Magnetic Flux Distributions in Transformer Core Joints

S. Sundara Mahalingam
Assistant Professor,Department of Electrical & Electronics Engineering, Mepco Schlenk Engineering College, Sivakasi, Tamilnadu, India
sundar.eee@mepcoeng.ac.in

Abstract— **Transformer is an essential and expensive component in the power system. Even though transformer losses are small percentage in total power transferred (<0.5% in large power transformers), it produces localized heating which can affect normal operation of the transformer. Hence, it is very significant to understand how the losses arise and to estimate these losses accurately as much as possible. So that we can consider necessary steps at design stages itself to find the ways for reducing the losses. Accurate estimation of core loss of transformer is a critical issue at transformer design stage. In order to optimize the transformer core design, the influences of core parameters on core loss performance need to be analysed. The magnetic flux distribution in transformer core joint regions has been analysed by finite element method as a function of various core parameters. In this paper, the effects of core joints, core materials, overlap length, and air gap length on core loss performance are examined. It is inferred that losses increased as overlap length between adjacent lamination increased.**

Keywords **Finite Element Method, Core loss, Core joints, overlap length, step lap joint**

I INTRODUCTION

It is important to understand in detail the behaviour of localized flux distribution in transformer core in order to optimize the core construction and accurate estimation of core losses. Because accurate estimation of core losses are more important in their design and specifications for economic reasons otherwise higher losses than predicated will lead to financial penalties and lower losses gives less pay pack to designers and manufactures. The main factors which increase the loss in laminated core are non uniform flux, difference in magnetic path length, rotating flux, interlaminar short circuit, stress, and transverse flux [3-4]. These factors can be controlled by selecting optimized core design with various core parameters such as core joints, core materials, lamination thickness, number of steps, number of layers per step, overlap length, air gap length. It is fact that there is no analytical relationship with effect of these parameters on core loss performance. There are two different joint stacking patterns normally used to manufacturing of core i.e. single step lap and multi step lap which depends on loss requirements and manufacturing capabilities. The aim of this paper is not to endorse one method to another but to give general information about the core joint parameters and the loss distributions. It has been reported that the power losses in full size transformer cores are reduced as much as up to 5% or even 10% compared to SSL configurations [1]. But MSL has disadvantage of increased costs of core assembling. It can be noted that examinations of the optimum core construction and most suitable magnetic characteristics of core material are possible using finite element method. T. Nakata, N. Takahashi [2] also investigated the effect of the step lap joint design on core losses. This paper presents magnetic flux distribution analysis in Z direction with flux density range of 1.2T to 1.7T. From this analysis, we can estimate accurate core loss and optimize core joint configuration.

II ELECTROMAGNETIC ANALYSIS AND SIMULATIONS

An electromagnetic analysis with FEM was realized to determine the magnetic flux distribution and to compute losses in lamination steel. The analysis of transformer core model in three-dimensional (3D) models with its exact number of laminations causes several problems such as very long simulation time and needs great amounts of computer resources (RAM, hard disk). So by considering these problems, 3D core model can be replaced by 2D simulations to analyse various core parameters [5-6]. In this paper, vector potential is used for 2D modelling of the core which is justified by Maxwell equations B = rot A.

Hence (∇ x ($\upsilon\nabla$ x A)) = J. In 2D problems, we assume that vectors A have only one component, perpendicular to the XY plane. So the possion equation of magnetic vector potential will be

$$\frac{\partial}{\partial x}\left(\vartheta \frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\vartheta \frac{\partial A}{\partial y}\right) = J_z$$

is the magnetic reluctivity i.e. inverse of magnetic permeability (μ)

In 2D fem, flux density is given by

$$B^2 = \left(\frac{\partial A}{\partial x}\right)^2 + \left(\frac{\partial A}{\partial y}\right)^2$$

After flux density calculation, total core loss can be obtained from the following

$$W = \sum_{i=1}^{n}(Vol)_i \int_0^{B_i} (H_i \, dB_i)$$

Where,

H_i - Magnetic field intensity in mesh
(i) B_i- Magnetic field density in mesh
(i) $(Vol)_i$ - Volume mesh (i)
n - Number of meshes

Here we assume that vector potential A does not vary along X axis so component of $B_y = 0$ and A can vary only along Y direction. So magnetic flux lines are parallel to the equipotential lines of A i.e. along X axis. By symmetry, the magnetic field on the horizontal segments in upper region and lower region should be uniform. So A1 vector potential assigned in upper region where as A2 with same magnitude and opposite polarity. The difference between the potentials A1 and A2 gives magnetic flux per meter (wb/m).

