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PERFORMANCE ANALYSIS OF A DISTRIBUTION TRANSFORMER USING ANSYS MAXWELL

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Abstract- The purpose of this study is to verify the theoretical calculations of a three-phase transformer by analyzing its magnetic field behaviors and losses under no-load and full-load working conditions using an advanced simulation program that runs based on finite elements method (FEM). This paper presents detailed explanations on defining the parameters and obtaining the results, and also the calculation method for determining the magnitude of the magnetic field and the core and ohmic losses of the transformer. The reliability of the analysis is confirmed by theoretical calculation results.

Keywords: Electrical Motor, Transformer, Finite Elements Method, FEM, Magnetic Field.

1. INTRODUCTION

The developments of technology and the growth of human population are key contributors to the rising electricity demand. Transformer as one of the most important elements in power system also needs to keep up with the rapid changes in the industry. The transformer loss has an important role in the analysis of product reliability. These losses are generated by the windings, the magnetic core, the tanks and other metallic components in the transformer. Many optimizations are done to reduce the losses of transformer. With the advanced of numerical software analysis, transformer design optimization is able to be done without prototyping the product. Computer-based analysis helps understanding the behavior of the transformer as efficient as possible.

2. FINITE ELEMENTS ANALYSIS

Numerical method solves mathematic problems such as partial differential equations that cannot be solved with analytical method using arithmetic operations [1]. The advance of digital computer makes a faster and more accurate solution of electromagnetic problems with complex structures and boundary conditions possible. Numerical method uses a different linear equation system although having the same concepts with analytical method [1]. Each method has its own advantages and disadvantages.

Finite Elements Method (FEM), which is the most popular method for solving electromagnetic field problems, is preferred among various numerical solution methods [2]. The Finite Elements Method (FEM) can offer solutions of differential equations in different disciplines such as electromagnetic, magneto static, heat transfer, structural mechanics, fluid dynamics and acoustic waves [3]. The biggest advantage of the Finite Elements Method (FEM) is its ability to analyze complex models. The logic of the Finite Elements Method (FEM) can be summarized as following [4];

1) Reducing the number and size of solution regions to sub-regions with limited value
2) Deriving the obtained equations using relevant technique
3) Combining the sub-regions
4) Solving the system equations

The solution region consisting of sub-regions is called mesh. Figure 1 shows mesh elements created in this analysis. For a better and more precise solution the sub-regions can be divided into smaller sub-regions or smaller mesh regions. The solution becomes more precise as the mesh elements created are smaller and finer. Accuracy and simulation time depend on the number of mesh elements. The accuracy increases as the number of mesh element increases, however the simulation time is also increasing and the time needed to finish the analysis is getting longer [3].

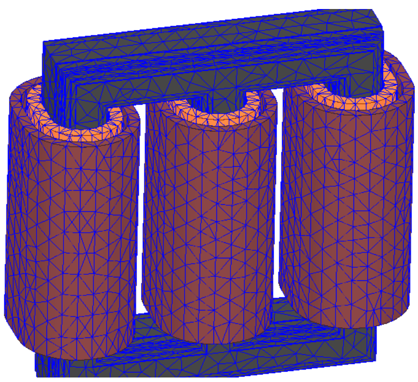

Figure 1. Mesh elements created in the analysis

3. TECHNICAL PARAMETERS AND THE DESIGN OF THE MODEL

The parameters of the transformer examined in this study and also the data considered in designing the 3D model of the transformer are shown in Tables 1 and 2.

Table 1. Parameters of the 250 kVA transformer

Model	Hermetic	
Power	250 kVA	
Input Voltage	11 kV	
Output Voltage	0.4 kV	
Primary Current	13.12 A	
Secondary Current	360.84 A	
Frequency	50 Hz	
Number of Phase	3	
$\%I_0$	1.75%	
Connection Group	Dy_n11	
No-Load Losses	288-300 W	
Load Loss	HV_{DC}	1 202 W
	LV_{DC}	961 W
	AC_{loss}	109 W
Magnetic Flux Density	1.49 T	
Temperature	Environment	40 °C
	Oil	60 °C
	Windings	65 °C
Cooling Type	ONAN	

