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Electromagnetic Field and Total Loss Analysis of Transformers by Finite Element Method

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Abstract:
In the design of transformers, determining the optimum values of the design parameters, the system in which the transformer will be used and the electrical power to be transferred are important for the continuity and safety of the system. It is very important for transformer design to know the electromagnetic field distribution and losses by creating electrical model of transformers. In this paper, the theoretical, experimental and numerical analysis of the transformer were carried out. With the ANSYS @ MAXWELL-3D, simulations were carried out to determine the electromagnetic fields generated in transformer cores and windings for the purpose of efficient and safe operation of transformers. The results obtained during the study were calculated in real time. With the ANSYS @ MAXWELL-3D package software, the magnetic field and magnetic flux distribution of the transformer, especially in the case of transient events, are investigated. In addition, the core and copper loss of the transformer were examined experimentally, theoretically and numerically and comparisons were made. In this paper, by taking into consideration the electromagnetic field model, the core and winding design of the transformer were made and the equivalent circuit parameters were determined. In this paper, short circuit test and open circuit test of transformers were carried out and field analyzes of transformers were performed and cores and copper losses were calculated and compared. The effect of ferromagnetic properties on core losses was determined, problem areas were determined, and the effect of magnetic field density and flux intensity on losses were determined. These results proved the accuracy of the FEM method used.
*Keywords:*Transformer, Finite Element Method (FEM), Electromagnetic Flux, Transformer Losses.

I. Introduction

Transformers in general means are the devices that provide the safe and high efficient transport of the electricity produced in the power plants until the electric machines and electronic products are reached. The main losses of the transformers are the losses of iron and copper.The main cause of iron losses come from uneven distribution of the variable magnetic fluxes in the core and the distortion in the core.Design criteria must be taken into account to ensure the optimum balance between the cost and performance of the transformer [1, 2]. Various methods have been developed and studies have been carried out.

The design and modeling of a three-phase core-type transformer with coils and terminals using magnetostatic analysis in the ANSYS Maxwell simulation platform is described in detail at Ref [3]. ANSYS Maxwell's finite element method with 30 MVA power of the transformer 2-dimensional and 3 dimensional core losses are calculated separately for 50 Hz and 60Hz frequencies are compared in Ref [4]. By using the ANSYS Maxwell software, due to the inrush current and short circuit current the forces which is occured in the the single phase shell type 10 MVA power transformer windings is investigated [5]. The Finite Element Method, which is the most up-to-date calculation method with four commonly used calculation methods, was compared with two practical examples [6]. Magnetic circuit theory and finite element method with a voltage of 100 KVA and 11 / 0.4 kV voltage values and triangular star connection structure of the 3-phase, dry type distributor with the finite element method (FEM), the flux density and current density in the transformer to check the initial assumption data transformer was analyzed [7]. It has shown that when the transformer is designed, according to the result which is obtained from the FEM is a good criteria for cost analyzis. And also efficiently designed can be made by using FEM [8]. The electromagnetic characterists and model of the transformer are clearly presented by analyzing a real transformer model with 3 inputs and 5 outputs [9].

The losses of 100 kVA mid-leg with 60 ° angle T-shaped 3-phase distribution transformer for different frequency values were tested in the unloaded state and the losses were examined [10]. The current formula of 3 sub-formulas used in the calculation of core losses is discussed and compared with the loss data provided by the steel manufacturers [11]. To calculate the transformer unload losses in other word the core losses, the accurancy of different models of numerical methods was investigated [12].The ANSYS Maxwell program analyzes the finite element method for Maxwell's equations and develops a network of self-adaptations and develops the most appropriate network of finite elements according to the problem. The number and quality of the network created by the user in the program affect the accuracy of the finite element analysis. The aim of this study was to investigate the magnetic field density, magnetic field strength, magnetic flux distribution, current density, core losses of transformer, and copper losses in windings with ANSYS Maxwell 3D package software.

In this paper, ANSYS Maxwell software, which is a commercial program, was used to analyze the field distribution of the 3D transformer model and to display the output result data at designated points. In the theory section, 3D model of single phase 90VA transformer used in the feeding of electronic circuits was investigated by using ANSYS Maxwell. Analytical, numerical and experimental results were compared.

2. Electrıcal Model of Transformer

In practice, the losses on the transformer must be taken into account in the actual models of the transformers. Copper losses, core losses (hysteresis losses and eddy current losses) and leakage wisdom should be taken into consideration in the creation of such a model. Considering these criteria, various measurements and experiments are performed to find the equivalent electrical model of the transformer.

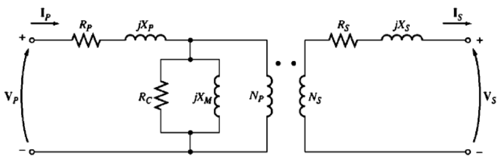


Figure 1. Transformer equivalent electrical model [13]

2.1. Measurement of Winding Resistance

Wheatstone and Kelvin bridge circuits are used in industry to measure winding resistances. In the laboratory environment winding resistances can be measured in 2 ways. Directly using the Ohmmeter or by applying DC current below the nominal values.

In the case of using an ohmmeter, the primary winding resistance Rp measured by ohmmeter during this measuring time the secondary winding terminal is open circuit. And the secondary winding resistance Rs measured by ohmmeter also during the measuring time the primary winding terminal is open circuit.

