International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 1 (2018) pp. 238-244

Prediction of Hotspot Location in a Power Transformer Considering Stray Losses using FEM

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Abstract

The location of hotspot in a power transformer is the key parameter in prediction of the life of Transformer. But conventional methods for this purpose are expensive. Hence a field based analysis is carried out using Finite Element Method (FEM). Hotspot is majorly influenced by Stray losses of the transformer, thus it is evaluated using FEM. This analysis is used to predict the hotspot location in the Power Transformer. To calculate Stray losses in stray parts of Power Transformer such as tank walls, flitch plate, clamps and bolts, an analysis method of FEM is used. Data from industry is taken up for the verification and validation of stray loss calculation. This is a 31.5 MVA, 115±9×1.67%/6.3 kV unit with Z=12.06% and a YNd11 connection, ONAF cooled,3 Φ transformer.

Keywords: Finite element method – Hotspot - Power transformer - Stray losses - Thermal model

INTRODUCTION

Power transformers represent the largest portion of capital investment in transmission and distribution substations. There is an increasing need for utilities to manage and extend the life of critical transformers require reliable prediction of the loss of life expectation. The life of a transformer is majorly governed by its thermal limitations [1][2]. The distribution of magnetic leakage field and stray loss are very important in optimizing the design cost and preventing local overheating. The scope for optimal design of power transformer is very less than the original existing model, because the efficiency of common transformer is almost 99%. But you consider the number of transformer linked in power system; the economic power benefits are very large. So, the study to improve efficiency of power transformer is needed, and accurate loss analysis is preceded to perform loss reduction. In the design of large power transformers, it is very important to determine as accurately as possible the amount and space distribution of stray losses due to leakage of magnetic flux, occurring in the winding and other metal parts. Many researchers and transformer manufacturers have proposed different analysis methods to calculate and reduce the stray losses in flitch plates, frames, and tank walls for eliminating the local overheating and efficiency decreasing [3][4]. Most transformer manufacturers still use the semi-empirical formulae to calculate stray losses and predict the maximum temperature rise. However, these methods are too oversimplified so that the results are inaccurate, or based on empirical techniques with questionable validity. Due to the complicated construction of power transformers, the stray losses in structural parts of power transformers, especially for the concentration regions of eddy current which are induced by leakage field, may cause local overheating Most of the power transformers are strongly restricted by thermal regulation specifying hot-spot temperature inside the transformer tank [5]. Therefore, it is essential to predict those temperature rises accurately and take some measurements to reduce the eddy current losses and eliminate the hot spots.

Based on electromagnetic analytical formulation linked with thermal finite element method, Paper [6] proposed 3-D methodology for the heating hazard assessment on transformer covers. Taking account of the temperature dependence of the heat transfer coefficient and of the conductivity, the paper [7] established a strong coupling between the thermal and electromagnetic equations to calculate eddy loss and predict temperature distribution of bushing adapters in three-phase generator step up transformer.

Loading capability of power transformers is limited mainly by winding temperature. As part of acceptance tests on new units, the temperature rise test is intended to demonstrate that, at full load and rated ambient temperature, the average winding temperature will not exceed the limits set by industry standards. However the temperature of the winding is not uniform and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with conventional methods considering the effect of displacement current $T-\Omega$ method is adopted to calculating the stray losses in metal structural parts of power transformer.

$$E = \sigma + \varepsilon \, \frac{\partial^{-1}}{\partial t} \, \nabla . T$$

The above equation is Governing equation in eddy domains

[11]. this coupling analysis has two steps. Firstly, the stray losses of electromagnetic model should be calculated to obtain the heat source. Next, the thermal model is solved with the

heat source obtained from electromagnetic analysis. Considering the material properties affected by temperature, such as: heat transfer coefficient, the conductivity and the curve of B-H.

FEM FORMULATION EQATIONS

Coupled field finite element method is a numerical procedure for obtaining boundary values of mathematical model in our case that would be a transformer model[20]. The principle of the method is to replace a continuous domain by number of sub domains, which are usually referred to as elements whose behavior is modeled by interpolation function containing a few unknown values at the nodes of the element. The variable values and conditions of transformers have taken as the domains of the model. In evaluating mathematical model these following steps are important.

