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METHODS FOR REDUCTION OF STRAY LOSS IN HIGH CURRENT LV REGIONS OF LARGE POWER TRANSFORMERS USING FEM ANALYSIS

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ABSTRACT

In large power transformers, more than 20% of the total load loss is the stray loss in structural components. The biggest part of stray loss takes place in the transformer tank. As the transformer ratings increase, the stray loss problem becomes increasingly significant resulting in higher temperatures and local hot spots that reduce the transformer life. Analytical and numerical methods have been applied for the evaluation of stray loss. Stray losses in transformer covers depend on the distribution of leakage flux produced by strong induced fields. Due to the heavy current flow in Low Voltage (LV) windings, the strong magnetic flux linking the transformer tank causes over heating of the tank walls which are near the high current bushings of transformer. While considering the LV side the current may even goes to around 9000A for a generator transformer for the kind we have considered. This work presents a 3-D Finite Element Analysis of the tank walls to verify the solution of overheating problem. The overheating results are analyzed and discussed for the case of a 290MVA 235/15.75 KV generator transformer.

Keyword: stray loss, induced fields, local hot spots, leakage flux, generator transformer,

INTRODUCTION

Power and distribution transformers are expensive and vital components in electric power transmission and distribution systems. The statistics of failures in power transformers are as follows: tap changers are the main source of faults that is about 41 percent, 19 percent with that of windings, 3 percent with the core, 12 percent with the terminals, and 13 percent with the fluids and tank. Failures due to hot spot in the tank are included in this 13 percent. So, it is very important to analyze the causes and consequences of tank hot spots as well as to present solutions to the problem of heating of tank. In huge power transformers, leakage flux production is considerable and it generates hysteresis and eddy current losses in these magnetic structures. The loss, considerably reduce the efficiency of transformer and also cause damage to the insulations nearby. In order to reduce the losses in the magnetic structures, various measures like magnetic shunts and electromagnetic shields are used. With the use of improved and more efficient FE packages, the computation of these losses have made possible accurately. In this work, experiments done with a model to improve accuracy of calculations with varying the distance of the LV leads to the tank wall. With that methodology, stray losses in the magnetic structures of large power transformer is estimated. Also with the influence of changed lead orientation like arrangement and placement, on stray losses in tank and core clamps are investigated.

Evaluation of stray losses has been done using different methods and the methods are:

- Two-Dimensional Methods
- Three-Dimensional Formulations
- Three-Dimensional Finite Element Method (FEM) Analysis.

After the evaluation of stray losses, the different methods to reduce the heating of transformer tanks are incorporated to avoid the heating of transformer tanks.

More than 20% of the total load loss is the stray loss in power transformer structural components. The biggest part of stray loss takes place in the transformer tank. As the ratings of transformer increase, the stray loss problem also increases resulting in higher temperatures and local hot spots that reduce the transformer life. Stray losses in transformer covers depend on the distribution of leakage flux produced by strong induced fields. In large power transformers, extreme temperature rise can occur as a consequence of these stray fields from heavy current carrying conductors (HCCC) and from windings so it should be taken in to account and calculated vigilantly. This article discusses the eddy current losses generated in a transformer tank walls that are related to the magnetic leakage fields.

In the presented work, analysis methodology is validated with a model of transformer tank-plate and three leads of copper. The same has been used to calculate eddy current losses in transformer tank wall caused by high current carrying copper leads with different connections. Only a part of the model of the tank has been considered which is in the vicinity of high current carrying conductors. A 3D analysis has been done as the magnetic fields and the loss distribution in tank and structures in the transformers are three-dimensional. The overheating results are analyzed and discussed for the case of a 290MVA 235/15.75 KV generator transformer.

In the following sections, different lead positions are presented in Section 2, introduction to FEA and ANSYS Maxwell 3D is explained in Section 3, Section 4 describes the results and discussion. Conclusion of the paper is summarized in Section 5.

