FEM 2D AND 3D DESIGN OF TRANSFORMER FOR CORE LOSSES COMPUTATION

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Abstract: *Accurate simulation and prediction of losses in power transformer is important during transformer lifetime but also during the design stage. Paper presents the simulation model of transformer based of Finite Element Method that allows calculation of core losses and magnetic flux density in transformer cross-section. Two different models are constructed for 2D and 3D simulation. Obtained results are compared with experiments. Finally, flux density in both models is calculated and obtained results are presented for different time steps.*

Keywords: CORE LOSSES, POWER TRANSFORMER, FEM MODELS, MAGNETIC FLUX DENSITY

1. Introduction

Modeling of power transformers and their accurate simulation has been always a challenging task for engineers worldwide. Power transformers are the most expensive element in energy distribution networks therefore accurate prediction of transformer operation as well as possible malfunctioning has been always an issue among engineers. Heindl *et al.* propose high frequency models of large power transformers required for analysis of transient interaction between the transformers and the power system [1]. Ozgonenel and Kilic propose an algorithm and transformer model for identification of different internal faults, which lead to transformer outage [2]. During recent years Finite Element Method (FEM) gained a popularity for modeling various nonlinear materials and permanent magnets under the variety of conditions, employing sinusoidal waveforms and practically any other pulsed wave form of excitation [3] –[5]. FEM has been used for calculating transformer parameters in cases when partial discharge in transformer winding occurs [6]. In recent years, various powerful softwares have been developed for calculation of transformer parameters, operating modes and different type of losses [7]. Paper presents 2D and 3D model of power transformer for calculating core losses and magnetic flux density at transformer cross-section. Core losses are calculated at no-load for 50 Hz voltage supply, therefore only the low voltage winding is energized with rated voltage. Calculations are based on data of three phase transformer 115/13.8 kV, 60 Hz and 30 MVA with tested core losses of 23.7 kW.

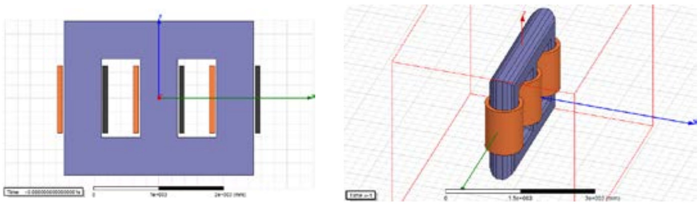


Fig. 1 Transformer 2D and 3D model

Computer animation has been used for presenting the magnetic flux density in core cross section. Flux density is calculated for different time intervals. Knowledge of flux density allows parts of transformer core close to the point of saturation to be detected and transformer construction to be modified in terms of avoiding saturation of core, high losses and low efficiency factor.

2. FEM models

Based on real transformer dimensions and geometry the FEM models have been constructed for 2D and 3D simulation of low frequency transient electromagnetic fields. The basic procedure of transient simulation includes spatial and temporal discretization of the physical equations. There are several approaches to do spatial discretization: finite differences, finite elements and finite volumes. The finite element method is widely used in engineering practice because it can model complex inhomgeneous, anisotropic materials and represent complicated geometry using irregular grids [8]-[9]. FEM solves the set of Maxwell equations for a given excitation and frequency. Transient simulation is performed by domain decomposition along time-axis (TDM-time decomposition method) to solve all time steps simultaneously, instead solving a transient problem time step by time step [7]. In both transformer models, boundary conditions are defined on object outer geometry as well as properties of all materials. Magnetic core is characterized with B-H curve of magnetization and thin laminations. They are input in both transformer models (Fig. 2). Specific core losses P are input as well, and core losses are calculated for one specific frequency, in this case 50 Hz (Fig. 3).