1) Discretzation of the domain
2) Derivation of the element equations
3) Assembly of the elements
4) Solution of the system of equations

The manner in which the domain is discretized will affect the computer storage requirement, the processing time, as well as accuracy of the numerical results. High order functions, although more accurate, but also more complicated formulation. Hence, a simple and basic linear interpolation is still widely used[17]. The expression for the unknown solution in an element, say element *e*, in the following form

$$\emptyset^{le} = \sum_{j=1}^{n} N_j^e \emptyset_j^e \qquad (2)$$

Where n is number of nodes in the element, $\emptyset_j^e$ the field value at node *j* and the expansion function which is also known as basic function or shape function.

Derivation of Element Equations:

There are few methods to derive the element equations. One of the popular approaches is given below. Derivation Using Variation Method: The functional of the system can be expressed as a summation of integration over each element. Thus for real valued problems one has

$$F(\emptyset') = \sum_{e=1}^{M} F^e(\emptyset'^e) \qquad (3)$$

Where M is the total number of the elements and

$$F^e(\phi'^e) = \int_{\Omega e} \phi'^e L \phi'^e d\Omega - 2\int_{\Omega e} f \phi'^e d\Omega$$

Substituting the equation in above equation and F^e with respect to nodal field values, we obtain

$$\frac{1}{2}\frac{\partial F^e}{\partial \emptyset_i^e} = \sum_{j=1}^{\pi} \int_{\Omega e} N_i^e L N_j^e d\Omega - \int_{\Omega e} f N_i^e d\Omega; i = 1,2,3$$

This can be written in matrix form as

$$\frac{1}{2}\left\{\frac{\partial F^e}{\partial \phi^e}\right\} = [K^e]\{\phi^e\} - \{H^e\}$$

Where [K^e] is an n*n matrix and {H^e} an n*1 column vector with their elements given by

$$\frac{1}{2}\left\{\frac{\partial F^e}{\partial \phi^e}\right\} = [K^e]\{\phi^e\} - \{H^e\}$$

$$H_i^e = \int_{\Omega e} f N_i^e d\Omega$$

Note that the element matrix [K^e] is symmetric ince L is self-ad joint. For the couple field thermal modeling of FEM we consider the 2 dimensional transformers so that potential differential equation is of the form of

$$-\frac{\partial}{\partial x}\left[\alpha(x,y)\frac{\partial \emptyset(x,y)}{\partial x}\right] - \frac{\partial}{\partial y}\left[\beta(x,y)\frac{\partial \emptyset(x,y)}{\partial y}\right] + \gamma(x,y)\phi(x,y) = f(x,y) \qquad (4)$$

Where $\emptyset(x,y)$the unknown field is $\alpha(x,y), \beta(x,y) and\, \gamma(x,y)$ are the known parameters associated with the physical properties of the geometry, and f(x,y) is the source or excitation function. The ordinary two-dimensional Laplace equation, Poisson equation and Helmhltz equation are only special forms of above equation.

To illustrate the transformer model in finite element boundary element methods, we choose the formulation with following notations

$$\phi(\bar{r}) = E_z(\bar{r}), \psi(\bar{r}) = \frac{1}{\mu_{r(\bar{r})}}\frac{\partial E_z(\bar{r})}{\partial n}, u(\bar{r}) = \frac{1}{\mu_r(\bar{r})}, v(\bar{r}) = \epsilon_r(\bar{r}) \qquad (5)$$

For TM incidence and

$$\phi(\bar{r}) = H_z(\bar{r}), \psi(\bar{r}) = \frac{1}{\epsilon_{r(\bar{r})}}\frac{\partial H_z(\bar{r})}{\partial n}, u(\bar{r}) = \frac{1}{\epsilon_r(\bar{r})}, v(\bar{r}) = \mu_r(\bar{r})$$

for TE incidence. And then

$$F = \iint_R \{u(\bar{r})\nabla\emptyset(\bar{r}) - k_0^2 v(\bar{r})\emptyset(\bar{r}).\emptyset(\bar{r})\}ds - \int_{\Gamma} \emptyset(\bar{r})\psi(\bar{r})$$

