Journal of Energy

VOLUME 63 | 2014

journal homepage: http://journalofenergy.com/

Saravanan Selvaraj
Crompton Greaves Ltd. India
Saravanan.Selvaraj@cgglobal.com

Dr. Ronny Mertens
CG Power Systems. Belgium NV
Ronny.Mertens@cgglobal.com

Geert Caluwaerts
CG Power Systems. Belgium NV.
Geert.Caluwaerts @cgglobal.com

Mahesh B. Varrier
Crompton Greaves Ltd. India
Mahesh.Varrier@cgglobal.com

Rafiq Mathersa
Crompton Greaves Ltd. India
Rafiq.Mathersa@cgglobal.com

INVESTIGATION OF IMPACT OF MAGNETIC SHUNT PARAMETERS ON TEMPERATURE DISTRIBUTION IN TRANFORMER TANKS

SUMMARY

A set of reduced order models are developed to validate finite element based calculation of temperature distribution in solid and laminated magnetic structures in transformers with high current carrying conductors. Model details, measured and calculated losses and temperature of the models are presented. Effect of magnetic shunt type and its alignment with respect to stray flux direction on temperature distribution in the reduced order model are analyzed.

The magneto-thermal coupled field analysis methodology is applied to estimate the temperature distribution in Multi-Utility transformer, showed temperature higher than expected. Different cases of tank cover plate with electromagnetic shield , thicker magnetic shunts, and with non magnetic cover plate are analyzed to reduce the temperature.

With the modified shunt arrangement, the transformer passed the test as temperature were reduced by 100˚C.

Key words: Transformer, HCCC, Stray losses, Magnetic shunts, FEM, Magneto-Thermal.

1. INTRODUCTION

Magnetic leakage flux emanating from the windings closes through tank and core clamps. Stray field from heavy current carrying conductor (HCCC) distributes along its length and passes through the magnetic structures [1]. As the rating of the transformer increases above 150 MVA, the magnetic leakage field strength increases proportionately [2]. This not only increases losses but also leads to local hot spots and hence shortens insulation's life. In transformers like furnace transformers, generator transformers, multi-utility transformers, excessive temperature rise can occur as a result of stray fields from HCCC. Magnetic shunts and electromagnetic shields are used to reduce the losses in core clamping structure and transformer tank. To reduce eddy current losses generated by field of constant flux i.e. winding leakage flux, magnetic shunts are widely used. The losses generated by field of constant excitation i.e. field from HCCC, can be reduced by (a) changing to non magnetic material (b) using magnetic shunts and (c) using electromagnetic shields [1]. The magnetic shunt parameters like arrangement, geometry and placement has to be selected carefully otherwise it may increase temperature of tank portions in between the shunts and also near its ends. For optimal selection of those parameters, prediction of magnetic flux distribution in the solid and laminated magnetic structures are vital. For accurate estimation of magnetic flux distribution in solid magnetic structures, nonlinear surface impedance formulation (SIBC) is widely used [8,9] and is incorporated in most of the commercial FEA packages. Modeling of magnetic shunts and electromagnetic shields using Finite Element Software are explained in [4,7].

In this research, to improve the accuracy of Finite Element Calculations with magnetic shunts, experiments are done with a reduced order model representing magnetic structures in stray field from HCCC. The influence of shunt parameters on losses and temperature rise in the magnetic plate are tested. Based on the results, an accurate magneto-thermal coupled field analysis methodology for calculating temperature rise in magnetic structure is developed.

