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Analysis of the Effects of Different Frequency Values on the Loss of Transformers

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Abstract

Accurate simulation and loss estimation in power transformers are crucial for both the design phase and useful life of the transformer. In this study, core losses and magnetic flux densities of a power transformer for different frequency values are calculated. For this, ANSYS @ MAXWELL software based on the Finite Elements Method (FEM) and the 3D simulation model of the transformer were examined. The results obtained from simulations performed at 50 Hz and 60 Hz frequencies were compared with theoretical and experimental results. It has been observed that increasing the frequency causes increased heat and loss in the core of the transformer.

Keywords: Core loss, power transformer, magnetic flux density, frequency.

1. Introduction

Modeling and correct simulation of power transformers has always been a challenge for engineers. Power transformers are one of the most expensive elements of the energy system. Therefore, the prediction that the transformer is working correctly and possible malfunctions have always been a problem for engineers. High frequency models of power transformers are recommended for analysis of transient interaction between transformers and power system [1]. An algorithm and transformer model is proposed to identify different internal faults that cause power interruption in the transformer [2]. In recent years, the Finite Element Method (FEM) has been widely used to model various nonlinear materials and permanent magnetization of these materials [3-5]. In cases where partial discharge occurs in transformer winding FEM is used to calculate transformer parameters [6]. In recent years, various powerful software have been developed to calculate transformer parameters, operating modes and different types of loss [7]. In this paper, the 3D power transformer model given in Fig. 1 is presented below to calculate the core losses and magnetic flux density in the transformer section. Since the core losses are calculated in case of transformer operation at 50 Hz frequency without load, only the low voltage winding is energized with nominal voltage.

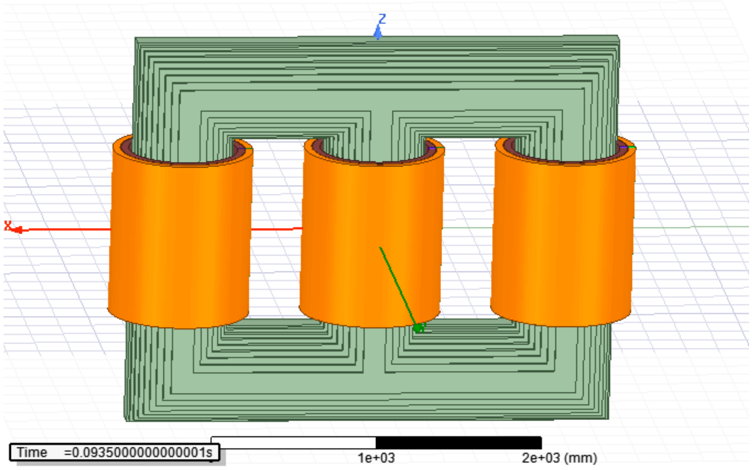


Fig. 1. 3D model of the transformer

The distribution of the magnetic flux density in the core section is shown by simulation. Flux density is calculated at different time intervals. Flux density information helps to identify parts of the nucleus near the saturation point. Depending on the flux density information, the saturation characteristic of the nucleus and the core losses are determined depending on the characteristic and the transformer design can be modified to optimize them.

2. Modeling of Transformer and Electromagnetic Accounts

Based on the actual transformer dimensions and geometry, FEM models are created for 3D simulations of low frequency temporary electromagnetic fields. The basic process of transient simulation includes regional and temporal separation of physical equations. There are various approaches for regional separation, such as finite differences, finite elements and limited volumes. Finite Element Method (FEM) is the most widely used method in engineering applications. With this method, complex, non-homogeneous and anisotropic materials can be modeled and complex geometries can be analyzed using irregular meshes (mesh) [8-9].

FEM solves Maxwell's equations based on a given excitation and frequency value. Simulation is accomplished by field parsing along the time axis to simultaneously solve all time stages. In the designed transformer model, boundary conditions, outer geometry and the properties of all materials are defined on the design in the program environment. The magnetic core is characterized by the B-H curve of magnetization and fine laminations. These characteristic features are used in the simulation of the transformer model. The characteristic B-H curve of the material used in the core is given below in Fig. 2. The P-B curve, which is the specific core losses given in Fig. 3 below, is also introduced in the simulation environment and the core losses are calculated for the frequencies of 50 Hz and 60 Hz.

