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Finite Element Analysis of Transformer Clamping Structure to Study Effect of Copper Shield on Structural Losses and Winding Eddy Losses

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The losses due to transformer leakage field comprise a small percentage of the power in a transformer. Yet these losses produce localized heating which can compromise its operation. The stray field strength increases rapidly with growing rating. The stray flux intruding into the structural parts gives rise to eddy currents in them. The resulting eddy current losses may be considerable, thereby increasing the load loss of transformer [1, 5]. The objective of this work is to calculate stray losses in magnetic structures of 400 MVA 1-phase, 500–230 kV auto transformer and study the effect of copper shield on structural losses and winding eddy losses, using commercial software package Magnet (Infolytica Corp.) based on finite element method (FEM). Due to presence of non linear magnetic materials, the sinusoidal source with 60 Hz frequency induces non-sinusoidally varying magnetic fields. A transient solution (which calculates time varying magnetic field) is required for calculating fields in non-linear materials. However, this requires more computational resources. Therefore Time harmonic solution (which calculates field at 60 Hz frequency) with linear magnetic materials is used for this analyses. Further, 3D time harmonic analysis has been done to analyze the effect of varying Cu shield thickness on loss density and finally its effect on winding eddy losses has been investigated.

Keywords: *Eddy current, Cu shield and Time harmonic.*

1.0 INTRODUCTION

The paper investigates effects of Cu shield on the stray losses occurring in core clamping structure of the core and how it affects leakage field pattern which in turn changes eddy losses occurring in winding of power transformer. The 3D geometric model of power transformer was made and solved with finite element method. The time harmonic analysis is used to investigate the discussed problem. On this basis, we calculated the leakage magnetic field around the coils at nominal current loadings. Further, radial and axial field values are calculated inside each conductor and eddy losses in common winding are calculated with and without Cu shield.

2.0 LOSSES IN TRANSFORMER

Transformer is the most efficient machine in power system with efficiency more than 99%. However, manufacturers want to attain even higher efficiency and in turn become more competitive in the market of power transformers hence it is important to calculate transformer performance as accurately as possible. Accurate calculations of stray losses of a power transformer based on numerical model may also improve transformer structure in terms of reduced losses and increased overall efficiency [4].

The stray losses in the power transformer are composed of additional losses in windings and

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of losses which are originated in transformer's structural parts (Figure 1). The losses in the windings are the subject to a power and voltage level of the power transformer. The additional losses in the windings and in the construction, due to leakage magnetic field can not be separately measured.

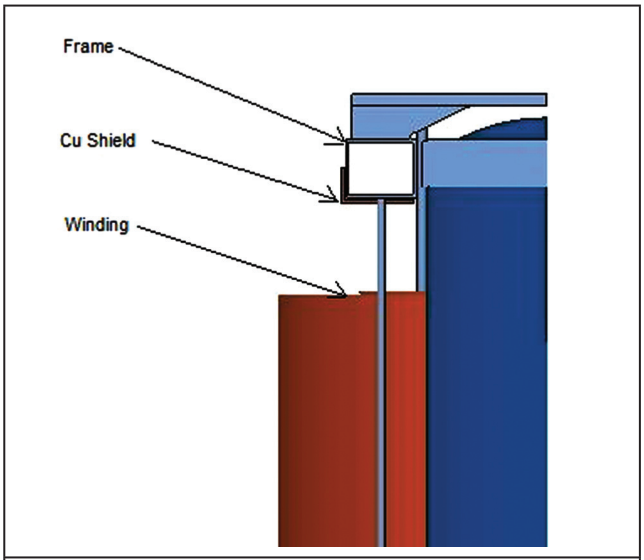

FIG. 1 QUARTER MODEL OF TRANSFORMER CORE WITH UPPER FRAME, Cu SHIELD AND WINDINGS.

The additional losses in the windings can be accurately calculated using two-dimensional axi-symmetric finite element model of the transformer but for an accurate calculation of stray losses in the construction parts and to study effect of Cu shield on winding eddy loss, the 3D finite element model of the power transformer must be used.

3.0 METHODOLOGY

A. Surface Impedance Boundary Condition

The 3D model of power transformer is used for time harmonic solver based on finite element method. The transformer dimensions are measured in meters and for detailed electromagnetic analysis a very large number of finite elements would be needed. This would be especially true if the electrically conductive parts, such as tank walls and yoke clamps are treated as volumes. It is necessary to realize that they should be described by very dense finite element mesh, due to small depth of magnetic field penetration in to conducting parts [2–3]. Dimensions of each finite element in tank walls and clamps should be in the size class below millimeter. So the number of finite element would increase above software computational possibilities. For this purpose, so-called surface impedance is introduced [7–8]. This will significantly reduce the number of finite elements and allow the calculation of losses in the tank walls and other transformer's construction parts. Leontovich [9] presented a simple form of the boundary condition for highly conducting bodies, which relates the electric field intensity (E) and the magnetic field intensity (H) at each point on the conductor surface as

$$n \times E = Z_n n \times (n \times H) \qquad .... (1)$$

Where n is the outwardly directed unit vector normal to the surface and Zs is the standard surface impedance. Eqn. (1) represents the standard Rytov–Leontovich impedance boundary condition. For a good conductor, of conductivity σ and permeability μ, the surface impedance Zs in Eqn. (1) is taken to be

$$Z_S = R_S\,(1+j) \qquad .... (2)$$

Where $j = \sqrt{-1}$ and Rs is the surface resistance.