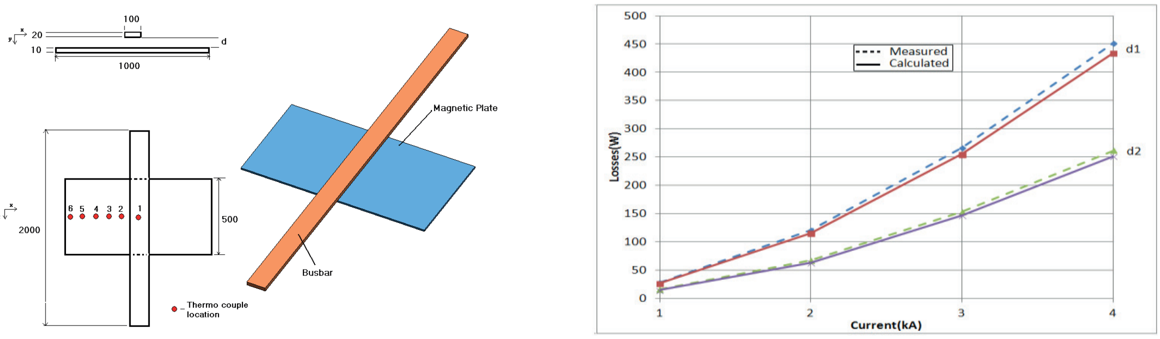
With that improved calculation methodology, temperature distribution in cover plate of a 440 MVA multi-utility transformer is evaluated

2. ANALYSIS METHODOLOGY

For a realistic simulation of the magnetic field distribution in magnetic structures in transformer, the computer model needs to be validated with experiments. Due to difficulties with measurement in power transformers, reduced order model representing different phenomena in transformer are widely used [3,5,6]. Such models for verifying the stray fields from HCCC are developed . To improve accuracy of calculations , properties of the Mild Steel plate and M4 grade CRGO steel sheets are measured using Electrical Steel Tester from BROCKHAUS Measurements and are used in FEA. For electromagnetic calculations and coupled field magneto thermal calculations, MagNet software and ThermNet software are used. In this section, experimental validation of calculation of temperature distribution in solid magnetic structures and laminated magnetic structures are discussed.

2.1. Bus bar- Magnetic Plate Model.

In first set of experiments, losses generated in MS plate due to magnetic field generated by copper busbar is measured. To ascertain repeatability of loss measurements, the tests are conducted at various current (1 kA- 4 kA) in the busbar and at various distances between bar and plate. Figure 1a shows the geometric details of the model. The losses in the plate is measured based on the procedure mentioned in [5]. Temperature distribution on surface of the plate is measured using Type J Thermocouples and position of the thermocouples are also shown in Figure1. Six thermocouples are fixed on MS plate and three thermocouples are used for measuring ambient temperature. Temperature is measured at regular intervals (≈30 minute) upto steady state condition.

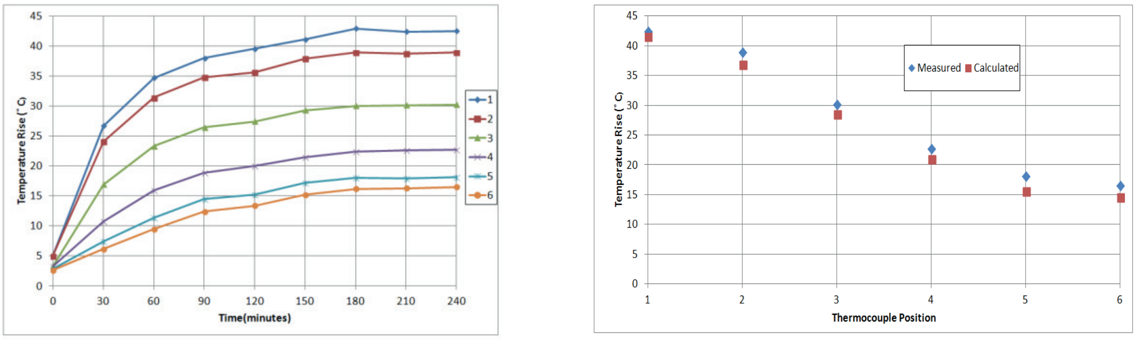


(a) (b)

Figure 1. (a) Bar Plate model; (b) Comparison of Plate Losses

The eddy losses generated in the MS plate are calculated using non linear SIBC. Figure 1b shows the variation of the plate loss with the current and distance. Also it is clear that the calculated values are in close agreement with measured one. As shown, the losses increases squarely proportional with current flowing in the bar and to $d^{-0.5}$, where d is the distance between the bar and the plate. These data reconcile the curves published in [10].