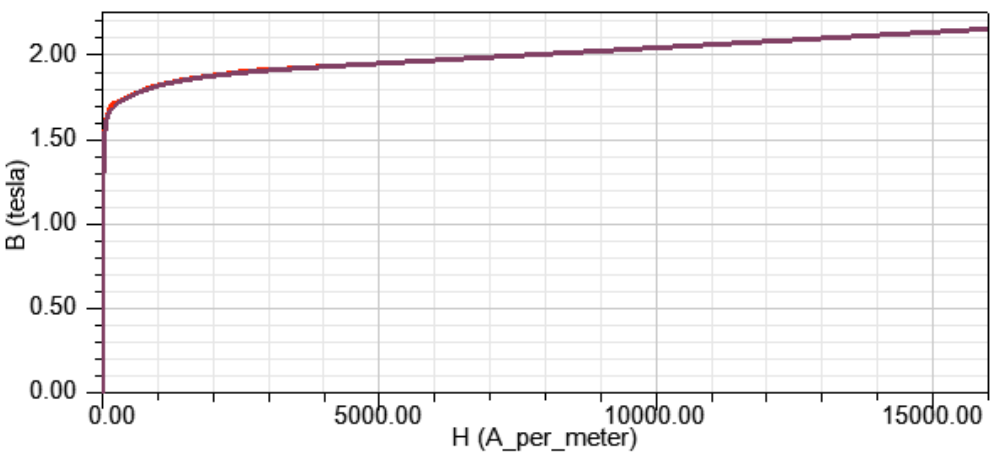


Fig. 2. B-H curve of core laminations

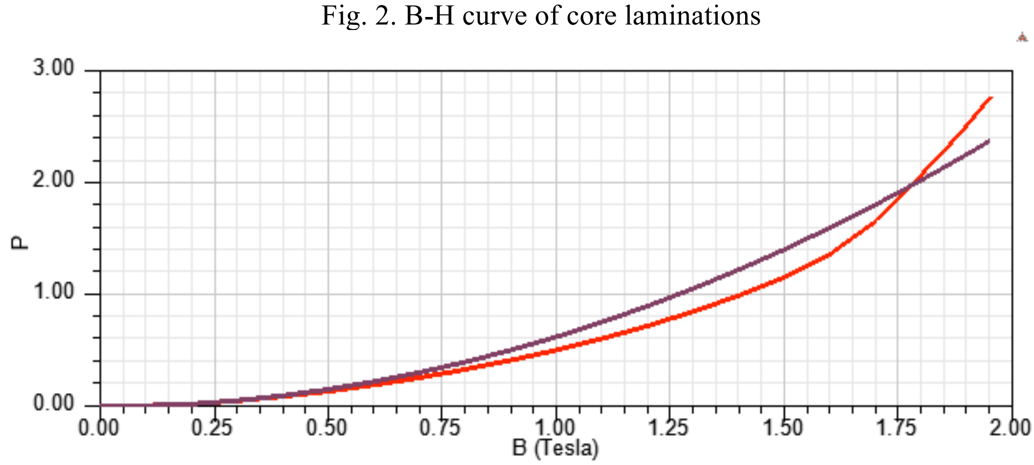


Fig. 3. P-B curve of core losses

Where; B is the magnetic flux, H is the magnetic flux intensity and P is the losses per kg. Also, the red curve is the actual curve. The black curve is the regression of the original curve.

The properties and parameters of the transformer designed in ANSYS@MAXWELL environment are given in Table 1 below.

Table 1. Design features of the transformer

Rated Power	15 MVA
HV	33.000 V
LV	11.000 V
Core loss	12.500 W
Copper loss	97.000 W
HV Winding Resistance	1.7 Ω
LV Winding Resistance	40 mΩ
%U_k	%11
Io	% 0.44
HV connection	Delta

LV connection	Star
HV turn number	135
LV turn number	665
HV phase current	784 A
LV phase current	156 A
Current density	1.8 A/m^2

In general, core loss (Pc) is divided into two components: hysteresis losses (Ph) and eddy current losses (Pe). According to the Steinmetz equation, the measurement and calculation of core losses are done with the normally varying Mag-B and frequency of sinusoidal flux of the frequency. These measurements and calculations are often modeled with a bi-term function of the form depending on the standard coil.

