“Thermal Modeling and Evaluation of Large Transformer Tank”

Major Project Report

Submitted in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

Barot Saurabh

(13MEEE02)

Department of Electrical Engineering

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

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CERTIFICATE

This is to certify that the Major Project Report entitled "**Thermal Modeling and Evaluation of Large Transformer Tank**"submitted by **Mr. Barot Saurabh (13MEEE02)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him/her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Barot Saurabh Jayantilal

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Abstract

Transformer thermal performance impacts transformer life and reliability through degradation of insulation and increased losses; hence it is a critical issue in design aspects. In previous decades maximum ratings of the large transformers were 315 MVA / 400 kV, which has increased to 500 MVA / 800 kV. As power system capacity is growing, higher rating transformers are being purchased by the utilities. On the other hand manufacturers are also kept under market pressure to optimize the design leading to large risks of failure if not properly analyzed. Thermal behavior of transformer depends on magnetic shunt provided to inner surface of tank wall, leakage flux density, viscosity of oil (which changes with temperature), physical parameters of applied materials, geometry of core and windings, type of cooling and heat transfer. Objective of this project is to reduce Hot-Spot Temperature (HST) on Tank Wall (side walls of the main tank)-Flange Bolt region (bolted joint of tank and cover) and Yoke Clamp (support for yoke beams). Due to lack of magnetic shielding and non-linearity characteristics of magnetic field, stray loss occurs in flange bolt region, which is needed to be minimized to maintain the reliability of transformer. Meanwhile the cooling of transformer will be considered to reduce the temperature of tank wall. Calculation of stray losses is complex due to non-linearity of magnetic field, inability of isolating exact stray loss components from tested load loss values.

Such calculation can also be done by Finite Element Method. FEM enhances the ability to represent transformer characteristics and performance, has been used in the work to measure temperature distribution on tank walls. Implementations of 2-D/3-D FEM analysis to a typical large generator transformer has been carried out in Ansoft - MAXWELL for the project to predict (a) eddy and stray current losses at flange bolt region and yoke clamp joints. Analysis results of Ansoft Maxwell software are imported in ANSYS Workbench software to visualize the temperature distribution at the flange bolt region and yoke-clamp joints. Results of ANSYS Workbench results have been verified by the actual values of test results of the same transformer tested in the UHV Test Lab at LTI, Alstom Grid India Ltd, Vadodara. By this work, conclusion has been derived that magnetic shielding can be provided at the flange bolt region of the transformer to bypass the magnetic field. Another conclusion for yoke-clamp has been derived that during manufacturing process of large power transformer, tightening of the yoke-clamp bolt must be check and confirmed with standards otherwise it may lead to hot-spot formation at the joints of yoke-clamps. In this thesis, physics of large transformer and its thermal model are considered for evaluation of large transformers.

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Chapter 1

Introduction

- Power system capacity is growing at higher rates compared to past few decades. It has been seen that utilities are moving towards the increased ratings of the power transmission for financial benefits and to stay in the competitive market. To fulfil this purpose, utilities are using costly higher rating power equipments. Owing to this reason, utility managers need to optimize the asset value of every power equipment. Large power transformers are expensive and play a vital role in power system network. Unexpected outage of large transformers causes long power supply interruptions which financially affects the utilities and also impacts the reliability of power supply. Manufacturers have to optimize the design of transformers to meet the requirements of customers for higher risk of failures, reduction in weight and size due to transportation constraints to stay in the competition. Smaller size of transformer leads to increased effect of leakage flux on metallic parts, which produces heat losses i.e. temperature rise beyond the tolerable limits. Local hot-spots may occur in metallic parts if the magnetic shunts and shields are not provided properly of proper ratings, vulnerability of cooling system and poor heat transfer. Accurate prediction of Hot-Spot Temperature is indeed to improve utilization of transformer as it is considered as the most influencing limiting factor of transformer loading and life.

1.1 Problem Identification

Thermal performance of transformer impacts transformer life and reliability through degradation of insulation and increased losses; hence thermal performance becomes critical issue in design and loading aspects. Design of large transformers has been restricted by means of size and transportation issues. As a result, leakage flux density increases with optimum size which induces temperature rise in metallic parts of large transformers. Owing to stray losses, higher temperature rise occurs in tank body and other metallic parts which affects the life of transformer by degradation of mineral oil, paint of the tank and by impairing the sealing system. Local hot-spots may occur in metallic parts owing to increased stray losses.

In case of bolted transformer tank and cover, leakage field and high current fields induces the current and forces the currents to complete their path through the flange-bolt region. If the circulating currents are large, hence hot-spots may occur in the flange-bolt region which reduces reliability of the transformer, i.e. it is necessary to reduce the adverse effects of leakage flux, to maintain the cooling process and to provide proper insulation in the large transformer so that heat transfer can easily take place.

1.1.1 Effects of Temperature Rise:

• Local overheating can jeopardize the properties of mineral oil and impair the sealing system.

• Deterioration of winding insulation and high current carrying conductor winding

• Degraded insulation overheating tends to produce dissolved gasses and acoustic emission.

• Acoustic emission may reduce breakdown strength of transformer mineral oil.

• Paint loss of the tank on the location of hot-spots

Figure 1.1: Paint loss owing to overheating of bolted region

1.1.2 Methods to Detect Thermal Fault:

• Fiber optic sensors - These sensors are being placed inside the transformers at different locations.

• Thermal image - Temperature of the tank wall and hot-spots and location of hot-spots can be seen by thermal camera.

• Cooler Control Cabinet - Winding Temperature Indicator (WTI) and Oil Temperature Indicator (OTI).

• Dissolved Gas Analysis - Ratio of , and indicates the level of thermal fault i.e. it indicates the temperature of the fault.

• Hydrogen Detection. [IEC 60599]

1.2 Objective

- To study and perform Electromagnetic Analysis of Generator Transformer in an Electromagnetic software (Ansoft Maxwell) in order to measure the magnetic field strength and stray losses in the metallic parts.
- To perform Hot-Spot Temperature measurement (thermal analysis) of transformer tank – flange-bolt region and yoke-clamp for tight bolts, loose bolts and shield provided bolts by FEM analysis in ANSYS Workbench.
- Correspondingly to study the modifications in tightening measures of bolts during manufacturing process of large transformer and magnetic shielding to reduce effect of stray losses in flange bolt regions that occurs due to lack of magnetic shielding in case of damaged gaskets.

1.3 Scope of Work

- Electromagnetic (EM) analysis of large transformer has been shown in various literatures, however literatures on EM analysis of regions where magnetic shunts are not provided, are few and yet EM analysis for loose bolts at yoke clamps of large generator transformer has not been carried out. Such EM analysis of flange bolt region and yoke-clamps, where magnetic shunts are not provided have been carried out in this thesis.
- Finite Element Analysis has been carried out in FEA based EM software (Ansoft MAXWELL) to observe the adverse effects of leakage field at the flange-bolt region and yoke clamp for different cases of bolts tightness.
- Magnetic shielding is provided at flange bolts after EM analysis of loose bolts at flange bolt region to reduce the magnetic flux intensity (H) in the same area which leads to reduction in hot-spot temperature rise of the flange-bolt region.

- FEA results of these three different cases of tight bolt, loose bolt and shield provided bolts have been analyzed in ANSYS Workbench in order to measure heat losses due to stray currents induced by leakage field at the flange-bolt region and yoke clamp.
- Hence the life and reliability of the transformer can be increased by reducing the adverse effects of the hot-spots to the transformer mineral oil, paint and joints.

1.4 Literature Survey

[1] M. Pradhan and T. Ramu, "Prediction of Hottest Spot Temperature (HST) in Power and Station Transformers," IEEE Trans. on Power Delivery, vol. 18, no. 4, October 2003.

- Thermal stress on a large transformer causes degradation of insulation. Transformer life mainly depends on the insulation health of the transformer. Authors have proposed a method to predict the hottest-spot temperature in the winding region of large transformer. M. Pradhan and T. Ramu worked for mathematical model of large transformer by mathematical formulations of Boundary Value Problem (BVP) for Heat Conduction Equations (HCE) for steady and unsteady condition of transformer. Heat Transfer Coefficient (HTC) calculation is done with using Nusselt number, Rayleigh number, Grassof number and Mean Nusselt number. Theoretical approach for calculation of Hottest-Spot Temperature (HST) and Top Oil Temperature (TOT) is much accurate with tests results on site measurement.

[2] J. Galvan, S. Adame, R. Perez, R. Valdez, P. Georgilakis and G. Loizos, "Reduction of stray losses in flange-bolt regions of large power transformers," IEEE Trans. on Industrial Electronics, Vol. 61, No. 8, August 2014.

