Research on Short-circuit Strength in Power Transformer Windings Considering Residual Stress

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In the process of power transformer conductor winding, there is some residual stress in the winding cross section, which will produce adversely effect on the winding short-circuit strength. The existing studies of power transformer winding short-circuit strength did not consider this residual stress. This paper deduces the calculation model of the residual stress which produced in the winding process of the circular conductor. Taking the test transformer as an example, the inner winding radial short-circuit strength is simulated and studied. The results show that the compressive component and tensile component are both included during the winding process, the residual stress is adversely effect on annular radial compressive stress and warping stress, the influence of the annular compression stress is not obvious, the deviation is 3%, but the influence of the radial buckling stress is very big, the deviation is 52%.

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

I. Introduction

IT is unavoidable for power transformer to suffer from sudden short circuit, which will cause the windings suffer enormous axial phase and amplitude phase short-circuit force. It will seriously affect the winding insulation and cause winding deformation or pull off the wire winding. The short-circuit strength insufficient is the main reason of transformer accident [1]. Many scholars committed to reserch the reason of the anti-short circuit ability insufficient causes winding deformation and establish the reasonable calculation of the model [2], [3]. So far, the finite element model is one of the most effective method [4], [5].

Although the above-mentioned documents propose variety methods to improve the winding short-circuit strength problem, but they did not consider the effect of the residual stress impact on the transformer short-circuit strength during the winding wounding.

This paper deduced the transformer calculation model of winding wounding process producing residual stress, taking the test transformer as example, calculated and researched amplitude phase short-circuit strength, considered the adversely effect of the residual stress.

II. Mechanism Analysis

The transformer windings are usually wound to form a ring structure, the straight copper wire will generate part strain at the wire cross section, which results the wire compressed in inner surface, and stretched in outer surface, as shown in Fig. 1.

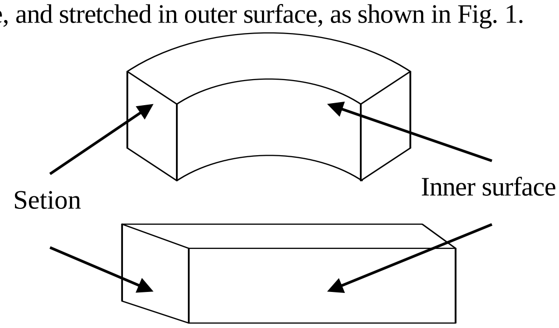

Fig. 1. Winding diagram

The residual stress will not affect transformer winding strength in the rated operation, but under the short-circuit condition, the huge short-circuit current flows through the winding, the axial direction leakage magnetic field and the circumference direction short-circuit current in the windings produce the radial electric, the outer winding suffers tension in circumference direction, namely ring tensile force, which will enlarge the diameter. The inner winding suffers pressure in the circumference direction, namely ring compression force, has the tendency of deformation in the direction of the core, as shown in Fig. 2. The direction of ring compression force on inner winding and the residual stress are the same, which had not been considered before in the study of the short circuit strength. The transformer winding may be damaged under the impact of less than expected load.

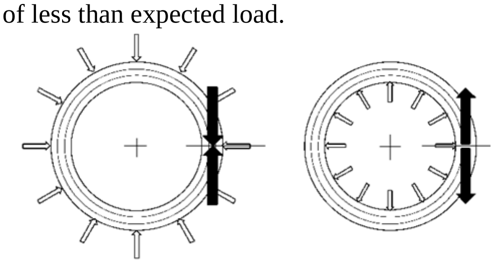

Fig. 2. The stress diagram

III. Calculation Model

A. Residual Stress

Transformer winding is usually made into a ring-shaped structure. As in Fig. 3. Based the displacement measurement [6], ignores the amplitude phase changes, can get

$$P^*A^* = PA = Q^*B^* = QB = y \tag{1}$$

The strain of inner surface projection PQ can be expressed as

$$\varepsilon = \lim_{Q\to P}\left(\frac{P^*Q^* - PQ}{PQ}\right) \tag{2}$$

Provided, before winding the neutral plane circumference is plane l, after winding the inner surface circumference is l^*, strain expressions can be expressed as follows

$$\varepsilon = \lim_{l\to 0}\left(\frac{l^* - l}{l}\right) \tag{3}$$

By Ramberg-Osgood relationship, the initial stress can be got

$$\frac{\varepsilon}{\varepsilon_0}=\frac{\sigma}{\sigma_0}+\frac{3}{7}(\frac{\sigma}{\sigma_0})^m \tag{4}$$

σ is the stress, ε is the strain, ε_0, σ_0 and m are coefficient, the experimental measurement values of correlation coefficient are 0.000 6755 / 74.53 MPA and 12.6 respectively.