CASES UNDER CONSIDERATION

A. Introduction

In case of large power transformers the input and output leads that carry the current in to and out of the windings can be placed in different ways. These leads are made of copper and are carrying high amount of current. Due to the high current flow in the leads, there is a bigger chance in flux linkages on the tank wall near the current carrying leads. In normal transformers the output leads from two windings are connected to a common point and the output lead from the third winding is taken through another point away from the other two winding leads. In such case there is an imbalance in the resultant current and hence the flux. As the two lead outputs are not cancelling out each other there is a resultant flux that cause extra heat on the tank surface causing hotspot. This condition is explained as the first case. The second case is the modified case for the same case 1 model. The main aim of this second model is to lower or reduce the over-heating of the tank wall. Through the second model it has showed that the heating of the tank could be reduced highly by the assembling of the three leads together.

For power transformers, the main factors affecting over heating of the tank walls depend on:

- amount of current through the lead **(i)**
- distance of lead from tank wall **(L)**
- Length of lead passing near tank wall.
- number of leads carrying the same current (same phase current) **(n)**

In normal transformers the LV leads close to the tank wall having high current causes flux linkages on the tank walls near the leads. Due to this heavy leakage flux heating of tank also increases resulting in transformer damage. So here in this work in order to remove over heating of the tank wall, a new lead position is considered as shown in figure.3. Here the three leads are placed at same place there by summing up the flux to zero like kirchoff's current rule. The surface heating will be highly reduced in this case. Heat on tank wall can be calculated using the equation 2.1,

$$\textbf{Heat on tank wall} = n \times i / L \qquad (2.1)$$

The value of this relation should be less than 40. (It is an experimental value used by manufacturers while positioning the leads and designing the size of tank). If the distance between tank wall and lead is increased to higher value it will result in the large size of transformer. Also more amount of oil is required, resulting in increased cost.

B. Lead Connection

The lead connection according to which the input to the model is given is depicted in the figure.1. For W winding, the phase current is 10630.583<0^o. For V winding the phase current is 10630.583<120^o and for U winding, the phase current is 10630.583<240. So for the first lead, the two inputs will be from V and U winding respectively, for second lead the inputs will be from W and U winding and for third lead the input will be from V and W windings respectively. The output from the first lead is 10630.583<180^o, for second lead is 10630.583<-60^o and for third lead is 10630.583<60^o.

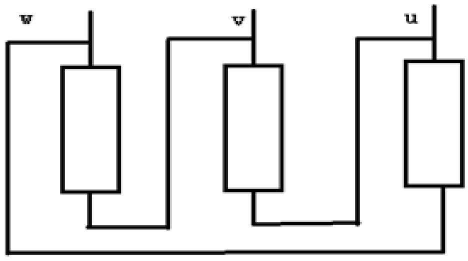


Figure.1 Lead Connection.

In this work two different orientation of the output leads are considered. The two lead positions are explained as case 1 and case 2.

C. Case 1

In normal transformers the output leads from two windings are taken through nearby path and are connected to a common point and the output lead from the third winding is taken through another path away from the other two winding leads. In such case there is an imbalance in the resultant current and hence the flux. As the two lead outputs are not cancelling out each other there is a resultant flux that cause extra heat on the tank surface causing hotspot. This condition is explained in the first case. The model has been created in ANSYS MAXWELL 3D software. The fig.2 shows the first case considered in this work.

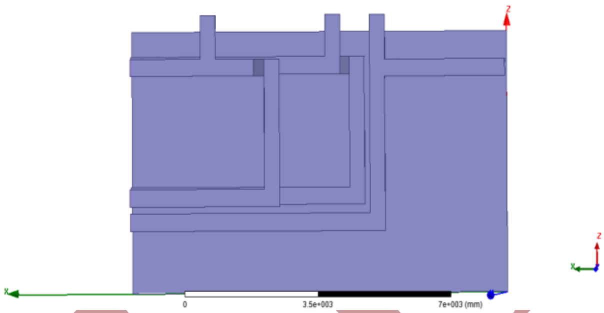


Figure.2 Model for Case1.

D. Case 2

The second case is the modified case for the case 1 model. The main aim of this second model is to lower or reduce the over-heating of the tank wall. Through the second model it has showed that the heating of the tank could be reduced highly by the assembling of the three leads together. Figure 3 shows the modified model. In this the three leads are in same location proceeding through nearby paths. Here due to this type of lead orientation the fluxes of three leads get neutralized. So it won't over heat the transformer tank wall.