- Hot-spots generated in the flange-bolt regions of large power transformer tanks are produced by the induced stray currents, flowing through bad contact between transformer tank and tank cover near the high current bushing. According to IEEE standard C57.12.10-2010, tank cover must be welded to the tank. But both can be bolted if customer specifies it. If the bolts are not tight enough, hot-spots may produce leading to degradation of transformer mineral oil and impair the sealing system, the painting of the tank and the insulation of high current conductors. To come out from this problem few solutions have been employed; (a) use of magnetic shunt, (b) use of electromagnetic shield and (c) varying the distance of LV leads to wall. Due to copper's high conductivity, Authors proposed a solution of installing bridges of copper links in the flange bolt region. This link provides a low magnetic path for stray current owing to keep the tank and tank cover at same potential. The nuts and bolts used in this technique are of non-magnetic stainless steel to reduce corrosion, ensuring good contact with walls of the tank which leads to avoid overheating of bad contact. For experimental results, this solution was performed on 420 MVA, 20/230 kV Generator Transformer in Mexico. After satisfactory operation of 9 years with periodic maintenance, hot-spots were seen at flange-bolt region due to loose connection. The proposed solution solved the overheating problem and which is verified by Finite Element Simulation also. Stray losses by 3-D numerical simulation and Temperature distribution by 3-D Steady State Thermal Analysis were calculated. To simulate a laminar free convection, a uniform convection boundary was placed at flange bolt region, bolt, nuts and washers. Here Heat-Transfer variable (h) is taken as variable and varied between 0 to 25 W/(°C) using steps of 0.001 W/(°C) until difference between measured and calculated temperature is less than 0.7. Properties and characteristics used for tank cover, LV leads, nuts, bolts and washers are mentioned in the paper. Simulation shows that if there is no loose contact between tank and cover then a loss density value of 523.9 W/ was found at flange bolt region with max. temp. of 84.47°C. In case of loose connection, a loss density value of 3393 W/ with 386.6°C temp. was detected. After installing copper link, though there was loose connection between tank and cover, a loss density value of 550 W/ with 84.84°C temp. was detected. Authors divided the tank cover in five zones and compared the measured stray current and temp. with the calculated ones. Maximum difference was of 14% and 0.6% for stray current and temperature comparison respectively.

[3] C. Guerin, G. Tanneau and G. Meunier, "3D Eddy Current Losses Calculation in Transformer Tanks Using the Finite Element Method," IEEE Trans. on Magnetics, Vol. 29, No. 2, March 1993

- Leakage flux increases with overloading condition of transformer leading to eddy losses in tank, windings and other metallic parts such as clamping beams and shields. Which causes hot-spots and overall temperature rise in transformer. As the current in the two windings have opposite signs and different values, a leakage flux exists and is considerable in these parts of the tank. Authors have mentioned two different numerical methods of two different field computational softwares named FLUX3D and TRIFOU. Verification of these methods is given by practical test results. To solve Maxwell's equations, Authors have presented a numerical method with FLUX3D programme. Formulations for non-conducting regions, conducting regions and thin sheet regions are presented for eddy current calculation. For non-conducting region Total and Magnetic Scalar Potential Method and for conducting region Magnetic Vector Potential (A) and Electric Scalar Potential (V) – AV Method with Coulomb Gauge is imposed. For thin regions, skin-depth (α) is considered for calculations. If mesh problems occur due to small α in relation to the other dimensions of the solid insulating regions, eddy current can be calculated by surface impedance for regions with a reduced skin depth. Another method of TRIFOU programme uses the magnetic field as a state variable in conducting region with edge elements. Expect this change; all calculations are as AV-method for conducting regions. Authors have shown the coupling problem of electrical circuit elements with electromagnetic ones which is solved by present. Comparing the results of FLUX3D method with tank permeability, it shows that for $\alpha > e$, results for eddy currents by Volume AV and Shell AV methods are same. In the opposite case ($\alpha < e$), results are similar only till relative permeability of the tank is 30. Afterwards the difference is due to meshing problems. Comparison of FLUX3D results with tank thickness showed that eddy losses reduces with increase in tank thickness. Both the software packages gives same results with 5% difference. By comparing all three methods of formulation, it was clean that Volume AV formulation gives good results at higher computational cost with limitation of low permeability of 30. Parametric analysis of eddy current and core permeability is shown where losses reduces with relative permeability of magnetic core.

[4] S. Ho, Y. Li, R. Tang, K. Cheng and S. Yang, "Calculation of Eddy Current Field in the Ascending Flange for the Bushings and Tank Wall of a Large Power Transformer," IEEE Trans. on Magnetics, Vol. 44, No. 6, June 2008

- The leakage magnetic field is prone to cause unequal distribution of eddy current losses which tend to overheat metallic parts of the transformer. Hence it has become important to analyse the distribution of the leakage magnetic field in metallic parts to calculate eddy current losses. Afterwards thermal analysis can be done on the eddy current loss calculation. Due to transportation constraints the size of the transformer is optimized causing more electromagnetic (EM) load density in the tank wall and other metallic parts connected to tank. EM fields tends to induce eddy losses in the metallic parts, hence these fields need to be mitigated carefully. The shield provided inside the tank wall is not very effective in reducing such fields. In this paper, 3-D open boundary eddy current fields are evaluated with Coulomb Gauge Condition by means of the Magnetic Vector Potential in the Finite Element Analysis. These vector potential equations are introduced with Boundary Condition, where the Weighted Residue equation gives the mathematical model. In the model the Uniqueness Condition is satisfied. By solving such equations the magnetic flux, eddy current and losses can be evaluated. Experimental approach with test results is shown in the paper. To solve overheating problem due to heavy leakage flux at the end windings and heavy current leads, 3-D eddy current field at every metallic part where losses are to be determined, is calculated and analysed. According to the paper, in 720 MVA / 500 kV transformer, it is found that the total loss is 1799 kW, which is the sum of the constant loss of 320.4 kW and the load loss of 1478.6 kW. Authors suggested to use the steel with low magnetic permeability instead of A3 steel for the ascending flange of the bushing. Though this makes the complex of 3-D eddy current field calculation, it reduces the losses upto 40% as compared to A3 steel plates. Local overheating problem is eliminated by this solution. In accordance to reduce the maximum flux density and maximum loss density, concept of installing the silicone sheets made Magnetic Bypass Plates (MBP) is introduced. With MBP, losses in the clamp plates tend to reduce as the EM fields are providing path for leakage field. Hence there is no local overheating in the clamp plates. In this paper authors have designed the parameters of the MBP such that it reduces the maximum loss density in the plates by 94%.

Chapter 2

Heat Transfer in Large Transformers

The Electric circuit and Magnetic circuit are two sources, which causes losses and temperature rise in the metallic parts of the transformer. Large transformers are made of optimum size due to transportation constraints and competency in market. It leads to increment in leakage flux which produces stray losses in all the metallic parts and causes heat production. Such losses, and core losses, copper losses (losses) and stray losses in windings causes heat production in transformer. These losses may create Hot-Spots in windings and metallic parts attached to the main body of the transformer. It leads to degrade the insulation and jeopardize the mineral oil properties. To maintain the transformer life as per predicted life-span, it becomes necessary to reduce the transformer temperature to maintain the quality of the insulation. For cooling and insulation, transformer mineral oil is circulated in all parts of the transformer. Heat transfer is done by mineral oil as heat transfers from higher temperature to lower temperature.

2.1 Modes of Heat Transfer

Heat transfer is done by three modes in the transformers:

Figure 2.1: modes of heat transfer

2.1.1 Conduction

Heat transfer takes place from higher temperature to lower temperature. In case of large transformer, windings and other metallic parts (i.e. Tank body, joints, yoke clamp) are of higher temperature due to the eddy and stray losses. As transformer mineral oil is at lower temperature, heat transfer takes place from windings, core and metallic parts to the mineral oil. From core and other metallic parts, heat flow takes place without any resistance. But in case of windings, heat flows through the insulation paper which has its own thermal resistance i.e. temperature drop takes place in insulation.

Temperature drop in insulation can be calculated by heat transfer equation:

$$\Delta\theta = Q * R_\tau$$

Where;

Q = Power loss in Watt (heat flow)

Rτ= Thermal Resistance (°C/W)

t_i= Insulation Thickness (m)

k = Thermal Conductivity (W/m*°C) and

A = Cross-sectional area ( )

2.1.2 Convection

Convection plays important role in heat transfer from inside of transformer. Principle of convection is: oil changes its volume, pressure, viscosity and density relation with temperature. As transformer is loaded, it starts heating in first few hours. Heat transfers takes place from windings, core and metallic parts to mineral oil due to conduction. Oil density decreases with increase in temperature. As hot oil density is lower than cold oil, it transfers toward the upward side of the transformer tank and flows into the radiators connected with the main tank. Gravity plays role in moving cold oil downwards due to greater density than hot oil. This effect is termed as 'Buoyancy Effect.' Thus, Natural Convection of oil takes place in transformer. Oil flow speed can be increased by means of Pumps. Hence it is termer as Forced Convection. Hot oil rises upwards and transfers its heat to outside ambient through radiators and tanks. The convective heat transfer is expressed by:

$$Q = h * A(T_{surface} - T_{fluid})$$

Where;

Q = Heat Flow (Watt)

h = Heat Transfer Coefficient ($W/m^{2}{}^{\circ}C$)

A = Surface Area (m^2)

$T_{surface},T_{fluid}$ are in °C

2.1.3 Radiation

Heat transfers from one medium to another in the form of waves. Conduction and convection moves the hot oil to radiators. Radiators are provided with number of radiator fins, which increases radiators contact area with ambient air. Hot oil flows in the radiator fins from upward to downward. During oil flow, oil dissipates its heat energy to the ambient air in the form of waves. Hence, cooling process takes place n radiator by means of radiation. Heat transfer by radiation is expressed by the Stephan-Boltzmann law:

$$Pr = \eta \, EA_r(T_s^4 - T_a^4)$$

Where;

η = Stephan-Boltzmann constant

A= Surface Area for Radiation (mm^2)

T_s= Average Temperature of Radiating Surface (°K)

T_r= Ambient Air Temperature (°K)

E = Surface Transfer Coefficient

2.2 Temperature Coefficient

The Temperature Coefficient refers to relative change of a physical property when temperature is changed by 1 K. Heat transfer from metallic parts depends on Temperature Coefficient of particular metal as every metal has different temperature coefficient. Temperature coefficients are of three types:

i) Negative Temperature coefficient (NTC)

ii) Positive Temperature Coefficient (PTC)

iii) Reversible Temperature coefficient (RTC)

In a specified temperature range NTC occurs if a physical property of material lowers with increasing temperature. NTC avoids local overheating problems. RTC is referred to residual magnetic flux density changes with respect to temperature. Increased resistance of metal with increase in temperature refers to PTC. Electrically coupled positive temperature coefficient resistivity polymer to one of the windings leads to provide protection over-current short circuit and thermal overheating conditions. It further reduces the spacing of electrical and thermal protection of transformer.