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

Where, kh, kc and n are coefficients that depend on lamination, material thickness, conductivity and other factors [10].

In this study, the calculation of core losses are made according to:

$$P_c = P_h + P_e + P_{excess} = K_1 B_m^2 + K_2 B_m^{1.5} \tag{2}$$

Eddy current loss:

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

Hysteresis loss:

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

Excessive loss:

$$P_{exces} = k_e (f B_m)^{1.5} \tag{5}$$

For that reason:

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

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

The k_1 and k_2 coefficients are obtained by minimizing the function. Eddy current loss coefficient is calculated as follows:

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

Where; σ conductivity and d is the thickness of the lamination layer.

In this case, core losses in transformer models are defined as total losses for a specific frequency such as 50 Hz or 60 Hz (P-B curve). When the design of the transformer model is started with the starting frequency of 60 Hz and the model frequency is changed to 50 Hz, both the amplitude of the input phase voltage and the factor of the transformer are reduced. This prevents the transformer from overheating when the operating frequency of the transformer is changed from 60 Hz to 50 Hz. Because when the frequency is changed, the currents passing through the windings do not change. Power losses are calculated at both operating frequencies. For core losses, only one energetic winding should be considered. An exponentially increased voltage source is applied to eliminate sudden currents and shorten the simulation time as given in Fig. 4 below.

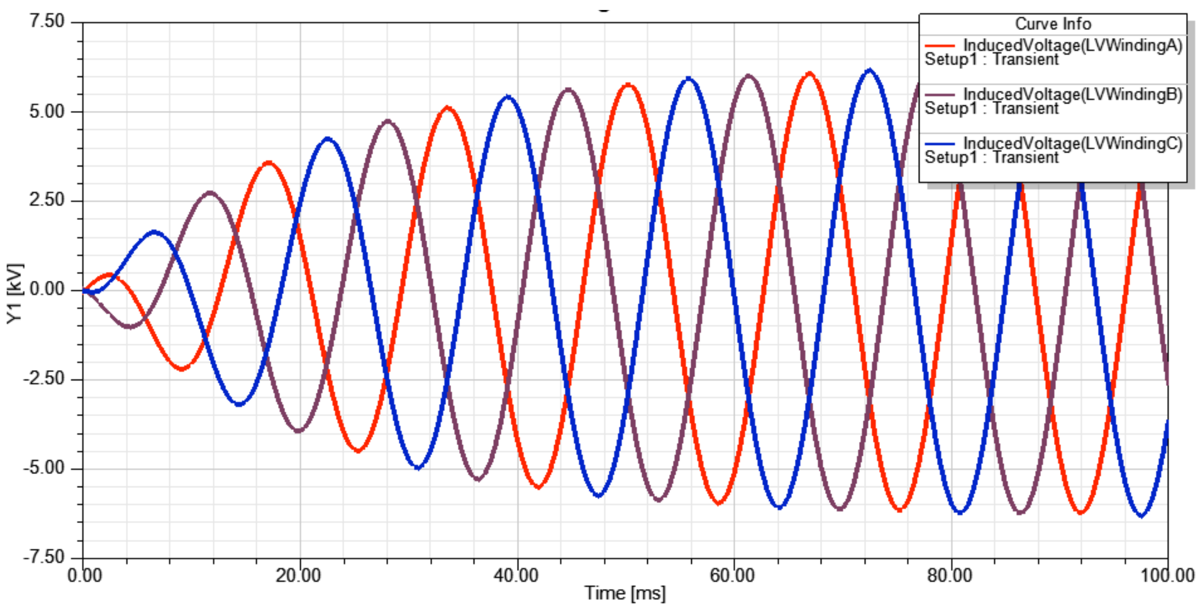


Fig. 4. Input voltage at 50 Hz

In order to calculate the magnetic flux density B, the magnetic vector potential A must be present. For this purpose, all model geometry is divided into many elements, usually triangles, where A is approximately matched by a simple function. Mesh (mesh) formed by finite elements in 3D model is presented in Fig. 5.