Table 2. Parameters of the transformer core and windings

HV Winding	
Material	Aluminum
Number of Turns	1810
Winding Height	462 mm
Layer Width	33 mm
LV Winding	
Material	Aluminum
Number of Turns	38
Winding Height	540 mm
Layer Width	26 mm
Core	
Thickness	0.23 mm
Cross-Sectional Area	18.360 mm^2
Core Length	596 mm
Core Height	700 mm

The material of the transformer core is M3-Type electrical steel. Hysteresis curve is one of important issues in defining a core material. The Hysteresis curve shows the relationship between magnetic field density (B) and magnetic field intensity (H). In Maxwell, the curve is created automatically by writing the B and the H values in the given table or by importing the .txt file holding the B and the H values.

For iron loss calculation, parameters such as B-P curve, mass density, frequency, material thickness and conductivity need to be specified. The B-P curve shows the iron loss characteristics [8]. Hysteresis loss factor (K_h) and Eddy Current loss factor (K_c), which are used in no-load loss calculation, are calculated automatically based on the specified parameters.

4. EXCITATION CIRCUIT DESIGN

Feeding system of a transformer in Maxwell Transient analysis is done by connecting the transformer to an external excitation circuit. This method is carried out by another electrical circuit design program. In this study, Twin Builder, software from ANSYS, is used to build the feeding system for the transformer. Maxwell and Twin Builder are connected through co-simulation.

The external excitation circuit shown in the Figure 2 is designed according to the connection group of the transformer. The transformer analyzed in this study is connected in delta-star connection.

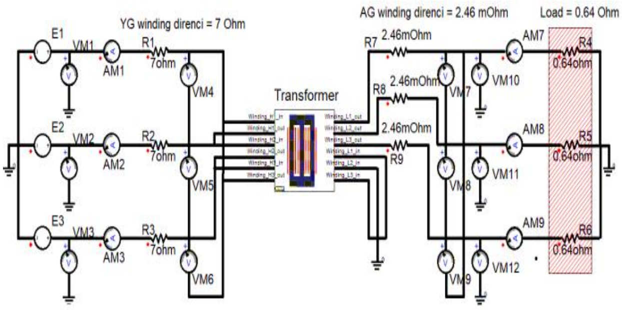

Figure 2. Delta-star connected external excitation circuit

5. SIMULATION ANALYSIS

5.1. Analysis Steps

In this study, a 250 kVA distribution transformer is modeled and analyzed with ANSYS Electronics Desktop. Maxwell is one of the features of ANSYS Electronics Desktop and is a computer-based simulation program widely used for analyzing electrical machines. ANSYS Maxwell is a software package that runs analysis using Finite Elements Method (FEM) [5]. ANSYS Maxwell provides information about behaviors of a system by creating 2 or 3 dimensional models in digital environment. Modeling and analysis of a transformer with ANSYS Maxwell are generally performed according to the flow chart in Figure 3 [5].

In this study, a 3-dimensional transient analysis is performed on a transformer. A 3D model analysis gives better results than a 2D model. It is determined that losses result obtained from a 3D analysis is closer to its values obtained from real measurement [6]. Another advantage of doing analysis in 3D is the ability to examine electromagnetic forces from different angles. However, 3D analysis has one major disadvantage. 3D model uses more mesh elements in its analysis. For this reason, it takes so much time to only run a 1 seconds-long 3D analysis [7]. In transient analysis, solution and sampling time need to be determined carefully. A smaller sampling time will result in more precise waveform and a more accurate analysis. Sampling time is selected depending on the period of the system. In this study, sampling is taken at every 0.2 milliseconds. Thus, 100 samples are taken in one period.

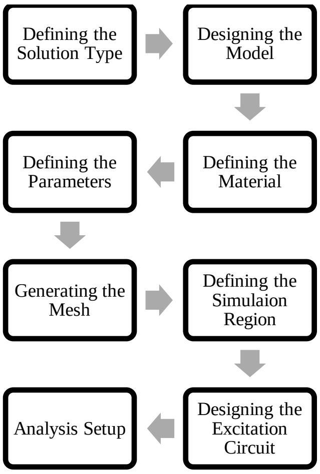

Figure 3. A basic flow chart of a transformer analysis

5.2. No-Load Analysis

The applied input voltage waveform of the no-load analysis is given in Figure 4. The input voltage of each phase starts from zero and gradually rises to its steady-state condition. The effective (RMS) value of the applied input voltage is 11 kV.

