Study of Stray Losses Reduction through Finite Element Method

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Abstract-***This paper presents modeling and analysis of leakage flux in transformer with and without aluminium shield by Finite Element Method (FEM) to reduce the stray losses. The transformer is simulated on Maxwell 14.0 software . The study describes variation in leakage flux and magnetic flux density with and without shielding and total losses variation with and without aluminum shields on tank walls.***

Keywords-*Finite element analysis, Maxwell 14.0, leakage flux, stray losses, electromagnetic aluminium shields.*

I. INTRODUCTION

Transformer is an important link between power producer and consumer. Transformers play critical roles in delivering power to distribution equipment for homes, commercial establishments and industrial facilities. Although transformer is very efficient devise in power system, (efficiency is more than 99%), its efficiency decreases with increase in load above its rated capacity. As the load current in transformer increases above its rated capacity, losses in transformer namely ohmic losses due to current and stray losses due to increase in leakage flux, increases. In large distribution transformer, current flow in the low voltage windings increases swiftly with increase in load thereby resulting in a strong leakage magnetic field. In such case additional losses in metallic structure (tank, elevated seat, flange and the tank etc.) are significantly increased. These losses contribute large part of the load loss in transformer and it is unevenly distributed in metallic structure. The loss which is concentrated in a small area often causes the considerable local overheating [9].

Transformer Insulation is deteriorated gradually and leads to the failure because it is often exposed in the electric field, moisture, high temperature, mechanical stress and so on [1]. The most important factor that governs life expectancy of the transformer is the hot-spot temperature value [8-9]. It is important to determine the temperature rise of transformer with load to decide the amount and duration of over load up to that it can work without any failure.

Finite element method (FEM),as well as other numerical techniques, have been extensively applied in the analysis of electric machines and transformers. Two dimensional FEM is proposed in Ref [10-12] for simulation and study of behaviour of power and distribution transformers. Finite Element Method is used because of its ability to predict accurate and cost effective eddy current losses and magnetic field distribution in the materials whose electrical conductivity and magnetic permeability affect the losses.

In this paper, the finite-element method is used to envisage the variation of leakage flux and flux density for load current of 50A. A 3-D transformer model is considered to analyze the leakage flux and flux density in core and tank and total losses (i.e. copper, core, stray).

II. FINITE ELEMENT METHOD (FEM)

Finite Element Method (FEM) is one of the most popular numerical techniques used for computer simulation. The key advantage of the FEM over other numerical techniques in engineering applications is the ability to handle nonlinear, time-dependent and complex geometry problems. It is difficult to analyze a transformer by conventional methods because of its nonlinear nature. The FEM analysis includes these effects by choosing material magnetic permeability for each additional structure domain. The FEM techniques are extensively used to analyze magnetic field distribution in nonlinear medium. The FEM mapping of the flux distribution within the transformer for several situations was considered. Algorithm for Finite Element Analysis of transformer is explained in flowchart in fig .1. To set up Maxwell design the general procedure is:

- Insert a Maxwell design into a project.
- Draw the model geometry.
- Specify the solver type.
- Assign material characteristics to objects.
- Assign boundaries and excitations.
- Add parameters for which you want to solve.
- Specify mesh settings.
- Set up any optimetrics you want to run.
- Run the simulation.

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- View solution results, post-process results, view reports, and create field overlays.

III. TRANSFORMER MODELING

A three-phase, three legged, core type typical transformer is simulated in Maxwell 2-D as shown in fig. 2. Dimensions and specification of the proposed transformer are given in Table 1. The core and windings are made by CRGO steel and copper material respectively. The LV windings are simulated to analyze the effect of variable load and faulty

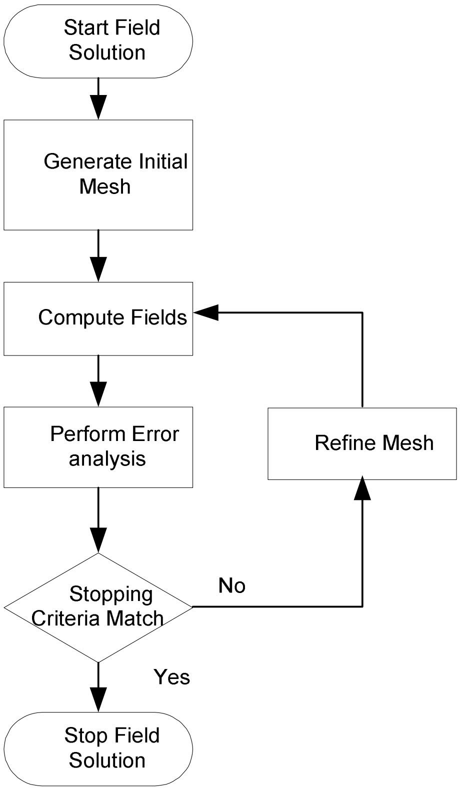

Fig. 1. Flowchart of Algorithm for Finite Element Analysis

condition on leakage flux and magnetic field density of transformer. For simulation, low voltage (LV) winding is modeled with 10 coils per phase and 76 conductors per coil.

