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3D FEM OPTIMAL DESIGN OF TRANSFORMER COVER PLATES TO DECREASE STRAY LOSSES AND HOT SPOT TEMPERATURE

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Abstract- The most important criterion of a transformer cover plate design is to decrease hot spot temperature caused by stray magnetic field. It can be significantly achieved by reducing the cover plate losses using a suitable geometry of stainless steel insert (SSI). This study proposes a 3D Finite Element (FE) Method (FEM) optimization design of cover plates for a 1600 kVA, 400 V three phase distribution transformer using a suitable geometry of SSI to overcome the local overheating and keep the temperature below 140 °C. Leakage losses and hot spot temperature in the cover plate are estimated in the case of with and without SSI. According to the given results there is a considerable agreement between the calculated losses in 3D FEM and analytical method and has a good agreement with experimental results. The study shows a considerable reduction in the cover plate losses and hot spot temperature with only inserting a very small SSI. The applied approximation for loss and temperature calculations is sufficiently fast which can be used moderate computer resources.

Keywords: Stray Loss, Tank Cover, Hot Spot Temperature, 3D Finite Element (FE) Simulation, Stainless Steel Plate, Distribution Transformer.

I. INTRODUCTION

The magnetic field produced by the low voltage currents of transformer generates eddy current losses increasing the temperature of cover plate resulting serious overheating in the regions near the high current conductors. This degrades oil and isolating material and then affects negatively the reliability of the transformer [1, 2, 4]. Thus in the design of transformer cover plate the phenomenon of hot spot should be considered to avoid the hazarding temperature. This can be significantly achieved by reducing the cover plate losses using a suitable geometry of SSI [1, 3, 5-7]. The most important criterion of a transformer cover plate design is to decrease hot spot temperature and keep it below 140 °C [2]. FEM is one of the best estimation method for the leakage losses calculation in the cover plate [3, 5-7]. Furthermore, it can also be done by analytical method calculation for both linear and nonlinear behavior of the steel plate [1, 2, 8-10].

This study proposes a 3D FEM optimization design of cover plates for a 1600 kVA, 400 V three phase distribution transformer using a suitable geometry of SSI to overcome the local overheating and keep the temperature below 140 °C. The stray magnetic field losses and hot spot temperature are estimated in the case of with and without SSI.

II. STRAY LOSSES CALCULATION BY ANALYTICAL METHOD

A. Stray Losses

By the use of Poynting's vector formulation it is possible to compute leakage losses P_s on the surface of steel cover plate in time harmonic magnetic fields as

$$P_s = \sqrt{\frac{\omega\mu}{8\sigma}} \iint |H_{ms}(x,y)|^2 \, dxdy \tag{1}$$

where, ω is the angular frequency, μ is the magnetic permeability and σ is the linear electrical conductivity of the material, H_{ms} is the peak of the magnetic field at a point (x,y) on the surface of conducting plate in the Cartesian coordinate system [8].

B. The Surface Magnetic Field

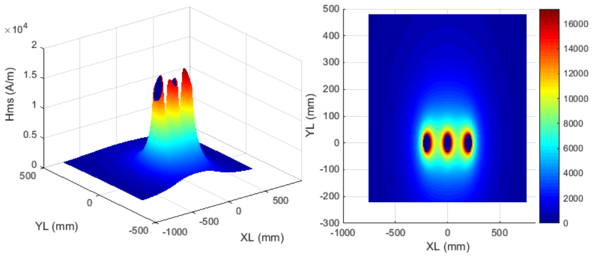
According to (1) for analytically calculating the eddy current losses the maximum of the magnetic field intensity on surface of plate is necessary. Applying RMS definition of magnetic field yields $H_{ms}^2 = 2((1/T)\int_0^T H^2(t)dt)$.