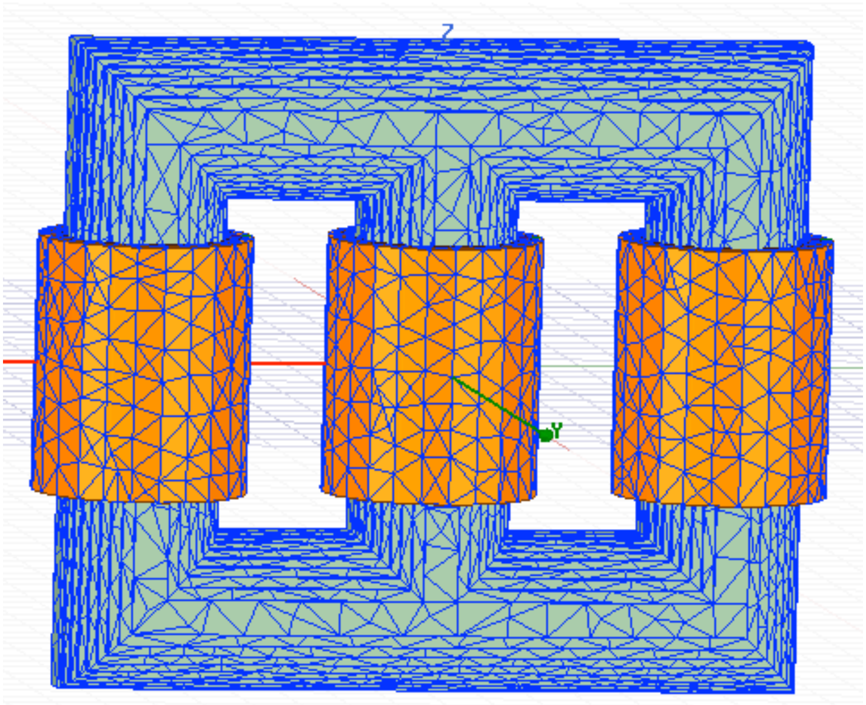


Fig. 5. Mesh in transformer models.

3. Simulation and Analysis of the Model

In transient simulation, analysis is performed for predefined time interval and time step. From the simulation of the 3D model of the designed transformer, core losses were obtained for two different frequencies of 50 Hz and 60 Hz. Core losses are calculated by taking the average of the total losses obtained over the given time interval over time.

3.1. Analysis of Losses

From the simulation of the 3D model, core losses and magnetic flux distribution were obtained for two different frequencies of 50 Hz and 60 Hz. Graphs of core losses, eddy current losses and hysteresis losses depending on all the above variables are presented in the Figs below.

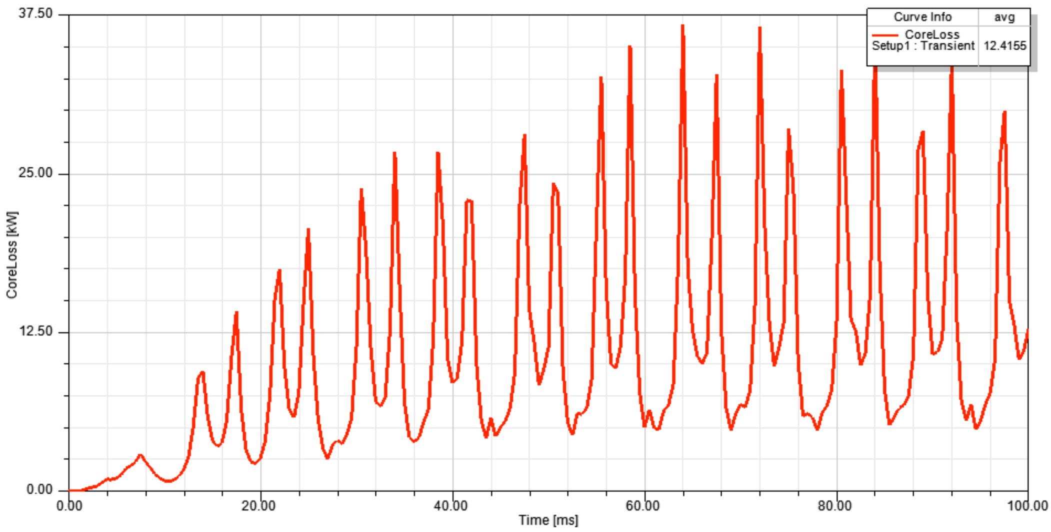
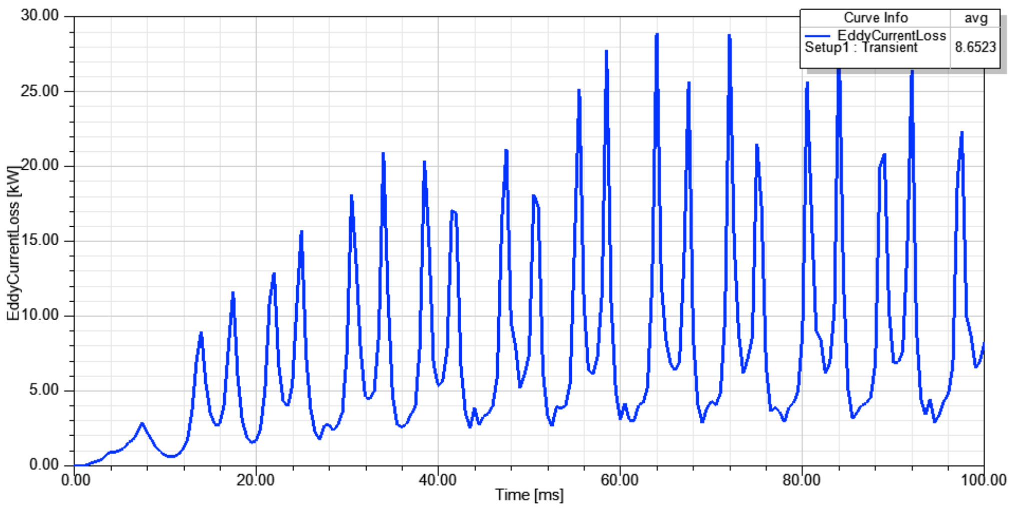


