FEM Analysis of Single Phase Shell Type Transformer at Different Core Temperatures

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***Abstract*— This paper presents FEM analysis on impact of temperature of the core on electrical parameters in 1:1 shell type transformer. For the comparison of open circuit voltage and No-Load current at two different temperatures of core, the designed transformer model is supplied by a constant voltage source. From the FEM analysis it is observed that, to maintain the output voltage constant the designed model is taking low value of current with respect to the increase in temperature. At a constant frequency of 50Hz, if the core temperature increases from 300K to 600K, the core loss is decreased. Other parameters of the core like flux density distribution at various limbs of the shell type transformer are observed. The FEM studies have been carried out by using QuickField software with more than 2K nodes to improve the accuracy of analysis.**

Keywords—Finite Element Analysis; Core temperature; Transformer; Core Loss

I. INTRODUCTION

In the design of electric machines iron loss calculation is one of the measurable parameter to analyze the performance of the machine. The analysis and prediction of iron loss through solid physics bases are evolved from Steinmetz [1], popularly known as two term model and three term model by Bertotti [2] are considered for design of machines working in magnetic fields. Out the mentioned models two term model gain popularity due to simple calculation. The accuracy of two term model was improved by variable hysteresis and eddy current loss [3]. The variation of circuit parameters when coil wound on ferromagnetic materials with various effects like external magnetization [4], temperature [5] of the core are already been evaluated through experimental analysis.

Since temperature is one of the most important parameter while operating heavy machines at peak loads for long run. The machines are designed to operate at room temperature, but the operating conditions are different. Taking temperature effect on loss in to consideration N. Takahashi [6]-[8] has verified the temperature dependency of losses in a ring specimen, billet heater and concluded that core losses are decreasing with temperature. The temperature dependencies of losses in Mn-Zn Ferrites are analyzed by T.Chiba [9]. Calculations of eddy current loss in steel laminations are derived by J. Gyselinck. Jörg Schützhold [10] has verified temperature dependence of losses in various electrical machines [13] the measurements is clearly noticing the decrement in core losses. [14], [15] S. Rao has presented the experimental verification of change in induced voltage and FEM analysis at constant current.

Separation of winding loss from thermal dependency was proposed by Rafal Wrobel [11] in electromagnetic devices. The transformer equivalent circuit with all types of losses was proposed in [13] by J. Schützhold. The iron loss estimations in are depending on the temperature. But, the behavior of the current in the primary coil which helpful in deciding the iron loss estimation is not discussed. In addition to the above the flux and current density distribution in windings are not clearly mentioned.

In this paper a constant voltage source is fed to the model to calculate the amount of current drawn by the primary winding for variation in the core temperature. The shell transformer model is considered in this analysis with 1:1 turn ratio and the transition temperature from the core to windings is assumed to be zero.

II. TEMERATURE DEPENDECIES ON PROPERTIES OF CORE

A. Core Loss

The transition energy required for charges in ferromagnetic material was decreased by increasing temperature, which in turn affects the decrement in hysteresis loss. This hysteresis loss decrement can be shown by decrement in the area of the hysteresis loop area as shown in Fig.1.

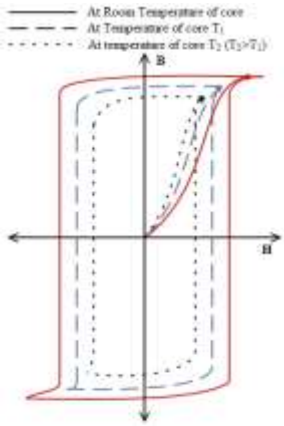


Fig. 1. Hysteresis loop at various temperatures of Ferromagnetic material.

The iron loss models independent on temperature of the iron core are as follows: The two term model proposed by Steinmetz is given by Eqn. (1).

$$P_{Core} = K_h f B_m^2 + K_c f^2 B_m^x \quad (1)$$

The Bertotti's expression of core loss for a maximum flux density B_m (Tesla) and frequency f (Hz) is the sum of hysteresis, eddy current and excess losses. The expression for core losses is given by Eqn. (2).

$$P_{Core} = K_h f B_m^2 + K_c f^2 B_m^2 + K_e \left(f B_m \right)^{3/2} \quad (2)$$

where K_h, K_c and K_e are coefficients of the hysteresis, eddy current and excess losses respectively.

The temperature dependent iron loss model taking considerations about both the variation of hysteresis and eddy current losses are given in Eqn. (3).

$$P_{Core} = K_h(T, f, B_m) f B_m^2 + K_c(T, f, B_m) f^2 B_m^2 \quad (3)$$

The hysteresis and eddy current coefficients are dependent on temperature, frequency and flux density. Finally the variable loss coefficients are providing the best solution in the loss analysis. The decrement in the eddy current loss is due to increased resistance of the core with respect to temperature. This affects the circulating current in the core laminations.