III Z PLANE MODELING

The magnetic characteristics of cores with single step lap (SSL) and Multi step lap (MSL) have been analysed using finite element method taking into account of eddy current and magnetic saturation. In the single step lap, two steps were used per group for overlap where as multi step lap used five steps per group for overlap The magnetic characteristics of cores with single step lap (SSL) and Multi step lap (MSL) have been analysed using finite element method taking into account of eddy current and magnetic saturation. In the single step lap, two steps were used per group for overlap where as multi step lap used with five steps per group for overlap as shown in Fig.1.

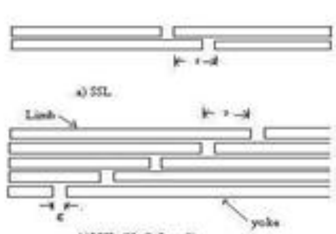


Fig.1. Investigated types of overlap arrangement a) SSL b) MSL

The following major parameters which affect magnetic characteristics of cores have been investigated grades of steel, operating flux densities, overlap length, air gap length, and number of layers per step. Due to periodic repetition of lamination steel to whole transformer, consider only finite number of laminations groups. The average induction in the laminations steel along X axis is enforced by appropriate Dirichlet boundary conditions on the upper and lower boundary of the model.

A. Flux Distribution analysis in Single step lap joint

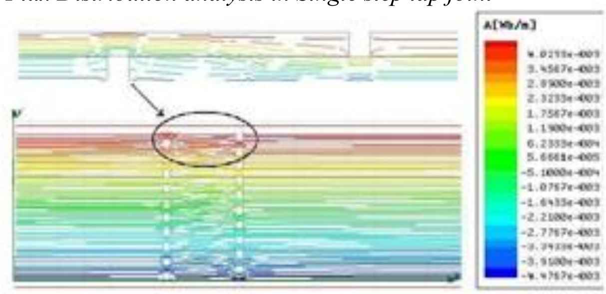


Fig.2. Magnetic flux lines in single step lap joint at induction 1.7T

Fig 2 shows flux lines in single step lap joint of core with air gap length g=0.2mm and overlap length s= 2mm, while overall flux density 1.7T. While assembling the transformer core, unavoidable air gaps present at joints. The magnetic flux travels between the overlapping laminations of yokes and limbs due to presence of air gaps at the joints. The magnetic flux passes to next layer of laminations when it meets high reluctance air gap. When these laminations are saturated, flux crosses the air gaps. This flux distortion causes additional localized losses.

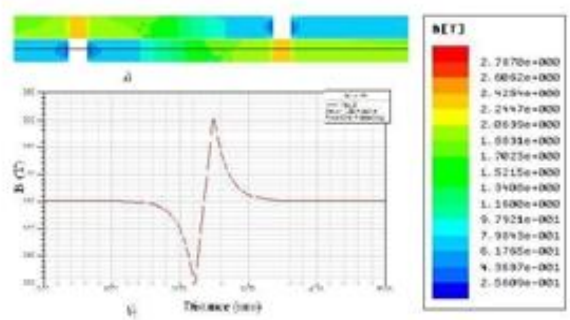


Fig.3. Magnetic Flux density distribution in single step lap joint
a) B plot b) Along line

At a sufficiently large distance from the gaps, the flux in the laminations is nearly uniform. Near the gaps there is a significant vertical flux component. So flux density in the lamination steel area shunting the air gap rises upto 2.6T while in the next gap of same layer is 0.7T as shown in fig. 3.