Mesh generation is one of the most critical aspects of engineering simulation. Mesh generation consist of dividing the model into number of triangle units (in case of Maxwell 2-D model) and

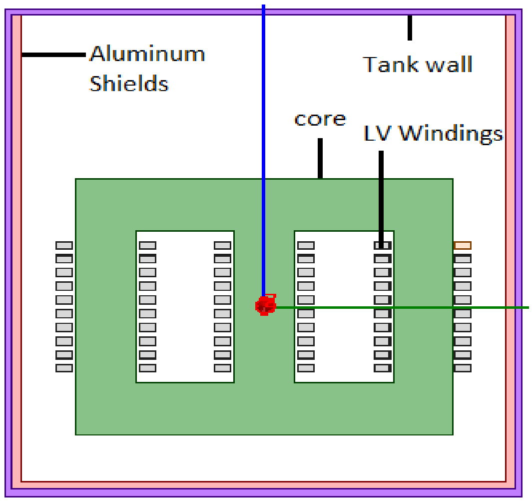

Fig. 2. Front view of transformer

tetrahedron units(in case of Maxwell model). Maxwell calculates magnetic vector potential with help of (1) at each vertex using numerical techniques [19].

$$\nabla \times \left(\frac{1}{\mu}\right) \nabla \times \bar{A} = \bar{J_e} - j\omega\sigma\bar{A} + \omega^2\bar{A} \qquad (1)$$

Where

$\bar{A}$	Magnetic vector potential,
μ	Magnetic permeability,
σ	Electrical conductivity,
ω	Power frequency,
J_e	Current density,
$-j\omega\sigma\bar{A}$	Induced current density,
$\omega^2\bar{A}$	Displacement current density.

From above calculated magnetic vector potential, magnetic flux density at each vertex is calculated by using following Maxwell equation.

$$\bar{B} = \nabla \times \bar{A} \qquad (2)$$

Where

$\bar{B}$	Magnetic flux density,
$\bar{A}$	Magnetic vector potential.

More the number of cells more, accurate result is produced. But too many cells may result in long solver runs, and few may lead to inaccurate results. Fig. 3 illustrates the length based mesh model of the transformer. The maximum length of the element is 50mm and the maximum number of element is 8000.

Table.1: Transformer Dimensions

Name	**Value**	**Unit**
Core Diameter	40	mm

Window width	100	mm
Window height	150	mm
Width of side wall	4	mm
Width of top and bottom wall	6	mm
Stages	9	No.
Distance between core and tank wall	40	mm
Distance between yoke and tank wall	120	mm
aluminium foils shields thickness	6	mm

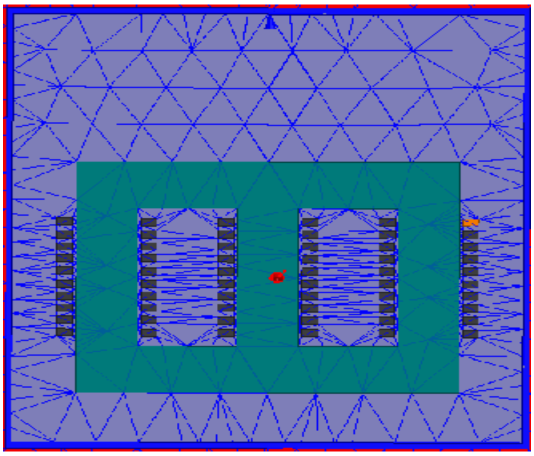

Fig. 3. Mesh model of the transformer

IV. STRAY LOSSES CALCULATION

In many large distribution transformers, high current in coil will cause a very strong leakage magnetic field. A series of additional losses will appear in the various structures of a transformer (oil tank, enclosure, flange and the tank along, etc.). These losses not only account for a large part of load loss in the transformer, but it is unevenly distributed in the metal structure. The distribution of leakage magnetic field in a transformer is the main cause of stray losses and is must to understand in order to avoid failure due to overheating.

Stray losses mainly consist of additional losses in the windings and of losses originate in different construction parts. These losses are difficult to measure separately. Hence two dimensional finite element model of transformer is used which can be seen in fig.2.