And

$$\phi(\bar{r}) = \phi^{INC}(\bar{r}) - \int_{\Gamma}\left[G_0(\bar{r},\bar{r}')\psi(\bar{r}') - \phi(\bar{r}')\frac{\partial G_0(\bar{r}\bar{r}')}{\partial n'}\right]dl'$$

The implementation of the proposed thermal model is explained by considering an industrial transformer. The rating of the considered transformer is This is a 31.5 MVA, 115±9×1.67%/6.3 kV unit with Z=12.06% and a YNd11 connection, ONAF cooled, with single phase core type construction. Fig.1 shows the geometry of the transformer and gives the dimensions of the transformer in SI unit system. The winding is divided into two halves. Each limb contains a half of the LV winding over which a half of HV winding is wound on. The implementation is started with dividing the transformer geometry into finite number of elements. The size of each element can be taken according to the accuracy level desired and the ability of the processing tool as well as our convenience. Next is the application of Finite Element Analysis (FEA) to the geometry to calculate the flux distribution.

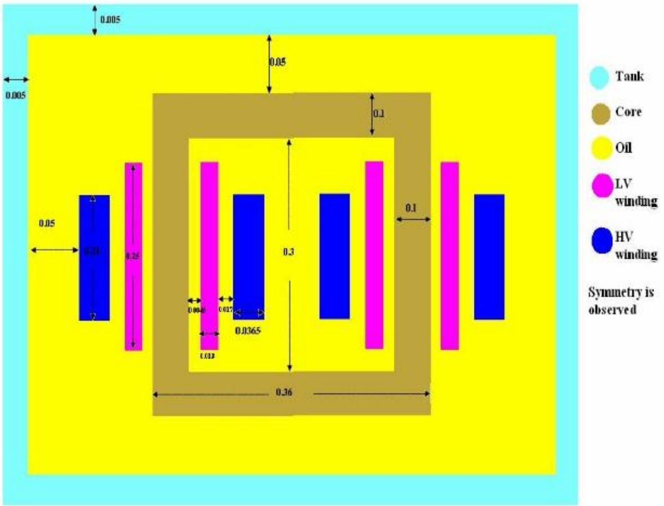

Figure 1: geometry of the transformer

STRAY LOSS COMPUTATION AND MINIMIZATION METHODS

An important factor in the design of power transformers is the stray loss evaluation. From an economic point of view proper shielding demands thorough knowledge of stray loss distribution in the different constructional parts. Of these parts the tank is the most important one, since a considerable proportion of the stray losses arise in it when un shielded[11]. One of the tasks of this analysis is to determine the losses in a transformer tank, especially when it is unshielded. And also compare the same when it is shielded for finding the effectiveness of shielding in reducing the stray losses. A concentric wound transformer along with its stray fittings is shown in fig 6. Here the shielding is provided along the tank wall with a CRGO material. This problem is analyzed using ANSYS to determine the stray losses with and without shielding.