2.3 Heat Transfer Coefficients (HTC)

Heat Transfer Coefficient is the proportionality coefficient between transformer oil and metallic parts. As the value of heat transfer coefficient increases, convective heat transfer increases. Hottest-Spot Temperature calculation can be done by mathematical formulation of Boundary Value Problem (BVP) by Finite Henkel and Fourier Transforms. [5]. HTC calculation becomes indeed to determine boundary functions for respective surfaces, for which surface the analysis will be carried out. HTC depends on winding size, winding type, duct dimensions, oil viscosity, type of oil circulation, heat flux distribution, oil thermal properties, type of surface, type of tank applied on tank surface, tank geometry, etc. Corrections have been given for temperature dependence of the thermal and physical properties of oil, such as viscocity (µ), specific heat , volumetric expansion (β) and thermal conductivity . Some of the heat transfer empirical relations and relevant formulae in natural convection are mentioned below:

i) Local Nusselt number for laminar flow in vertical plates of the radiator banks:

$$nu_{б} = 0.6R_{б}^{0.2}$$

or

$$nu_{б} = 0.6(G_{rб}pr)^{0.2}$$

Where,$R_б$or $G_{rб}$ and are the local Rayleigh and Grassof number based on heat flux at chacteristic dimension.P_r is the Prandtl number of transformer oil.P_r is the dimensionless ratio of kinematic viscosity and thermal diffusivity.

In this case of heat transfer, P_r controls the relative thickness of the momentum and thermal boundary layers. $P_r \leq 1$ indicates heat transfer is very quick compared to oil viscosity and effective radiating surface needed is lesser. [12]

Grassof number shows the relation between buoyancy and viscosity within transformer oil. Rayleigh number is the product of Grassof number and Prandtl number. [13]

For a uniform wall heating flux, Rayleigh number is:

$$R_б = \frac{g ß \ C_p \rho_{oil}^2 q_w \delta^4}{k_{oil}^2 \mu}$$

Grassof number in natural convection for vertical plates can be computed as;

$$Gr\delta = \frac{g ß (T_s - T_a) L^3}{\mu^2}$$

where;

g = acceleration due to earth gravity

β = volumetric thermal expansion coefficient

T_s= surface temperature

T_a= ambient temperature

L = chacteristic length

μ= kinematic viscosity

ρ_{oil}= density of transformer oil (kg/m^3)

ii) Mean Nusselt Number in this case can be computed as:

$$nu_m = [1.25 nu_\delta]_{\delta=1}$$

iii) Heat Transfer coefficient (HTC) can be calculated as:

$$h_\delta = \frac{nu_\delta k_{oil}}{\delta}$$

After knowing h_m for a particular surface, temperature difference between metallic surface and oil can be found out, dividing the h_m by the heat flux through the surface. Calculation for HTC across top and bottom surface, oil temperature gradient and viscosity computation at different oil temperature have been done in existing literature. [1]

2.4 Heat Transfer in Core Structure

Transformer core is one of the active parts of the large transformer. As the core carries the most of the magnetic flux of the windings, it is tend to produce heavy eddy current in the core. If this current is not reduced, it may lead to excessive heating of the transformer. In order to reduce the effect of eddy current in core, it is made up of 'N' numbers of thin metallic sheets with very thin insulation of Lacquer (0.02 mm), Sodium Silicate (0.01-0.015 mm), Phosphate coating (0.005 mm), Magnesit (0.00 mm), Oxide layer (0.005mm) and Carlite (0.001 – 0.003 mm) [Karsai]. These sheets are insulated on one side with above insulating layers. These sheets reduces the eddy currents to flow in the whole region of the core. Hence decreased value od eddy current leads to the decrease in the temperature of the core.

Earlier, Hot-rolled sheets were used for manufacturing of cores. But after invention of Cold-rolled sheets, hot-rolled sheets were almost replaced in every transformer core manufacturing process due to their eminent benefits over hot-rolled sheets.

Benefits of cold-rolled sheets:

- Low core Loss and Magnetising power

- Core saturation increases to 2.03 T where hot-rolled sheet saturates at 1.5 T.

- Sheet thickness reduces which leads to higher stacking factor of core. Available volume of core increases upto 97%, which is 0.97 stacking factor.

(Stacking factor: It shows the available active volume of the core. If Staking factor (S.F.) is taken at 100 %, then the volume of the core will be least compared to any S.F., but it is not feasible in the manufacturing process of core. That is the reason why core is made up of several slots, so that cutting of the sheets can be done easily and material cost reduces.)

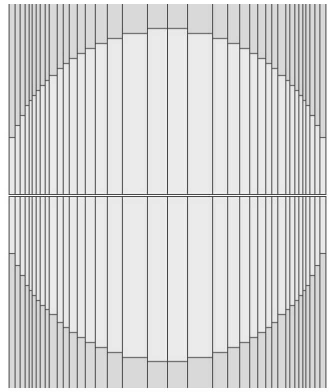

Figure 2.2: Cross Section Of Middle Core Limb

Fig. 2.2 and 2.3 shows the cross section of the core limb which is almost circular with 0.97 S.F. The S.F. close to 1 indicates that middle limb of the core structure is almost circular and consist of least CRGO material's volume in order to reduce the cost of CRGO.

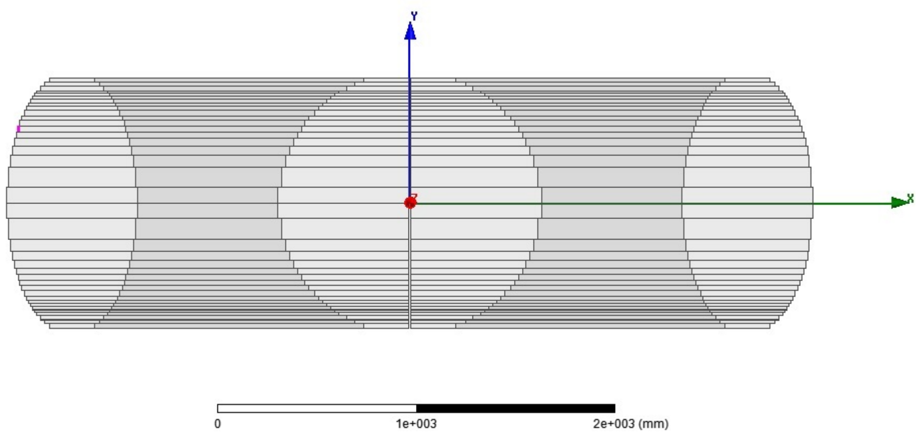

Figure 2.3: Top View of Core

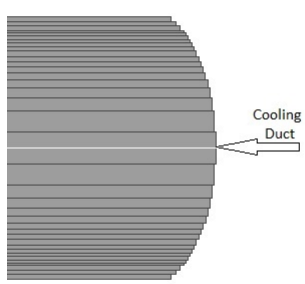

Figure 2.4: Cooling Duct in Core

Fig. 2.4 shows the cooling ducts given the manufacturing process of the core at "Alstom Grid

Ltd." Alstom has derived 0.97 stacking factor to achieve minimum volume of core. Even after using the sheets for manufacturing, eddy currents flow through the sheets and increases the temperature of core. To reduce this temperature, several cooling ducts are provided in the core for heat transfer through mineral oil.

2.5 Heat Transfer in Windings

Transformer windings are the assembly of 'N' number of turns and forms an electrical circuit related with one of the voltages specified to the transformer. The most common types of the winding coils are (a) Helical, (b) layer and (c) disk type of windings.

Now a days "elliptical" shaped windings are used in manufacturing process of windings at "Alstom Grid Ltd." to model the regulatory windings. Alstom Grid has its own Patent of the Elliptical Shaped winding, which is placed on the 3rd leg of the core in order to reduce the distance of LV winding's inner diameter to outer diameter of core limb. The reduced distance improves the impedance between LV and HV windings, which tend to increase transformers efficiency.

Copper is the most popular metal to use for windings, however Aluminium is also increasingly being used for smaller transformer windings. Large transformers of higher ratings have very high currents flowing in LV winding, which can be even more than 13000 A. It clearly indicates that load losses I^2R losses (Heating) of the large transformers have higher contribution to the total losses of the transformer. Higher values of losses leads the transformer towards the higher temperature which is not suitable for long operation of transformer.

Thus, it becomes necessary to reduce the temperature of the windings. I^2R losses are fixed for different loading conditions, hence only option to reduce temperature is to give proper cooling to the windings.