For temperature calculation , thermal analysis of the MS plate is coupled with magnetic field analysis. In the magnetic field analysis, the eddy losses are calculated by considering the temperature dependent resistivity of MS plate. Heat transfer in the MS plate is caused mainly by natural convection and radiation. For MS plate, natural convection heat transfer coefficient (h) is calculated using the dimensionless natural convection correlations. Figure 2a shows the temperature at the thermocouple locations with respect to time . Temperature of the MS plate reaches steady state after 3 hours. Temperature is highest in the portion of the MS plate closest to the bar and in this arrangement it decays to minimum beyond a distance of about 300 mm. Since the analysis is done with approximate h values, the calculated temperatures are slightly lesser than the measured one.



(a)

(b)

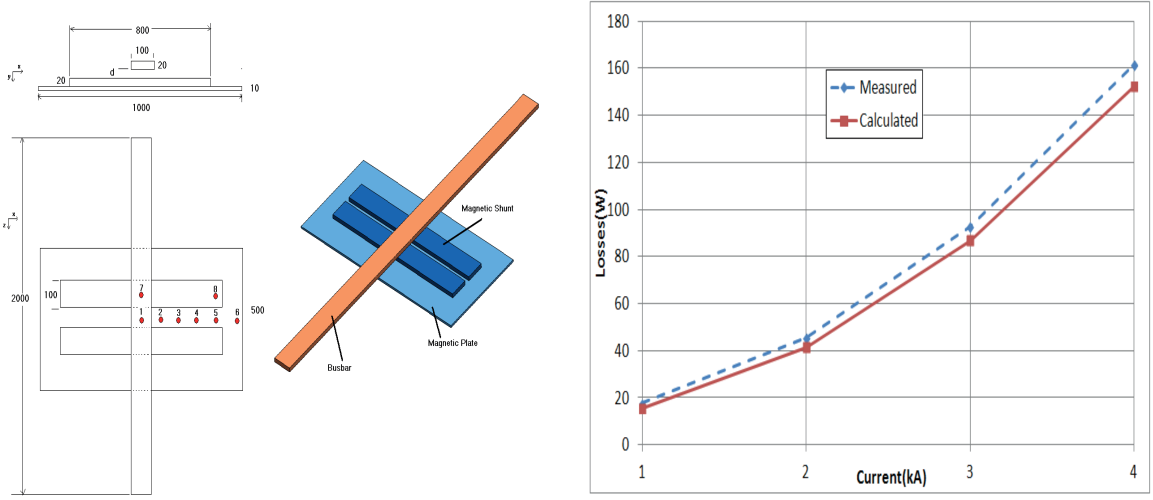
Figure 2. (a) Temperature rise at Thermocouple Positions; (b) Comparison of Temperature rise

2.2. Bus bar- Magnetic Plate and Magnetic Shunt Model.

In second set of experiments, losses generated in MS plate, shielded with width wise magnetic shunt , due to magnetic field generated by copper busbar is measured. To ascertain reduction of plate losses, losses generated in the magnetic shunts are measured separately. Figure 3a shows the geometric details of the model.

Temperature distribution on surface of the plate is measured using Type J Thermocouples and position of the thermocouples are also shown in Figure 3a. Apart from six thermocouples in MS plate, two thermocouples are placed on top surface of magnetic shunt. Temperature is measured at regular intervals (≈30 minute) upto steady state condition. The laminated magnetic shunts are modeled as a homogenous volume having anisotropic permeability and conductivity. Figure 3b shows variation of the plate loss with current. Also it is evident that calculated values are in close agreement with measured one. By comparing Figure 1b & 3b,it is apparent that the magnetic shunts significantly reduces (≈65%) losses in the magnetic plate.

Thermal analysis is done similarly as explained in the previous section. For magnetic shunts, natural convection heat transfer coefficient is calculated separately and thermal conductivity is calculated based on its volume ratio. Figure 4a shows the temperature at the thermocouple locations with respect to time. Temperature of the MS plate and magnetic shunt reaches steady state after 3 hours.