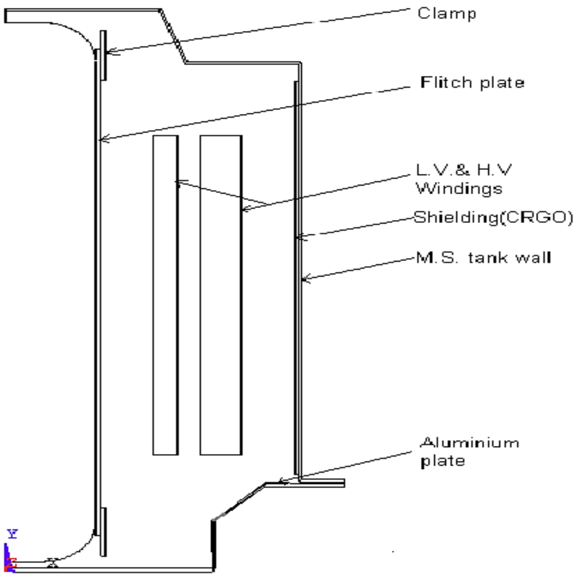

Figure 2: Transformer axis-symmetric model

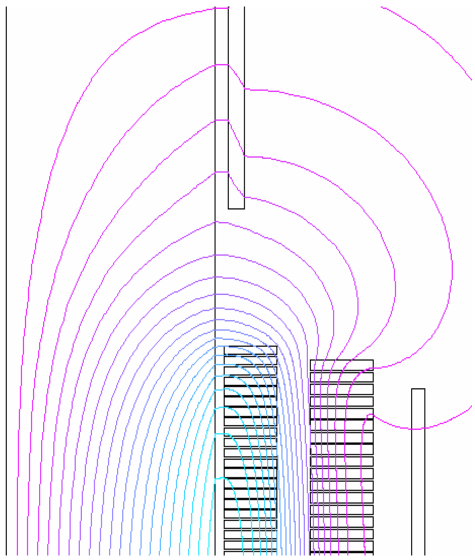

Figure 3: Detailed transformer field solution

From Fig 3 it can be seen that the component of the leakage flux has its greatest concentration at the interface between the two windings and then decreases progressing away from the gap between the windings.

Table1 gives the values of material properties used in the analysis.

Table 1: material properties as used in analysis

Sl. No.	MATERIAL	MUXX(1/ $_{o}$ $_{r}$)	SIXX(1/)
1	Copper	795800	58000000
2	Transformer oil	795800	0
3	CRGO steel	400	4000000
4	Structural steel	800	4000000

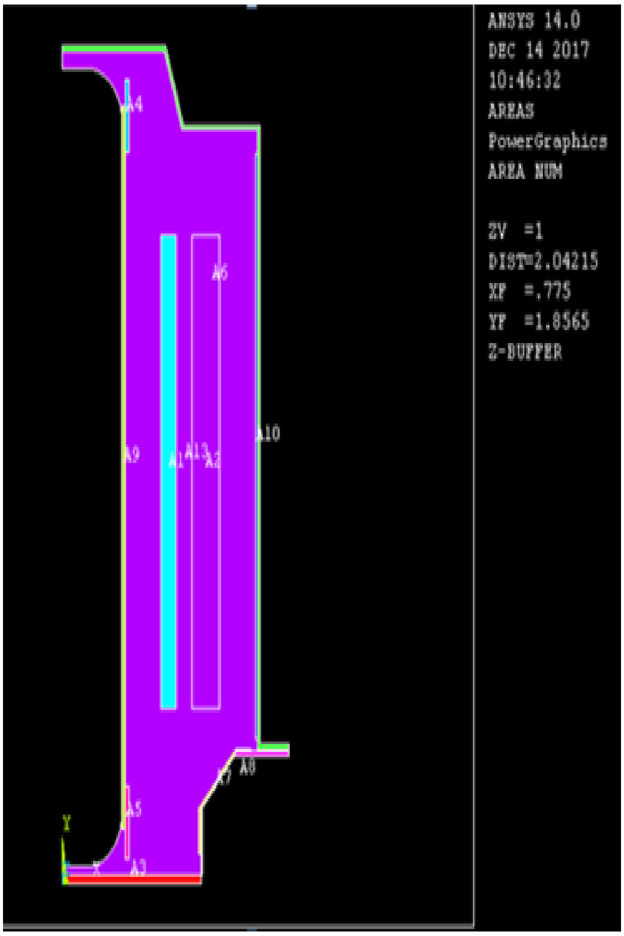

Figure 4: FEM power graphic model of transformer

Fig. 4 gives power graphic model of transformer geometry. Fig.5.and 6 shows the stray field pattern with and without magnetic shield. The colors shown in the plot define a range of values and not a single value. The inner LV winding typically has a higher attraction of the leakage flux due to the high permeance of the core. The leakage flux in the HV winding is divided between the core and the core clamps and other structural parts [23]. In the process of modeling, certain assumptions [18] are made, without affecting the accuracy of the results, to make the analysis simple.. The coils are modeled as solid copper lumps, whose properties were determined accordingly considering the various spacing inside. The current density will be the Ampere-turns of the original winding divided by the cross sectional area of the actual winding. The secondary winding Ampere turns are calculated based on the primary winding ampere turns and magnetizing ampere turns required by the core.