Fig. 6. Core loss of the model at a frequency of 50



Hz

Fig. 7. Eddy loss of the model at a frequency of 50 Hz

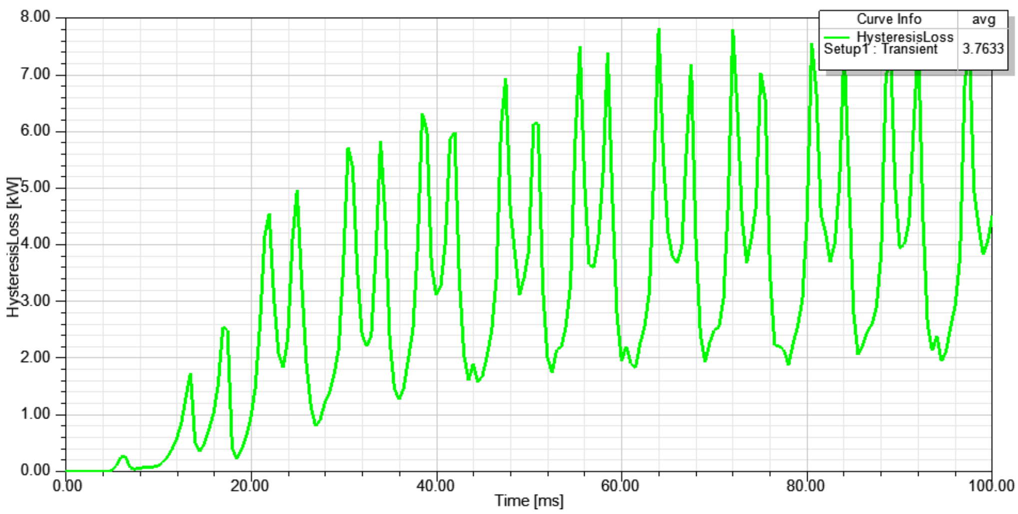


Fig. 8. Hysteresis loss of the model at 50 Hz frequency

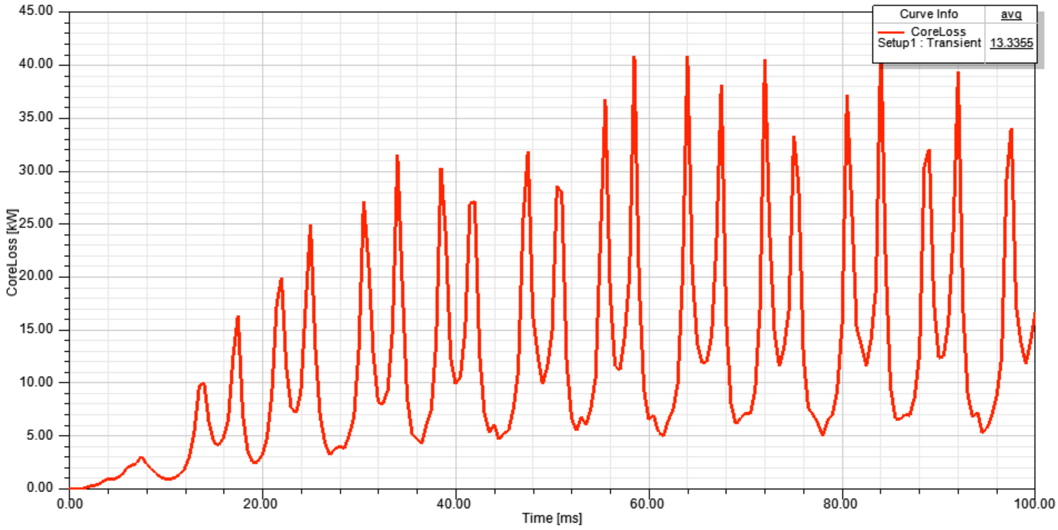


Fig. 9. Core loss of the model at a frequency of 60 Hz