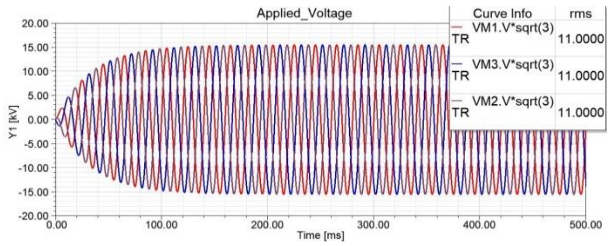

Figure 4. Input voltage of the transformer

Since the primary side is delta connected, the values of its phase and line voltage are the same. According to the analysis result, the effective (RMS) value of the primary induced voltage is 11 V and the line voltage of the secondary side of the transformer is 399.98 V. The voltages of the primary and secondary windings are shown in Figures 5 and 6, respectively.

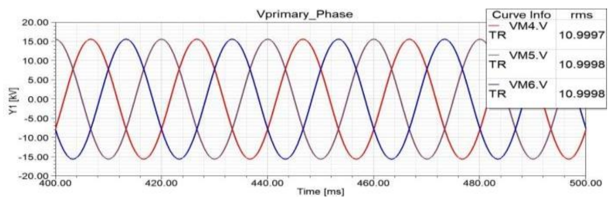

Figure 5. Phase voltage of the primary winding

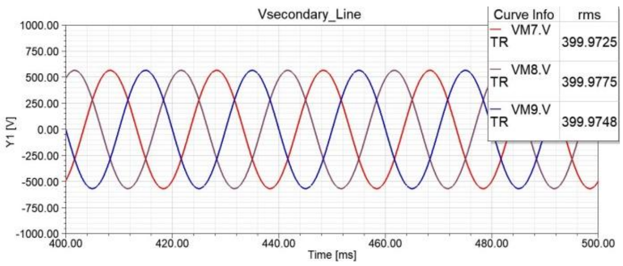

Figure 6. Line voltage of the secondary winding

In this simulation analysis, the no-load current is taken from the primary side or the high voltage winding. Since the no-load current is often represented as percentage, there will be no different whether it is obtained from the low or the high voltage side of the transformer. The waveform of the current under no-load condition is given in Figure 7. The no-load current of each phase of three phase three-legged transformer is not exactly the same. A three-phase three-legged transformer is imbalanced by the reason than the middle leg is magnetically shorter than the other two outer legs [9]. Considering the path taken by the flux is shorter, the flux from the middle leg is shorter than that of the left and right leg. Thus, the effective (RMS) value of the current passing through the middle leg is lower than the one passing through the left and the right leg [9].

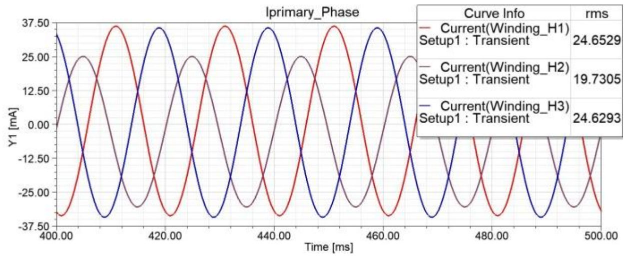

Figure 7. No load current of the three-phase transformer

RMS value of the no-load current is found to be 23 mA. The percentage value of the no-load current is calculated by the equation down below:

$$I_0\% = \frac{\text{No Load Phase Current}}{\text{Nominal Phase Current}} = \frac{23.0042\times10^{-3}}{13.12}\times 100\% = 0.175\% \quad (1)$$

Since the no-load current is obtained from the high voltage or the primary side, the nominal value of the primary current is used in the formula above. The percentage value of the no-load current given in the transformer's nameplate is calculated to be 0.177%.