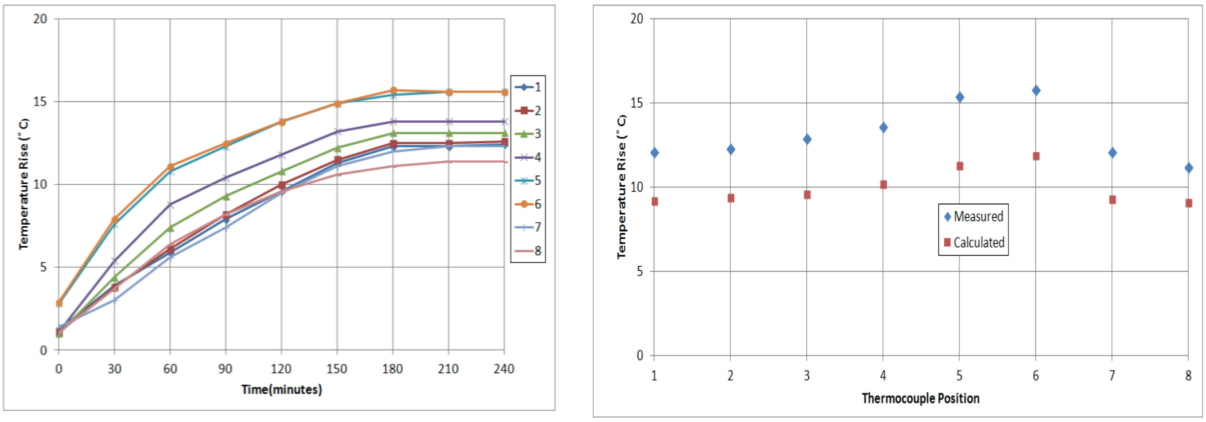


(a)

(b)

Figure 3. (a) Bar Plate Shunt model; (b) Comparison of Plate & Shunt Losses

In contrast to Figure 3a, temperature is lowest in the portion of the MS plate closest to the bar and in this arrangement it increases to maximum near the ends of the shunt. Whereas in the magnetic shunt, temperature is maximum near the busbar and minimum at its ends. This is due to the eddy currents generated in the top laminations. From Figure 2b &4b, it is evident that with magnetic shunts, hotspot temperature in the MS plate is significantly reduced (≈40%). Since the analysis is done with approximate h values and shunt model, the calculated temperatures are lesser than the measured one.



(a) **(b)**

Figure 4. (a) Temperature rise at Thermocouple Positions; (b) Comparison of Temperature rise

The discussion in this section demonstrates the validity of the analysis methodology for temperature distribution in the magnetic structures.

3. RESULTS AND DISCUSSION

3.1. Effect of Magnetic Shunt Type & Alignment.

Based on the arrangement, the magnetic shunt type is referred as width-wise or edge-wise when plane of laminations is parallel or perpendicular to the tank wall respectively. As mentioned in [11], effectiveness of widthwise shunts are lesser than edge wise shunts due to its lower effective permeability. Also significant reduction of stray losses in 360 MVA/500 kV transformer with edge wise shunts is [2].But in both the cases, stray losses due to winding leakage flux is considered and electromagnetic shield is recommended for field from HCCC [11]. Since usage of electromagnetic shield for reducing losses due to HCCC is not economical , mainly magnetic shunts are used in large power transformers.

Apart from the shunt type, alignment of shunts with respect to leakage flux direction is also important parameter. Hence for checking sensitivity of shunt type and its alignment direction on temperature distribution in magnetic plate, model shown in figure is analyzed using the methodology discussed in previous section. In figure 5a &5b, the magnetic shunts are aligned parallel & perpendicular to magnetic flux direction respectively.