Stray losses can be calculated with the help of surface impedance [20] .Final surface impedance is calculated from (3-7). Surface impedance gives relation between electric and magnetic field at the surface of conductor.

$$Z_{sl} = \frac{E_s}{H_s} = \frac{1+j}{\delta\sigma} \quad (3)$$

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

$$Z_{snl} = \sqrt{\frac{3}{4}}1.69\frac{1}{\sigma\delta}(1+0.5j) \quad (5)$$

$$f(H_s) = \frac{1}{1+\frac{H_s}{H_k}} \quad (6)$$

$$Z_{sn} = f(H_s)Z_{sl} + \big(1 - f(H_s)\big)Z_{snl} \quad (7)$$

Where

E_s Electrical field intensity at surface

H_s Magnetic field intensity at surface,

j Current density,

σ Electrical conductivity,

δ Depth of penetration of leakage flux

H_k Knee value in non linear B-H curve

Z_{sl} Surface impedance of linear conductor

Z_{snl} Surface impedance of non linear conductors

Z_{sn} Final surface impedance

$f(H_s)$ Weighted function

The stray losses can be calculated with the help of final surface impedance (8).

$$P_{sn} = \frac{1}{2}\iint R_e(Z_{sn}).|H_s|^2 dA \quad (8)$$

V. MAGNETIC FIELD ANALYSIS

Study of stray losses reduction techniques reveals that the stray losses can be reduced through shielding of construction parts by using materials of less electrical and magnetic conductivity to alter the path of the leakage flux [21]. In this paper, effect of aluminium shielding at the inner surface of tank has been analyzed in distribution transformer of 50 KVA transformer.

The field line distribution in transformer with and without aluminium electromagnetic shields is demonstrated in fig.4and fig.5 respectively. Fig 4 illustrates magnetic field line distribution in transformer without shielding at 50A current. In fig.4, it can be seen that the leakage flux is high in the tank walls, causing high-power losses in tank walls due to eddy current effect. These losses account for stray losses. The circle in fig. shows strength of the leakage flux entering in tank walls.

To reduce stray losses, electromagnetic shield of aluminum is applied to inner walls of transformer.Fig.5 illustrates magnetic field line distribution in transformer with shielding at 50A current as current rating of LV winding of general distribution transformer of 50 KVA. The leakage flux in the tank walls is reduced as shown in fig.5 which results in less loss in tank walls.

Limb clamps were not considered in our model as they usually are made up of stainless steel and hence do not contribute to losses significantly. Cross section area of the winding and current density over this cross section is taken same throughout our simulation. Also most of the leakage flux cuts the side tank walls than top and bottom tank walls; only side walls of transformers are shielded and simulated though FEM.

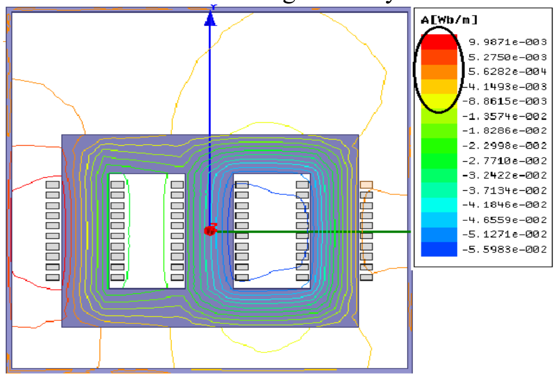

Fig. 4. Magnetic flux in transformer without shields at 50A current

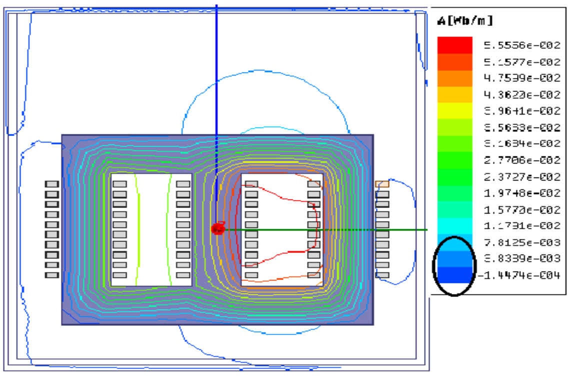

Fig.5. Magnetic flux in transformer with shields at 50A current

Fig. 6-7 represents magnetic flux density distribution in transformer with and without shielding at 50A current. Without electromagnetic shielding, magnetic field density increases in tank wall due to which stray losses and temperature of transformer increase and subsequently efficiency decreases. It can be seen from fig. 6-7 that there is a change in magnetic flux density in tank walls. It changes from 3.4 Tesla(in case of without shielding) to 2.1209 Tesla(in case of with shielding).