Magnetic flux is directly related and proportional to no load current, since the flux is produced in response to the current. Therefore, the magnetic flux and the no load current waveforms are the same. The relationship between magnetic flux and current is shown in the equation down below.

$$Ni = R\Phi \quad (2)$$

In order to find the maximum value of the magnetic flux density, the cross-section area of the core must be known [4]. The magnitude of the magnetic flux density is calculated by using equation below.

$$B_{max} = \frac{\Phi_{max}}{A} = \frac{0.0273\,\text{Wb}}{0.0187\,\text{m}^2} \cong 1.46\ \text{T} \quad (3)$$

In three phase transformers, there is a 120-degree phase difference between each leg of the transformer [10]. Under no load condition, the magnetic flux distribution and magnetic flux vector in the core of transformer at the time instant of 92 ms are shown in Figures 8 and 9, respectively. As shown in the figures, each leg of the transformer has different distribution due to the phase difference. Conclusions can be made from the figures as follow;

1. At 92 ms, the magnetic flux density of the left leg of the transformer is higher than the other two legs.

2. At 92 ms, the flux of the left leg of the transformer flows upward to the positive direction. Thus, the instantaneous value of the magnetic flux is positive.
3. At 92 ms, current passes through the left leg of the transformer is higher than the other two legs.

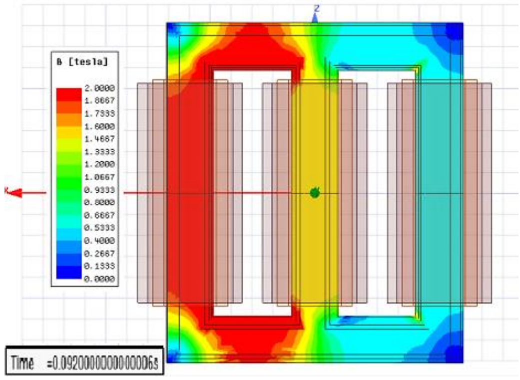

Figure 8. Magnetic Flux Distribution (at 92 ms)

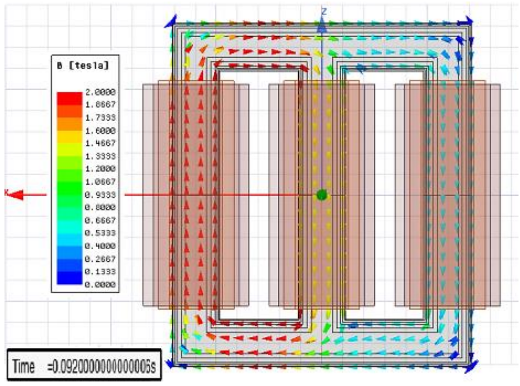

Figure 9. Magnetic Flux Vector (at 92 ms)

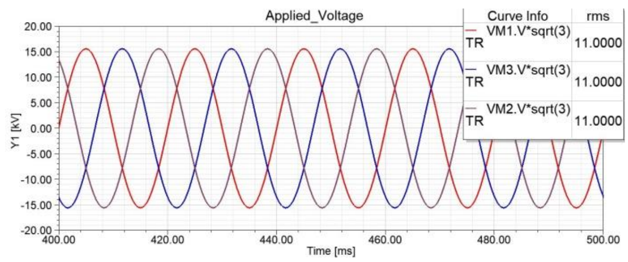

Figure 10. Waveform of the input voltage under full load condition

5.3. Full-Load Analysis

When determining the maximum load of a transformer, the connection group of the transformer must be taken into consideration. In this analysis, the load is star-connected to the secondary side of the transformer.

Similar with the no-load analysis, the input voltage and current of each phase starts from zero and gradually rises to its steady-state condition. The waveform of the input voltage under full load condition within 400-500 ms time range is shown in Figure 10. The induced primary and secondary voltages obtained as result of the simulation are shown in Figures 11 and 12. The waveforms of the primary and secondary currents under full load condition are shown in Figures 13 and 14, respectively.