Secondary winding AT = (Primary AT – Magnetizing AT)

The tank is assumed to be rectangular which is valid for most of the transformers. The cooling system employed is supposed to be ONAN. All the above assumptions are valid for most of the transformers

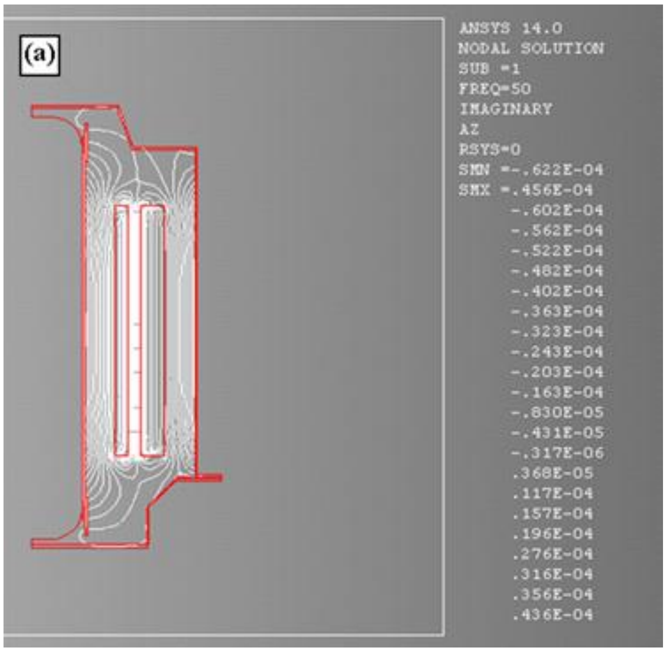

Figure 5: stray field pattern without shield plate, in plane (x,y)

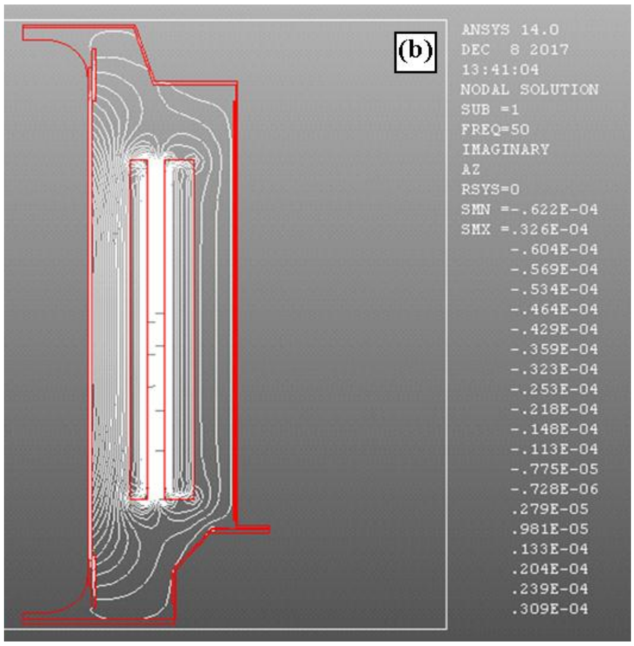

Figure 6: stray field pattern with shield plate, in plane (x,y)

DEVELOPMENT OF THERMAL MODEL

The following points are to be understood while building up the thermal model [15]

$$W_h = K_h (B_m)^{1.6} f \quad \text{Watts/Kg} \qquad (6)$$

$$W_e = K_e (K_f x B_m)^2 f^2 t^2 n \quad \text{Watts/kg} \qquad (7)$$

Where, K_e and K_h are material constants that are found out experimentally, f is the frequency of the alternating flux, B_m is the maximum value of operating flux density, K_f is the form factor of the ac wave form, $t$is the thickness of each lamination of the core and *n* is the number of laminations in the core. The sum of W_h and W_e give the value of core losses.

For the considered transformer, the parameters used in building the model are shown in table 2, the results of which are presented in fig. 4.2 and 4.3. The values of coefficients Kh and Ke of the core are 0.005 and 2.523 respectively. The value of form factor Kf is taken as 1.1 while the thickness of lamination t was 0.27mm. The weight of the core was 76.75 kg.