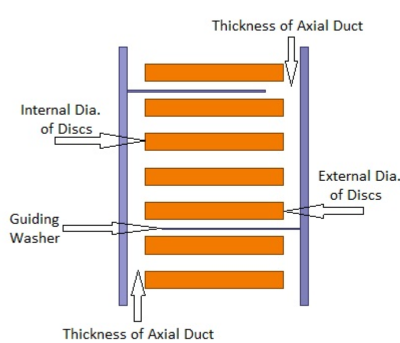

Figure 2.5: Guiding Washers and Cells in Winding

Heat transfer from winding happens due to conduction of heat between winding and oil. Fig. 2.4 illustrates the simplified cooling arrangement via oil flow by placing number of guiding washers. Guiding washers nothing but they guide oil flow in particular direction. After some number of turns one washer is placed between copper conductors, which provides only one path for mineral oil to flow through. One section of no. of conductors between two guiding washers is called a cell. Thus oil flow can be directed cell by cell as per the need of cooling. Oil enters from the bottom of the winding and then flows through the guided path only which ends at the top of the winding, which improves the cooling of windings and helps to keep the winding temperature within the limits.

2.6 Heat Transfer in Structural Parts

Heavy current flow in transformer windings gives temperature rise in terms of I^2R losses. But stray magnetic field of windings induces eddy currents in the metallic parts of the transformer, which gives local temperature rise in the metallic parts. Large transformers have high current flowing through its current carrying conductors, which results into high magnetic field strength in the whole region of transformer's geometry.Metallic parts which are made up of ferromagnetic materials, comes in the vicinity of the high magnetic field strength and induced eddy currents gives local temperature rise. Such situation doesn't occur in the smaller transformer of lesser ratings (i.e. distribution transformers).

Metallic parts like yoke clamp and flinch plates, which are near to the windings compared to tank walls, may get overheated due to eddy currents. If temperature of such parts exceeds 135°C over a large surface area, it would result in local hot-spot and degradation of mineral oil will start. Degradation of the mineral oil costs transformer its lifespan which is not desired. Hence it is advised to proper material volume for yoke clamps and flinch plates, and connecting areas which are tightened by bolts should be tight enough so stray losses stay at minimum level.

2.7 Aging of Insulations

Insulating materials are prone to degrade with lifespan of the large transformer. The mechanical, chemical and electrical properties of insulating materials (based on cellulose) are tend to modified by aging. Overloading transformer for a long period may cause damage to the properties of the insulating materials. Such degraded insulating material causes local hot-spot and if hot-spot exceeds 300°C then degraded insulation even may turns to dark gray due to overheating and starts chemical process with mineral oil. Such chemical process produces gases like CH_4, C_2H_2, C_2H_4 and C_2H_6 which jeopardize the properties of mineral oil.

2.8 Modes of Cooling

Cooling of transformer occurs by means of conduction, convection and radiation. Mineral oil is circulated in a closed path of transformer geometry via inlet pipe at bottom of transformer, windings - guiding washers, core – cooling ducts of core, yoke clamp and flinch plates, top tank and back to radiators to cool down. This circulation can be natural or forced, depends on the loading condition of transformer.

2.9 Comments

Large transformers are being made even compact due to competitive market and transportation constraints. Smaller sizes increases effects of eddy current because of higher value of magnetic flux intensity which arises due to reduced distance of windings to metallic parts.

Large transformers carries higher values of current in windings owing to their higher ratings, which leads to higher magnetic flux intensity (H) in the transformer. Higher value oh 'H' induces higher eddy currents in metallic parts which tends to increase temperature of such parts or may create the hot-spots.

Transformer lifespan directly gets affected due to temperature rise of any part. Hence it becomes necessary to reduce the adverse effects of temperature rise of metallic parts which is done by constant cooling. Cooling of transformer is done by circulating mineral oil in the entire region of transformer. Heat is dissipate by means of conduction, convection and radiation which are explained in section 2.1

Heat transformer coefficient plays a vital role in heat dissipation from any part. As the value of HST increases, heat transfer increases.

To increase rate of heat transfer several cooling ducts and guiding washers are provided in core and windings respectively. By proper speed of oil flow, heat transfer can be done efficiently during different loading conditions.

Aging of insulation plays vital role in degradation of mineral oil properties, insulation layers may get damaged due to continuous overloading of transformer for a long period.

Chapter 3

Effects of Electromagnetics in Large Transformer Tank

Power Transformers operates at a very high magnitude of current which means it consist of very high amount of magnetic field. Most of the magnetic flux passes through the closed path of the Transformer Core. But generally 14 – 16 % of the magnetic flux does not pass through the core and leaks out from the core. This magnetic flux is Leakage Magnetic Field, which induces eddy currents in the metallic parts of the transformer and produces stray losses. These losses are the main cause for the high temperature rise of the metallic parts.

Leakage Impedance plays vital role in specifications of the transformer to impact the transformer design. Physical parameters of the transformer and leakage impedance / reactance are related with each other. Leakage reactance relies on the height & diameter of windings, clearances between windings, Ampere Turn of any one winding. Leakage reactance is inversely proportional to the height of windings whereas in proportion to the other dimensions given as above.

3.1 Eddy Losses

Transformer load loss consists of eddy losses (I^2R losses) and stray losses. Increased amount of leakage field in large power transformers induces stray field in structural components of transformer. The stray flux passing trough conducting parts induces eddy currents in structural components and windings.

3.1.1 Skin Depth

Thickness of structural components and skin depth (depth of penetration) are very important parameters in describing behaviour of a structural component subjected to an electromagnetic field [3]. At a distance of one skin depth in a metal, power density comes to only e^{-2} times the power density at surface.

Skin depth can be termed as the distance at which the field penetration in a metal sheet exponentially decreases (in terms of field intensity and current intensity) to e^{-1} i.e. upto 36.8%.

Field at the surface of a good conductor decreases rapidly as it passes few skin depths in a metal sheet.

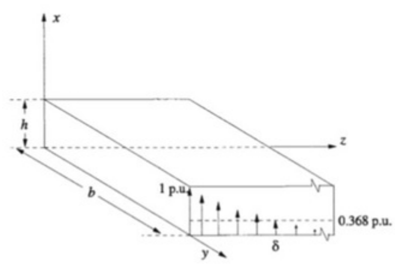

Figure 3.1: Penetration of field inside of a metal sheet

Poynting Theorem represents the law of conservation of energy applied to electromagnetic fields. In which pointing vector can be expressed as the product of source field (E) and magnetic flux density (H),

$$P = E * H$$

This expresses the instantaneous density of power flow at a point.

Total losses in the transformer tank can be predicted by integrated by specific loss in its internal surface.

3.1.2 Saturation Effect

Structural components may face saturation effect owing to leakage field and high current field near high current leads. Magnetic field saturation is considerable for calculation of eddy losses. For eddy current losses solution, step function of magnetization curve (fig. 3.2) is the easiest way to consider the saturation effect for analytical solution. It can be expressed by

$$B = (singofH)B_s$$

Where, B = flux density

H = magnetic field intensity

it is sinusoidal ($H_0 \sin wt$) at the surface. (fig. 3.3)

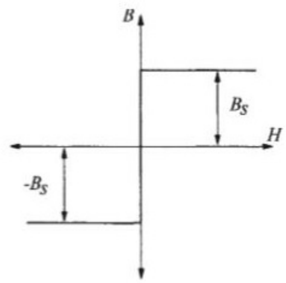

Figure 3.2: step function magnetization curve

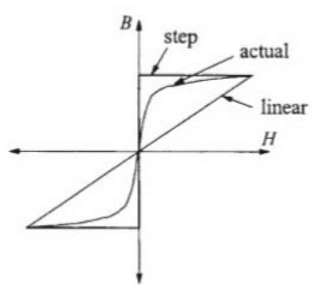

Figure 3.3: practical-linear-step characteristics of B-H curve

Here skin depth is maximum depth at the field will penetrate at the end of each half period of sinusoidal wave of H. Actual B-H curve lies between step and linear B-H characteristics. [10]

3.2 Stray Losses

Effect of stray loss is particularly sever in large auto-transformer in which actual impedance on equivalent two-winding is higher which results high value of stray leakage flux. In case

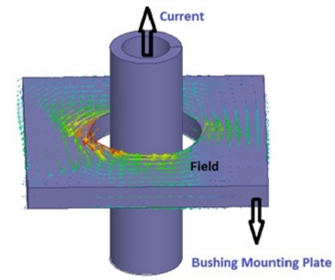

Figure 3.4: Tangential excitation_Bushing mounting plate

of generator and furnace transformer, high current carrying leads causes stray losses which results in hot-spots. These reasons may impact on transformer life and reliability if effective shielding measures are not implemented. Stray loss reduction about 3 to 5 kW facilitates a competitive advantage to manufacturing companies. Stray losses are of 20% of total load loss in large transformers. So they need to evaluated and controlled properly. If not controlled properly, stray losses increases total load loss of transformer causing its efficiency. Stray loss computation is difficult to compute because of following reasons:

- Non-linearity of magnetic field
- Difficulty in quick and accurate computation of stray field and its effects
- Inability of isolating exact stray loss components from tested load loss values
- Limitations of experimental verification methods for large power transformers

3.2.1 Factors Influencing Stray Losses

- Magnitude of the stray flux – Losses increases as the magnitude of stray flux increases.
- Frequency and Resistivity – Stray losses increases with increase in frequency of supply voltage and resistivity of structural component.
- Type of excitation – Tangential and radial excitation

As shown in fig. 3.4, the leakage field is tangential to the bushing mounting plates. Tangential field is directly proportional to the source current of high current leads. Whereas, leakage field on transformer tank wall is radial as shown in fig 3.5. In such case, for computation of stray losses, only radial component of incident field can be considered as proportional to the source current. To evaluate this tangential component, radial component of the incident field is solved by Maxwell's equations.