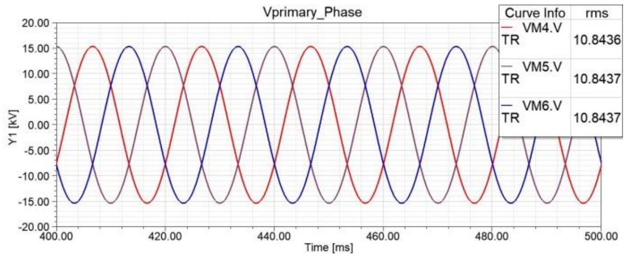

Figure 11. Waveform of the primary voltage under full load condition

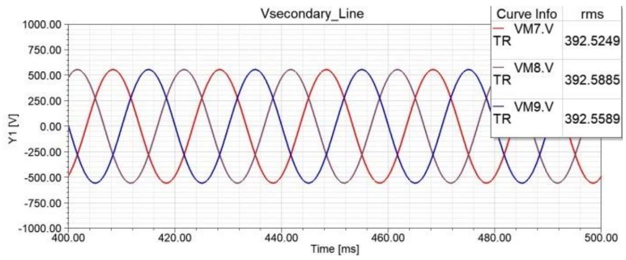

Figure 12. Waveform of the secondary voltage under full load condition

The transformer used in this simulation study is a 250 kVA transformer. This transformer changes the line voltage from 11 kV to 400 V. The nominal currents can be calculated as follows.

$$S = \sqrt{3} I_{line} V_{line} \tag{4}$$

$$I_{line}(prim) = \frac{S}{\sqrt{3} V_{line}(prim)} = \frac{250000}{\sqrt{3} \times 11000} = 13.12 \text{ A} \tag{5}$$

$$\text{Delta connected} \rightarrow I_{phase}(prim) = \frac{13.12}{\sqrt{3}} = 7.57 \text{ A} \tag{6}$$

$$I_{line}(\sec) = \frac{S}{\sqrt{3} V_{line}(\sec)} = \frac{250000}{\sqrt{3} \times 400} = 360.84 \text{ A} \tag{7}$$

$$\text{Star connected} \rightarrow I_{phase}(\sec) = 360.84 \text{ A} \tag{8}$$

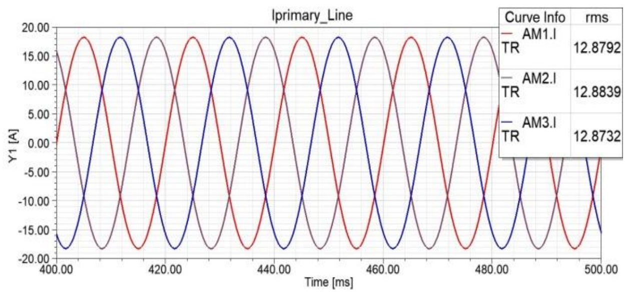

Figure 13. Waveform of the primary current under full load condition

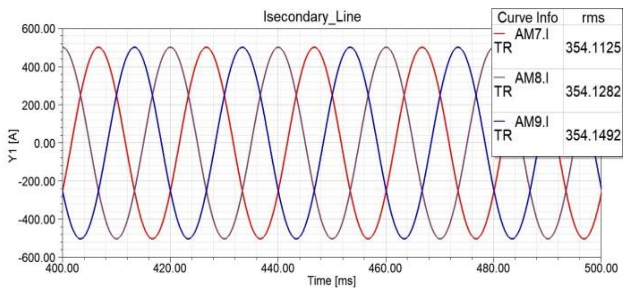

Figure 14. Waveform of the secondary current under full load condition

5.4. Loss Analysis

The power losses are found with the help of the field calculator function in Maxwell. The losses of a transformer are divided according to its operation condition; no-load and full-load working condition. Determining the losses of a transformer is an essential task that must be performed because they are one of the main causes of losing time and money in the industry. The general classification of the transformer losses is shown in Figure 15.

