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3D Finite Element Analysis of the Stray Loss in Power Transformer Structure Parts[*]

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ABSTRACT

In order to analyze the leakage magnetic field and stray loss in power transformer, leakage magnetic field and stray loss in structure parts of a power transformer are calculated by three-dimensional (3-D) non-linear time harmonic finite element method (FEM). The results show that stray loss and loss density in structure parts are large and which may lead to local overheating and affect performance of the transformer. The magnetic shields are used to reduce the stray loss and loss density of power transformer. Effects of these shields on stray loss and loss density of structure parts are discussed. The results show that stray loss and local overheating can be reduced and eliminated effectively by adding magnetic shields. It provides some references for the analysis of stray loss and optimization design in transformer.

Keywords: Finite Element Method; Stray Loss; Leakage Magnetic Field; Local Overheating; Magnetic Shields

1. Introduction

Power transformer is the core of energy conversion and transmission in power network, which is also the most important and expensive equipment. So it will have an essential impact of power network whether the transformer is safe, reliable and economic operation or not [1]. With the increase of capacity of the transformer, the magnetic leakage field is increasing which may enlarge the stray loss in the structure parts of power transformer. In the large power transformer, leakage magnetic field generated by the winding current will produce losses in the metal structure parts, and these losses is part of the transformer load losses, it often tend to local overheating because of its unevenly distribution. So it is quite necessary to study the magnetic leakage and stray loss deeply and accurately [2,3].

In this paper, a practical power transformer model of type SZ10-50000kVA/110kV was applied to research the stray loss problem in large power transformer by using 3-D nonlinear time harmonic analysis. Detailed calculation and analysis was proceeded in order to determine the concentration of stray loss in transformer structure parts, and magnetic shields were used to reduce stray loss and prevent local overheating.

2. 3D Calculation Model and Calculation Method

The 3-D finite element model in this paper is established

as shown in **Figure 1**. The analysis has been made with the following simplification and assumptions: 1) The 1/2 model of whole transformer model is established in order to reduce the computational time; 2) All field quantity sinusoidal variation with time, do not consider the high-order harmonic; 3) eddy current, circulation in winding and eddy current in iron core are being neglected.

Non-linear magnetic properties of tank, core and magnetic shields material were considered to calculate leakage magnetic field and stray loss. Magnetic shields material was disposed as anisotropic material based on "homogenization method [4,5]", anisotropic of the shield conductivity analog laminated effect. According to the continuity condition of B/H between silicon steel sheet and air, the permeability of magnetic shields along lamination direction (y-direction) can be described as the following equation:
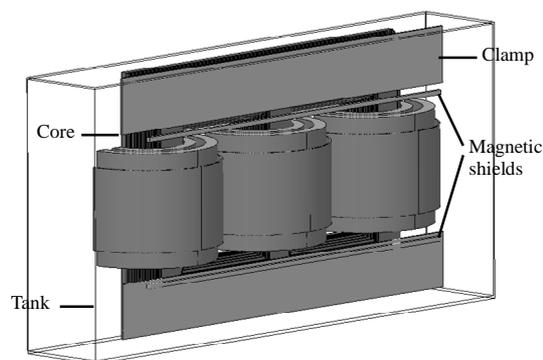
Figure 1. Structure diagram of winding.

$$u_y = u_0 / (1-c) \tag{1}$$

where u_y is permeability of magnetic shields along lamination direction, u_0 is permeability of vacuum, c is lamination coefficient, taken as 0.97. The permeability of the other two directions u_x and u_z are given by B/H curve.

The eddy current generated in the silicon steel sheet near the winding side can not be ignored, the model of conductivity:

$$\sigma = \begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix} = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & c\sigma & 0 \\ 0 & 0 & \sigma \end{bmatrix} \tag{2}$$

In the other silicon steel sheet, the model of conductivity can be governed by following equation:

$$\sigma = \begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix} = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma \end{bmatrix} \tag{3}$$

According to Maxwell equations, transformer steady state magnetic field problem can be described as:

$$\nabla \times \frac{1}{\mu_e}\left(\nabla \times \overline{A}\right) = \overline{J}_s - \sigma \frac{\partial \overline{A}}{\partial t} \tag{4}$$

where μ_e is permeability, $\overline{A}$ is magnetic vector potential, $\overline{J}_s$ is current density, σ is conductivity.