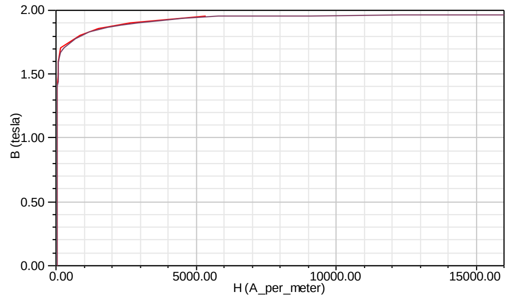


Fig. 2 B-H curve of core laminations

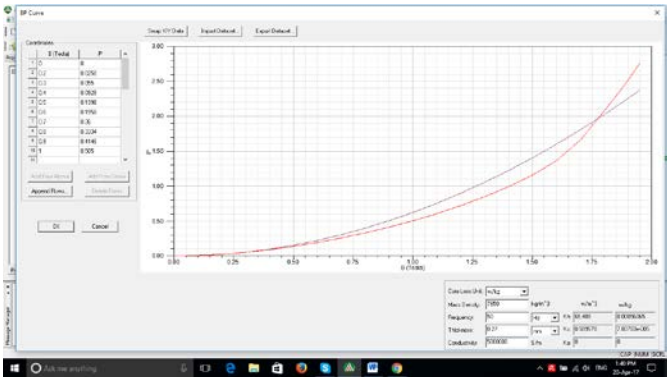


Fig. 3 P-B curve of core losses versus flux density

Traditionally, core loss P_c has been divided into two components: hysteresis losses P_h and eddy current losses P_e. According to the Steinmetz equation, measurement and calculation of core losses are normally made with sinusoidal flux density of varying magnitude-B and frequency-f. These measurements and calculations are based on the standard coil and frequently are modeled by a two-term function of the form:

$$P_c = P_h + P_e = k_h f B^n + k_c f^2 B^2 \tag{1}$$

k_h, k_c and n are the coefficients which depend on the lamination, material thickness, conductivity as well as other factors [10]. This formula is applicable up to the maximum flux density of B of 1 T, which is not the case in electrical machines and transformers.

In this paper, calculation of core losses is done according to:

$$P_c = P_h + P_e + P_{excess} = K_1 B_m^2 + K_2 B_m^{1,5} \tag{2}$$

Where the eddy current losses are:

$$P_e = k_c \left(f B_m \right)^2 \tag{3}$$

The hysteresis losses are:

$$P_h = k_h f {B_m}^2 \tag{4}$$

and the excessive losses are:

$$P_{excess} = k_e \left(f B_m \right)^{1.5} \tag{5}$$

Therefore:

$$K_1 = k_h f + k_c f^2 \tag{6}$$

$$K_2 = k_e f^{1.5} \tag{7}$$

The eddy-current loss coefficient is calculated as:

$$k_c = \pi^2 \sigma \frac{d^2}{6} \tag{8}$$

Where σ is the conductivity and d is is is the thickness of one lamination sheet. Coefficients K_1 and K_2 are obtained from minimization of function:

$$f\left(K_1 K_2\right) = \sum \left[P_{vi} - \left(K_1 B_{mi}^2 + K_2 B_{mi}^{1.5} \right) \right]^2 = \min \tag{9}$$

Where P_{vi}, B_{mi}- the i-th point of the data on the measured loss characteristic curve. The other two loss coefficients are:

$$\begin{aligned} k_h &= \left(K_1 - k_c f_0^{\,2} \right) / f_0 \\ k_e &= K_2 / f_0^{1.5} \end{aligned} \tag{10}$$

where f_0 is the testing frequency for loss curve.

In this case, core losses are input in transformer models as total losses for one specific frequency 50 Hz or 60 Hz (P-B curve). Since the starting transformer model is for 60 Hz, besides changing the model frequency to 50 Hz, the amplitude of input phase voltage ($13.8 \cdot \sqrt{2} / \sqrt{3}$ kV) is reduced for factor 5/6, as well as power rating of the transformer. This keeps the same currents in windings and avoids transformer overheating when 60 Hz transformer is run with 50 Hz voltage supply. For both frequencies, power losses are calculated. For core losses, only a single energized winding needs to be considered. An exponentially increasing voltage source is applied in order to eliminate inrush current and the needs for an unreasonably long simulation time (Fig. 4).