B. Flux Distribution in Multi step lap joint

Similarly in multi step lap joint also, flux lines are distributed uniformly in steel and jumps in air gap region as shown in fig 4. Due to step arrangement, flux density distribution almost uniform over whole steel package as shown in fig. 6. In fig. 5, it shows the representation of lines to identify flux density distribution in MSL. In case of SSL, flux density distribution is sinusoidal in nature where as in MSL, flux density reduced only in air gap region. So MSL is more efficient than SSL. But number of layers per step and number of steps in a group also need to be considered.

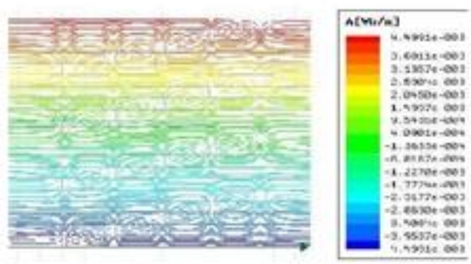


Fig 4. Magnetic flux lines in Multi step lap joint at B=1.7T

Fig 5. Sketch for identification of plot lines in MSL

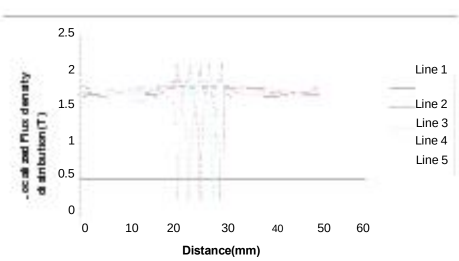


Fig. 6 Flux density distribution in MSL at B=1.7T

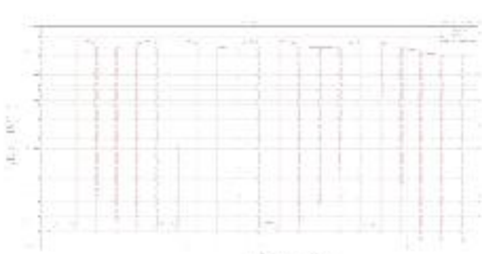


Fig. 7 Flux density distribution in normal direction along line 6

The flux density distribution along line 6 of Fig. 7 is taken in the interlaminar gap between two groups i.e. along normal direction. The flux density gets reduced in air gap between lamination and again increased in steel package.

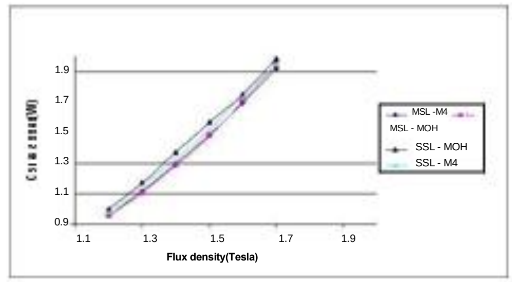
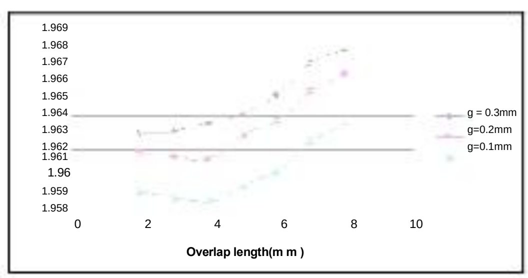


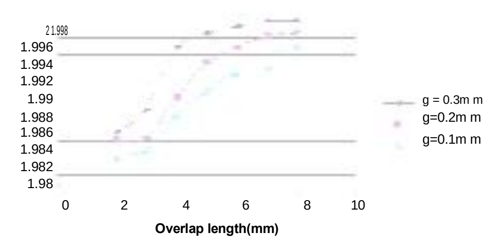
Fig.8. Comparison of core losses between MSL & SSL with two different materials

The no-load losses depend on the magnetic flux density at which the transformer operates as well as the physical characteristics of the magnetic material. So these effects were studied for different material i.e. 0.27 mm thickness of grain orientated steel M4 and MOH and for various operating flux densities from 1.2 T to 1.7T. The results of this simulation on how much losses of MSL core deviate from those of a SSL joint core are represented in fig 8. It can be seen that there are much improvement which can be attained by replacing SSL by MSL. Due to joint contribution, losses in SSL are about 5% loss increase from MSL.