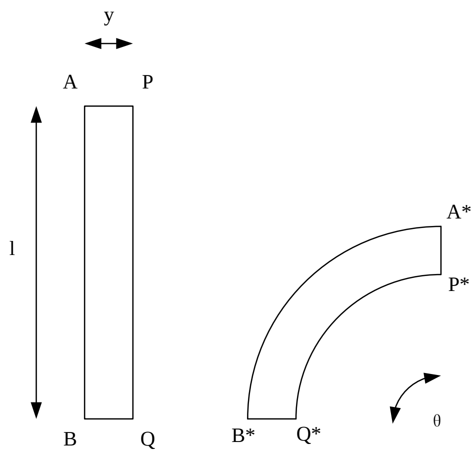

Fig. 3. The parameters schematic

B. Electromagnetic Force

To couple with the structure field, use A-V method for electromagnetic field calculation，the calculation equation is

$$-\nabla\cdot\frac{\partial\left(\varepsilon_0\varepsilon_r\nabla V\right)}{\partial t}-\nabla\cdot\left(\sigma\nabla V-J^e\right)=0 \tag{5}$$

The calculation equation of magnetic field is

$$\sigma\frac{\partial A}{\partial t}+\nabla\times\left(\mu_o^{-1}\mu_r^{-1}\nabla\times A\right)=J^e \tag{6}$$

Structure field constraint equation is

$$m\frac{d^2u}{dt^2}+\zeta\frac{du}{dt}+ku=f \tag{7}$$

Structure field and electromagnetic field coupling are realized by computing the power density, as in

$$f=J\times B \tag{8}$$

The Lorentz force is substituted into structure field, as in

$$\nabla\cdot\sigma+f=\rho\vec{u} \tag{9}$$

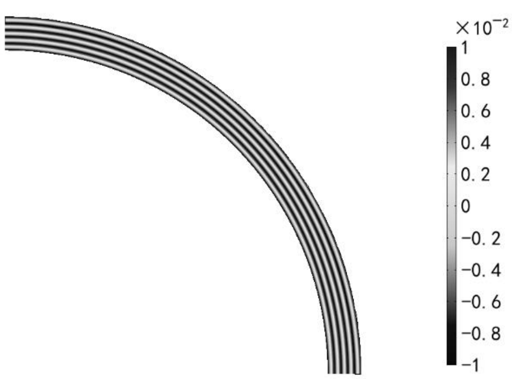

Fig. 4. The residual stress diagram

C. Analysis on Application Model

Taking the test transformer ODFPS-250 000 MVA / 500 kV as a model, by finite element calculation method, calculate the residual stress of inner windings, the result is shown in Fig. 4. The overall winding residual stress distribution in the radial direction is a zigzag shape, as shown Fig. 5, in the past research, the distribution of radial electromagnetic force load which impact on the inner winding is monotone linear, the residual stress and the radial distribution of electromagnetic force load is inconsistent.

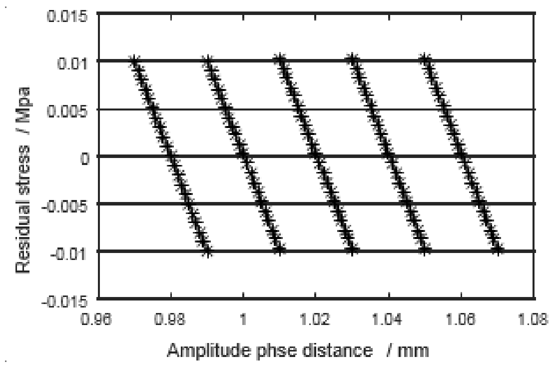

Fig. 5. The residual stress diagram

The rated current of the transformer product is 1 057.9A, the short circuit current peak is 17 752.7A, the numerical calculation results of the average ring compression stress and radial buckling stress are shown in Table I.

TABLE I
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	No residual stress	Residual stress
Compression stress/Mpa	60	62
Buckling stress /MPa	469	222

IV. Conclusion

This paper considers the residual stress influence on the transformer winding short-circuit strength. The residual stress distribution is not uniform from inside to outside, and the stress analytical expressions is invisible in current research results, so uses the finite element numerical method to solve the problem of distribution of residual stress, the study has shown that the method is effective to solve the problem. The results can be used to guide the transformer design.

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