The Biot-Savart law is a well-known equation used to calculate the magnetic field vector $H(t)$ at a point in space for a given current distribution. Therefor for a three-phase current bushing the maximum magnetic field at any considered point on the cover is expressed as

$$H_{ms}(x,y) = \frac{I_m A}{2\pi}\sqrt{\frac{1}{x^2+y^2}} \times \\ \times \sqrt{\frac{3(x^2+y^2)+A^2}{x^4+y^4+2x^2y^2\text{-}2A^2x^2+2A^2y^2+A^4}} \tag{2}$$

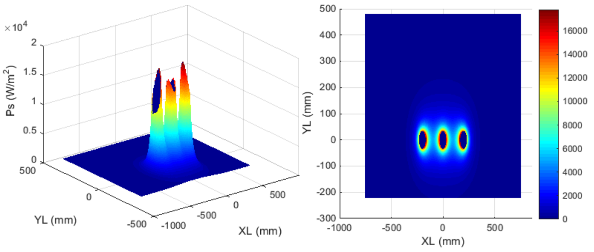
where, I_m is the peak value of current and A is the distance between the current conductors [8, 14].

Figures 1 and 2 demonstrate analytical calculation of stray losses and maximum magnetic field on cover plate for a 1600 kVA, 400 V three phase distribution transformer using Equations (1) and (2), respectively in the cases of 3D and 2D views which has been done in MATLAB. The required parameter given in section III and Table 1. As a result the maximum of magnetic field intensity is around and between the conductive current. But the most stray losses of cover is between the bushings. It means the considered region is very important for optimal design procedure of cover plate.



(a) (b)

Figure 1. Analytical calculation of maximum magnetic field intensity for a 1600 kVA, 400 V three phase distribution transformer without SSI: (a) 3D display, (b) 2D display



(a) (b)

Figure 2. Analytical calculation of stray losses for a 1600 kVA, 400 V three phase distribution transformer without SSI: (a) 3D display, (b) 2D display

III. ELECTROMAGNETIC AND THERMAL BACKGROUND

A summary explanations of the equations and boundary conditions that were used to solve the 3D eddy current losses and hot spot temperature on the tank cover are given here.

The 3D eddy current problem equations which is applied in the simulation of transformer cover plate using A-φ potential formulation as following

$$\nabla\times\frac{1}{\mu}\nabla\times A+\sigma\frac{\partial A}{\partial t}+\sigma\nabla\varphi=0 \quad \text{in} \quad \Omega_1 \tag{3}$$

$$\nabla\times\frac{1}{\mu}\nabla\times A=J_s \quad \text{in} \quad \Omega_2 \tag{4}$$

which, Ω_1 and Ω_2 are eddy current and other regions respectively, A is the magnetic vector potential, φ is the electric scalar potential, J_s is a source current density. For a sinusoidal field variation $j\omega$ is substituted by $\partial/\partial t$ into Equation (3) [15, 16].

Eddy current density in the steel plate can be observe by $J=\sigma E$ and the loss density $P(r)$ at any position r is obtained using Equation (5) as [10]

$$P(r)=\frac{1}{T}\int_0^T \sigma E^2(r,t)dt \tag{5}$$

In the case of computation of the hot spot temperature in cover plate, the authors are interested to observe the steady-state thermal model by means of the Poisson's equation as follows:

$$\frac{\partial}{\partial x}(k_t\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k_t\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k_t\frac{\partial T}{\partial z})+P(r)=0 \tag{6}$$

where, T is the temperature, k_t is the thermal conductivity [8].

The thermal boundary conditions are given by radiation and convection as [8];

$$q=-\varepsilon_r\sigma_r(T^4-T_a^4)-h_c(T-T_a) \tag{7}$$

where, ε_r is emissivity coefficient for the steel cover plate equals to 0.23, T_a is the surrounding temperature, and σ_r is the Stefan-Boltzmann constant. h_c is the convection heat transfer coefficient.

Natural convection heat transfer coefficient between the horizontal plate and ambient (h_c) is computed using basic thermal theory. Rayleigh number is given by $R_a=G_r.P_r$ where G_r and P_r are the Grashof and Prandtl numbers respectively. The Nusselt number for natural convection heat transfer is then calculated as $N_u=0.15R_a^{1/3}$ valid for $8\times10^6<R_a<10^{11}$, whereas the heat transfer coefficient is calculated as [11];

$$h_c=N_u k_t/l \tag{8}$$

Therefore, the convection heat transfer coefficient of cover plate approximately equals to $5\,[\text{W/(m}^2\text{.K)}]$.