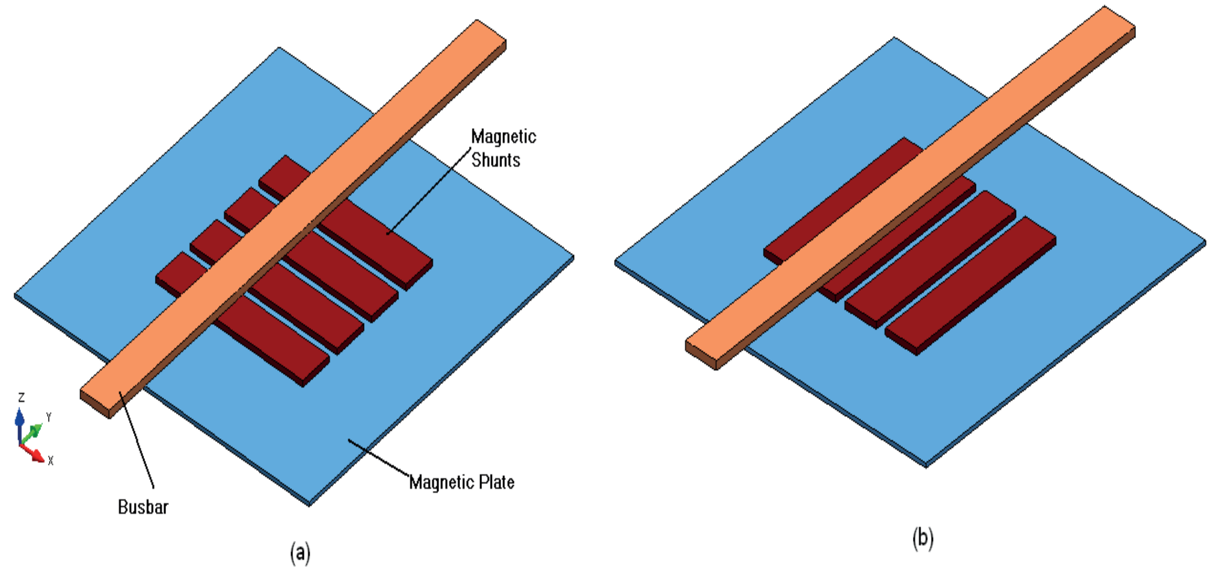


Figure 5. (a) Bar plate with parallel magnetic shunts; (b) bar plate with perpendicular magnetic shunts

Table 1.Effect of shunt arrangement of losses and temperature

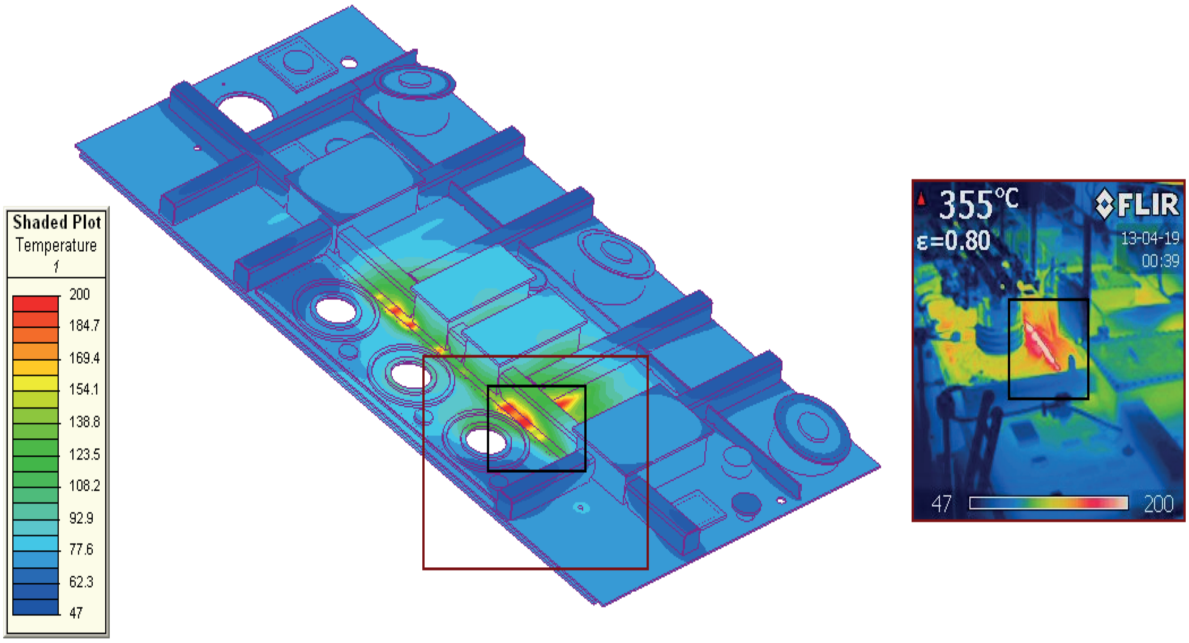
Configuration	**Plate losses (W)**	**Maximum loss density in plate (kW/m^2)**	**Maximum temperature in plate (˚C)**
Without shunt/shield	464.3	1.8	67.3
Width wise Parallel	230.1	2.8	46.8
Edge wise Parallel	256	2.4	52.3
Width wise Perpendicular	341.6	3.1	57
Edgewise Perpendicular	476	1.9	76