Table 2: values of thermal resistivity and capacitances used

Material	Thermal conductivity	Specific Heat Capacity
CRGO core	26 W/mK	450 J/kg°C
Copper winding	400W/mK	386 J/kg°C
Transformer Oil	0.72W/mK	2060 J/kg°C
Structural Steel	45W/mK	400 J/kg°C
tank		

Once the loss in each core block is obtained, we proceed towards building the thermal model. we built the equivalent circuit for each block of the finite element model. Only the blocks corresponding to the core and coils contain current sources, as they are the heat generating elements. Resistances and capacitances are present in all elements. In this way, electrical equivalent block simulating the thermal behavior is built for each element, which when interconnected together give the thermal model for the entire transformer geometry. This electrical equivalent of thermal model which when solved for potentials at different nodes gives the temperatures at the nodes.. Fig. 7 and 8 shows the thermal model built for the considered transformer and indicates flux density distribution without and with magnetic shield.

The following points are to be understood while building up the thermal model.[14]

1. The tank outer surface acts as a heat sink to ambient and hence is modeled accordingly.
2. Ambient is taken as ground and hence the obtained thermal profile shows the rise in temperatures above the ambient
3. Symmetry is observed in the equivalent circuit to ensure the heat flow from the center of the transformer towards the tank.

These models reveal the maximum flux density variation within the transformer under with and without magnetic shields. The observed values are represented in table 3.

Table 3: Comparison of stray losses with and without shielding

Calculated value of stray losses from FEM		
Names of the loss (in KW)	**Without shielding**	**With shielding**
Total stray loss	11	7.5

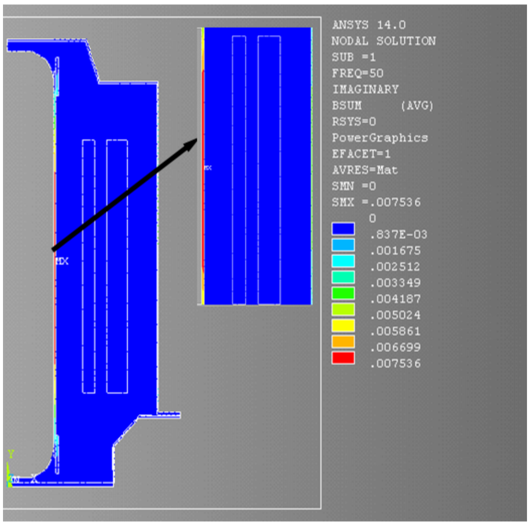

Figure 7: Flux density distribution without shield (shunt)

Table 4: Measured rated losses (kW) for the 31.5 MVA transformer.

P_{dc}	Load Losses P_u	Stray Losses P_{EC} + P_{SL}
123.9	146.3	22.4

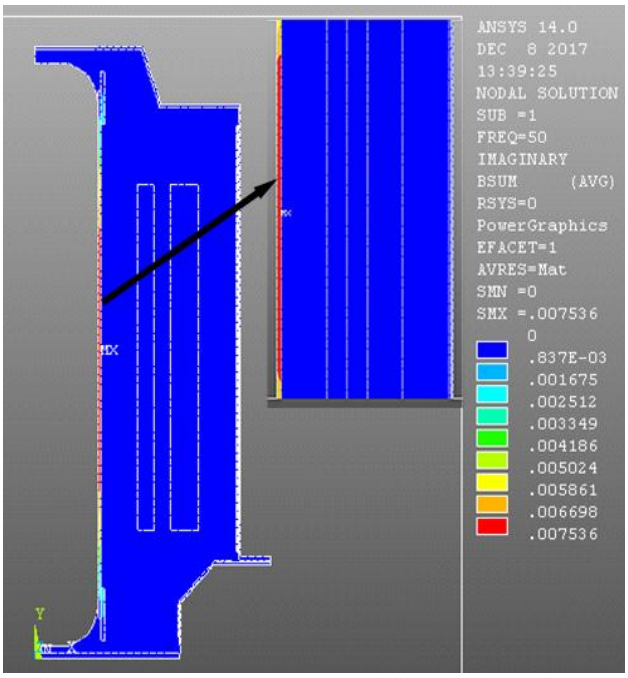

Figure 8: Flux density distribution without shield (shunt)

CALCULATION OF PARAMETERS OF THE THERMAL MODEL

Calculation of Source Values:

The sources in the thermal model represent the heat generation in the element. So, the value of losses calculated in the each block is used as the source values in the thermal model[19]. There is no heat generated in the oil and therefore there are no sources in the oil blocks in the thermal model. The losses in Copper are I^2R losses, which are calculated using the current densities in the windings [20]. The total losses in the LV or HV copper are calculated and since the copper losses are symmetrically and evenly distributed (which is a very valid assumption), it is distributed equally in the four blocks representing the corresponding coil. The losses in the core blocks are calculated using the values of flux density with the formulae given in equations (1) and (2).