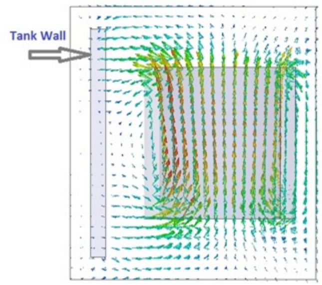

Figure 3.5: Radial excitation_Tank wall

3.2.2 Stray Losses in Yoke Clamps

Magnetic field of windings incidents on yoke clamps of yoke beams. Yoke clamps are made of magnetic steel instead of non-magnetic steel owing to difficulty to machine and cost. Stray losses in yoke clamps can be reduced by shunting yoke clamps with aluminium. Thickness of mild steel used for yoke clamps is kept small as to reduce the stray losses if the non-magnetic steel is used for yoke clamp. Stray losses can be evaluated in the yoke clamp region by Finite Element Analysis, so that the modification can be done to the aluminium shielding of the yoke clamps.

3.2.3 Heat Losses in Transformer Tank

Major part of total stray losses of transformer occurs in the main tank walls due to the large area. Radial component of stray flux gives rise to the eddy losses in the transformer tank. Hot-spots can be mitigated by the good thermal conductivity of tank wall and oil convention in the transformer.

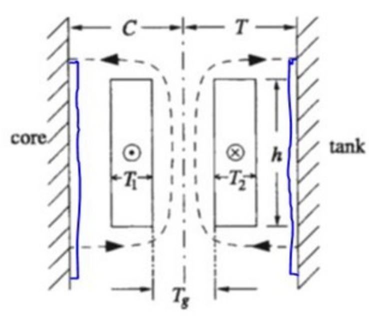

Figure 3.6: Leakage flux passing through tank walls

Where, C and T are distance of core and tank from the inter winding gap centre (T_g) To control stray losses in the main tank wall sections, magnetic shield are provided to the inner surface of the transformer. Magnetic shunts provides low impedance path to the leakage field so most of the leakage field doesn't passes through the tank walls. But as this shunt is unable to eliminate the effect of leakage flux as some amount of leakage flux passes through the tank walls. Losses in the tank can be calculated by evaluating the radial field of leakage component at every point. A much higher distance between tank and winding is required in this approach [9] to make the tank's influence negligible for interaction with magnetic flux, that is governed by the equation $T \leq H$.

3.3 Heat Losses in Flange-Bolt Region

Hot-spots generated in the Flange-Bolt region of large power transformer tanks are produced by the induced stray currents, flowing through bad contact between transformer tank and tank cover near the high current bushing. According to IEEE standard C57.12.10-2010, tank cover must be welded to the tank. If the bolts are not tight enough, stray currents flow through the loose joint causing heat losses. Hot-spot may produce leading to degradation of transformer mineral oil, high temperature of hot-spots may impair the sealing system, the painting of the tank and the insulation of high current carrying conductors.

Analysis of the temperature rise of the bolted joints between the tank and cover is an important aspect of electromagnetic field calculations. Leakage field and high current fields induces the current and forces the currents to complete their path through the flange-bolt region. If the circulating currents are large, local hot-spots may occur in the flange-bolt region.

3.3.1 Hot-Spot Formations in Flange-Bolt Region

More than 20% of the total load loss is the stray losses in the large transformer structural components. Major stray loss occurs in the main tank of the transformer. Ratings of the large transformers have been increasing during few decades. Owing to compact size of these transformers, impact of leakage flux increases on transformer metallic parts. If the joints are tight without any gap i.e. contact of tank and cover is good (fig.3.7 and 3.8), then leakage flux does not have any major impact on the flange-bolt region. If the contact is loose somehow (fig.3.9), then leakage flux passes through bad contact between transformer tank and transformer cover and induces stray current to flow in the flange-bolt region. This induced stray current circulates in flange bolt region causes heat losses. Hot-spots may exceed 400°C temperature in large transformer because of bad contact. This electromagnetic phenomenon can jeopardize the properties of mineral oil.

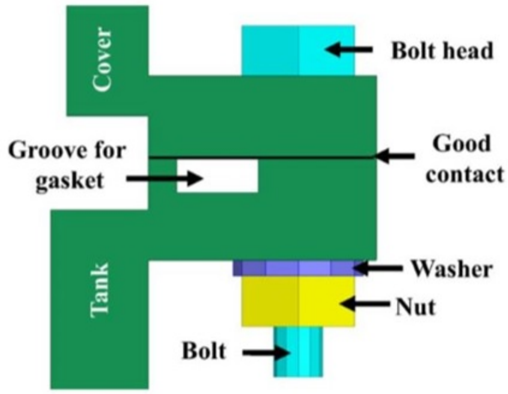

Figure 3.7: Good contact between Tank and cover

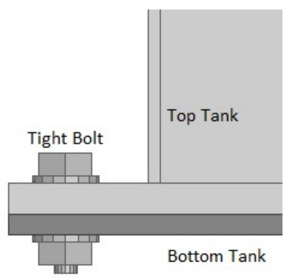

Figure 3.8: Tight Contact between Top Tank and Bottom Tank

Good contact between tank and cover (fig. 3.7) results into more than twice the reluctance of the flange-bolt set than one side of tank [18]. Furthermore, the magnetic field strength H on the surface is 1.4 times higher than the H of solid parts of the flange [18].

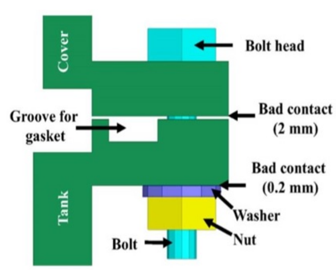

Figure 3.9: Bad contact between tank and cover

If the contact of bolt between tank and cover (fig. 3.9) is loose i.e. nitrile gasket is having a gap, the maximum limit for magnetic field strength (H) is 40 A/cm for safer operation of transformer without any hot-spot. If the H exceed its maximum limit, heat losses occurs at flange-bolt region [19].

3.3.2 Problem Identification of loose joint

• The induced currents due to leakage and high current fields may concentrate in the large cross sectional area of the flanges causing local overheating of the area, which leads to deterioration of the gaskets over a period of operational time.

• If magnetic steel bolts are used, they can increase magnetomotive force due to a bad electromagnetic contact of tank and cover, leads to greater magnetic strength on bolt surface causing high eddy current losses in the magnetic steel bolts.

• If the tank and the cover are not at the same potential i.e. ground potential, it may lead to overheating of the flanges.

3.3.3 Methods to Reduce and Avoid Heating

• In intent to come out from heating problems in flange-bolt region due to loose contact, few methods have been adopted.

i) Use of magnetic shunts [20, 21]

ii) Use of electromagnetic shields [21, 22]

iii) Varying the distance of the LV leads to tank wall [22]

• Loosening process that occurs over time in the force that holds tightly the bolt, can be avoided by using Belleville Washers. These washers have property of expansion to maintain strong connection (fig. 3.10) [2].

• Another solution can be done by providing a copper link across the loose contact of tank and cover. Configuration of given scheme is shown in (fig. 3.10). Owing to its high conductivity, copper is selected as a shorting path for the stray current which provides a low impedance path to flow stray currents. The nuts and bolts should be of stainless steel to reduce corrosion, ensuring good contact with tank wall, thus it helps to avoid overheating of the flange-bolt region.

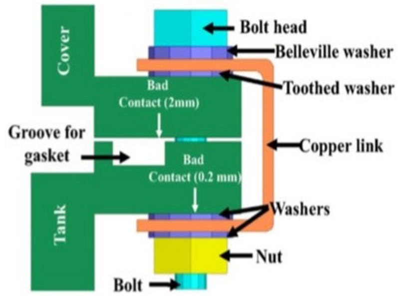

Figure 3.10: Shorting path for stray current, use of copper link

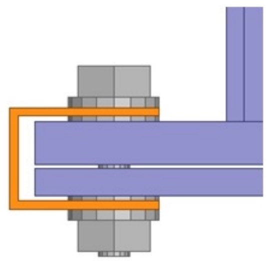

Figure 3.11: Copper link between Top Tank and Bottom Tank

Copper link provided across the inadequate contact (fig. 3.11) ensures good electrical contact between tank and its cover. Induced high current circulates through the flanges separately but if the shielding is provided, current flows from the shield and heat losses at the flange-bolt region reduces. After providing the shield, the maximum limit for magnetic field strength (H) does not exceed 40 A/cm value i.e. no heat hot-spots occurs.

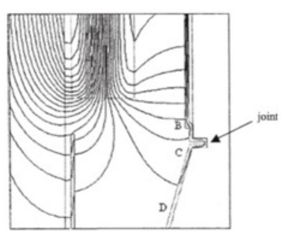

Figure 3.12: Joint between top and bottom tank

As seen from the above fig. 3.12, it is clear that a magnetic shunt is indeed to provide in the flange bolt region. Magnetic shunt provided inside the transformer tank wall ends at the flange bolt region at point B and then again a shunt is provided between point C and D. Hence, due to absence of shunt, leakage field impacts the flanges and damages the gaskets. Therefore it is indeed to provide a magnetic shunt in the flange bolt region.