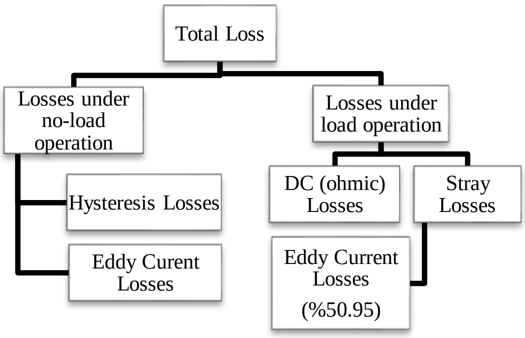

Figure 15. General classification of the transformer losses

Transformer under no-load operation produces core loss. The core loss of a transformer includes two main components; Eddy Current and Hysteresis Losses. The core losses obtained from the simulation for the transformer considered in this are shown in Figure 16. Generally, Hysteresis Losses are responsible for more than half of the total core loss [11]. The core loss is calculated as [4].

$$P_e = k_c\ f^2 B_{\max}^2\ V = 56.612\ \text{W} \tag{9}$$

$$P_h = k_h\ f\ B_{\max}^n = 234.855\ \text{W} \tag{10}$$

$$P_{core} = P_e + P_h = 291.467\ \text{W} \tag{11}$$

Losses obtained under load operation generally consist of Ohmic Losses and losses reflected on the windings due to the eddy current effect [10]. In Maxwell, eddy current effect can only be applied to a solid material [4]. For example, since the core is defined as a solid material, eddy current losses in the core can be calculated for the no-load analysis. The turns number of primary and secondary winding is 1810 and 38, respectively.

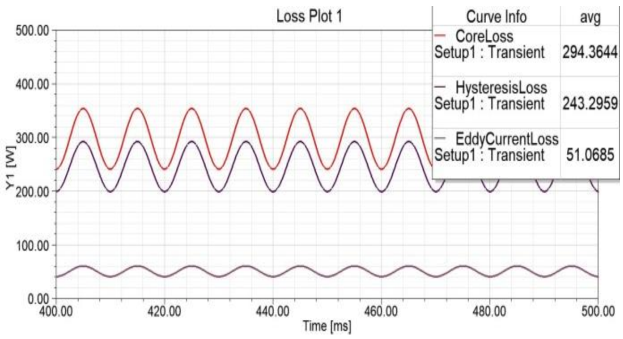

Figure 16. Core loss obtained from the simulation with average value of 294.36 Watts

Since the winding numbers are high, it is not possible to draw the conductor 38 or 1819 times. When modeling the transformer design, the windings are drawn in one piece, not in layers, and defined as a stranded material. Because of this reason, the eddy current effect cannot be applied to the windings. Thus, losses reflected on the windings due to the eddy current effect are not calculated in this study. The total Ohmic Loss for each phase in the transformer is calculated using equations as follows.

$$P_{CU} = I_{(\text{pr})}^{\ 2} R_{(\text{pr})} + I^2_{(\text{sec})} R_{(\text{sec})} = 401.13 + 320.33 = 721.46\ \text{W} \tag{12}$$

$$\rightarrow P_{HV(DC)} = 3 \times 401.13 = 1203.39\ \text{W} \tag{13}$$

$$\rightarrow P_{LV(DC)} = 3 \times 320.33 = 960.99\ \text{W} \tag{14}$$

Figure 17 shows the total Ohmic Losses calculated in each phase. Stranded Loss refers to the Ohmic Losses in the external excitation circuit. On the other hand, the StrandedLossR shows the Ohmic Losses calculated using direct excitation StrandedLossR is zero since this simulation study is done with an external excitation circuit [4].

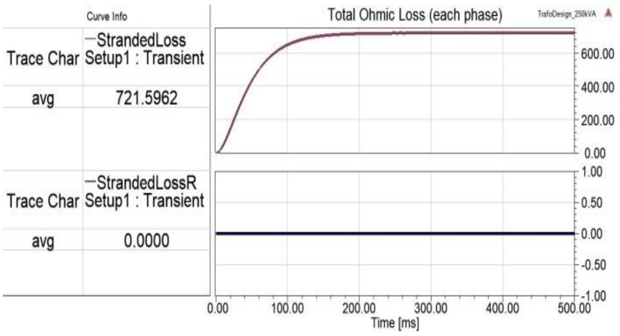

Figure 17. Ohmic Loss obtained from the simulation with total value of 721.6 Watts

The Ohmic loss for high and low voltage winding can also be obtained separately for a more detailed analysis result. Figure 18 shows that the Ohmic loss for each phase of the high and low voltage is 400.8 W and 322.4 W, respectively.