B. Permeability (μ)

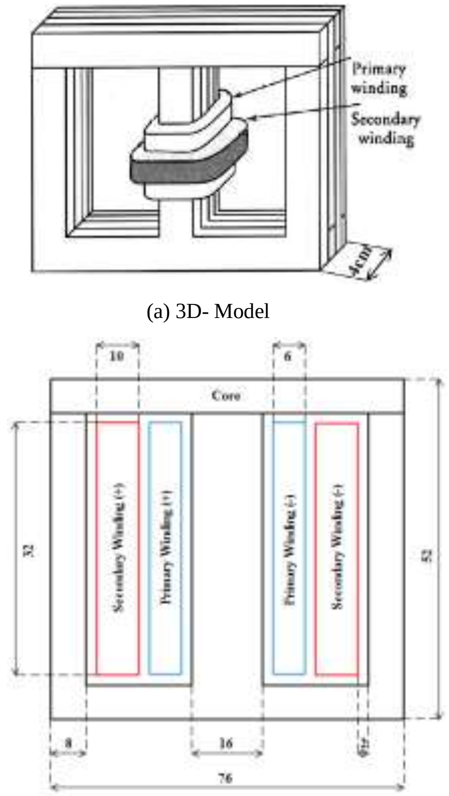
According to the he Hopkinson effect on the ferromagnetic material permeability of core will reaches maximum just before the Curie temperature. The increase in permeability is due to sudden decrement in the magnetic anisotropy of the material. The permeability is a main reason for increment in the production of induced EMF as mentioned in [7], this will also affect the magnetizing current of the machines.

$$\mu = 1 + \chi \quad (4)$$

After the Curie temperature the core material will enters in to paramagnetic state where the core losses are more.

III. DESIGN OF 2D FEM MODEL

For AC magnetic analysis, the design of 2D transformer is modeled by using Quickfield software. For FEM analysis, the Quickfield software is a simple and powerful tool. In Fig. 2 (a) & (b), shown the 3D model and equivalent 2D cut section view of a shell type transformer respectively. The shell consists of primary and secondary windings which are wounded on the central limb and each winding is insulated by each other as shown in Fig. 2(a) & (b) respectively.



(a) 3D- Model

(b) Cut section view of 2D-Model

Fig. 2. Shell transformer 3D & 2D models

An ample investigation on shell type transformer has been carried out with specifications tabulated in Table - 1.

Table 1. Specifications of shell type transformer modeled in Quickfield software

Parameter	**Value**
The thickness of core	4 cm
Height of core	52 cm
Width of core	76 cm
Each window area	792 cm^2
Width of outer core limb	8 cm
Width of middle core limb	16 cm
The total area of the core	560 cm^2
Width of primary winding insulation	2 cm
Primary winding area of occupation	320 cm^2
Primary and secondary windings copper conductor area	20 cm^2
Copper conductivity	$56x10^6$ /m
Permeability	1

Furthermore, the left and right window winding portions are indicated as v1+ and v1-. Similarly, the secondary winding is indicated as v2+ and v2-. The transformer boundaries are modeled to have a less leakage flux which means that boundaries have zero magnetic potential.

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Fig. 3. shows the electrical equivalent circuit connections of windings in Quickfield. On both the primary and secondary's, the winding connections are in series and the v1+ and v1- directions are changed depending on the Dot connection, to indicate the induced EMF polarities.

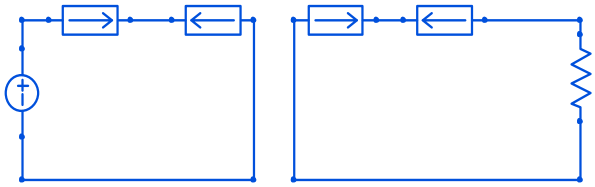


Fig. 3. Electrical equivalent circuit connections of windings

A voltage source of 0.6 V peak value is connected to primary winding. The secondary winding is shorted with a 1000MΩ resistance which will make the circuit open, because of the higher value of resistance. Fig. 4 shows the complete designed mesh model of a shell transformer with winding labels.