Chapter 4

Finite Element Analysis of a 200 MVA Generator Transformer

- Finite Element Method (FEM) enhances the ability to represent transformer characteristics and performance. By 2D and/or 3D analysis, effective values of the potential stress, Magnetic flux density, current density, Magnetic shield directions, Ohmic losses, temperature analysis of any electrical equipment can be done.

- For a Large Power Transformer's electromagnetic shield analysis, a 200 MVA, $765/\sqrt{3}kV$ / 21 kV Single Phase Generator Transformer is considered in this work. This large transformer was manufactured in 'Alstom T & D India Ltd., PTI, Vadodara' during the year 2011. Testing of this transformer was done in the test facility available upto 1200 KV capacity at Alstom - Vadodara during May-2011. This transformer is in service since 2011 at UPPTCL, Varanasi, India.

- FEM is a well-known numerical technique and a very sophisticated tool which is widely used by researchers, scientists and engineers. In practical implications 'Finite Element Analysis (FEA)' term is used instead of 'Finite Element Method Analysis (FEM)'. Flux3D, TriFOU, Ansys, Maxwell, JMAG, MAGNET, Comsol, Opera, FEMM are well-known developers for FEM Analysis.

- Finite Element Analysis is done in Ansoft Maxwell software in which Magnetostatic and Eddy Current Analysis are performed. Magnetostatic Analysis gives information about the magnetic field intensity at a given object. Eddy current analysis gives information about magnetic field density, magnetic field intensity, potential forces, torques, shields and impedance caused by external AC currents and external magnetic shield. Finite

Element Analysis works by creating small tetrahedrons at the surface or the volume of an object. To solve the Maxwell's equation and to obtain the solutions of the set of algebraic equations, Ansoft Maxwell divides the entire object's surface into small building blocks called tetrahedrons in 3D or in 2D analysis.

4.1 Geometry of Transformer

- 200 MVA, $765/\sqrt{3}kV$ / 21 kV single phase Generator Transformer carries 9523.81 A rated current in LV winding and 452.82 A rated current HV winding. Higher value of currents causes higher value of 'H' in the transformer, so minimum distance is maintained between windings and other structural parts like yoke-clamps, flinch plates and Tank assembly in order to optimize size constraints.

4.1.1 3D Model of Generator Transformer

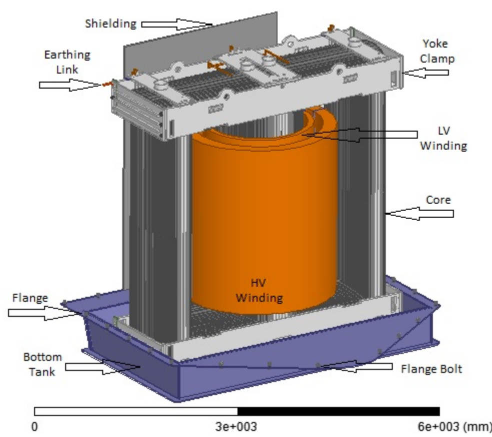

Figure 4.1: 3D Model of Generator Transformer

- Total height of the transformer tank is approx 4700 mm, width is approx 4600 mm and depth is approx 4400 mm. Shielding is provided in the LV side of the transformer. Fig. 4.1 shows the inner geometry and bottom tank of the generator transformer.

4.1.2 Yoke Clamp and Tank Walls

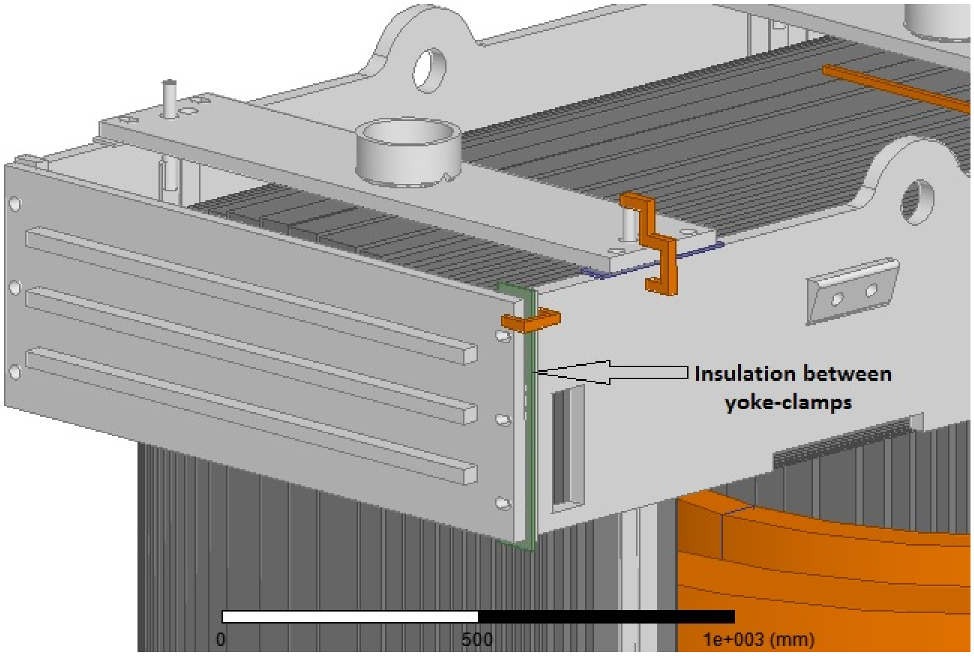

Figure 4.2: Insulation between Yoke-clamps Joints

- Yoke-clamp joints in the LV side (Fig. 4.2) are insulated by glass fiber sheets in order to open the closed path of the yoke clamp in order to prevent the current to flow in closed loop of the yoke-clamps. Thus, because of glass-fiber sheets between joints of yoke clamps, all induced current flows towards the earthing link.

- Tank Walls and yoke-clamps have been assigned Mild Steel (M.S.) which has relative permeability of 1000, bulk conductivity of $5 * 10^6\, s/m$, thermal conductivity of $45W/(m - °C)$, mass density of $7651kg/m^3$ and specific heat of $481J/(kg - °C)$.

4.1.3 Core Structure

- Core structure have been divided in four parts (described in section 4.3) and have been given cooling ducts among them. Thus core structure is electrically isolated by each other. In order to give earthing to induced currents in core, four parts of the cores are connected by one single earthing link.

- CRGO material is assigned to the core structure. Relative permeability of CRGO is 2500, thermal conductivity is $26kg/(m - °C)$, mass density of $7651kg/m^3$and specific heat of $450J/(kg - °C)$.

- In order to create the effects of laminated core, 0.97 stacking factor has been given to the CRGO material with vertical stacking direction

4.1.4 Windings

- Windings have been modelled using typical solid cylinders and copper material was given to these cylinders. In order to give excitation to these windings, one section in vertical direction has been modelled for each winding.
- Relative permeability of copper is 0.999991, bulk conductivity is $58 * 10^6 s/m$, thermal conductivity of copper is $400 kg/(m - °C)$, mass density of $8933 kg/m^3$ and specific heat of $385 J/(kg - °C)$.

4.1.5 Bolts, Nuts and Washers

- Bolts and Buts have been modelled using polygon of six sides. Length (rod) of the bolt is modelled using 16 sides of polygon. Washers for bolts have been modelled using polygon of 16 sides. The reason behind choosing polygon shape instead of circular shape is that the sides of the polygon simplifies the meshing on the region of bolt, whereas circular shape takes more time and complexity of the meshing increases.

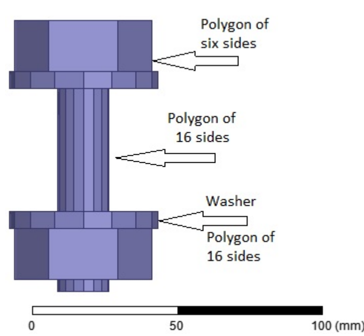

Figure 4.3: Bolt, Nut and Washer

- Stainless Steel is used to assign bolts, nuts and washers. Relative permeability of Stainless Steel is 1, bulk conductivity is $1.1 * 10^6 s/m$, thermal conductivity of $13.8 kg/(m - °C)$, mass density of $8055 kg/m^3$ and specific heat of $480 J/(kg - °C)$.

4.2 Mesh Operation

- To solve the algebraic equations, Ansoft Maxwell software performs Automatic or Manual Mesh operation on the entire surface of the object.

- Simulation of a 200 MVA, 765/$\sqrt{3}$ kV / 21 kV Single Phase Generator Transformer is done in Ansoft Maxwell. Ansoft Maxwell software first performs the mesh operation on the entire surface of the transformer to get the solution as user desire. It creates the complex mesh of the small tetrahedrons on the surface of each element, complexity of such mesh lies on the complexity of the surface of the object and user inputs for meshing.

- Maxwell software offers two basic choices for meshing initially when user gives inputs for meshing: (i) Automatic and (ii) Manual.

4.2.1 Automatic Mesh

- User can select automatic meshing for setting up basic mesh on the surface of an object.

- Automatic meshing even offers two methods for meshing:

1. **Ansoft Auto**

- Selection of Ansoft Auto mesh is the easiest way to create complex meshing on any surface. It creates simple meshing on simple surfaces / flat surface whereas it creates complex meshing where critical shaped surfaces are present.

1. **Ansoft TAU Mesh (strict mesh)**

- If user want to select particular type of meshing on particular subject and that too with very strict meshing, which much complex than any other meshing, TAU Mesh can be selected. It can be even complex if size of elements are specified by user. Number of elements can be controlled by the user.