Calculation of Thermal Resistances:

The thermal resistance of an element represents the opposition offered by the element to the flow of heat through it in either direction, which is represented by resistors. The value of thermal resistance of each element depends on the material property of thermal conductivity in Watts/mK[19]. Fig.5.1 shows such an individual element. If x and y are the dimensions of the element in X and Y directions respectively, z is the Z-direction depth, which is the core thickness, same for all the blocks and is the thermal conductivity of the material, R is calculated according to the formula given below.[22]

$$R_{horizontal} = \rho(x)/(yz) \qquad (8)$$

$$R_{vertical} = \rho(y)/(xz) \qquad (9)$$

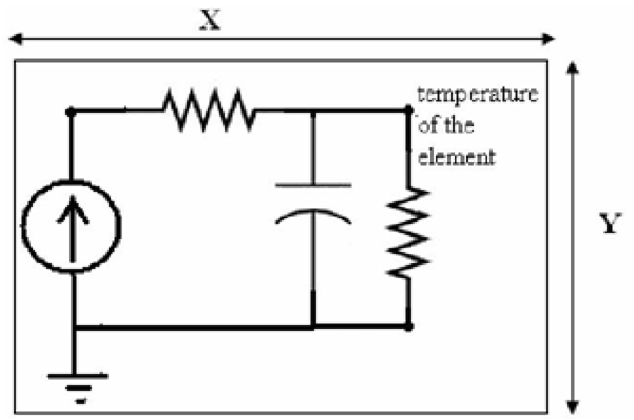

Figure 9:.Single element representation with dimensions

Calculation of Thermal Capacitances:

Thermal capacitance of an element represents its capacity to store the heat, which causes a rise in its temperature. It is calculated by multiplying the value of specific heat capacity

The results are super imposed on the transformer geometry to assist understanding. This way we have simulated the temperature profile of transformer and a comparison of the temperature values with those of design values is also presented in table 5. The values denoted is the potential at the nodes of the electrical equivalent circuit, which is actually the temperature rise above ambient.

This shows that the model developed is sufficiently accurate enough to predict the transformer interior temperatures [12].

The 2-D FEM calculations can be used in a simple way to calculate the hot spot factor. The H factor can be predicted as the ratio of the calculated winding losses that generates the hot spot to the total winding average losses and is as follows

[22]:

$$H = \left(\frac{P_{W-\max}(pu)}{P_{W-ave}(pu)} \right)^{0.8} \qquad (10)$$

Where

$P_{W-\max}$ are the winding losses at the hottest spot location (pu)

P_{W-ave} are the average winding losses (pu).

The hot spot factor is = 1.27 ≈ 1.3

Table 5: comparison with practical values

TEMPERATURE	DESIGN VALUE	OBTAINED VALUE FROM THE THERMAL MODEL
Winding Temperature	60 ºC	62 ºC
Top Oil Temperature	55 ºC	59 ºC

CONCLUSION

A thermal model that can monitor the thermal profile of the transformer has been successfully presented. A FEM model was adapted and used to predict the transformer accurate stray losses. The knowledge of flux density was used with conductor dimensions to predict the eddy losses for a specific design. The model can be used to calculate the eddy loss in individual turns/discs, to locate the winding hot spot location, and to predict the hot spot factor H. Such information is very important for winding hot spot determination.

The flux density plot of the frame indicates that the coil side has large flux density than that of the tank side, and that the case with a shunt has a smaller flux density distribution, when compared to the case without. The table shows the total stray losses in transformer without, and with, wall shunts. It can be seen that the reduction of stray losses significantly reduces the losses and hot spot temperature and improve the efficiency and life span of the transformer.