IV. FE SIMULATIONS

The basic dimensions of cover plate given in Figure 3 can be varied in the terms of the non-magnetic slits wide, B, the distance A between the bushings and the diameter D of the bushing holes.

Time-harmonic 3D FE simulations have been employed in Maxwell software [12] at 50 Hz to calculate and analyze stray losses in a transformer cover plate at the following cases are: i) without SSI, ii) with SSI. In the simulation configurations it is assumes that the magnetic behavior of the steel plate is linear.

The computation model in Figure 3 has the thickness 7.5 mm. The cover steel has relative permeability of 500 and electrical conductivity of 6.8×10^6 [S/m]. Non-magnetic SSI has a relative permeability of 1 and an electrical conductivity of 1.1×10^6 [S/m]. The copper conductors of bushing current has a relative permeability of 1, radius of 10 mm and electrical conductivity 58×10^6 [S/m] [1].

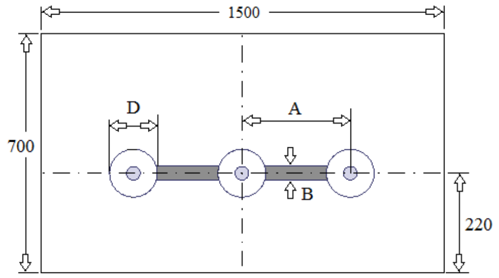


Figure 3. Computation model of transformer cover (Dimensions are in millimeters)

The investigation was performed for four different current of power transformer and the results are shown in Table 1. For different values of conductor current the distance *A* between the bushings is 250 mm and the diameter *D* of the bushing holes is 70 mm [1]. The results of analytical and numerical calculations of eddy current losses are compared with the experimental results [1] in Table 1 and Figure 4.

Table 1. The measured, analytical and numerical calculated stray losses in tank cover [1]

I (A)	Measured Losses (W)	Analytical Cal. Losses (W)	3D FEM Cal. Losses (W)	%
1000	246	247	245.8	0.09
1500	487	555	553	13.5
2000	917	987	983	7.2
2500	1442	1542	1594	10.5

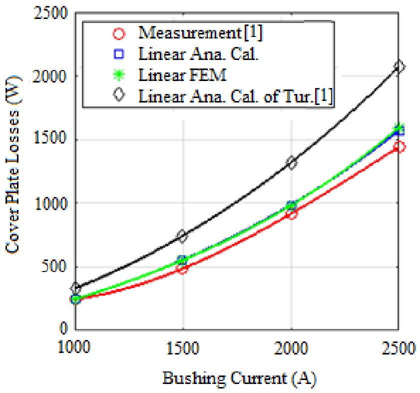


Figure 4. Results of eddy current losses obtained from different methods

Diamond and circle marker symbol in Figure 4 shows the linear model calculations and measurement of cover losses respectively by Turowski [1], but asterisk and square ones denotes linear model calculations of stray losses in the 3D FEM and the considered analytical method, respectively. The analytical calculations of losses has been done in Field Calculator Interface of Maxwell software using both Equations (1) and (2). Solid lines are obtained based on a cubic interpolation in MATLAB environment.

It is evident in Figure 4 and Table 1 that there is a good agreement between the results of measured and the numerical methods (maximum error of estimate is %13.5) and it demonstrates the validity of the 3D FEM linear calculations for estimation of cover plate losses.

There is also considerable agreement between the calculated losses in linear model of analytical method and 3D FEM. Therefore, the mesh number used in the 3D FEM simulation is acceptable (Figure 5).

The total number of 150000 finite elements were used in the simulated model. To calculate the stray losses in the penetration depth of the cover plate two layers of 0.6 mm each, both on the top and bottom surface, were applied (Figure 5). There has not been considered any layers of small finite elements in SSI due to large skin depth (67.9 mm) in comparison with plate thickness (7.5 mm).