The stray loss of transformer is generally consist hysteresis loss and eddy current loss. The eddy current loss can be calculated by the following equation:

$$p = \int_v \frac{J_s \cdot J_s}{\sigma} dv \tag{5}$$

The average eddy current loss of time-harmonic field can be governed by following equation:

$$p_e = \int_v \frac{\overline{J_s \cdot J_s}}{\sigma} dv = \int_v \frac{\overline{J_{0rms} \cdot J_{0rms}}}{\sigma} dv \tag{6}$$

The hysteresis loss can be introduced in leakage magnetic field calculated on the basis of $W_h - B_m$ curve.

$$p_h = \sum_{i=0}^{N} p_h^{(i)}\left(B_m^{(i)}\right)\sigma V^{(i)} \tag{7}$$

where p_h is hysteresis loss, N is number of finite element units, $p_h^{(i)}$ is hysteresis loss of the i unit, $B_m^{(i)}$ is peak flux density of the i unit, σ is conductivity, $V^{(i)}$ is volume element.

The total stray loss p can be governed:

$$p = p_e + p_h \tag{8}$$

3. Verification of Calculation Method

Leakage magnetic field and stray loss were calculated for type SFP-17000 kVA/37.6 kV practical transformer and transformer loss reference model TEAM Problem 21-B，TEAM Problem 21c-M1，TEAM Problem 21a-0 in order to confirm the calculation method effectiveness of leakage magnetic field and stray loss. The practical transformer leakage magnetic field test position diagram is shown in **Figure 2**. Calculation value (contain shields) and measured value of stray loss in steel plate of three models comparison results were shown in **Table 1**.

In **Figure 2**, the position II is near outer surface of C phase winding, from the winding center to the end. Calculation value and measured value of magnetic flux density amplitude direction component (By) comparison results was respectively shown in **Figure 3(a)** and **(b)**. The loss calculation error was less than 2% in **Table 1**; Calculation result and measured value was consistent in **Figure 3**, therefore, the loss calculation method used in the paper is effective.

4. Analysis of Calculation Results

4.1. Calculation and Analysis of Loss

In this paper, The MagNet software was using to calculate eddy current field and structure parts loss in transformer. And further, stray loss distributions in the tank wall and yoke clamp were discussed.

The loss density distribution of yoke clamp surface and tank side wall inner surface were respectively given in **Figure 4** and **Figure 5**. Maximum loss appears in the
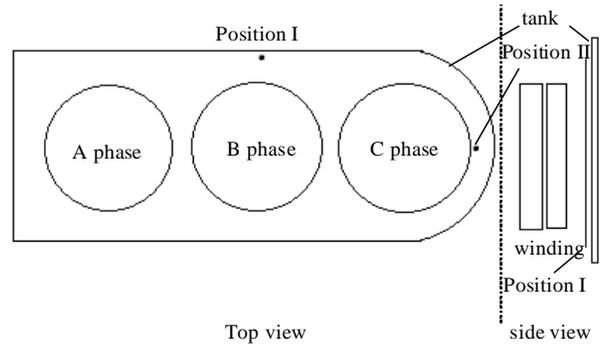
Figure 2. Test position of leakage magnetic field.

Table 1. Comparison of calculation value and measured value of loss.

Model	Measured value/W	Calculation value/W	Error/%
TEAM Problem 21-B	11.97	12.20	1.92
TEAM Problem 21c-M1	3.72	3.66	1.6
TEAM Problem 21a-0	9.17	9.24	0.76