$$R_s = \frac{1}{\sigma\delta} \qquad .... (3)$$

With δ denoting the skin depth

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad .... (4)$$

And ω is angular frequency. Eq. (1) is applicable at the points on the conductor surface, where δ is much smaller than the local radii of curvature. In surface impedance boundary condition (SIBC) method, the mesh of the conducting region is not used and therefore no field is calculated inside it, which is numerically more efficient. Ahuja *et al.* [6] used this method to calculate eddy losses in the tank plates due to leakage flux.

B. Winding Eddy Losses

Eddy loss per unit surface area of a conductor is given by [2]

$$P_e = \frac{H_0^2}{\sigma\delta}\left[\frac{e^{\xi} - e^{-\xi} - 2\sin\xi}{e^{\xi} + e^{-\xi} + 2\cos\xi}\right] \quad .... (5)$$

Where ξ = 2b/δ.

When dimension (thickness) of the conductor is quite small as compared to its depth of penetration for 2b << δ i.e., ξ << 1

$$P_e = \frac{H_0^2}{\sigma\delta}\frac{\xi^3}{6} = \frac{H_0^2}{\sigma\delta}\frac{8b^3}{6\delta^3}$$

$$\Rightarrow P_e = \frac{H_0^2}{\sigma}\frac{8b^3\omega^2\mu^2\sigma^2}{24}$$

$$\Rightarrow P_e = \frac{1}{3}(\mu H_0)^2\sigma\omega^2 b^3 \quad .... (6)$$

Now, if the thickness of the winding conductor is t, then substituting b = t/2

$$P_e = \frac{1}{3}B_0^2\sigma\omega^2\left(\frac{t}{2}\right)^3 = \frac{\omega^2 B_0^2 t^3 \sigma}{24} \quad .... (7)$$

It is more convenient to find an expression for the mean eddy loss per unit volume (since the volume of the conductor in the winding is usually known). Hence, dividing by *t* and finally substituting resistivity (ρ) in place of conductivity, we get the expression for the eddy loss in the winding conductor per unit volume due to axial (By) and radial (Bx) components of leakage field (Figure 2) are

$$(P_e)_{axial} = \frac{\omega^2 B_y^2 t^2}{24\rho} \quad .... (8)$$

$$(P_e)_{radial} = \frac{\omega^2 B_x^2 w^2}{24\rho} \quad .... (9)$$

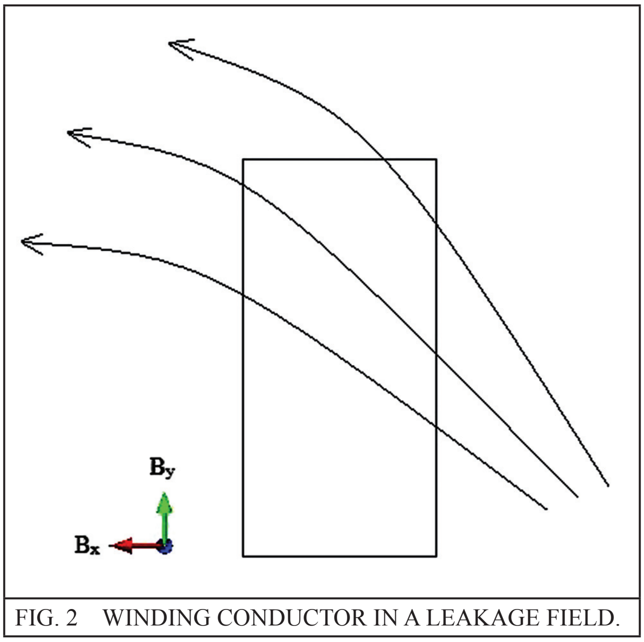

FIG. 2 WINDING CONDUCTOR IN A LEAKAGE FIELD.

4.0 3-D MODEL OF TRANSFORMER

The 3D finite element model is made based on dimensions of a 400 MVA 1-phase, 500 kV-230 kV auto transformer. All the numerical calculations of magnetic fields and eddy current losses were done by commercial software package MagNet (FEM).

The electric connections between the coils and the tank wall insulator as well as limb clamps were not taken into account. Tank plates are modeled without stiffeners. Nonmagnetic materials (insulating materials) are not considered. To reduce complexity, HV side and LV side are analyzed separately and windings are modeled as copper cylindrical shell with ampere turns. Laminated core is modeled as solid block.