For each configuration, losses, loss density and temperature in the magnetic plate are calculated and reported in Table 1. It manifest that the shunts, particularly edgewise shunts, kept perpendicular to leakage flux direction results in higher losses and hotspot temperatures. In width wise perpendicular case, the maximum temperature is observed between the shunts because of maximum incident flux in those regions. In remaining cases it is observed near the shunt ends.

3.2. Case Study.

Multi-Utility transformer is typically designed to accommodate various load connection configurations and various output voltage requirements. Multiple Go-Return Busbars are connected to the Low Voltage winding circuitry to achieve these requirements and excessive losses are generated in the magnetic structures in vicinity of these HCCC.

In this particular transformer, the HCCC are placed above the active parts and are closer to cover plate. Based on the incident flux density on the cover plate, magnetic shunts are designed and attached to the cover plate. During heat run test, the transformer is failed due to extreme hotspots on the cover plate. In order to troubleshoot the hotspot issues, initially stray flux distribution and temperature distribution in the cover plate are calculated without magnetic shunts and with magnetic shunts. Figure 6 shows comparison of calculated and measured temperature distribution in the cover plate. In the portion of the tank between shunts and near its ends higher temperature is observed. Basis for these excessive temperature can be appreciated from the results from previous part of this section. It is obvious that analysis methodology calculates temperatures close to measured one.



(a) (b)

Figure 6. (a) Temperature distribution in cover plate; (b) Thermo graphic

Then various alternatives viz. nonmagnetic cover plate, copper shields, magnetic shunt with higher thickness etc.. are analyzed to reduce the hot spot temperature . From these , a cost effective & feasible solution is selected and is implemented in the transformer cover .

Temperature distribution on the cover plate calculated with modified shunt arrangement is shown in Figure 7. By comparing Figure 6a &7 , it is clear that significant reduction (100˚C) of hotspot temperature is achieved with the modified shunts. Finally the transformer is tested with modified shunt arrangement and it successfully cleared the heat run test. It is observed that the measured temperatures are well below the guaranteed values.