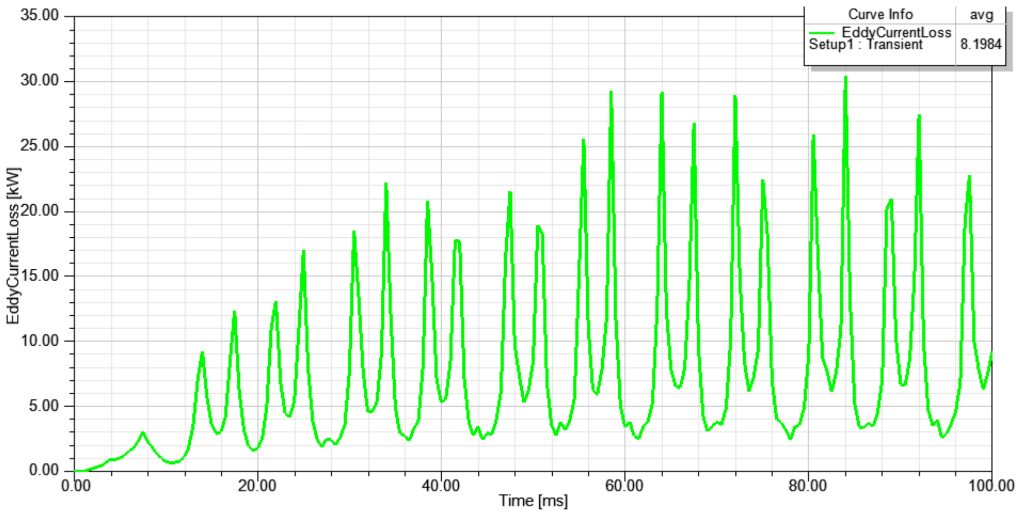


Fig. 10. Eddy loss of the model at a frequency of 60 Hz

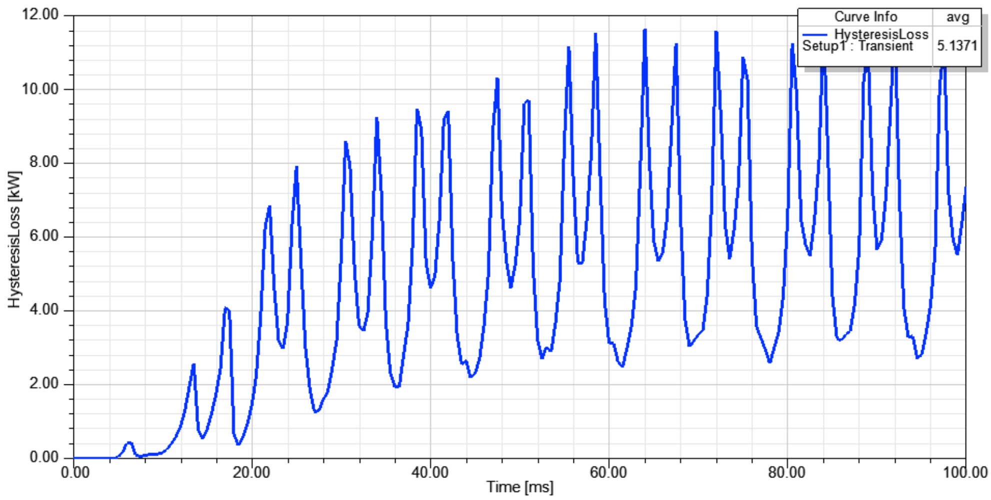


Fig. 11. Hysteresis loss of the model at a frequency of 60 Hz

The loss values of the transformer at different frequencies are compared in Table 2 below.