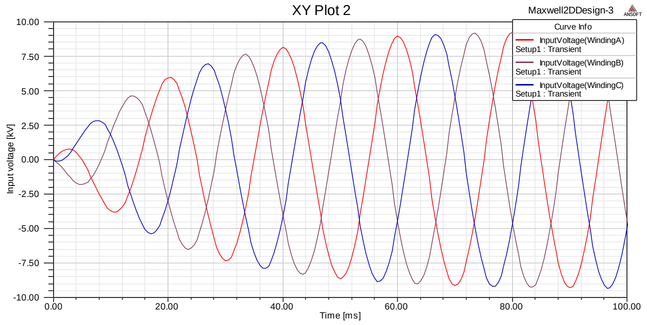
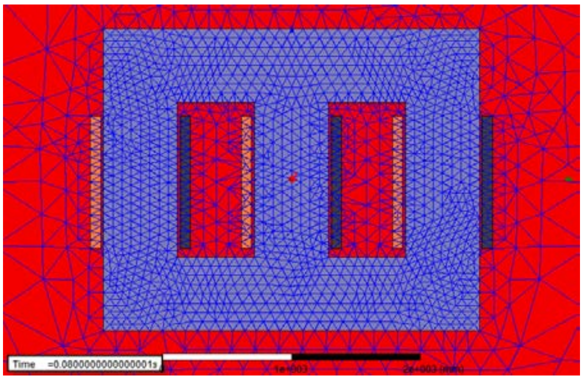
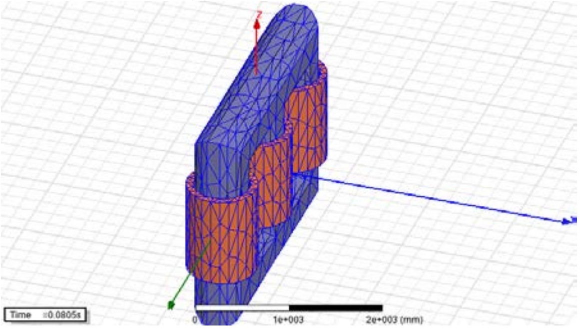


Fig. 4 Input voltage at 50 Hz

In order magnetic flux density **B** to be calculated, magnetic vector potential **A** must be found. For that purpose, the whole object geometry is divided into numerous elements, usually triangles, where **A** is approximated by a simple function. Created mesh of finite elements in 2D and 3D model is presented in Fig. 5.



(a) Mesh at 2D model



(b) Mesh at 3D model

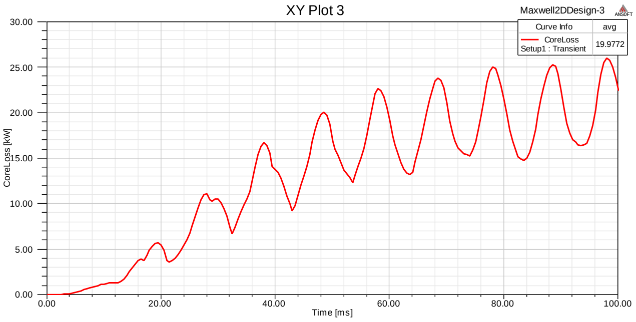
Fig. 5 Mesh at transformer models

The 3-D magnetic transient solver can calculate [7]:

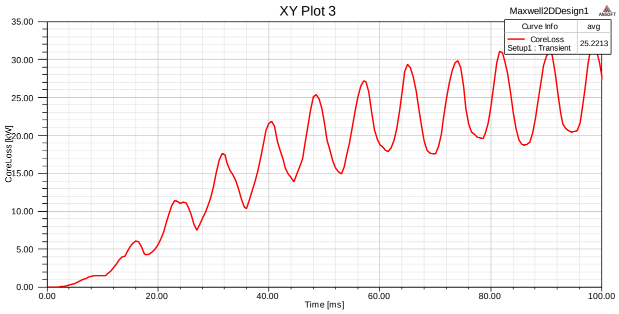
- the end-field effect as end-winding field effect and/or the influence of different stack lengths on the overall losses.
- core loss prediction due to a magnetic field component normal to the lamination stack.
- effect of time-controlled current/voltage wave forms on operating point conditions.
- eddy-current effects induced into conductive materials.