1. **Ansoft Classic Mesh**

- Such method is the simplest and fastest meshing method of the software. It performs meshing by plotting lesser number of tetrahedrons by increasing the length of elements. Such methods saves computational time at cost of accuracy in analysis results than the results derived by strict meshing.

4.2.2 Manual Meshing

- Manual Meshing methods have number of options to improve the size and complexity of mesh as user desire. Various options have been given for curved surfaces, skin depth meshing, nos. of elements in mesh, maximum length of elements in mesh, etc.

4.3 Selection of Mesh Type

As Ansoft Maxwell offers several options to perform mesh operation on given object/objects, comparison of Ansoft Classic Mesh and Ansoft TAU Mesh has been given below.

First Ansoft Classic mesh was performed in order to visualize the difference between Mesh types.

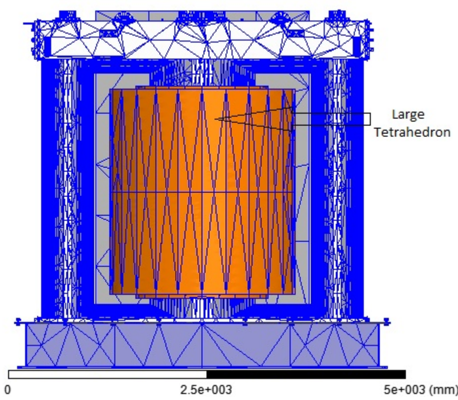

Figure 4.4: Ansoft Classic Mesh on Geometry

Fig. 4.4 shows the simple meshing method plotted on the geometry. It consist of 40000 nos. of Finite Elements (FEs).

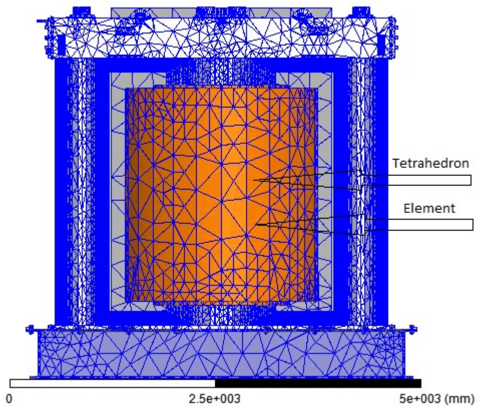

Figure 4.5: Ansoft TAU Mesh on Geometry

Fig. 4.5 illustrates the Ansoft TAU meshing method plotted on the geometry. It consist of 65000 nos. of FEs.

Table 4.1: Comparison of Nos. of FEs

Type of Mesh	**No. of Finite Elements**
Ansoft Classic Mesh	40000
Ansoft TAU Mesh	60000

Table 4.1 shows the comparison of two types. By comparing the nos. of FEs, and from fig. 4.5 it is visible that the resolution of TAU Mesh is higher on the surfaces of model than Classic mesh. Comparing these results, Ansoft TAU Mesh has been selected to perform the further analysis in the software.

As seen from the fig. 4.5, Meshing operation in the software has been done in such a way that accurate results can be derived, i.e. mesh resolution is higher where surfaces are critical (like Bolts, Yoke-clamps sides)

A surface, where resolution is not much high, mesh operation is tolerable i.e. tetrahedron size (or element length) is comparatively larger than the critical surfaces' mesh tetrahedron size (or element length). Critical surfaces like curved surfaces, strict meshing is done so that the results on these surfaces remain in large resolution.

Software also provides the advantage of duplicating the mesh on the duplicated/dummy objects in the software i.e. if any object is repeated in the model which is of same dimensions (ex: core parts and bolts), then in order to save the computing time; mesh can be copied from the main object which duplicated in the software to different co-ordinates in the model. Though mesh is duplicated/copied on other dummy objects. Here one point should be noticed that simulation/analysis is always done separately for all duplicated objects because effect of magnetic field will differ from point to point in the model.

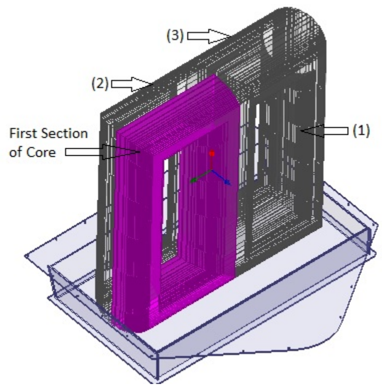

Figure 4.6: Duplicate Objects of Core Structure

To take advantage of such 'Duplicate Mesh' option, core is divided into four parts as shown in fig. 4.6. Only the highlighted part (First section of core) shown in the fig. 4.6 was imported from CAD file of the core structure, another three parts (1), (2), and (3) were duplicated in the Ansoft Maxwell software in order to duplicate/copy the mesh of the imported part to the duplicated parts of the core structure. Three parts have been duplicated in such a way that cooling ducts of the core doesn't get affected and the active volume of the core model remains same according to the actual core. Same process was has been performed on the bolts of the flanges. One bolt was modelled in the MAXWELL and then 24 other duplicates were created.

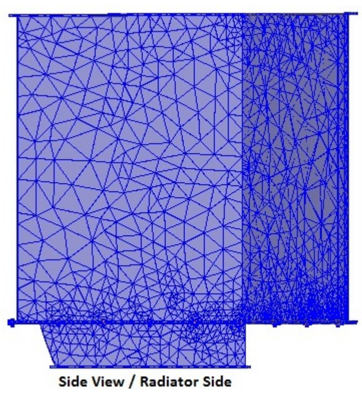

Figure 4.7: Mesh Operation On tank Wall

Whereas, tank wall surfaces (Fig. 4.7) are flat in this case, tetrahedron size is comparatively larger than complex surfaces. Though for more accurate results, mesh size can be refine upto desired level.

4.4 Analysis

Eddy Current Solution uses Adaptive analysis in Ansoft Maxwell as mentioned in [27].

While Adaptive Solution is in progress, initial mesh is solved by system iterations in order to improve the accuracy of the solution where high resolution of error is possible.

Adaptive analysis is performed in several steps:

A field solution is generated by Maxwell Software by using specified/automatic mesh. Accuracy of the solution is determined by the %Error factor in the analysis setup.

Accuracy can be derived by adding 'Maximum Number of Passes' and 'Refinement per Passes'.

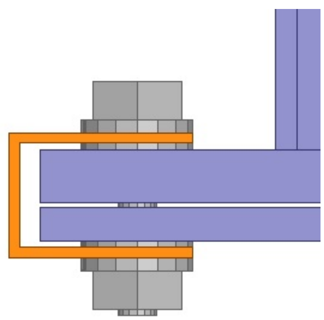

Figure 4.8: Flow Chart for Mesh Generation

As seen from the flowchart (Fig. 4.4), Maxwell Computes the fields by iterations until %Error lies within a specified range. As the stopping criteria are met by the solution, Maxwell gives output to user.

4.5 Simulation Results

Large Transformer Ratings:

Rated Power: 200 MVA

Rated Voltage: $765/\sqrt{3}$ kV (HV), 21 kV (LV)

Rated Line Current: 452 A (HV), 9523.81 A (LV)

Single Phase Two Winding Transformer, 5 Taps on HV Winding

Max Temperature Rise over an Ambient of 50°C of Top Oil: 40°C Max Temperature Rise over an Ambient of 50°C of Avg. Winding: 45°C

Impedance without Regulating Winding at 200 MVA: 15%

In case of a Large Transformer, due to high value of leakage reactance, leakage field intensity increases to higher extend. This causes large amount of eddy currents to flow through metallic parts. As a result, temperature of these parts rises in proportion to eddy currents.

In case of Large Generator Transformers, high current owing through current carrying leads causes temperature rise and Hot-Spots, which directly affects the lifespan of the transformer.

Hence, it becomes necessary to understand the behaviour of the Electromagnetics inside the transformer. Owing to this reason, a 200 MVA Large Generator Transformer is simulated in Ansoft Maxwell software.

A current excitation of 9523.81 A is applied to LV winding which is having 43 nos. of turns.

Analysis Setup: Maximum nos. of Passes: 10

Percent Error: 1

Refinement per Pass: 30%

Simulation has been divided in to two parts:

1. Flange-bolt region Analysis
2. Yoke-clamp Joint Analysis

Flange-bolt region has been performer for three different cases name as Case 1, Case 2 and Case 3. Case 1 is for good connection between top tank and bottom tank via tightly connected bolt, whereas in Case 2, a loose connection between top tank and bottom due to loosening of bolt is simulated. Case 3 is simulated for solution of shielding of loose joint via a copper link.

Yoke-clamp joint analysis is carried out in different case named as Case 4 and case 5. Case 4 is for tight connection between plates of the yoke-clamps. Case 5 is simulated to measure increased magnetic flux intensity (H) due to loosening of bolt between joints.

4.6 Case 1: Tight Connection Between Top Tank and Bottom Tank

Case 1 is simulated for tight connection between top tank and bottom tank (i.e. no gap between top tank and bottom tank) via a tightly connect bolt of stainless steel.

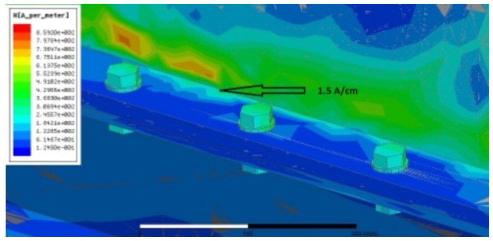

Figure 4.9: Field Intensity at Flange Bolt Region for Case 1

Fig. 4.9 shows the Magnetic Field Intensity (H) of 1.5 A/cm in the flange bolt region whereas H is higher in the Bolts made of stainless steel. Bolts are modeled in Maxwell which have length of 96 mm, radius of 18 mm, nut diameter of 48 mm, nut height of 18mm, washer radius of 52 mm and washer height of 6 mm.