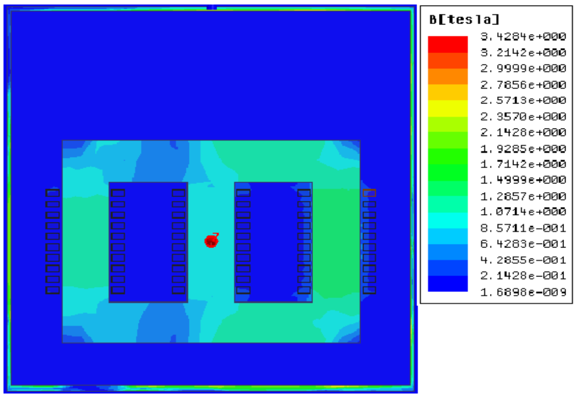

Fig. 6. Magnetic flux density in transformer with shields at 50A current

This verifies the reduction of leakage flux due to aluminium shielding. Therefore, with electromagnetic shielding, stray losses decreases and subsequently efficiency increases. Thus, it can be concluded from the above results that temperature of the tank walls is lesser in case of shielding.

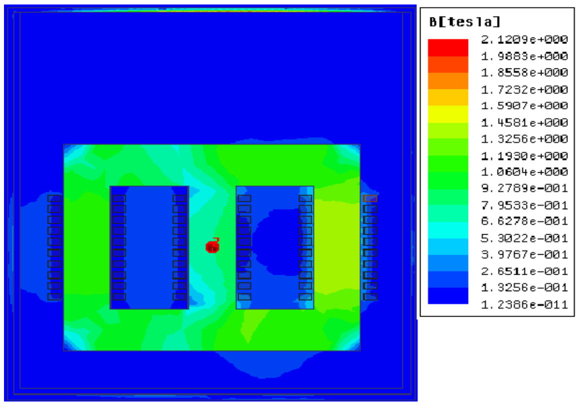

Fig.7. Magnetic flux density distribution in transformer without shields at 50A current

Total losses variation in transformer, with and without magnetic shielding, w.r.t. time is shown in fig. 8-9. Results are recorded from 60ms in case of without shielding. To evaluate the performance of shielding more accurately, total losses are recorded from 48ms in case of transformer with shielded walls

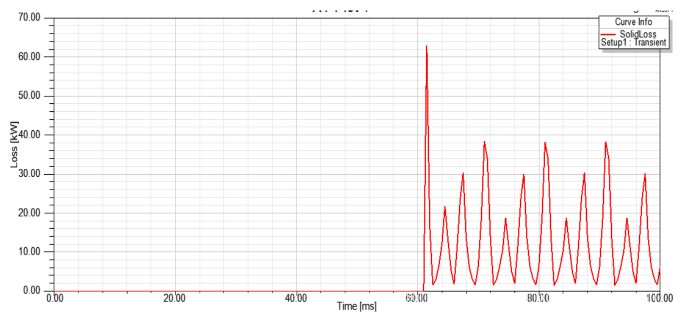

Fig. 8. Total Losses variation in transformer without shields at 50A current

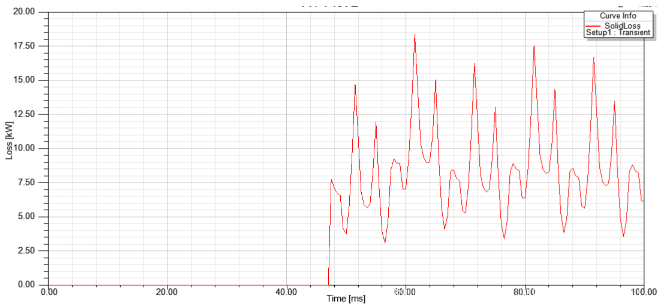

Fig. 9. Total losses variation in transformer with shields at 50A current.

Fig. 8-9 shows that the total losses with shielding, are significantly lesser than the total losses without shielding. In both the cases, transformer winding is supplied with same magnitude of current (50A) at same supply frequency(50Hz). For the same value of current, voltage and frequency, core losses and ohmic losses are constant and thus it can be concluded that drop in total losses in fig.9 is due to the reduction of stray losses because of shielding of about 50% reduction in losses.

VI. CONCLUSION

According to the obtained results and the above mentioned discussion, it is obvious that useful conclusions can be drawn from the Finite Element Analysis, regarding the leakage flux distribution and losses in transformer with and without magnetic shielding. The stray losses in transformer tank walls can be considerably reduced by magnetic shields of aluminium. As the losses in transformer increase, temperature of various construction parts also increases considerably reducing transformer's life and efficiency. How to eliminate local overheating and avoid overloading must be paid full attention for design and operation practice of distribution transformer.

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