3. Results and discussions

Transient simulation is run for predefined time and time step. Simulation results of core losses are obtained for two different frequencies 50 Hz and 60 Hz and for 2D and 3D model. Core losses are averaged over the time. For all above-mentioned variants, they are presented in Figs. 6. and 7.

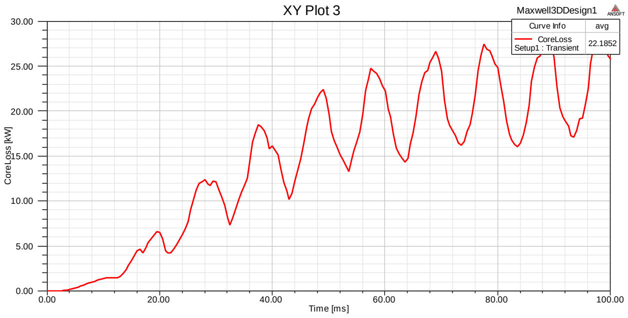


(a) core losses at 50 Hz

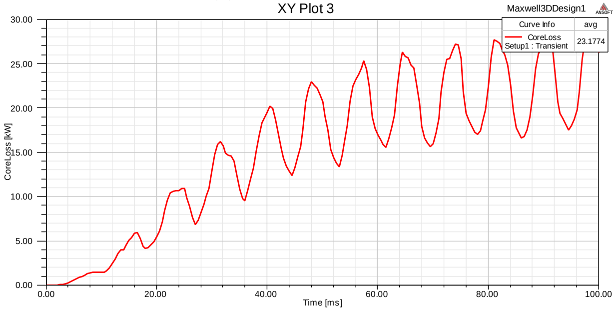


(b) core losses at 60 Hz

Fig. 6 Core loses at 2D model



(a) core losses at 50 Hz



(b) core losses at 60 Hz

Fig. 7 Core losses at 3D model

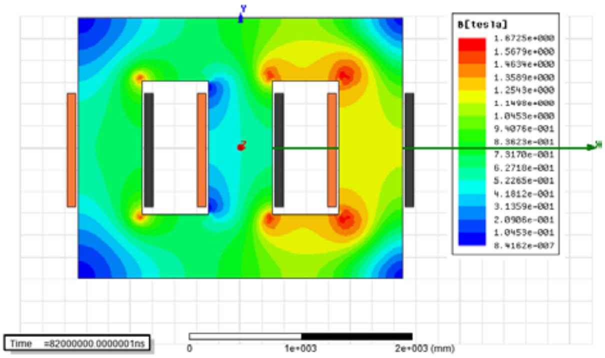
Core losses are averaged over the time interval from 80 to 100 ms. Their values in different models and frequencies are presented in Table 1.

Table 1: *Core losses at different models and frequencies*

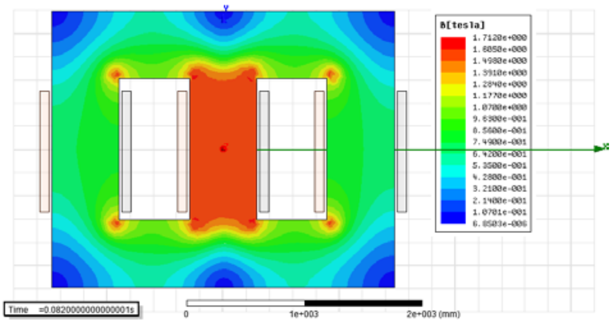
	2D model		3D model	
	50 Hz	50 Hz	50 Hz	60 Hz
Core losses [kW]	19.9	25.2	22.1	23.1

Comparison of results from Table 1 shows that there is a slight difference between the obtained values of core losses in 2D and 3D model of the transformer. The tested core losses at 60 Hz are 23.7 kW. Obtained results in both transformer models are close to the measured value of losses, which confirms the accuracy of presented models. Models are simulated for both frequencies of supply voltage 50 Hz and 60 Hz. As expected core losses are lower at frequency 50 Hz i.e. they should decrease approximately by factor 5/6. FEM model cannot consider all of the physical and manufacturing core loss effects in laminated core. These effects include mechanical stress on laminations, edge burr losses, step gap fringing flux, circulating currents, and variations in sheet loss values [7].