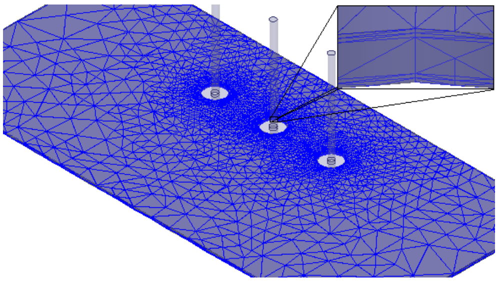


Figure 5. 3D Mesh: The total number of 150000 finite elements were used in cover plate of 1600 kVA distribution transformer without SSI.

Table 2. Numerical and analytical calculated stray losses in tank cover

S (kVA)	*I* (A)	*A* (mm)	*D* (mm)	Stray Loss Cal. (W) Analytical	3D FEM	%
630	909	150	55	190	195	2.6
800	1155	150	55	307	315	2.6
1000	1443	150	55	479	490	2.3
1250	1804	200	70	725	766	5.7
1600	2309	200	70	1233	1220	-1.1

Equation (1) demonstrates that the leakage losses of transformer cover varies with the square of conductor current in the case of without SSI. But experimental results in large power transformers in Table 1 and in Figure 4 shows that the induced tank losses varies less than the current squared as Deuring [13].

Table 3. 3D FEM calculated stray losses in tank cover of three phase distribution transformers with and without SSI

S (kVA)	*I* (A)	3D FEM Stray Loss Cal. (W) Without SSI	With SSI	%
1000	1443	490	354	-27.8
1250	1804	766	434.5	-43.3
1600	2309	1220	454	-62.8

The results of numerical and analytical computations of tank cover losses for five different power rating three phase distribution transformers and their cover plate designs [17] are given Table 2. There is a very good agreement between the linear model of 3D FEM and analytical method calculations.

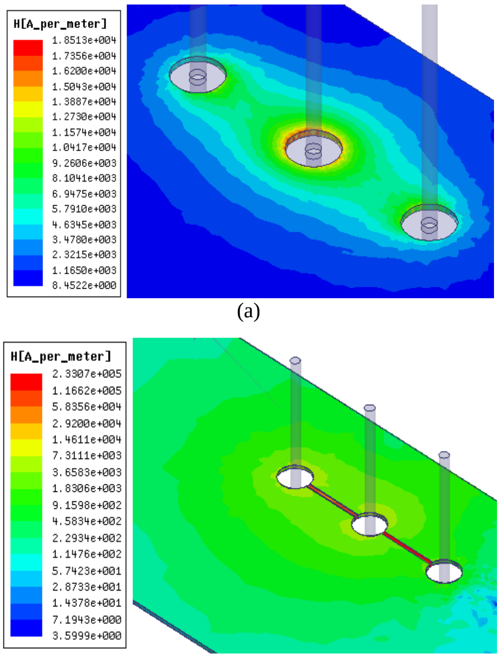
The temperature distribution of tank cover can be obtained with coupling the loss results obtained from Maxwell to ANSYS Steady-State Thermal [12]. As it shown from Table 4 the hot spot temperature of the cover plates for a three phase transformer with a power rating less than 1000 kVA is not critical. The optimal design of tank cover for a 1600 kVA, 400 V three phase distribution transformer is given in Table 4.

Table 4. Numerical calculated hot spots in tank cover of 400 V three-phase distribution transformers with and without SSI

S (kVA)	*I* (A)	Hot spot Temp. (°C)	SSI wide *B* (mm)	Reduced Hot Spot Temp. (°C)
1000	1443	174	1	118
1250	1804	231	2	134
1600	2309	331	15	112
1600	2309	331	12	119
1600	2309	331	9	128
1600	2309	331	8	133
1600	2309	331	7	140

The given outcomes in Tables 3 and 4 reveals reductions in stray losses and overheating on the cover plate while using small SSI (Figure 8).