Table 2. Loss values at different frequencies.

	Simulation results		*Theoretical results*
	50 Hz	60 Hz	50 Hz
Core loss (kW)	12.41	13.34	12.36
Eddy current loss (kW)	8.65	8.2	8.59
Hysteresiz loss (kW)	3.76	5.14	3.77

There is a difference between 50 Hz and 60 Hz core and copper loss values of the transformer. The core losses tested at 50 Hz are 12.5 kW. The designed model is simulated within both the frequencies of 50 Hz and 60 Hz. As expected, core losses were lower at a frequency of 50 Hz.

3.2. Electromagnetic Field Analysis

The operation of the core of the transformer close to the saturation point increases losses and heat dissipation, reduces efficiency. Therefore, the flux density was analyzed at different time intervals for both frequencies. The 3D magnetic flux density of the transformer is presented Fig. 12 below.

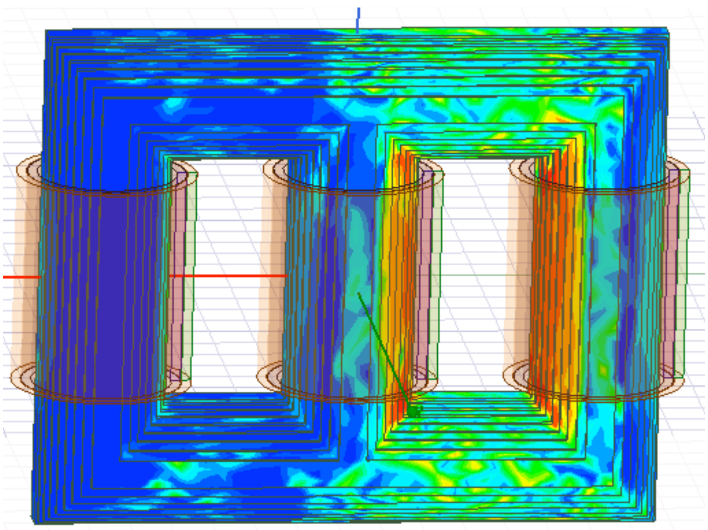


Fig. 12. Flux density distribution in 3D transformer model for 50 Hz frequency.

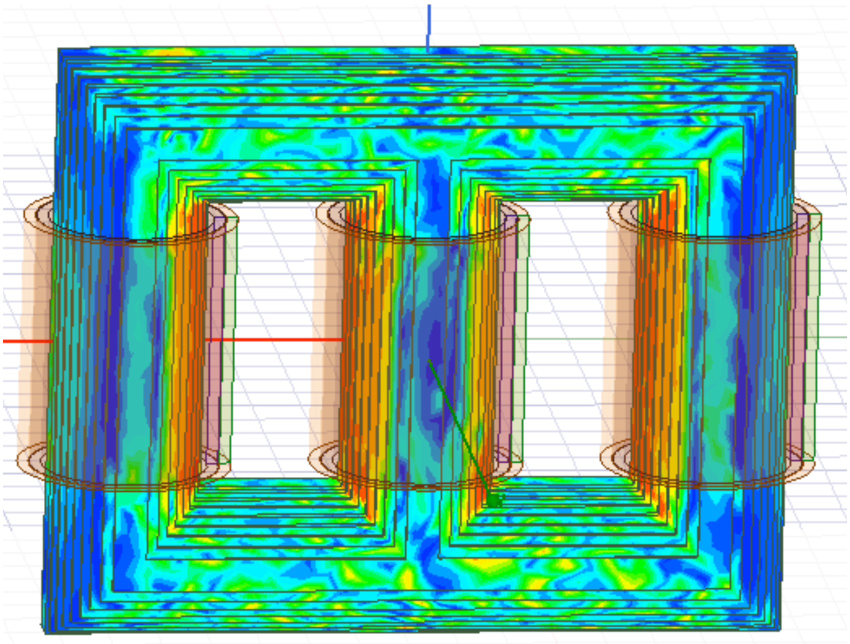


Fig. 13. Flux density distribution in 3D transformer model for 60 Hz frequency

It is clear that the flux density distribution in the core cross section of the transformer, which operates at 50 Hz and 60 Hz frequency without load, determines the saturation point well. As expected, the density of flux was higher than the frequency of 50 Hz at 60 Hz, since the loss of core occurred more in the model working at 60 Hz.