When the winding resistence being in very small value order the, resistance value can't measured with ohmmeter in Laboratory facilities, but instead using a variable DC power supply applied respectively to the primary and secondary winding ends , half of the rated current value, DC current applied to the transformer winding tips.

There are mainly two types of losses in transformers. These losses experimentally can be obtained by no load test and short circuit tests. Iron losses, obtained by no load test method. And copper losses are obtained by the short circuit test.

The power taken by the transformer in the no load operation gives the iron losses. Due to the small no-load operating current the copper losses are neglected also the iron losses are constant losses. Iron losses consist of the sum of hysteresis (Ph) and Fuko (Pfu) losses.

Hysteresis loss occurs as a result of the change of direction of the core molecules depending on the frequency. Fuko losses are the losses that occur in the form of heat caused by currents induced on the core.

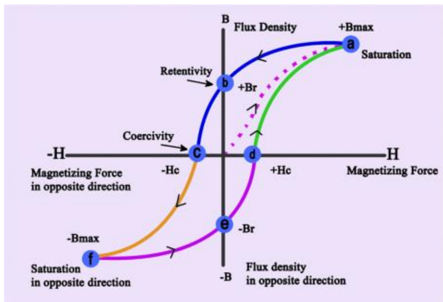


Figure 2. B-H cycle and saturation point [17]

The transformer no load loss is theoretically calculated as follows;

$$P_b = P_h + P_{fu} \quad (1)$$

$$P_h = K_h . f . (B_{max})^{1,6} \quad (2)$$

$$P_{fu} = K_{fu} . f . (B_{max})^2 \quad (3)$$

2.2. No Load Operation Test

This test’s target is to measure the core loss and magnetization inductance. When performing this test, the High Voltage winding terminals of the transformer are switched on and the nominal voltage is applied to the low voltage winding terminals. Since the transformer high voltage side is open circuit, the entire input current flows through the transformer excitation lever. Winding resistance and inductance is very small compared to Rc and Lm. When the Kirchof Voltage Law is taken into account, almost all of the applied voltage falls on the excitation arm. When the transformer is unloaded (when idle), the heat output is only composed of core losses. Since the test is applied at the rated voltage, there is a nominal magnetic flux in the core of the transformer (core) and the core losses are equal to the losses in the rated load. During this test, the input voltage, input current and input power of the transformer are measured. The easiest way to find the values of resistance and impedance (Rc and Xm) in excitation arm is to look at the admittance of the excitation arm. The total excitatory admittance was vectorally;

$$\mathbf{Y}_{\mathrm{eL}} = \frac{1}{R_{CL}} + \frac{1}{jX_{ML}} \quad 4$$

The total excitation admittance is calculated according to the low voltage side, the free current and voltage values as follows.

$$|\mathrm{Y}_{eL}| = \frac{|\mathrm{i}_{\mathrm{OC}}|}{|\mathrm{V}_{\mathrm{OC}}|} \quad 5$$

$$\text{Power Factor} = \cos\theta = \frac{P_{OC}}{|V_{OC}|.|i_{OC}|} \quad 6$$

$$\text{Power Factor Angle} = \theta = \cos^{-1}\left(\frac{P_{OC}}{|V_{OC}||i_{OC}|}\right) \quad 7$$

The L index indicated in the above formulas indicates that the measured values are relative to the low voltage side.

2.3. Short Circuit Test

The purpose of this test is to measure copper losses and small inductances in the transformer. In the short-circuit test, the low-voltage winding terminals of the transformer are short-circuited and the rated current is applied to the High Voltage terminals by means of a variable voltage source. In other words, the voltage is increased, in the high voltage winding terminals until the rated line current has passed. In power transformers, this voltage is expressed in Uk and usually ranges from 8% to 15% of the rated voltage.

Since the input voltage is low during the short circuit, a current is ignored which is neglected by the excitation arm of the transformer, thus, almost all of the applied voltage falls on winding resistances and inductances when the Kirchof Voltage Act is applied. The flux in the core is also low because the current passing through the excitation arm is very small, therefore, core losses are negligible according to losses at normal voltage level. The loss of power in this test consists only of copper losses. As the test is applied at rated current, copper losses are equal to copper losses at nominal load.

In this paper, the input voltage, input current and input power of the electronic circuit transformer which is studied are measured. The amplitude of the series impedances according to the high voltage side of the transformer (Z_{SEH});

$$Z_{SEH} = \frac{|V_{SC}|}{|i_{SC}|} \quad 8$$

$$\text{Power Factor} = \cos\theta = \frac{P_{SC}}{|V_{SC}|.|i_{SC}|} \quad 9$$

$$\text{Power Factor Angle} = \theta = \cos^{-1}\left(\frac{P_{SC}}{|V_{SC}||i_{SC}|}\right) \quad 10$$

When the value of the serial empedance is found as a vector value, due to the current lagging the voltage, the angle of the serial impedance being positive.

$$\mathbf{Z}_{\mathrm{SEH}} = \frac{V_{SC}}{i_{iC}} \angle(\theta) \quad 11$$

Total serial impedance of the electrical model of the transformer is $\mathbf{Z}_{\mathrm{SE}}$

$$\mathbf{Z}_{\mathrm{SEH}} = R_{ES} + \boldsymbol{j}X_{ESH} \quad 12$$

$$\mathbf{Z}_{\mathrm{SEH}} = (R_H + a^2.R_L) + \boldsymbol{j}(X_H + a^2.X_L) \quad 13$$

$$a = \frac{N_H}{N_L}$$

N_H:Number of HV winding , N_L:Number of LV winding

R_H: HV winding resistance, R_L:LV winding resistance

X_H:HV leakage reactance, X_L:LV leakage reactance; additional theoretically

3.EXPERIMENTAL ANALYSIS OF SINGLE PHASE TRANSFORMER

For the analysis and measurement of the single-phase transformer, an electronic circuit transformer with 90 VA apparent power is used.

