Stability Analysis of Power Transformer Windings Based on Electromagnetic-Thermal-Structural Coupling Method

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The instability behind buckling of inner windings in transformers is a kind of common and complicated failure. The stability model for design is proposed based on the assumption that in buckling calculation the geometry viz. the structural shape of windings is perfect without considering the plastic deformation and thermal effects, causing the risk of winding failure still exists even they meet the stability design. In this paper, the stability of transformer windings is analyzed using a coupled electromagnetic-thermal-structural analysis solution. The electromagnetic force, temperature rising, plastic deformation, buckling mode and critical load are calculated by the 3-D finite-element method. A case study is described in which the curve of stability coefficient is determined. It is found that a plastic deformation and a temperature rise may influence the stability of transformer windings greatly. The simulation results of this paper may be useful for the standard design of transformer winding stability.

Index Terms—**Power transformers, stability analysis, electromagnetic forces, couplings, thermal stability**

I. Introduction

Power transformer winding instability is a kind of serious accident, brings a great risk to the safe operation [1]. Sometimes, the power transformers withstanding inevitable short circuit impacts, caused by short time faults, are still hanging in network operation [2]. In this case, the windings of power transformer are not instable, but the ultimate bearing load of windings is reduced by partial residual deformation. At the time of the next short circuit impact, the ultimate bearing capacity will be much lower than the design value.

Current researches on short circuit strength of power transformer windings, as the hotspot, focus on the deformation calculation in aspects of amplitude and distribution. In contrast, the research on buckling strength focuses on the safety threshold of electromagnetic force load on windings, which is always in the normal direction before and after buckling. Related research results are rare [3-5] and the accepted buckling calculation model was presented in CIGRE Brochure 209 [6]. It is proposed based on the assumption that in buckling calculation the geometry viz. the structural shape of windings is perfect without considering the plastic deformation, causing the risk of winding failure still exists even they meet the stability design.

In this paper, an example of buckling strength analysis of power transformer windings is provided, considering the relationship among the plastic deformation, the thermal effects and the stability. In the case, the power transformer inner windings are simulated by using 3-D FEM.

II. PRINCIPLE

The mechanical force impacts on the power transformer windings produced by the changing short circuit current and the magnetic flux leakage. The forces on the inner winding direct inward and those on the outer winding direct outward, which has different effects on the mechanism of instability. In comparison, the inner winding subjected to compressive stresses is more likely to be instable. In this paper, the buckling strength of power transformer inner windings is calculated as an example.

The power transformer winding in alternating magnetic field bears the electromagnetic impacting load all the time. Especially they are much larger under short circuit conditions. The transformer may suffer from all kinds of short circuit faults inevitably and escape the complete damage. But the plastic deformation remains in the conductors made of copper. In that case, not considered in the accepted study above, the stability of power transformer windings extremely decreases

In the process of winding deformation generated by the electromagnetic impact force, the compressive stresses on the conductor sections are unevenly distributed in the circumferential direction, as shown in Figure 1, and unevenly distributed in the same conductor section. Accordingly, the possible plastic deformations are unevenly distributed. These phenomena are not reflected in the stable design.

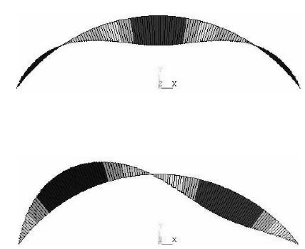

Figure 1: Compressive stresses distributed in the circumferential direction.

III. MODEL

As mentioned, the buckling strength calculation considering the residual deformation is a study on the problem of uneven distribution, which can be solved by the finite element method.

On the basis of Lorentz law, the electromagnetic volume force is deduced by crossing the magnetic flux densities and the current densities, represented by Maxwell Equation (1) and Electromagnetic force Equation (2).

$$\nabla\times\left(\frac{1}{\mu}\nabla\times A\right)=J \tag{1}$$

$$F=J\times B \tag{2}$$

The plastic deformations caused by electromagnetic force impacts are equivalent to the initial deformation in buckling calculation, represented by Stress-strain Equation (3).

$$\begin{cases} \sigma_{xy} + f = 0 \\ \varepsilon_{xy} = \dfrac{1+v}{E}\sigma_{xy} + \dfrac{v}{E}\sigma_z\delta_{xy} \end{cases} \quad (3)$$

The stability factor is introduced to characterize the influence of plastic deformation on stability, represented by Stability coefficient Equation (4).

$$\varphi \geq \frac{N_{cr}}{Af} \quad (4)$$

IV. EXAMPLE

A power transformer model has been analyzed under a worst-case short circuit condition. The purpose of the model is to simulate the impact resistance of the power transformer product with same wire gauges, so the iron core is replaced by a cylinder with enough strength, generating the same leakage magnetic field in short circuit test, as shown in Figure 2. In several experiments, short circuits flowed along the windings in series connection and short circuit impedances were measured at each one.

Figure 2: Power transformer model.

Table I shows the short circuit impedances measured and calculated. Through the comparison, it is found that the simulation model accurately simulates the leakage magnetic field and the plastic deformation changes the distribution of leakage flux.

TABLE I
CURRENTS AND IMPEDANCES

Sample	Current (A)	Impedance(%)
1	4034	2.967
2	5244	2.982
3	10384	5.681
4	10414	5.822

Figure 3 shows the temperature measured in the test on windings..

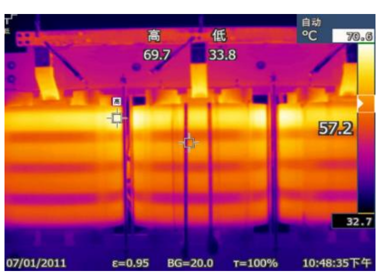

Figure 3: Temperature measured in the test on windings.

Load path tracing curves are shown as Figure 4. It is found that the critical electromagnetic force load on windings decreases with the increase of plastic deformation, which means the transformer winding stability coefficient considering the residual deformation will be far below the stability of the design reference value.

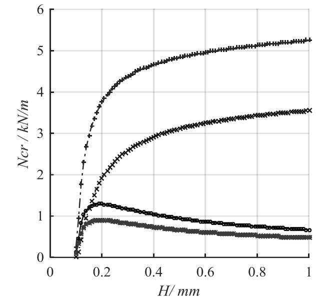

Figure 4: Electromagnetic force densities on windings

Stability factor curves under different residual deformation are shown as Fig.5.It is found that although the plastic deformation has seriously damaged the stability of windings, the influence of them is limited in a certain range.

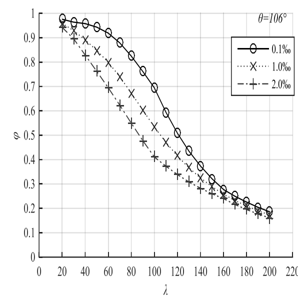

Figure 5: Electromagnetic force densities on windings

V. CONCLUSION

In this paper, a buckling strength analysis of windings considering the plastic deformation and the thermal effect is provided. The electromagnetic force, temperature rising, plastic deformation, buckling mode and critical load are calculated by the 3-D finite-element method and the stability factor curves are determined. The numerical results in a case study obtained from the proposed method are compared with those of experimental ones The results show that the plastic deformation and the thermal effect seriously damages the stability of power transformer windings.

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