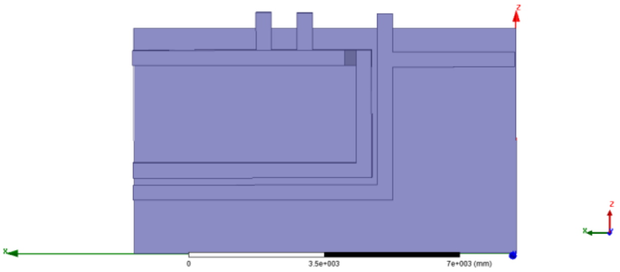


Figure.3 Model for Case2.

For the analysis of a model there are a lot of steps through which the model has to pass through. After the design of the model, each part of the model is assigned with the prescribed materials, their properties like relative permeability, bulk conductivity, magnetic coercivity, temperature etc. After material assignment excitation is assigned to the leads ie two inputs and one output for each lead. After completion of the total assignment, the analysis step starts. In analysis process first step is Finite Element Analysis. The details of FEA is given below. FEA done here is a part of Maxwell 3-D analysis. The model is analyzed using ANSYS Maxwell 3-D software. Fifth section gives a detailed explanation about the software Maxwell 3-D, its process cycle, solution types etc.

INTRODUCTION TO FEA AND ANSYS MAXWELL 3D

A. FEA

The study of behavior of components in real time conditions in computer aided engineering is achieved through Finite Element Analysis (FEA). The Finite Element Analysis is a computing technique that is used to obtain approximate solutions of Boundary Value Problems. It uses a numerical method called as Finite Element Method (FEM). FEA involves a computer model of a design that is loaded and analysed for specific results. The main advantages of FEA are:

- It reduces the amount of prototype testing, thereby saving the cost and time.
- It helps to optimize a design and it helps to create more reliable, high quality and competitive designs.

B. Maxwell 3D

Maxwell 3D is a high performance interactive software package that uses finite element analysis (FEA) to solve electric, magneto-static, eddy current, and transient problems. Maxwell solves the electromagnetic field problems by solving Maxwell's equations in a finite region of space with appropriate boundary conditions when necessary with user-specified initial conditions in order to obtain a solution with guaranteed uniqueness. It automatically generates nonlinear equivalent circuits and state-space models from field parameters that may be further used in system and circuit simulation analyses. This offers the ability to perform a comprehensive analysis of the component with its drive circuit, loads and other system parameters. It includes:

- Electric fields
- Magneto-static fields
- Eddy current fields
- Transient fields

RESULTS AND DISCUSSIONS

A. Eddy current analysis on tank wall

Eddy Current Analysis is performed by choosing the Eddy Current solution type. Applications that use Eddy Current Analysis can be solenoids, inductors, motors, stray field calculations and many others. The eddy current solver computes steady-state, time-varying (AC) magnetic fields at a given frequency –this is a frequency domain solution. All objects are stationary. The source of the static magnetic field can be: Sinusoidal AC current (peak) in conductors. Time-varying external magnetic fields represented by external boundary conditions. The quantities solved are the magnetic field (H) and the magnetic scalar potential (Ω). Current density (J) and magnetic flux density (B) are automatically calculated from the magnetic field (H). Derived quantities such as forces, torques, energy, and inductances may be calculated from these basic field quantities. Material permeabilities and conductivities can be anisotropic, but must be linear.

The software tool, based on Finite Element Method (FEM) is used for stray losses analysis. This involves estimation of 3-D eddy current losses in the structural parts and the resultant temperature rises. It calculates values of the magnetic field quantities at pre-defined locations in space, as a sum of field created by the current sources (windings, leads) with specified distribution of current. The transformer wall, comprising of LV leads are modelled for stray losses estimation.

B. Design Specifications

The tank wall is made of stainless steel. The three leads are made of copper. The phase current for is given as $10630.583<0^o$. For V winding the phase current is $10630.583<120^o$ and for U winding, the phase current is 10630.583<240. The output from the first lead is $10630.583<180^o$, for second lead is $10630.583<-60^o$ and for third lead is $10630.583<60^o$. A radiation boundary is given for the model. The leads are immersed in transformer oil. Eddy current effects are given to all the three leads. Ten adaptive passes have been selected for the analysis purpose.