3.1. Determination of The Winding Count of The Transformer

A Mantel type transformer was used for testing and analysis. The windings are wrapped around the middle leg. The input voltage of the transformer is 220 V AC and the output voltages are 12, 18, 24, 36, 42 and 48 V respectively. The primary and secondary connections of the transformer are shown in Figure 3 below.

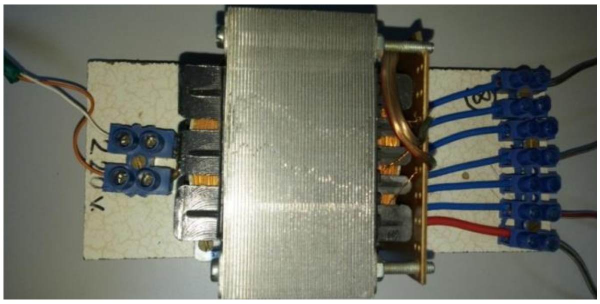


Figure 3. Primary and secondary connections of transformer with 1 input and 6 outputs with 90 VA power

The following steps were taken to determine the number of input and output windings of transformer windings.

- On the middle leg, 8 windings (third windings) are wrapped tightly with a fine copper wire around the outlet windings.
- 220V is applied to the ends of the high voltage (220V) windings.
- 2.34 V voltage was calculated from the ends of the third winding (having 8 windings).

- Since the winding number and winding voltage are known to be directly proportional;

  Using the Formula $\frac{V_1}{N_1}=\frac{V_2}{N_2}=\frac{V_3}{N_3}$

  $V_1=220V$, $V_3=2.34V, N_3=8$ winding; it is calculated that the input side (on the high voltage side) is winding 752.
- The number of windings on the output side (LV winding) 164 turns.

3.2. Measured Electrical Values of Transformer in Laboratory

Two different methods were applied to find winding resistances;

Method 1

The resistance values of the input and output windings were measured by using ohm meter when the transformer was not connected to any source. In this case the resistance value measured in the input winding of the transformer is about 21.13 ohms, while the output windings have 6 different voltage levels resistance values for each stage were measured and values are presented in Table 1.

Table 1. Values of the low voltage side winding resistors of the transformer.

Stage	Label Voltage (V)	Measured Voltage (V)	Resistance which is measured with 0 stage (Ω)
0	0	0	
1	12	12.2	0.41
2	18	17.9	0.51
3	24	23.8	0.66
4	36	36.4	0.89
5	42	42.3	1.04
6	48	47.9	1.20

Method 2

DC power supply was used. The nominal current values of the high voltage and low voltage windings were calculated and applied to the terminals of the DC current transformer with half of these current values, respectively. Winding resistances were calculated by using measured DC voltage and current values. The primary winding value and the secondary winding resistances in the 6th stage were calculated from the transformer's apparent power value;

$$S=V_P.i_P=V_S i_S \quad 14$$

90=220.i_P=48.i_S

$i_P=0.409A$, .$i_S=1.875A$

The value of the winding resistances of the high voltage and low voltage sides during the test is calculated by the following method.

To calculating the primary and secondary winding resistance the method which was described in stage 2.1 was used and so;

Half value of the primary winding DC current was applied and $i_{PDC}=0.20\ A$ and the measured voltage found that V_{PDC}= 4,3 V, than according to Ohm Law's the primary winding resistance calculated as; $R_P=\frac{V_{PDC}}{i_{PDC}}=\frac{4,3}{0.20}\approx 21,5\ \Omega$. By using the same method the secondary winding's resistance found as;

$i_{SDC}=0.938A$, $V_{SDC}=0.969\ V$ and

$$R_S=\frac{V_{SDC}}{i_{SDC}}=\frac{0,969}{0,938}=1,03\ \Omega$$

No Load Operation Test

The high voltage (220V) winding ends of the transformer opened and the rated line voltage (48V) was applied to the low voltage winding leads. The ammeter on the low voltage side was connected to the circuit in series and the open circuit current was measured as 152 mA. The magnitude of the calculated circuit admittance after this stage;

$$|Y_{OCL}|=\frac{|i_{OC}|}{|V_{OC}|}=\frac{152*10^{-3}}{48}=3,17*10^{-3}$$

The loss of the core in the open circuit of the transformer at Afşin Elbistan B T.P.P. / Electric Maintenance Workshop was measured as 4W as seen in Figure 4. Also in no load operation, 0.152 A current passed inside the LV windings measured with Ampermeter. Theoretically angle between this current and voltage was calculated as 56.7° therefore the core losses was calculated as:

$$V_{OC}=48V\ ,\ i_{OC}=0.152A\ ,\ \cos(\theta_{OC})=0.548$$

$$P_{OC}=(48)(0.152)(0.548)\cong 3.99W$$

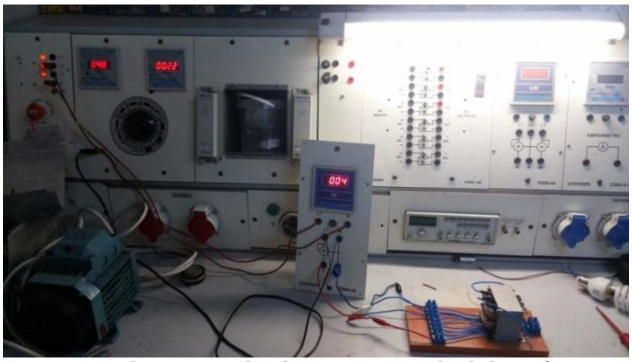


Figure 4. Core loss measured with Wattmeter in unloaded transformer test

Short Circuit Test

Low voltage (48 V) winding ends of transformer was short circuited. The high voltage winding leads were applied to the nominal line current (~ 400 mA) with a variable voltage source. As the test is applied at nominal current values, copper losses are equal to copper losses at rated load. The input voltage (Vsc), input current (Isc) and input power (Psc) of the transformer during the test were measured in Figure 5.

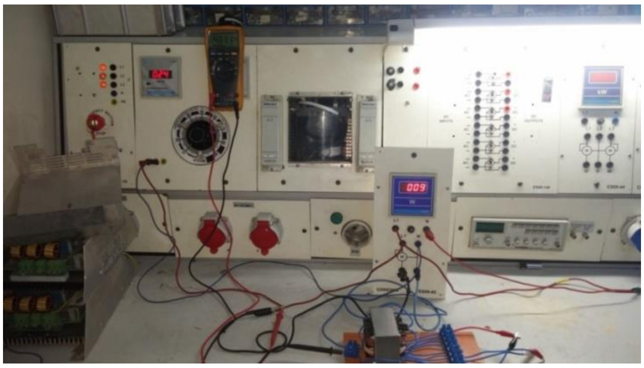


Figure 5. Copper loss measured by Wattmeter in short circuit test

$P_{SC} = 9W$, $i_{SC} = 0,4A$ ve $V_{SC} = 24V$

The amplitude of the serial impedance according to the high voltage side of the transformer;

$$|Z_{SE}| = \frac{|V_{SC}|}{|i_{SC}|} = \frac{24}{0,4} = 60\Omega$$

The power factor $=\cos(\Theta_{SC}) = \frac{P_{SC}}{|V_{SC}|.|i_{SC}|}$ and Power Factor angle $= \theta = \cos^{-1}\left(\frac{P_{SC}}{|V_{SC}||i_{SC}|}\right) = \cos^{-1}\left(\frac{9}{|24||0,4|}\right) = 20,36°$

The impedance angle is positive since the current is behind the voltage vectorically.

$$\mathbf{Z}_{\text{SEH}} = \frac{V_{SC}}{i_{iC}}\angle(\theta) = \frac{24}{0,4}\angle(20,36°) = 60\angle(20,36°)\Omega = 56,25 + \boldsymbol{j}.20,86$$

Total serial impedance of the electrical model of the transformer $\mathbf{Z}_{\text{SE}}$;

$\mathbf{Z}_{\text{SEH}} = R_{ES} + \boldsymbol{j}X_{ESH} = (R_H + a^2.R_L) + \boldsymbol{j}(X_H + a^2.X_L)$

$a = \frac{N_H}{N_L} = 4,58$ and $a^2 = 20,98$

$\mathbf{Z}_{\text{SEH}} = 56,25 + \boldsymbol{j}.20,86$

56,25=21,5+20,98.R_L

$R_L = 1,66\,\Omega$

Additionally, the relation between input and output impedances of the transformers

$X_H = a^2.X_L = 0,5.X_{ESH}$

$X_{ESH} = 20,86$ therefore,

$X_H = 10,43\Omega = 2.\pi.f.L_H = 100.\pi.L_H$, $L_H \cong 33\,mH$

$X_L \cong 0,49\,\Omega = 2.\pi.f.L_L = 100.\pi.L_L$, $L_L \cong 1,58\,m$H

However, the resistance of the transformer windings has been calculated theoretically and the copper loss in the transformer has been calculated due to these windings. Resistance of a conductive wire;

$$R = \rho.\frac{l}{A}$$

l length of the conductive wire, *A* cross sectional area of the conductive wire and ρ it is the coefficient of self-conductivity and this value for the copper winding conductor is $0,0175\Omega.\frac{mm^2}{m}$ in room conditions.

In the light of this information, it is necessary to calculate the length of the high voltage and low voltage windings separately to find the resistance of the windings. Both windings are known to be wound around the middle leg of the transformer. The average length of the 1 conductor around the transformer leg is 200mm, total length 752 * (0.2m) for 752 windings on high voltage side. All the calculated values presented Table 2.

The diameter of the conductor forming the high-voltage winding is 0.8mm, so the radius is 0.4mmand surface area $A = \pi r^2$ in this case high voltage winding resistance;

$$R_H = \rho.\frac{l_H}{A_H} = 0,0175\Omega.\frac{mm^2}{m}.\frac{752.(0.2m)}{\pi(0.2\text{mm})^2} \cong 20.95\,\Omega$$

Since there are 164 windings on the low voltage side, the total length is 164 * (0.2m).