C. Effect of overlap length and air gap length on core loss



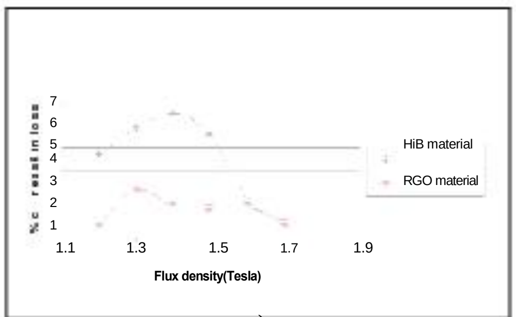
a)



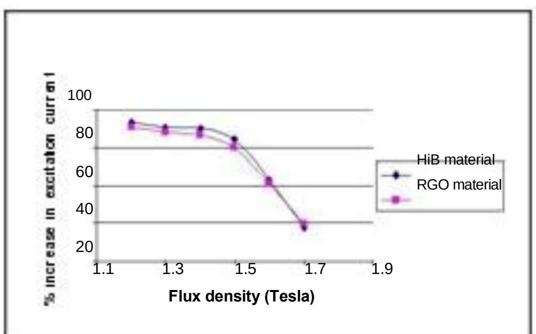
b)

Fig. 9 effect of overlap length and air gap length in MSL at B=1.7T
a) RGO b) HI-B

It was applied to analyse core losses and excitation current with multi step lap joint. The effect of overlap length and air gap length are also analysed for two different core materials in MSL. When increasing overlap length, magnetic mean path length of the core varied. In mitred case, uneven magnetic path length, air triangles at inner corner of core and transverse flux components becomes more predominant for localized joint loss. Core losses increases with overlap length and air gap length as shown in fig. 9



a)



b)

Fig.10. SSL versus MSL, a) % increase in loss b) % increase in excitation current

More precisely, at lower B the MSL configuration showed higher percentage of loss increase than SSL values, whereas at higher B this effect became inconsistent as shown in fig 10. Normally high permeability (HI-B) material is better performance than regular grain oriented (RGO) material.

IV CONCLUSIONS

1. While assembling transformer cores, air gap will naturally arise at the lamination sheets. These air gaps in conjunction with shifted core steel packages cause interlaminar flux components which leads to flux inhomogeneties and higher loss.
2. Loss increases depend upon the magnetic path length and local distribution of air gaps. With increase in air gap length and overlap length, core losses will be increased.
3. In lower flux density range, core performance is improved as compared to higher range of induction. The core loss performance varies with grade of material. Hi-B material has better than RGO steel.
4. The percentage increase in loss from non step lap joint to step lap joint is considerable less in higher operating flux density.

REFERENCES

[1] G. F. Mechler and R. S. Girgis, "Calculation of spatial loss distribution in stacked power and distribution transformer core," *IEEE Transactionsion Power Delivery*, vol. 13, no. 2, pp. 532-537, Apr. 1998.

[2]T. Nakata, N. Takahashi, and Y. Kawase, "Magnetic performance of step-lap joints in distribution transformer cores," *IEEE Trans. Mag.*, vol. 18, no. 6, pp. 1055-1057, Nov. 1982.

[3]Z. Valkovic, "Some aspects of additional losses in step-lap joints of transformer core," *The Int. J. for Computation and Mathematics*,vol.11, no. 1, pp. 137-140, 1986.

[4]Girgis, R.S., teNijenhuis, Ed G., Gramm K and Wrethag, J.E, "Experimental investigations on effect of core production attributes on transformer core loss performance," IEEE Transactions on Power delivery, Vol. 13, No. 2, April 1998, pp 526-531

[5]Mechler, G. F and Girgis, R. S. "Magnetic flux distributions in transformer core joints", IEEE Transactions on Power delivery, Vol. 15, No. 1 January 2000, pp. 198-203

[6] Ehsan Hajipour, Pooya Rezaei, Mehdi Vakilian, Mohsen Ghafouri,"Power Transformer No-Load Loss Prediction with FEM Modeling and Building Factor Optimization,"Journal of Electromagnetic Analysis and Applications, October 2011, 3, 430-438