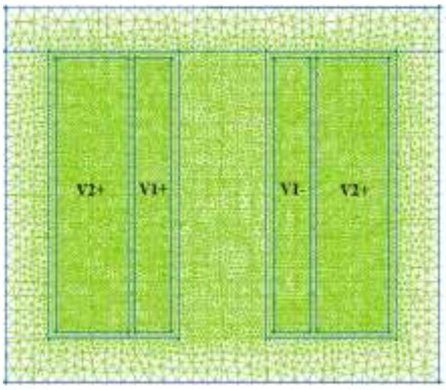


Fig. 4. 2D shell transformer meshed model

IV. Results & Discussion

The developed model is verified with two different core temperatures. The B-H curve data is collected from the library of MagWeb. In Fig. 5, shown the B-H curve at different temperature values considered for the FEM analysis. At low flux density, the slope of the curve is higher when compared to room temperature. But, the maximum flux density will falls below the room temperature when the core temperature increases.

The FEM analysis is divided in to two cases, such as core temperatures are at 300 K and 600 K. In two cases, the liner portion of the B-H curve is selected to measure the impact of the temperature for the analysis. Furthermore, a closed contour having a length of 256 cm and total volume of 0.016 m^3 is considered for total core loss estimation.

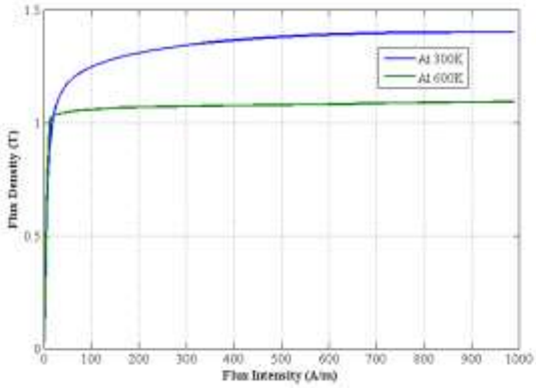
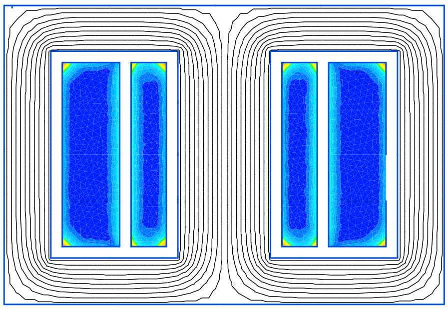


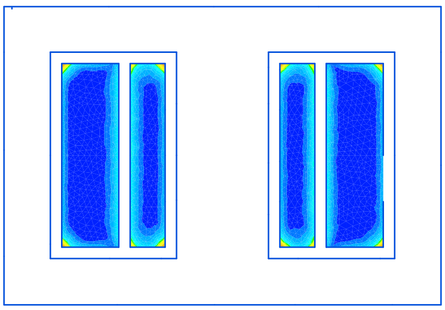
Fig. 5. B-H curve of the core at different temperatures

A. Case-1

As aforementioned in case 1, the temperature of core is fixed to 300 K. The voltage source supplies voltage of 1.5058v at angle of 89.678^0 to a primary winding which produces 3.75wb of magnetic flux in the core. Fig. 5(a) shows the high magnetic flux in the core at 0^0 temperatures, because of 0^0 phase angle of current. When the time reaches to 900 sec, the core flux reaches to zero value and is depicted in Fig. 5 (b). The maximum current density is observed as 5200 A/m^2.



(a) Current Density at 0^0

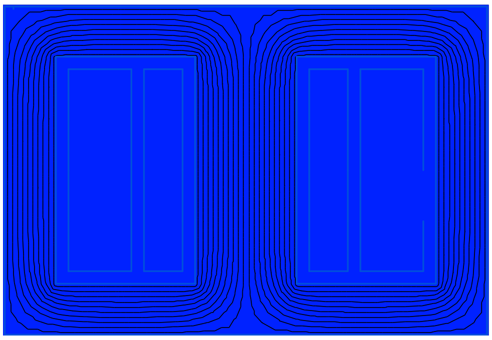


(b) Current Density at 90^0

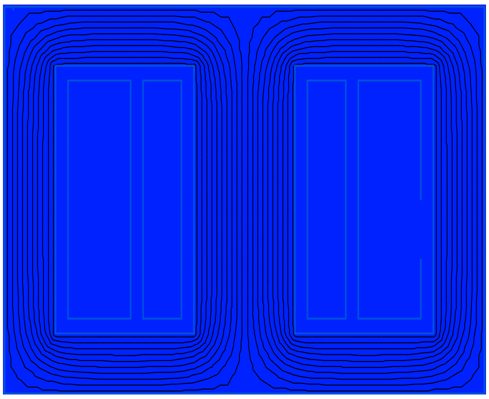
Fig. 5. Magnetic Flux and Current Denisty at 0^0 and 90^0

B. Case-2

In this case, the core temperature is fixed to 600K. The voltage source supplies a voltage of 1.7214V with a phase angle of 89.632^0. So the primary winding is excited by the current at 12A which produces 3.8wb of magnetic flux in the core. The magnetic flux distribution is same as case 1, which is already shown in Fig. 5. The maximum current density is observed as 5270 A/m^2. The power loss and voltage distribution of a shell type transformer is shown in Fig. 6 (a) & (b) respectively. It is observed that, the loss in the outer corner is less than the inner corner of core.