The conductor of the low-voltage winding is 0.4 mm in diameter, therefore the radius is 0.2 mm and the surface area is $A = \pi r^2$, in this case the low-voltage winding resistance;

$$R_l = \rho.\frac{l_l}{A_l} = 0,0175\Omega.\frac{mm^2}{m}.\frac{164.(0.2m)}{\pi(0.4\text{mm})^2} \cong 1.14\,\Omega$$

Table 2. Measured / calculated values of high voltage and low voltage winding resistors by different methods.

	Measured with Ohmmeter	Calculated by electrical model	Calculated by DC test	Calculated by conductive wire resistance
R_H	21.13Ω	21.5 Ω	21.5 Ω	20.95 Ω
R_L	1.20 Ω	1.66 Ω	1.03 Ω	1.14 Ω

Full Load Test

During this test, the transformer was supplied by low voltage (48 V) and 4 lamps were connected to the high voltage side. When adjusting the voltage from the input side to the input side, the rated current (~ 1,875A) was obtained from the ammeter until 48 V was given. A total of 82 lamps (3 * 24W and 1 * 10W) are connected in parallel to the high voltage side as a loadat the same time, the ampermeter measured 1.878 A (practical current value) and watneteden 82W.In the full load test, 4 lamps have connected to the high voltage (220 V AC) side of the transformer as shown in figure 6.

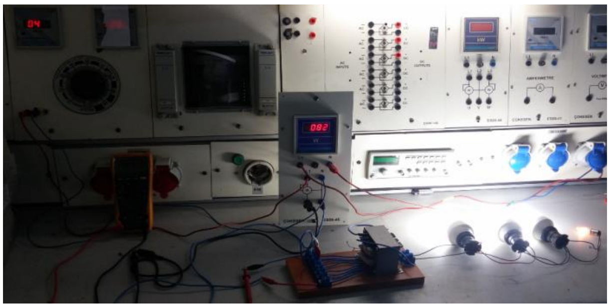


Figure 6. The load drawn by the load (lamps) in full load test was measured by Wattmeter

Copper losses were also calculated. In this scope, electrical power formulas were calculated by taking into consideration the input and output winding resistances and nominal current values.

$$P_H = {i_H}^2 . R = (0.409^2).(21,13) = 3,535\ W$$
$$P_L = {i_L}^2 . R = (1,875^2).(1.20) = 4,219\ W$$

Total copper losses in the winding theoretically is; $P_{SC} = P_H + P_L = 7,754\ W$

4.Modelıng Of Transformer Wıth Fınıte Element Method

FEM models based on real transformer dimensions and geometry are created for 3D simulation of low frequency transient electromagnetic field. The basic process of transient simulation involves the spatial and temporal separation of physical equations. In this paer, the model of transformer which is working on ANSYS Maxwell program interface is presented in Figure 7.

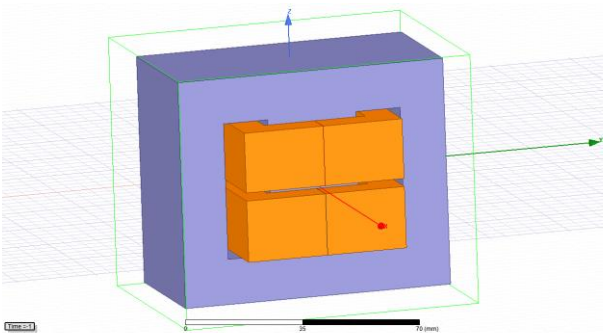


Figure 7. Transformer 3D model in ANSYS Maxwell Interface.

There are several approaches to spatial decomposition: finite differences, finite elements, and limited volumes. Finite Element Method is widely used in engineering application. With this method, complex, non-homogeneous and anisotropic materials can be modeled and complex geometry can be analyzed using irregular mesh.

The FEM solves the Maxwell's equations based on a given excitation and frequency. The transient simulation is performed by field parsing along the time axis to simultaneously solve all time stages. In both transformer models, boundary conditions, external geometry and properties of all materials are defined. The magnetic core is characterized by a B-H curve of magnetization and thin laminations.These characteristics are used in the simulation of both transformer models.Specific core losses are defined in the P özelde simulation environment and the core losses are calculated for a specific frequency of 50 Hz.Figure 8 shows the curve B-H of the magnetic material, Figure 9 shows the curves of specific core losses (B-P).

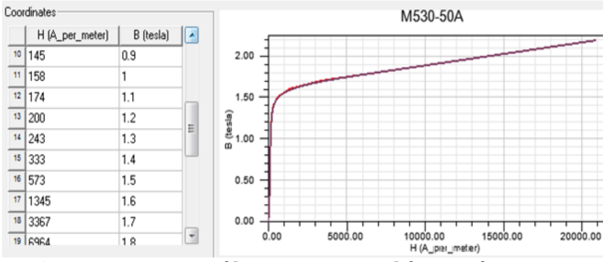


Figure 8. B-H curve of lamination material for transformer core

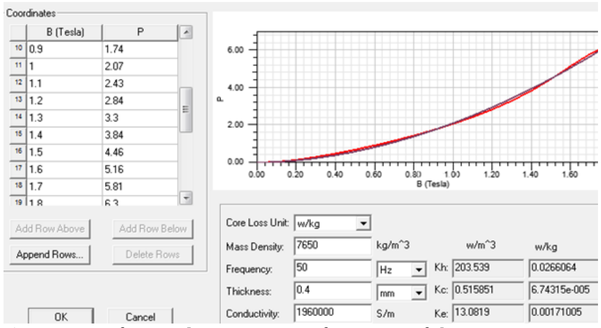


Figure. Specific core losses at 50 Hz frequency of the M530-50A type laminating material