Type	Stray loss	Hot spot factor	Hotspot/winding Temperature
Without shielding	11Kw	1	69.94 ^{O}C
With shielding	7.5Kw	1.3	48.15 ^{O}C

REFERENCES

[1] Dejan Susa, Matti Lehtonen, "Dynamic Thermal Modeling of Power Transformers: Further Development – Part I," IEEE Transactions on Power Delivery, October 2006

[2] Dr. Jan Declercq, Wim Van Der Veken "Accurate Hot Spot Modeling in A Power Transformer Leading to Improved Design and Performance", Transmission and Distribution Conference, 1999 IEEE Richard Bean, Transformers for the Electric Power Industry

[3] Glenn Swift, Tom S. Molsinki, Waldemar Lehn, "A Fundamental Approach to Transformer Thermal Modeling – Part I: Theory and Equivalent circuit," IEEE Transactions on Power Delivery, April 2001.

[4] A K Sawhney, A Course in Electrical Machine Design, Dhanpat Rai & Co. Publications

[5] Bharat Heavy Electricals Limited (BHEL), Transformers, 2nd edition, Tata McGraw Hill Publications

[6] Indrajit DasGupta, Design of Transformers

[7] S V Kulkarni, S A Khaparde, Transformer Engineering – Design and Practice, Marcel Dekker, INC

[8] IEEE Guide for Loading Mineral Oil Immersed Transformers, IEEE Std C57.91-1995 (Revision of IEEE Std C57.91-1981, IEEE Std C57.92-1981, and IEEE Std C57.115-1991)

[9] Stanley E. Zocholl, Armando Guzman, Scweitzer Engineering Laboratories Inc, "Themal Models in Power System Protection"

[10] .Chetan C Adalja, M L Jain, "An Investigation of Thermal Performance of Transformers using Optical Fibre Technology," EMCO Limited.

[11] Chetan C Adalja, M L Jain,"Analysis of Stray Losses in Power Transformers by 3-D Magnetic Field Simulation," Fifteenth National Power Systems Conference (NPSC), IIT Bombay, December 2008.

[12] S V Kulkarni, G S Gulwadi, R Ramachandran, S Bhatia, "Accurate Estimation of Eddy loss in transformer windings by using FEM Analysis"

[13] L. Susnjic, Z. Haznadar and Z. Valkovic, "Stray Losses Computation in Power Transformer," 2006 12th Biennial IEEE Conference on Electromagnetic Field Computation

[14] Ankireddypalli S. Reddy, Dr. M. Vijay Kumar, "Hottest Spot Evaluation of Power Transformer Design using Finite Element Method," Journal of Theoritical and Applied Information Technology.

[15] Dejan Susa, Matti Lehtonen, "Dynamic Thermal Modeling of Power Transformers: Further Development – Part II," IEEE Transactions on Power Delivery, October 2006

[16] Dejan Susa, Matti Lehtonen, Hasse Nordman, "Dynamic Thermal Modeling of Power Transformers," IEEE Transactions on Power Delivery, January 2005

[17] Masato Enokizono, Naoya Soda, "Finite Element Analysis of Transformer Model Core with Measured Reluctivity Tensor," IEEE Transactions on Magnetics, September 1997

[18] Koji Fujiwara, Takayuki Adachi, Norio Takahashi, "A Proposal of Finite-Element Analysis Considering Two-Dimensional Magnetic Properties," IEEE Transactions on Magnetics, March 2002

[19] Oluwaseun A. Amoda, Student Member, IEEE, Daniel J. Tylavsky, Senior Member, IEEE, Gary A. McCulla, Member, IEEE, and Wesley A. Knuth, Member, IEEE, "A New Model for Predicting the Hottest Spot Temperature in Transformers"

[20] Douglas J. Nelson and J. Patrick Jessee, "A Coupled Thermal Magnetic Model for High Frequency Transformers: Part I - Model Formulation and Material Properties," VOL. 15, NO. 5, IEEE Transactions On Components Hybrids, and Manufacturing Technology, October 1992

[21] W. H. Tang, Q. H. Wu, Senior Member, IEEE and Z. J. Richardson, "A Simplified Transformer Thermal Model Based on Thermal-Electric Analogy", IEEE Transactions on Power Delivery, July 2004.

[22] David W Hutton, Fundamentals of Finite Element Analysis, TMH Publications

[23] Software Manuals of ANSYS and MULTISIM