C. Estimation of stray loss in Tank for Case 1.

The software tool first calculates the ohmic losses and temperature due to the LV leads at the tank surface. Only one side of tank wall is modelled along with the 3 leads of LV windings (W, V, U) for the easy analysis of the tank. Fig.4 shows the Maxwell 3D analysis of case 1 showing the ohmic loss distribution due to the stray eddy current and electromagnetic flux on the tank wall. Due to this type of lead positioning the output current through the nearby two leads will not be neutralised and hence the flux linkages on the leads and tank walls will also be high. Due to this stray flux the tank wall ohmic losses get increased causing hot spots leading to tank damages.

It is important to note that the stray losses in such structural elements are quite low but the incident magnetic field on them can be quite high for the exposed area leading to unacceptable local hot spots.

Fig.4 & 5 shows the plot of eddy ohmic loss (W/m^2) and temperature profile (cel) from minimum to maximum value differentiated by a colour band from blue to red, red being the highest. The magnetic field impinging on tank wall induces eddy currents. The magnitude of normal flux density being the highest at top and bottom winding edges, it results in higher losses and hotspots in those regions of the tank.

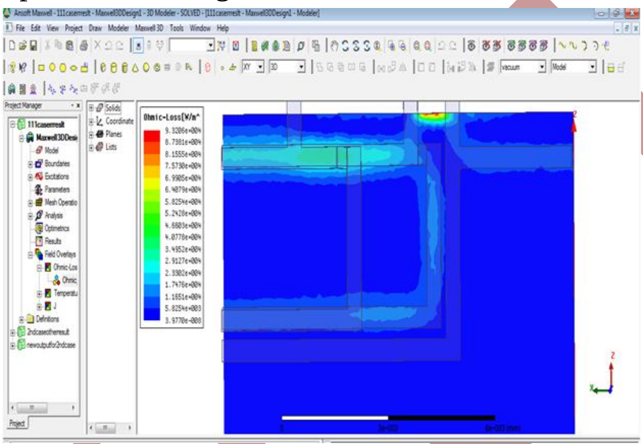


Figure.4 Ohmic Loss Distribution For Case 1.

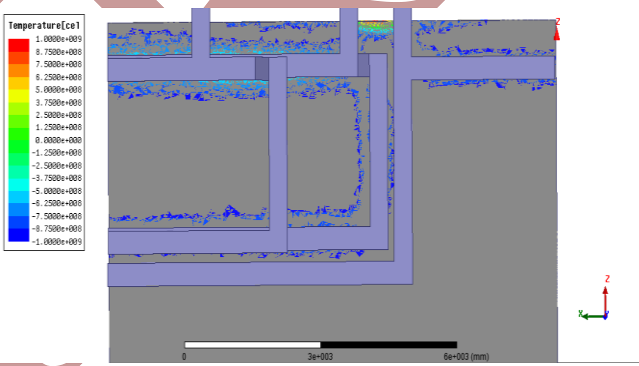


Figure.5 Temperature Profile for Case 1

Fig.6 shows the convergence plot with x axis as number of passes and y axis as energy error (%). While passing through each adaptive pass the refinement of the model takes place. The energy error has been reduced in each pass and the model converges at the 9th pass with an energy error of 0.79079.