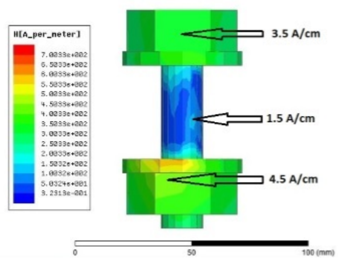

Figure 4.10: Magnetic Field Intensity at Bolt for case 1

Fig. 4.10 shows the Magnetic field Intensity of 1.5 A/cm in the length of the bolt whereas 4.5 A/cm in the nut of the bolt. If stainless steel bolt crosses Magnetic Field Intensity (H) beyond 40 A/cm, it starts heating and temperature increases at high value [2]. In current Case-1, bolts are tight enough between Top and Bottom tank, hence it has lesser value of H that critical value for heating. Which means when bolts are tightly connected, value of 'H' remains in the tolerable range i.e. less than 40 A/cm and no overheating takes place.

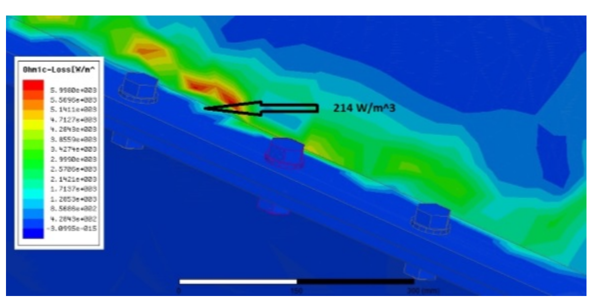

Figure 4.11: Ohmic Losses at Flange-Bolt Region for Case 1

Fig. 4.11 shows Ohmic losses in the flange bolt region for case-1. Maximum Ohmic loss in the flange bolt region is 214 W/m3. Hence temperature of the flange bolt region stays within limits and doesn't overheat due to excess loss.

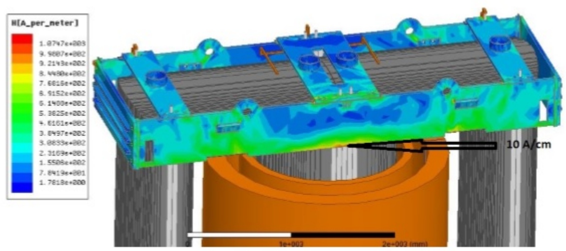

Figure 4.12: Magnetic Field Intensity at Upper Yoke Clamp

Fig. 4.12 shows the magnetic field intensity distribution at the Upper yoke clamp of the transformer. Maximum flux Intensity (H) reaches up to 10 A/cm in the middle of the yoke clamp.

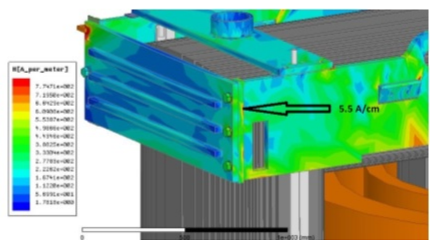

Figure 4.13: Magnetic Field Intensity at Upper Yoke Clamp Joint

Fig. 4.13 shows the magnetic field Intensity (H) in the bolted region of yoke-clamp. In scenario of the case-1, maximum H is 5.5 A/cm which tends to keep the temperature of the bolted region within the limits.

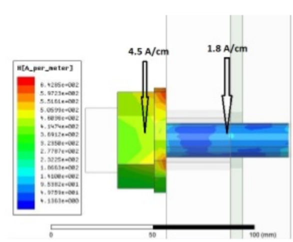

Figure 4.14: Magnetic Field Intensity at Yoke Clamp Bolt

Fig. 4.14 shows the Magnetic Flux Intensity in bolt of left upper yoke-clamp. H in the length of the bolt is 1.8 A/cm and 5.5 A/cm in the nut of the bolt. Both of these values of H are within the limits. Hence no temperature rise occurs.

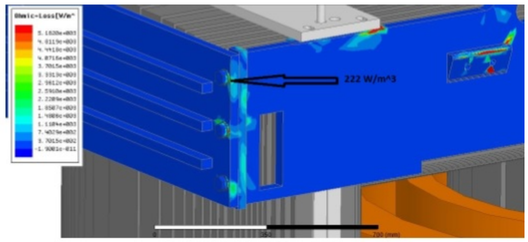

Figure 4.15: Ohmic Losses at Yoke Clamp Plate Joint

Fig. 4.15 shows the Ohmic losses in the joint of the left yoke-clamp plate. In scenario of case-1, maximum value of Ohmic losses is 222 W/m3.

4.7 Case 2: Loose Connection Between Top Tank and Bottom Tank

Simulation has been carried out for loose connection of the bolt between top tank and bottom tank. For simulation purpose, a 2 mm gap was introduced in the flange bolt region of the transformer, i.e. loose bolt condition was simulated.

Results shows the tremendous increase in the Magnetic Flux Density (H) which crosses 90 A/cm. If stainless steel bolt crosses H of 40 A/cm, then it starts heating. In case-2,

A very high value of H was seen which induces temperature rise in the flange bolt region. According to [2], temperature crosses 300°C which is very high from the limiting values.

Same analysis was carried out on the bolts of the yoke clamp with a gap of 2 mm to simulate a loose joint between clamping plates. Maximum value of H occurred of 50 A/cm which crosses the limit of the stainless steel bolt, i.e. it tends to temperature rise of the bolt.

4.8 Case 3: Magnetic Bypass Between Top Tank and Bottom Tank.

A copper link has been used to provide magnetic bypass in the flange bolt region to the loose bolts. As copper link provides low reluctance path, most of the magnetic field passes through the copper links instead of the stainless steel bolts. Due to this reason, Magnetic Field Intensity (H) at the surface of the bolts reduces and hence overheating can be reduced.

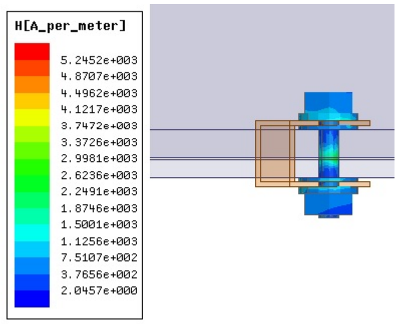

Figure 4.16: Magnetic Field Intensity in the Flange-bolt for Case 3

As seen from fig. 4.16, due to copper link, magnetic field gets bypassed from the stainless steel bolt and Maximum magnetic Field Intensity (H) comes around 30 A/cm in the stainless steel bolt. The value of 'H' doesn't crosses the limit and stays within limits. Hence, overheating of bolt doesn't occur and hot-spot temperature can be reduced to Case 1's bolt's temperature.

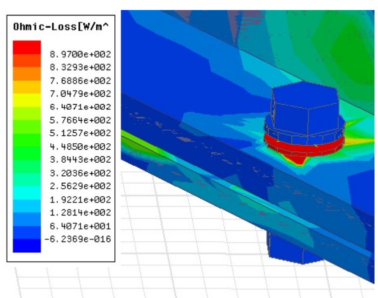

Figure 4.17: Ohmic losses for Case 3

Hence, after simulation results of case 3, it has been seen that the value of 'H' and 'Ohmic losses' remains in limit so that overheating can be avoided in the flange bolt region for case 3.

4.9 Comments:

- It has been seen that for case 1, when bolts are tight enough between metallic plate, magnetic flux intensity (H) doesn't crosses it's limits of 40 A/cm to start overheat.
- Hence no critical hot-spot has been found for case 1.

- While in Case 2, the Value of 'H' crosses it's critical limit for overheating and reaches upto 90 A/cm, Which is much greater than 40 A/cm. Thus, overheating in the flange bolt takes place due to high rush of eddy currents in the stainless steel flange-bolts.
- To overcome the problem of case 2, a magnetic bypass of copper can be connected to the bolts, which permits magnetic flux to pass through them and the value of 'H' decreases to tolerable limits. Thus overheating in the flange bolt region can be avoided and the adverse effects of overheating can be prevented.

Conclusion

- Magnetic Flux Intensity (H) increses if connection between two metallic parts is loose. In this work, Case 1 is with good contact between top tank and bottom tank and flange-bolt have maximum 'H' of 4.5 A/cm at the surfaces. If value of 'H' crosses 40 A/cm value then stainless steel starts overheaating.

- While in Case 2, maximum value of 'H' comes to 90 A/cm which is much higher than critical value, which leads to overheating of the bolt upto 300 °C . Hot-spot of 300 °C may jeopardize the sealing system and paint of the tank as shown in fig. 1.1

- A magnetic link can bypass the magnetic field from the stainless steel bolt in case 2. Case 3 consist of such analysis with a copper link provided as a magnetic link to bypass magnetic field from the loose stainless bolt. Thus magnetic field intensity has been reduced to 30 A/cm in case 3 which leads to temprature reduction in the flange-bolt area.

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Standards: • IEEE Standard C57.12.10-2010 • IEC 60076-1 – Power Transformers - General • IEC 60076-2 - Temperature rise for liquid-immersed transformers • IEC 60599 – Gas In Oil Analysis