In general, the 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 is done by Mag-B and the frequency of sinusoidal flux of the frequency.These measurements and calculations are often modeled with a two-term function of the form, depending on the standard coil:

In this paer, calculation of core losses is based on:

$$P_c = P_h + P_e = k_h f B^n + k_c f^2 B^2 \qquad 15$$

k_h, $k_c$and n are coefficients that depend on lamination, material thickness, conductivity and other factors.This formula is valid in cases where the maximum flux density is 1T, not for rotating electrical machines and transformers.

$$P_c = P_h + P_e + P_{excess} = K_1 B_m^2 + K_2 B_m^{1.5} \qquad 16$$

Eddy Curren Loss:$P_e = k_c (f B_m)^2 3$ 17

Histerezis Loss:$P_h = k_h f {B_m}^2$ 18

ExcessLoss:$P_{exces} = k_e (f B_m)^{1.5}$ 19

Therefore:$K_1 = k_h + k_c f^2, \quad K_2 = k_e f^{1.5}$ 20

Eddy Current Loss Coefficient:$k_c = \pi^2 \sigma \frac{d^2}{6}$ 21

σ: conductivity, d: lamination thickness

The coefficients K_1 and K_2 are minimized by the function:

$$f(K_1K_2) = \sum\left[P_{vi} - \left(K_1B_{mi}^2 + K_2B_{mi}^{1.5}\right)\right]^2 = min \quad 22$$

P_{vi}, B_{mi}- i-th point of the data on the measured loss characteristic curve.

The other two losses coefficient

$$k_h = (K_1 - k_c f_0^2)/f_0 \quad 23$$

$$k_c = k_2/f_0^{1.5}, \quad 24$$

where f_0The test frequency of the loss's curve.

In this case, the core losses in the transformer models are defined as the total loss for a specific frequency such as 50 Hz (P-B curve). For core losses, only one energy winding should be considered.In order to eliminate instantaneous currents and shorten the simulation time, an exponentially increased voltage source is presented in the following equations.

$$V_a = V_{peak}.(1 - \exp(1 - 50.t).\cos(2.\pi.50.t) \quad 25$$

$$V_b = V_{peak}.(1 - \exp(1 - 50.t).\cos\left(2.\pi.50.t + (\tfrac{2}{3}.\pi)\right) \quad 26$$

$$V_c = V_{peak}.(1 - \exp(1 - 50.t).\cos\left(2.\pi.50.t + \left(\tfrac{4}{3}.\pi\right)\right) \quad 27$$

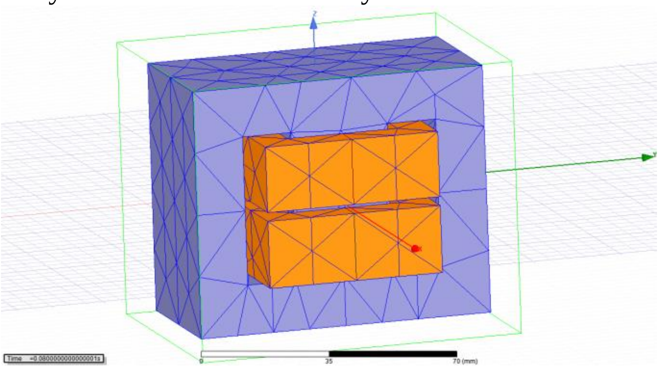
The magnetic vector potential A must be present for the calculation of magnetic flux density B.To this end, the whole model geometry is divided into several elements, usually triangles, where A is approximately mapped to a simple function.In the 3D model, the mesh formed by the finite elements is presented in Figure 10.With the 3-D magnetic transient, the following can be calculated;

The effect of different laminating stack lengths on total losses in windings.

Estimation of a normal magnetic core loss in the laminating stack due to the field component.

Effect of time-controlled current / voltage waveform on operating point conditions.

Eddy current effects induced by conductive materials.



Şekil 10. Transformer 3D model with meshes.

5. Sımulatıon And Result

5.1. Open Circuit Test

For the open circuit test, the analysis is performed for the predefined time interval and time step in the simulation connected to the transient solvent. In this simulation test, core losses for the 50 Hz frequency were obtained from the simulation of the transformer 3D model.The core losses are calculated by taking the average of the total losses obtained in the given time interval.The core loss curve obtained based on the above-mentioned variables is presented in Figure 11 below.

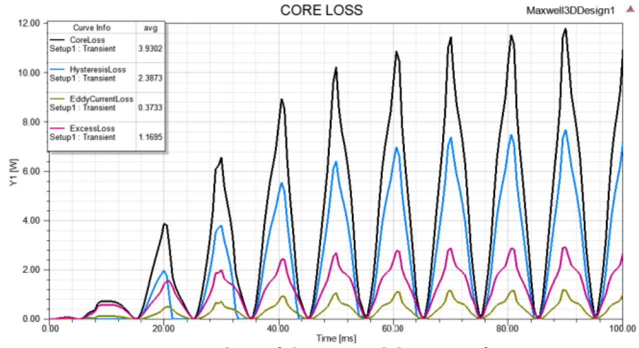


Figure 11: Core loss of the 3D model at 50Hz frequency

Core losses were obtained by taking the average of 80 to 100 ms time interval.The core losses obtained from the simulation of the transformer model are 3,9302 W.In order to confirm the accuracy of the results obtained from the transformer model, the results of the presented models are correct when compared to the 4W measured at 50Hz.