There are good agreement between the results of the magnetic field intensity and stray losses of a 1600 kVA, 400 V distribution three phase transformer obtained from 3D FEM and analytical calculations as shown in Figures. 6(a), 1(a) and in Figures 7(a), 2(a), respectively.



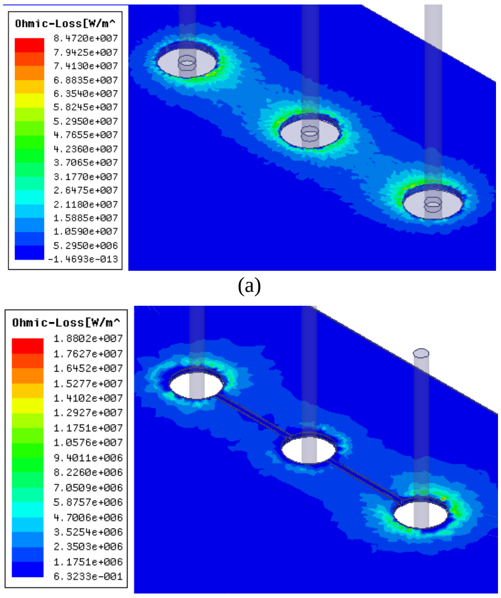
(a)

(b)

Figure 6. Magnetic field intensity in cover plate of 1600 kVA three phase distribution transformer: a) without SSI b) with SSI

By the use of non-magnetic SSI between bushing holes the magnetic field intensity is considerably increased in this region in comparison to without SSI, but the stray losses is dramatically decreased as seen in Figures 6, 7 and it can also be found from Equation (1) that the stray losses are proportional to the root of permeability μ.

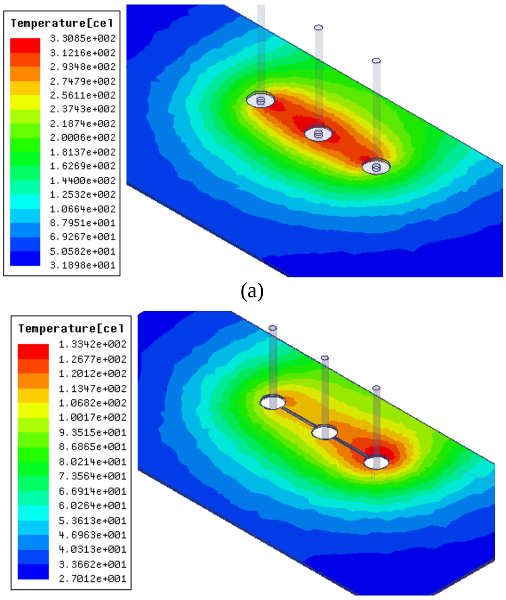
The used simulation time for each iteration to calculate the hot spot temperature is about 40 min in a system with configuration of Intel Core i3 1st Gen. 370M (2.4 GHz) processor, and 8GB RAM Memory. Therefore by the use of considered system the optimal design which to find the minimum wide of SSI with a few iterations has been done as demonstrated in Table 4.



(a)

(b)

Figure 7. Stray losses in cover plate of 1600 kVA three phase distribution transformer: (a) without SSI (b) with SSI



(a)

(b)

Figure 8. Temperature distribution in cover plate surface of 1600 kVA three phase distribution transformer: (a) without SSI (b) with SSI (8 mm)

V. CONCLUSIONS

This study proposes a 3D FEM optimization design of cover plates for a 1600 kVA, 400 V three phase distribution transformer using a suitable geometry of SSI to over-come the local overheating and keep the temperature below 140 °C. Leakage losses and hot spot temperature in the cover plate are estimated in the case of with and without SSI. According to the results obtained from this study there is a considerable agreement between the losses in 3D FEM, analytical methods and experimental results. The study shows a considerable reduction in the cover plate losses and hot spot temperature with only inserting a very small SSI. The applied approximation for loss and temperature calculations is sufficiently fast which can be used moderate computer resources.

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