Over the years, FEM proved to be a useful tool toll in numerical calculation of different electromagnetic quantities. It is especially useful in calculation of magnetic flux density in machines cross-section. Calculation of the magnetic flux density, based on empirical formulas, gives only approximate values of the flux density at different parts of the machine. Accurate predication of the flux density at different parts of the machines is important in the design process for predicting so-called week parts of the machine where core material is close to the point of saturation (knee of the B-H curve). Operation of the machine near to the point of core saturation increases the losses, heat dissipation and reduces the efficiency. Therefore, flux density is analyzed at different time intervals for both models and both frequencies. Fig. 8 presents the results for 2D model and Fig. 9 for 3D model respectively.

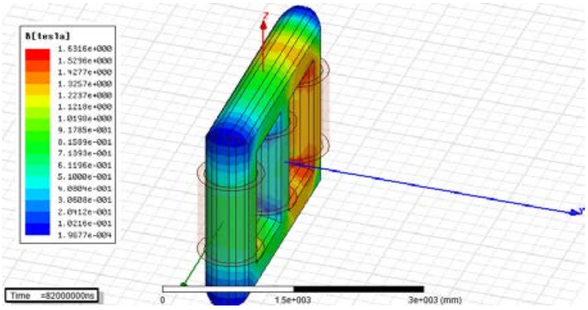


(a) flux density at 50 Hz

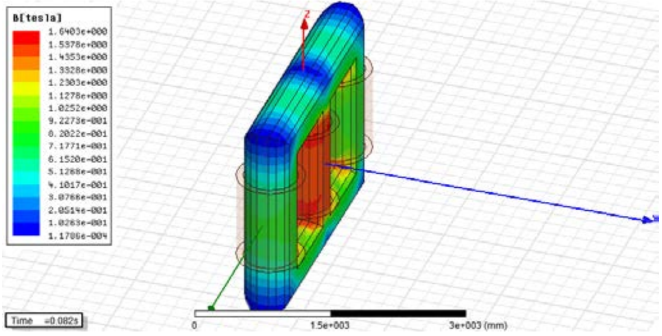


(b) flux density at 60 Hz

Fig.8. Flux density distribution at 2D transformer model



(a) flux density at 50 Hz



(a) flux density at 60 Hz

Fig. 9. Flux density distribution at 3D transformer model

From presented results in Figs. 8 and 9 it is evident that for both frequencies and in both models, transformer operates at no –load, with flux density distribution in core cross-section well bellow the saturation point (approximately 2 T- Fig. 2). As expected due to the bigger core losses at 60 Hz, the flux density is higher at 60 Hz than at 50 Hz power supply.

4. Conclusion

Knowing the losses in electrical devices is important in terms of the exploitation of the device but also in terms of its design. Therefore, accurate simulation models for anticipating the losses are helping the designers in their task to design energy efficient devices. Simulation model of transformer based on FEM is presented. Obtained 2D and 3D models allow calculation of core losses for three-phase symmetrical power supply. Models are powered with 50 and 60 Hz power supply. Due to lower frequency losses are reduced at 50 Hz , compared to 60 Hz power supply. Flux density distribution in transformer cross-section is calculated as well. Obtained results in all models have proved that transformer at no-load is operating well beyond the point of core saturation. Further research will be focused on calculating the core and copper losses for all operating modes and obtaining the efficiency factor of the transformer, based on simulation models and analysis.

5. References

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