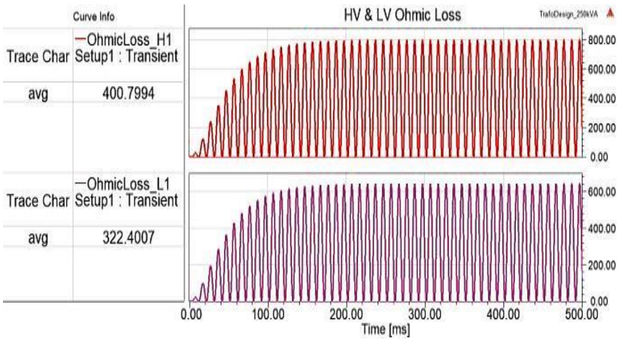

Figure 18. Ohmic Loss obtained for each phase

6. CONCLUSION

The results obtained from the simulation analysis and the information given on the transformer's nameplate are compared in the table below. The accuracy of the analysis is also calculated and included in the table as percentages. This study validates designed transformer and the results obtained help understanding the behavior of transformer for future analysis, optimization and developments.

Table 3. Analysis results and the percentage of accuracy

V (primary) Volt	Nameplate	11	%98.58
	Analysis Result	10.84	
	Calculation Result	11.023	
V (secondary) Volt	Nameplate	400	%98.14
	Analysis Result	392.56	
	Calculation Result	400.85	
I (primary) Ampere	Nameplate	13.12	%98.16
	Analysis Result	12.88	
	Calculation Result	13.12	
I (secondary) Ampere	Nameplate	360.84	%98.14
	Analysis Result	354.13	
	Calculation Result	360.84	
$\%I_0$	Nameplate	% 0.177	%98.87
	Analysis Result	%0.175	
B_{max} Tesla	Nameplate	1.49	%97.99
	Analysis Result	1.46	
	Calculation Result	1.49	
A m^2	Nameplate	0.0184	%98.37
	Analysis Result	0.0187	
Core Loss Watt	Nameplate	288-300	%99.01
	Analysis Result	294.36	
	Calculation Result	291.47	
Eddy Current Loss Watt	Analysis Result	51.07	-
	Calculation Result	56.61	
Hysteresis Loss Watt	Analysis Result	243.2	-
	Calculation Result	234.85	
HV (ohmic) Loss Watt	Nameplate	1202	%99.92
	Analysis Result	1202.4	
		400.8 (each phase)	
	Calculation Result	1203.4	
		401.13	
LV (ohmic) Loss Watt	Nameplate	961	%99.35
	Analysis Result	967.2	
		322.4 (each phase)	
	Calculation Result	961	
		320.33	

NOMENCLATURE

Symbols / Parameters

N : Number of turn $\quad$ i : Current (A)

V : Voltage (volt) $\quad$ R : Resistance (Ω)

P : Electric Power (W) $\quad$ Φ : Magnetic flux (wb)

B_{max}: Magnitude of the magnetic flux (T)

S : Power rating of transformer (VA)

f : frequency (Hz)

K_h : Hysteresis loss factor $\quad$ K_c : Eddy Current loss factor

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BIOGRAPHIES

Husnul Amalia Ariani was born in Balikpapan, Indonesia in 1997. She finished her school early and graduated from Electrical and Electronics Engineering Department, Gazi University (Ankara, Turkey) in 2018. Currently, she is a Master student at Gazi University. Her research interests are in the area of electrical machinery, power electronics and transformer.

Ires Iskender received his Ph.D. degree in Electrical and Electronics Engineering from Middle East Technical University (Ankara, Turkey) in 1996. Prior to joining the Department of Electrical and Electronics Engineering of Cankaya University (Ankara, Turkey), he worked as a Professor at Department of Electrical and Electronics Engineering in Middle East Technical University and Gazi University. His current research interests are energy conversion systems, renewable energy sources, electrical machine and power quality. He participated in and coordinated several research projects and he served as the panelist and referee for many academic or industry projects.

Mehmet Karakaya received his Ph.D. degree in Physic from Clemson University (South Carolina, USA) in 2015 and is presently an Assistant Professor at Electrical and Electronics Engineering Department in Gazi University. He has worked on storage device application, nanotechnology, and nanomaterial production, characterization and application.