When the results in Table 2 are compared, it shows that there is a difference between the core loss values obtained in the 3D models of the transformer. The core losses tested at 50 Hz are 12.5 kW. 3D models are simulated within both the frequencies of 50 Hz and 60 Hz. As expected, core losses are low at a frequency of 50 Hz. All physical core loss effects are not calculated with the FEM model. Unpredictable effects include variations such as mechanical pressure on laminations, edge roughness loss, gradual hollow flux, circulation current and sheet loss.

For accurate estimation of flux density in different parts of the transformer, it is important to correctly estimate the parts of the transformer, called the weak part, where the core material is close to the saturation point (B-H). Operation of the transformer close to the core saturation point increases losses and heat dissipation, decreases efficiency. Therefore, the flux density is analyzed at different time intervals for both frequencies.

4. Conclusions

Knowing the losses in electrical devices is important in terms of both design and use of the device. Therefore, estimating losses with the right simulation models helps designers design highly energy efficient devices. FEM based transformer simulation model is presented. The obtained 3D models provide the calculation of the main losses for the three-phase symmetrical power supply. Models are powered by 50Hz and 60Hz frequency power supplies. Losses occurring at 50 Hz are lower than losses occurring at 60 Hz due to low frequency losses. The flux density distribution in the transformer section was also calculated.

From the results obtained from all models, it has proven that the transformer which operates without a load works well above the saturation point of the core.

References

[1] E.I. Amoiralis, M.A. Tsili, A.G. Kladas, “Transformer Design and Optimization: A Literature Survey”, IEEE Transactions on Power Delivery, Vol. 24, No.4, pp 1999-2024, 2009

[2] P. S. Georgilakis, M. A. Tsili, and A. T. Souflaris, “A heuristic solution to the transformer manufacturing cost optimization problem,” J. Mat. Process. Technol.,vol. 181, pp. 260–266, 2007.

[3] Yugendrao K. N.,Structural Modeling of a Three Phase Core type Transformer using ANSYS Maxwell 3D, Internatıonal Journal Of Innovatıve Research In Electrıcal, Electronıcs, Instrumentatıon And Control Engıneerıng Vol. 4, Issue 4, April 2016, pp. 17-20.

[4] S. Vasilija, FEM 2D and 3D design of transformer for core losses computation, Scıentıfıc Proceedings XIV Internatıonal Congress "Machınes. Technologıes. Materıals." 2017– Summer Sessıon Volume V, 345-348.

[5] M.B.B. Sharifian, R. Esmaeilzadeh, M. Farrokhifar, J. Faiz, M. Ghadimiand G. Ahrabian, computation of a single-phase shell-type transformer windings forces caused by ınrush and short-circuit currents, Journal of Computer Science 4 (1):, (2008) 51-58.

[6] T. OROSZ, G. KLEIZER, T. IVÁNCSY, Z. Á. TAMUS, Comparison of methodsforcalculation of core-form power transformer’score temperature rise, Periodica Poly technica Electrical Engineering and Computer Science, 60(2), 2016, pp. 88-95.

[7] M. L. Myint, Y. A. OO, Analysis of distribution transformer design using FEA, International Journal of Scientific Research Engineering &Technology (IJSRET), Volume 3, Issue 4, July 2014, (773-775)

[8] N. A. M. Yusoff, K. A. Karim, S. A. Ghani, T. Sutikno, A. Jidin*Multiphase transformer modeling using finite element method, International Journal of Power Electronics and Drive System (IJPEDS) Vol. 6, No. 1, March 2015, pp. 56~64.

[9] Y. Chen, P.Pillay, An Improved Formula for Lamination Core Loss Calculation in Machine Operating with High Frequency and High Flux Density Excitation, IEEE, 2002

[10] User’s guide – Maxwell 2D/3D. 2019