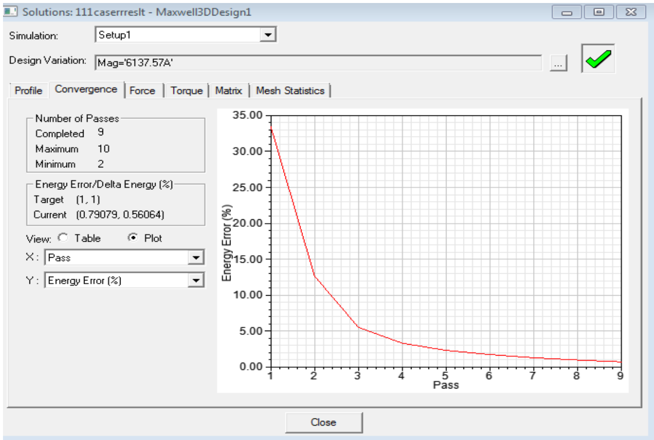
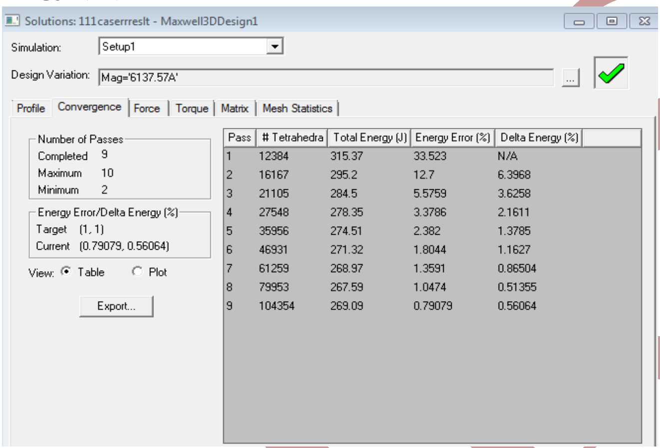


Figure.6 Convergence Plot for Case 1

Fig.7 shows the table showing number of passes, total number of finite elements or tetrahedra, total energy consumed in each pass for the refinement, energy error (%) and delta energy (%).



Pass	# Tetrahedra	Total Energy (J)	Energy Error (%)	Delta Energy (%)
1	12384	315.37	33.523	N/A
2	16167	295.2	12.7	6.3968
3	21105	284.5	5.5759	3.6258
4	27548	278.35	3.3786	2.1611
5	35956	274.51	2.382	1.3785
6	46931	271.32	1.8044	1.1627
7	61259	268.97	1.3591	0.86504
8	79953	267.59	1.0474	0.51355
9	104354	269.09	0.79079	0.56064

Figure.7 Convergence Table of Case 1.

D. Estimation of stray loss in Tank for Case 2.

Fig.8 & 9 shows the plot of eddy ohmic loss (W/m^2) and temperature rise profile (cel) from minimum to maximum value differentiated by a colour band from blue to red, red being the highest. Here in order to avoid over heating of tank wall, the leads are arranged in a different way ie modified in a different way.

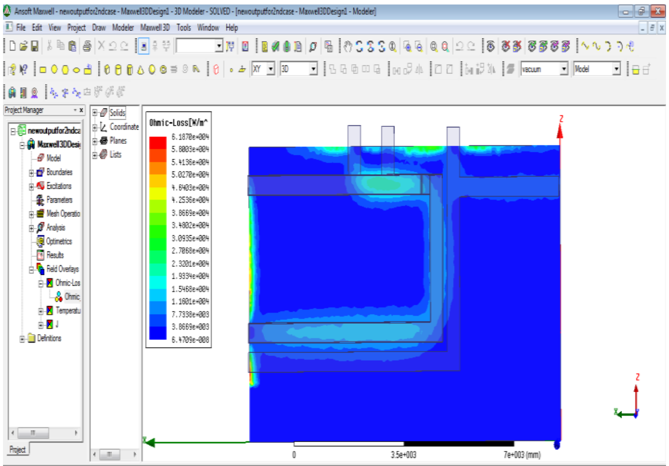


Figure.8 Ohmic Loss Distribution For Case 2.

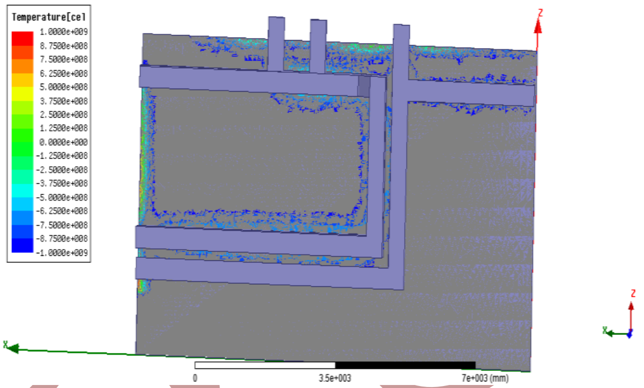


Figure.9 Temperature Profile for Case 2.