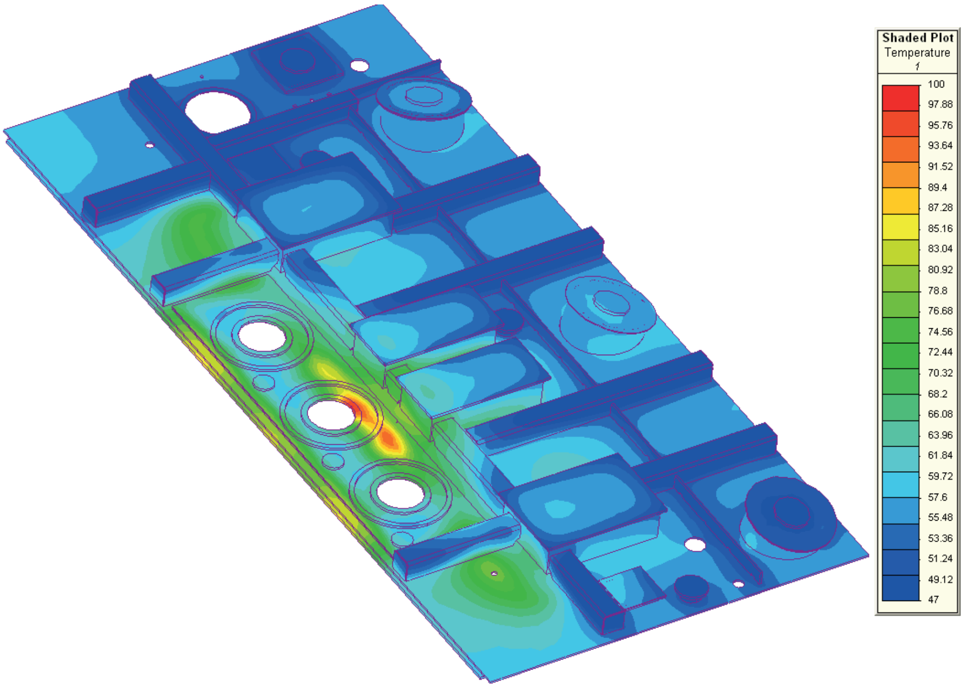


Figure 7. Temperature distribution in cover plate with modified shunt arrangement.

4. CONCLUSION

FEA calculations are validated using reduced order models. The results from reduced order models and transformer signifies the usages of magneto thermal coupled field FEA, for accurate prediction of temperature distribution in solid and laminated magnetic structures. The calculated losses and temperature are in close agreement with measured datas. Magnetic shunts , even though used for reducing losses, generates hotspots in transformer tanks due to its inappropriate arrangement.

REFERENCES

[1] Yang Junyou et al., New Preventive Measures against Stray Field of Heavy Current Carrying Conductors, IEEE Trans. Magn. vol. 32, No. 3, pp. 1489-1492, 1996.

[2] Chen Yongbin et al., Study on Eddy Current Losses and shielding Measures in Large Power Transformers, IEEE Trans. Magn. vol. 30, No. 5, pp. 3068-3071, 1994.

[3] Problem 21 family and Experimental Verification, IEEE Trans. Magnetics., Vol-40, No. 2,pp. 1394-1397, 2004.

[4] Barton, Loss calculation in Laminated steel utilizing Anisotropic Magnetic Permeability, IEEE Trans. Power Apparatus and Systems., Vol-99, No. 3,pp. 1280-1287, 1980.

[5] Cheng et al., Large Power Transformer-Based Stray-Field Loss Modeling and Validation,IEMDC.,pp. 548-555, 2009.

[6] Cheng et al., TEAM Problem 21 Family,Compumag., 2009.

[7] Sumei Yang et al., The Stray Loss on Magnetic Shielding in Power Transformers, 6th WSEAS International Conference on Applied Computer Science, pp. 420-425,2007.

[8] S.A.Holland et.al., Calculating stray losses in power transformer using surface impedance with finite elements, IEEE Trans. Magnetics., Vol-28, No. 2, pp. 1355-1358, 1992.

[9] Janne Nerg et. al., “A Simplified FEM Based Calculation Model for 3-D Induction Heating Problems Using Surface Impedance Formulations”, IEEE Trans. Magnetics., Vol-37, No. 5, pp. 3719-3722, 2001.

[10] K. Karsai, D. Kerenyi and L. Kiss, Large Power Transformers, Elsewier, Amsterdam-Oxford-York, 1987.[11] S. V. Kulkarni & S. A.Khaparde, Transformer Engineering – Design and Practice, Marcel Dekker, New York 2004.

[11] S. V. Kulkarni & S. A.Khaparde, Transformer Engineering – Design and Practice, Marcel Dekker, New York 2004