent deformation. Due to transformer short-circuit strength problem is complex dynamic characteristics, the analysis of the winding cumulative deformation features is very difficult, there is no quantitative research on the cumulative deformation of transformer winding under multiple short circuit condition.

Based on the 110 kV power transformer product, this paper puts forward the mathematical model to calculate the cumulative deformation of winding, with the method of magnetic field-structural field coupling, by three-dimensional finite element software to calculate and analyze the winding mechanical characteristics under the multiple short circuit condition, considering the effect of cumulative effect.

II. CUMULATIVE DEFORMATION PRINCIPLE

The transformer winding electromagnetic force is enormous under short-circuit condition, seriously will produce plastic deformation, or even pull off the wire, as shown in Fig. 1.

Copper wire is a typical plastic material, when the stress of copper wire is small, the stress and strain is a linear relationship, when the stress exceeds 400MPa，it occursthe permanent deformation. When the permanent deformation exceeds 0.2%, the stress and strain will be saturated, the slight increase in the stress will cause a sharp increase in permanent deformation. In the transformer design, 0.2% of the stress is as allowable stress.

Fig. 1. Winding deformation

When the winding elastic deformation occurs, according to the classical elastic mechanics theory, the stress-strain equation is as follows [6]

$$\begin{cases} \sigma_{ij,i} + f_i = 0 \\ \varepsilon_{ij=} \dfrac{1}{2}(u_{i,j} + u_{j,i}) \\ \varepsilon_{ij} = \dfrac{1+\nu}{E}\sigma_{ij} - \dfrac{\nu}{E}\sigma_{kk}\delta_{ij} \end{cases} \quad (1)$$

Electromagnetic force is equal to

$$f_i = f_m(e^{-0.02t} + 0.5 + 0.5\cos 2wt\text{-}2e^{-0.01t}\cos wt) \quad (2)$$

When the plastic deformation occurs in the winding, the yield surface changes, the initial yield criterion increaseswith the plastic strain, the cumulative deformation occurs, as shown in Fig. 2.

According to the plastic mechanics theory, the yield function *W* can be got

$$dW = \left\{\frac{\partial W}{\partial \sigma}\right\}^T [M]\{d\sigma\} + \frac{\partial W}{\partial \kappa} d\kappa + \left\{\frac{\partial W}{\partial \alpha}\right\}^T [M]\{d\alpha\} = 0 \quad (3)$$

Considering the influence of the n times of short-circuit current, the total plastic strain can be expressed as

$$\varepsilon^{pl} = \sum_{k=1}^{n} \Delta\varepsilon_k^{pl} \quad (4)$$

III. SHORT - CIRCUIT STRENGTH CALCULATION MODEL

By the Maxwell equation, the vector magnetic field A is as follows:

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = \frac{id(t)}{s} \tag{5}$$

The short-circuit current is as follows

$$i_d(t) = \sqrt{2} I_d(\cos\alpha^{-0.01t} - \cos(\omega t + \alpha)) \tag{6}$$

According to Lorentz's law, the force is as follows

$$F_r = \int_V J \times B_z dv \tag{7}$$

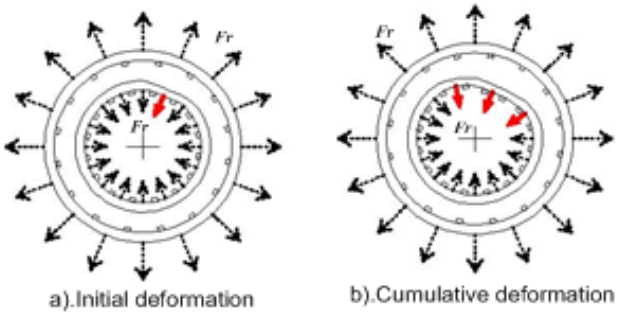

Fig. 2. Accumulative deformation in winding

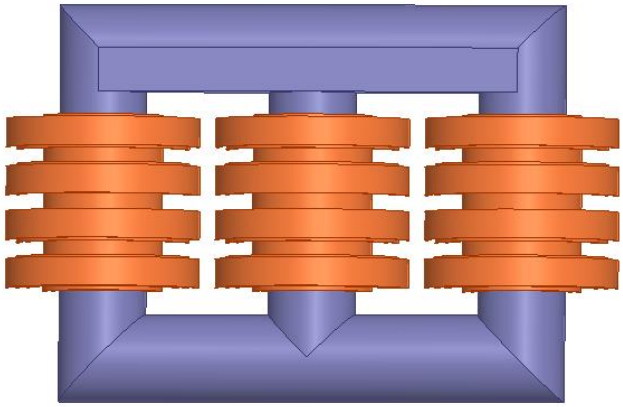

Fig. 3. 3-Dimensional finite element model of the transformer

IV. EXAMPLES AND ANALYSIS

In order to analyze the cumulative deformation of the winding under multiple short-circuit condition, take a double-winding 110kV transformer as an example to model the three-dimensional finite element model shown in Fig. 3. The short-circuit current of HV and LV are shown in Fig. 4.

Fig. 5 shows the stress-strain behavior of the windings under multiple short-circuit impulse condition.

It can be seen that the third short-circuit impulse before, the winding is deformed to elastic deformation, because the maximum stress value does not exceed the yield stress level. The results show that the proposed model can also be used to study the winding under the action of preload.

V. CONCLUSION

Based on the theory of elastic and plastic mechanics, the plastic deformation model of transformer windings is established in this paper, which is based on the theoretical analysis and simulation calculation of the cumulative deformation of the winding under the condition of multiple short-circuit condition. The accumulated deformation model of power transformer in this paper provides a theoretical basis for predicting transformer winding deformation, which provides a reference for the research and analysis of the short-circuit strength of power transformer winding.

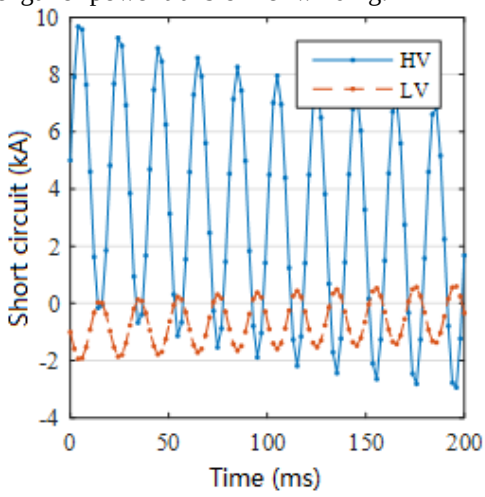

Fig. 4. Transient short current in HV and LV

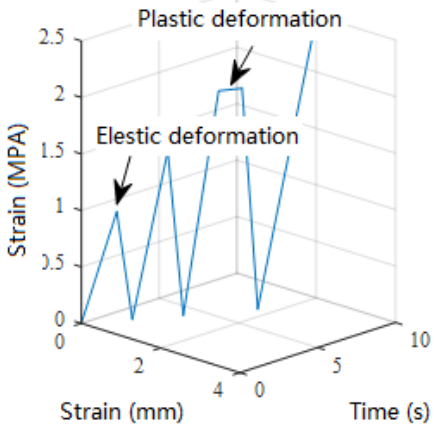

Fig.5 Cumulative strain–stress under multiple short-circuit faults

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