Table 3. Comparison of transformer's core losses

	Experimental Analyses Loss	ANSYS Maxwell numerical result
Core Loss (W)	4	3.9302

All the electromagnetic result are obtained at any instant of time between t=0-0.1 ms. Under 50 Hz frequency.

With the FEM model, all physical core loss effects are not calculated. Unpredictable effects, mechanical stress on laminations, loss of edge roughness,it includes variations such as gradual cavity flux, circulation current and layer loss.

It has been proved that FEM is a useful tool in the numerical calculation of different electromagnetic fields. It is especially useful for calculating the magnetic flux density in machine sections. Calculation of the magnetic flux density based on empirical formulas gives only approximate values of flux density in different parts of the machine.For the correct prediction of the flux density in different parts of the machine, it is important to correctly estimate the parts of the machine, which are called the weak parts of the machine, where the core material is close to the saturation point (B-H).Operation of the machine close to the core saturation increases losses and heat dissipation and reduces the efficiencyTherefore, flux density was analyzed at different time intervals.The 3D magnetic flux density values and the vector distribution in the open circuit test of the transformer are presented in Figure 12.

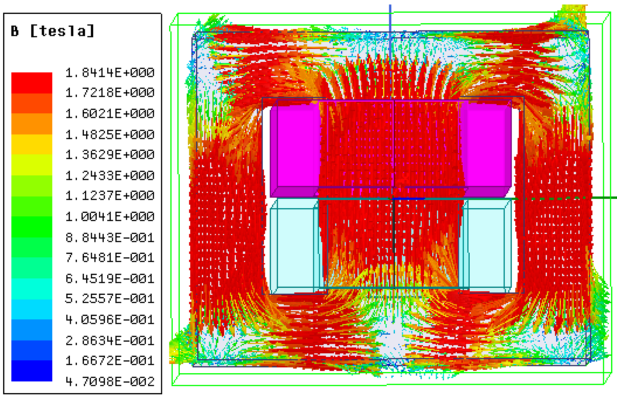


Figure 12. Magnetic flux density values and vector distribution in 3D transformer model core's

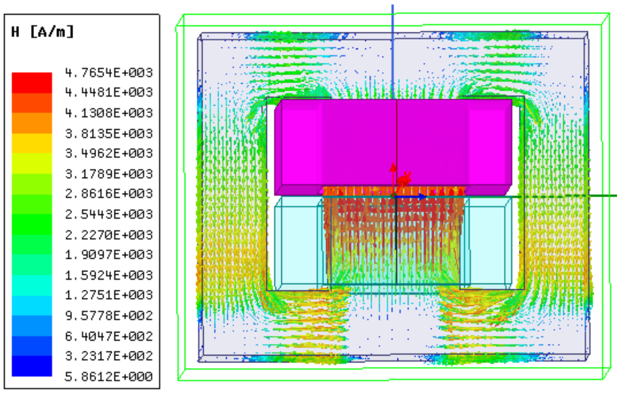


Figure 13. Magnetic field intensity value and vector distribution in 3D transformer model core's

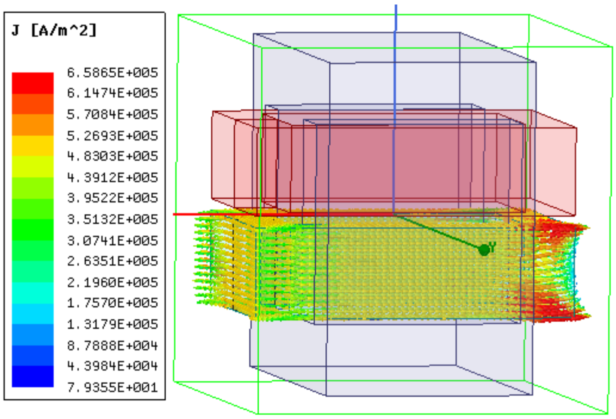


Figure 14. Current density value and vector distribution in 3D transformer model winding's

5.2. Short Circuit Test

As in the open circuit test, in this test, the analysis is performed for the predefined time interval and time step in the simulation connected to the transient solvent. In this simulation test, copper losses were obtained for the 50 Hz frequency from the simulation of the transformer 3D model.Copper losses are obtained by multiplying the square of the current passing through the windings by the resistance in the given time interval. The loss curve obtained based on the above-mentioned variables is presented in Figure 15 below.

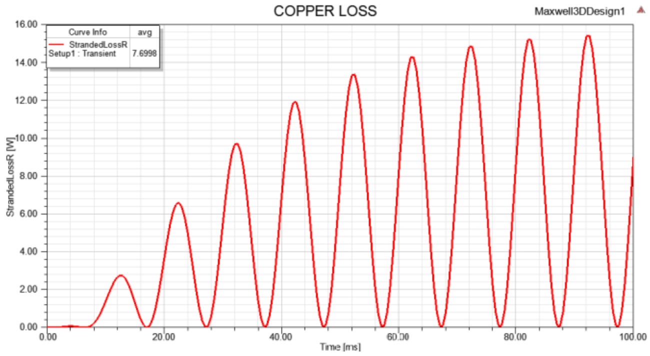


Figure 15. Copper loss of the 3D model at 50 Hz frequency

When the results in Table 5 are compared, the copper loss value obtained in the transformer model was 8,734 W. In order to confirm the accuracy of the results obtained from the transformer model, it is revealed that the results of the presented models are correct compared to the 9 W measured at 50 Hz.