(a) Position I
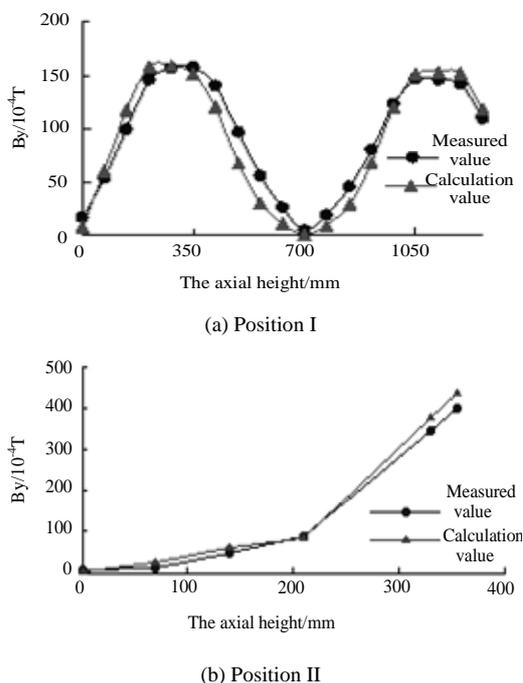
(b) Position II

Figure 3. Comparison of calculation value and measured value of magnetic flux density at assigned position.
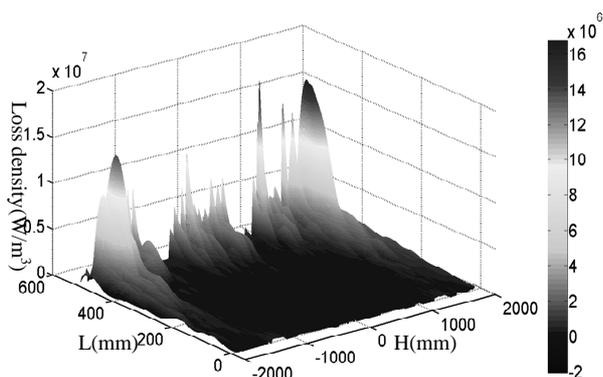
Figure 4. Diagram of loss density distribution on surface of yoke clamp.
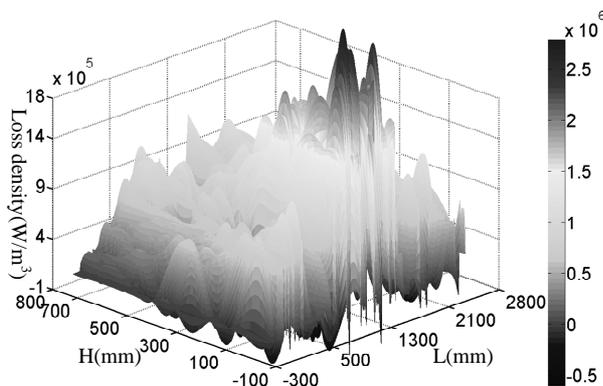
Figure 5. Diagram of loss density distribution on inner surface of tank side wall.

corresponding position of A and C phase end winding, and the maximum loss density appears in the lower clamp; the loss in transformer tank was mainly concentrated in the tank side wall near C phase and tank wall corresponding to the middle of the three-phase windings. The H and L in diagram were respectively expressed the length and height of the tank (or clamp). The length of the tank side wall and clamp were 790mm and 3760mm, and the heights were 2730mm and 535mm. The stray loss and loss density of transformer tank and clamp were shown in **Table 2**.

4.2. Calculation and Analysis of Loss by Adding Magnetic Shields

The stray loss uneven distribution of transformer structure parts can cause local overheating and affect the normal performance of transformer, through adding magnetic shields can reduce the stray loss.

Magnetic shields material with high permeability attract the leakage magnetic field into the magnetic shields, prevent leakage magnetic into tank and other structure parts, thereby reduce the stray loss in the structure parts of transformer. Transformer adding magnetic shields is shown in **Figure 1**. Loss density of tank and clamp adding shields was decline in **Figure 6** and **Figure 7**, maximum loss still appear near clamp and tank side wall, maximum loss density of clamp decreased by 43.1% compared to non-magnetic shields, maximum loss density of tank decreased by 11.1%. The maximum stray loss and loss density of transformer structure parts with magnetic shields as shown in **Table 3**.

Table 2. Loss and Loss Density of Transformer Structure Parts.