The transformer is not symmetrically builtup. The side of transformer with high voltage terminals is longer in comparison with the low voltage side so HV side and LV side are analyzed separately. The clamping plate magnetic steel was modeled with relative permeability μr = 200, and conductivity ρ = 1.05e-7 Ωm.

The main disadvantage of used method for eddy current losses calculation is that all electromagnetic quantities harmonically fluctuate by first harmonic. This is not the case when we deal with non-linear characteristic of iron. Because of this magnetic non-linearity the magnetic field in the material has non-sinusoidal form. Nevertheless, the losses are calculated relatively accurate.

5.0 RESULTS

Eddy current losses occurring in clamping structure and winding eddy losses are calculated for two different cases viz with and without Cu shields and results are recapitulated in Table 1. The plot for total loss for the case when Cu shield is not being used is shown in Figure 3.

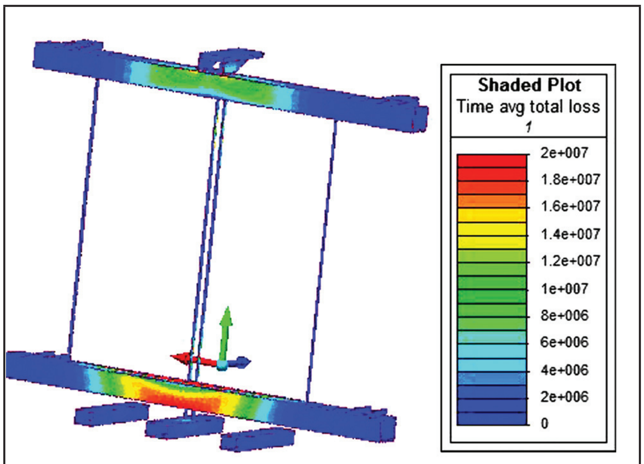

FIG. 3 LOSS DENSITY DISTRIBUTION IN HV SIDE FRAME (WITHOUT CU SHIELD).

It is evident from Figure 3 that middle part of upper and lower frame is subjected to high stray field and need protection. The losses occurring in lower frame are higher than the upper frame (Table 1) because of its closer proximity to windings.

The plot for total loss for the case when Cu shield is used is shown in Figure 4. It is clearly visible from Figure 4 that a Cu shield considerably reduces the effect of stray field and losses occurring in frame and tie rods are significantly reduced [10].

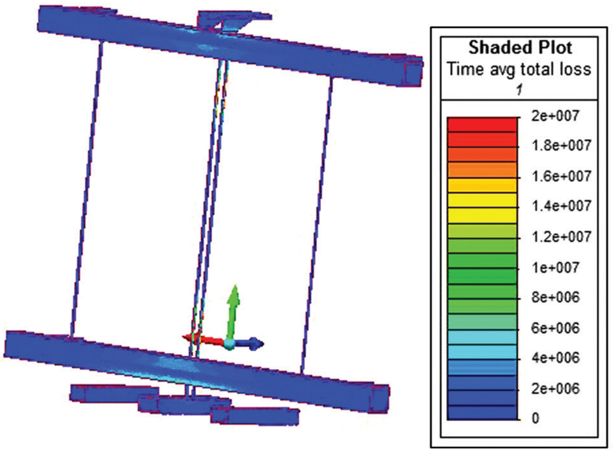

FIG. 4 LOSS DENSITY DISTRIBUTION IN HV SIDE FRAME (WITH CU SHIELD).

The Winding eddy losses are calculated for both with and without Cu shield for CV winding. In the case when Cu shield is being used, losses occurring in CV winding are 33.3 kW whereas in the case without Cu shield the losses came equal to 32.5 kW, so there is an increase of 0.8 kW.

6.0 CONCLUSIONS

Eddy current losses occurring in different structural part of transformer have been predicted.

TABLE 1

COMPARISON OF LOSSES OCCURRING IN TOP FRAME, BOTTOM FRAME, TIE RODS AND Cu SHIELDS

		Top frame	**Bottom frame**	**Tie rods**	**Cu shields**
Without Cu shield	HV Side (kW)	17.5	28.73	2.01	–
	LV Side (kW)	14.38	24.4	1.78	–
With Cu shield	HV Side (kW)	4.67	7.81	2.1	7.98
	LV Side (kW)	3.19	5.66	7.86	7.29

Inaccuracy of calculations can be mainly ascribed to mathematical simplifications and to material's nonlinear magnetic properties description. The results show the difference in eddy current losses occurring in top frame, bottom frame, tie rods and Cu shields and it can be deduced that the eddy current losses in transformer frame and tie rods can be reduced drastically with the use of shielding techniques. However metallic shielding has adverse effect on winding eddy losses and overall cost of material so it should be chosen judiciously keeping rating of the transformer in mind.

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