Table 4. Comparison of transformer copper losses values.

	Experimental Result	ANSYS Maxwell Analyze Result	Theoretical Result
Copper Loss (W)	9	7.6998	7.754

When the above table is examined, it is seen that ANSYS Maxwell Program 's result with FEM is different from the actual value obtained in experimental study. This is due to the fact that the practical winding structure in transformer is slightly different from the winding structure chosen in the ANSYS Maxwell program.This result confirms the design of the transformer and the accuracy of the FEM method used.

The magnetic flux density of the transformer, the magnetic field strength, the current density values in the windings and the vector distributions are presented in the following Figures 16,17 and 18.

All the electromagnetic result are obtained at any instant of time between t=0-0.1 ms. Under 50 Hz frequency.

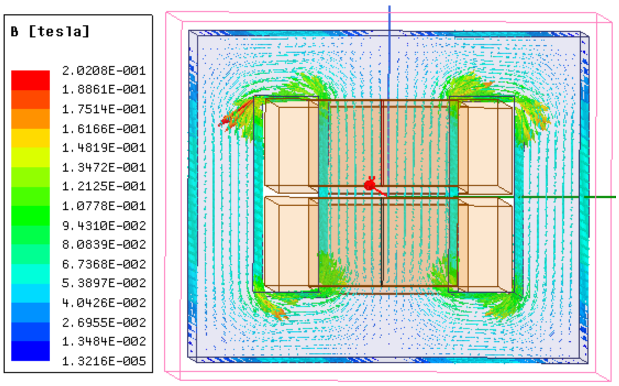


Figure 16. Magnetic flux density values and vector distribution in 3D transformer core's

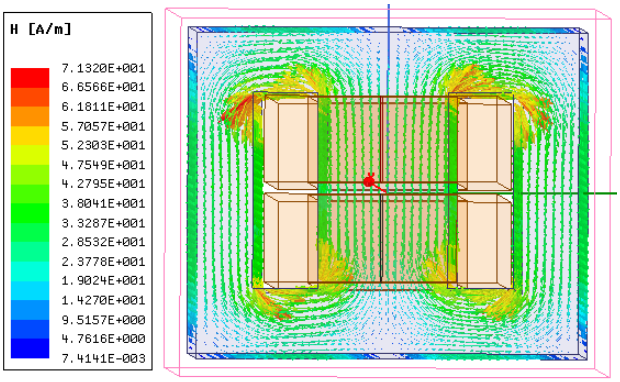


Figure 17. Magnetic field strength values and vector distribution in 3D transformer core's.

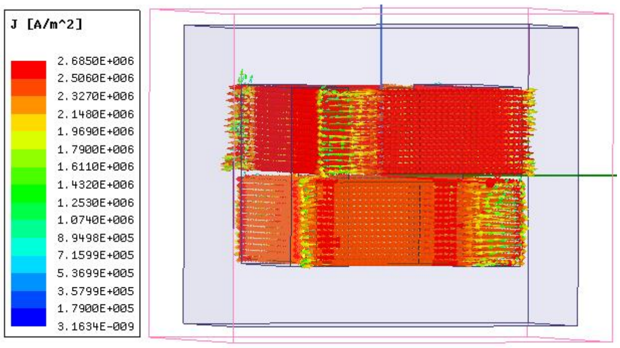


Figure 18. Current density values in the windings and vectorial distribution for 3D transformer model

6. Conclusıon

In this paper, FEM based transformer simulation model is presented. Simulation method based on FEM is proposed in this study. The resulting 3D models provided the main losses for single phase symmetrical power supply for analysis. Magnetic and electrical properties of core laminating material have been found to have a great effect on the occurrence of losses. The obtained theoretical, experimental and simulation results are compared for all working conditions. The results obtained from the simulation in normal conditions were found to be a difference of 0.7 % for the 3D model compared to the actual test results. Flux density distribution, flux intensity, current density and vector distribution of flux were determined in the transformer section. The results obtained from the 3D model proved that the transformer, which is no-load, works far above the point of saturation of the core. When both core loss and copper loss graphs were examined, it was seen that after the transient moment (t = 70 ms) the power functions changed over time depending on the frequency of 100 Hz, this confirms the accuracy of the design.

The results obtained in this study confirm the designed product.The model and results obtained show that the model is ready for production.

- The number of four faces is 10000 after the mesh is formed.
- The maximum magnetic flux density is 1.84 T.
- The core loss was 3.96 W and the copper loss was 8.73 W.

By reducing or increasing the distance between cores and windings, designers can achieve optimum designs using laminated electrical steels such as the core magnetic material M530-50A. Different solutions can be developed using methods such as FEM to reduce losses. Further studies and calculation of core and copper losses for all modes of operation, simulation models and analysis of the transformer's efficiency based on the analysis will enable optimum designs to be obtained. Thanks to the program, it is concluded that the transformer models can be transformed with the model parameters and the efficient transformer models can be obtained without losing the cost.

In the following studies for the core and copper losses for all operating modes efficiency of transformer based on calculation, simulation models and analysis more research and investigation on obtaining the factor will allow optimum designs to be obtained.

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