Component	Tank	Clamp
Loss density(W/m³)	1.8×10^6	1.6×10^7
Eddy current loss(W)	9846.76	4720.4
Hysteresis loss (W)	3603.79	942.68
Total loss(W)	13 450.55	5663.08
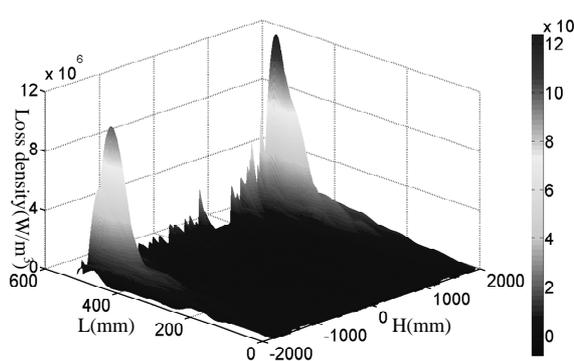
Figure 6. Diagram of loss density distribution on surface of yoke clamp with magnetic shields.
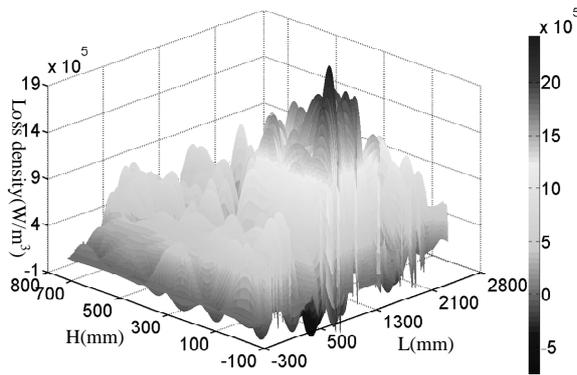
Figure 7. Diagram of loss density distribution on inner surface of tank side wall with magnetic shields.

Table 3. Loss and Loss Density of Transformer Structure Parts with Magnetic Shield.

Component	Tank	Clamp
Loss density(W/m^3)	1.6×10^6	9.1×10^6
Eddy current loss (W)	5708.37	2313.94
Hysteresis loss (W)	2626.9	579.46
Total loss (W)	8335.27	2893.4

4.3. Magnetic Shields Effect on Structure Parts of Leakage Magnetic Field

The magnetic flux densities of clamp surface with and without magnetic shields were shown in **Figure 8** and **Figure 9**. Magnetic shields provide a conduction path for leakage magnetic of transformer interface winding. It can be seen from the Figure, leakage magnetic flux density significantly lower by adding magnetic shields.

5. Conclusions

In this paper, 3D finite element method is used to calculate the stray loss of transformer structure parts, and the conclusions are as follows:
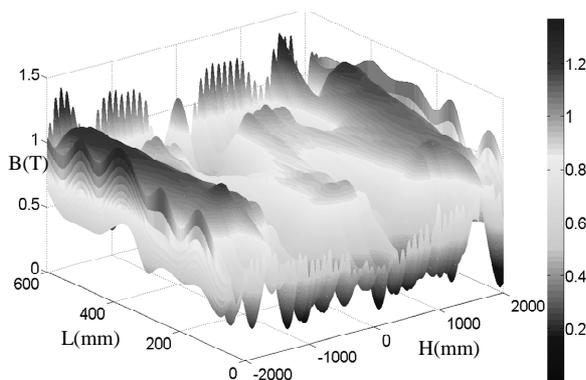
Figure 8. Diagram of magnetic flux density distribution on surface of yoke clamp with magnetic shields.
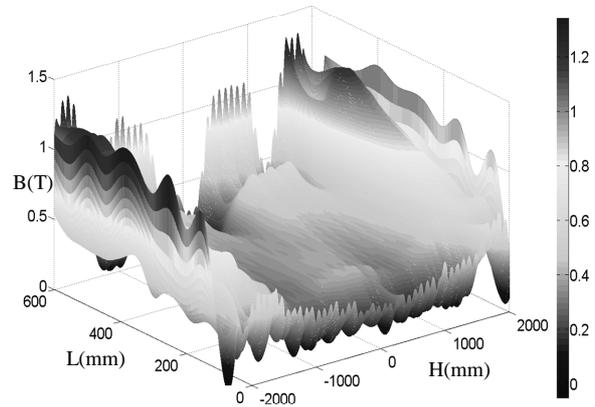
Figure 9. Diagram of magnetic flux density distribution on surface of yoke clamp without magnetic shields.

1) The results get by 3D finite element analysis are consistent with theoretical analysis, illustrate the validity of the method.

2) Loss and the loss density in the local place of transformer structure parts can be reduced effectively by adding magnetic shield. After adding magnetic shield to tank and yoke clamp, the maximum stray loss and loss density of tank are reduced by 38% and 11.1%, the maximum stray loss and loss density of clamp are reduced by 48.9% and 43.1%.

3) The density of magnetic flux leakage into the clamp is decreased obviously after adding magnetic shields.

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