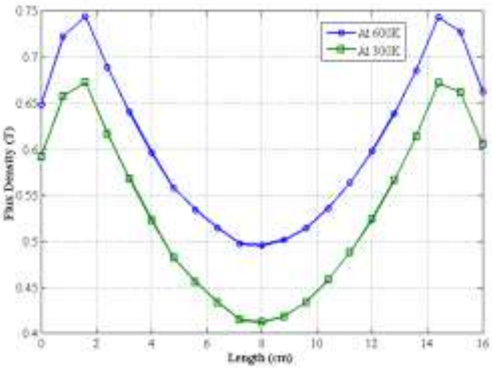
(a) Power Loss



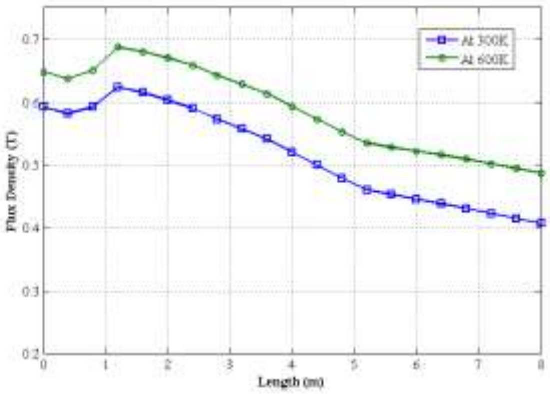
(b) Voltage

Fig. 6. Power loss & Voltage distribution in shell transformer

Fig. 7. shows the central and side limbs magnetic flux density variations at two different temperatures and various positions of the core. It is observed that, the magnetic flux density is increasing with a constant current. Moreover, the flux density is low at centre of central limb compared to sides. From Fig. 7 (a), the core permeability is observed as high, when the core temperature increases. Whereas in Fig. 7 (b), it is observed in the side limb, the flux density is increased with respect to the temperature of the core. Therefore, the power loss is also increases with respect to the temperature in the side limbs. The Table 2 presents the behavior of different parameters of shell transformer at two different temperatures. It is observed that, for a constant voltage, the core loss is reduced by increasing the temperature of the core.



(a) Flux density in the central limb



(b) Flux density in the side limb

Fig. 7. Flux density at various positions of core

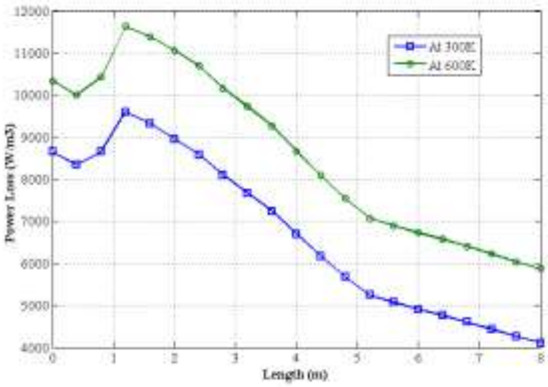


Fig. 8. Power loss in side limb in W/m^3

Table -2. Change of various parameters of core at different temperatures

Temperature of the core (K)	**300K**	**600K**
Current density (A/m^2)	2300	1860
Potential A (Wb/m)	0.0424	0.0484
Flux Density (T)	0.744	0.813
Strength H (A/m)	40.6	41.5
Power Loss Q (W/m^3)	4510	4230
Energy Density (J/m^3)	4.65	5
Core loss (Watts)	9.5491	9.538
Magnetic Flux (Wb)	3.75	3.8767
Flux linkage per one turn	1.7x10^{-7}	1.94x10^{-7}

Voltage of source (V)	0.6	0.6
Secondary voltage (V)	0.6	0.65

CONCLUSION

The FEM results are showing that for a constant voltage applied to the primary winding causes an increment in the secondary voltage as the core temperature is increasing. In addition to the above the current density in the core and maximum flux are also in the same manner. The increase in the temperature of the core affects the area of the B-H curve which will cause an increment in the flux density and flux in the core by improving permeability. As the core temperature rises the No-Load current is decreasing, further the analysis on effect on current variation will leads to a modified no load equivalent circuit in which all the parameters are temperature dependent can be developed. This modified equivalent circuit is useful in predicting the loss in machines at different temperatures.

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