Fig.10 shows the convergence plot with x axis as number of passes and y axis as energy error (%). While passing through each adaptive pass the refinement of the model takes place. The energy error has been reduced in each pass and the model converges at the 9th pass with an energy error of 0.73963.

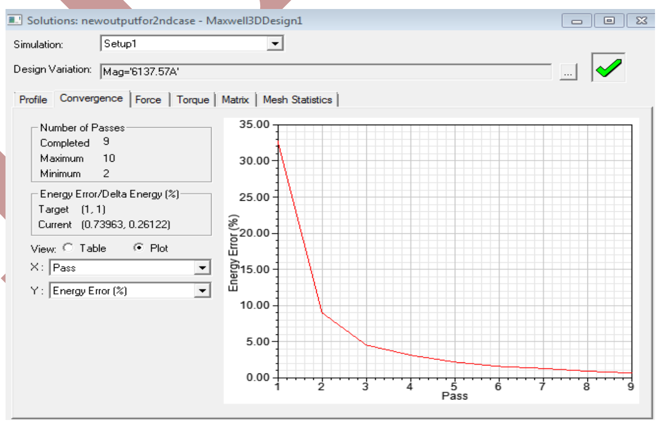


Figure.10 Convergence Plot of Case 2.

Fig.11 shows the table showing number of passes, total number of finite elements or tetrahedra, total energy consumed in each pass for the refinement, energy error (%) and delta energy (%) for case 2.

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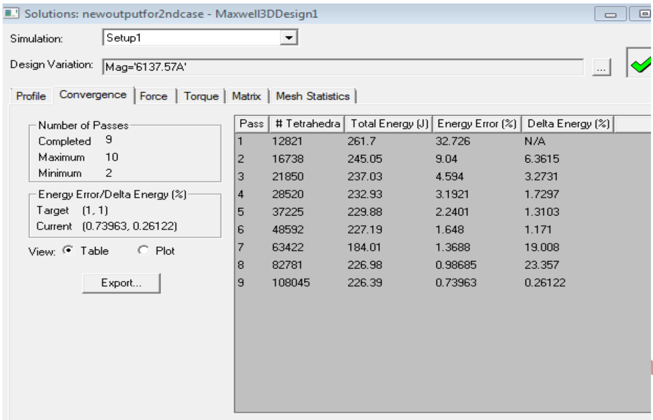

Figure.11 Convergence Table for Case 2.

E. Comparison of estimated results for case1 and case 2.

Table.1 Comparison of Estimated Results for Cases 1 and 2

description	First model	Modified second model
Ohmic losses (w/m^2)	9.3226e+004	3.0935e+004
Temperature (^{o}cel)	1.000e+009	0.000e+000
Energy error (%) after 9th pass	0.7907	0.73963
Delta energy (%)	0.56064	0.26122

From the table 1 it is clear that the stay losses have been reduced considerably thereby significantly reducing the temperature on the tank walls near the LV leads. Also energy error has been reduced for second case compared to first. Due to the reduction in ohmic losses the temperature has been reduced to nearly zero causing complete removal of hot spot.

CONCLUSION

The two models are analyzed using ANSYS MAXWELL 3D. For the first model after doing the analysis, it has shown that due to the imbalance in output current from the two leads the flux induced will produce ohmic losses in the tank surface near the two leads and also the temperature will be high there. So the 2nd model has been created, after analyzing the second model it has been shown that the ohmic losses has been reduced to a minimum value near the three leads. This is happened because of the neutralization of the 3 currents

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and hence the flux will also be neutralized. This will effectively reduce the hot spot in the tank wall.

- Proposed method can outperform and give better result.
- The ohmic loss reduction is achieved and temperature near the leads on tank wall was reduced.
- Convergence value is reduced for second model compared to first model.

So from these it is clear to conclude that the modified model (second model) is giving better results in hot spot removal than the existing model (first model).

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