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Comparison of FEA-Based Thermal and Loss Analyses of the Dry-Type Transformer Using Different Grades of Core Material

Seda Kul[1], **Süleyman Sungur Tezcan**[2]

[1]Department of Electrical & Electronics Engineering, Karamanoğlu Mehmetbey University, Faculty of Engineering, Karaman, Turkey
[2]Department of Electrical & Electronics Engineering, Gazi University, Ankara, Turkey

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ABSTRACT

This study presents a comparative simulation of electrical steels with different grain orientations in three-phase dry-type power distribution transformers. Electrical steels modeled as three-phase transformer cores are analyzed and compared. In this context, time-dependent simulations of three-dimensional transformer models were performed using the coupling method based on finite element analysis to determine core losses and thermal behavior differences. This study reveals the effects of different grades of core materials on time-dependent core temperature depend on power losses and magnetic flux density. For this purpose, a 100 kVA three-strand three-phase dry-type transformer was used to simulate and prove the concept, and the simulation results were compared. As a result, according to mathematical calculations, core losses for M3, M4, and M5 were 298 W, 340 W, and 402 W, respectively, while the error rates between them were found to be 2.95%, 1.1%, and 5.5%, with the simulation results. The maximum temperature values obtained as a result of the time-dependent thermal analysis according to these loss values are 70.71°C, 70.724°C, and 80.619°C, respectively. These results show how important the material selection is in terms of design, efficiency, and transformer life.

Index Terms—Dry-type power transformer, core loss, core material, thermal analysis of transformer, different grades

I. INTRODUCTION

In recent years, with the increase in energy demand, problems such as efficiency, heating, and cooling have become especially important in the design of electrical machines. Considering these situations, the importance of transformers used to transmit and distribute energy systems is increasing. Transformers are fundamental electrical machines that reduce or increase voltage levels in more efficient conditions. Therefore, the materials used in transformer design, efficiency, and temperature analysis are the issues to be considered. Dry-type transformer technology is one of the popular categories among the many transformer technologies, risky areas, and categories depending on the insulation system. They are preferred by many special industrial applications and environments requiring safety, non-flammable, and environmentally friendly, such as transit applications, marine systems, urban areas, etc. [1,2].

The temperature distribution in the core and windings is related to no-load loss and load losses. Therefore, the efficiency of the transformer is a crucial parameter for design and thermal analysis. Therefore, accurate loss estimation is essential before designing the transformer for industrial applications, especially for the dry-type transformer. There are two types of losses: core losses (no-load losses) and winding losses (load losses). An essential portion of losses is core losses, which are active power losses, depending on the specification of used electrical steel and the frequency and voltage of the excitation circuit. It accounts for over 70% of total power loss [3,4].

The core losses depend on the core material types directly. Electrical silicon steels and amorphous materials are standard for lamination transformer cores. However, core material and manufacturing costs are the main parameters in the industry. As a result, different thickness grades of silicon steels can be generally preferred to design the transformer core.

Researchers have dealt with and examined the causes of core losses in many ways in previous studies. Variables such as transformer connection type, overlaps, air gap length, core model, and core material directly affect core loss [5,6]. Many different methods have been used and examined

Corresponding author:
Seda Kul

E-mail: sedakul@kmu.edu.tr

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regarding the causes and solutions of core losses. Necessary comparisons were made using techniques such as core sizes and material changes, optimizing optimization methods to minimize these losses [7,8].

External voltage waveforms and harmonics are critical points for the losses and efficiency of transformers. Harmonics change the flux density distribution and saturation point; therefore, the loss proportion has increasingly changed [9-13]. Afterward, they presented magnetic flux shape, density distribution, and B-H characteristics influences. References [14-17] have studied temperature rise, thermal behavior, thermal aging, and the importance of the insulation system for performance, efficiency, and safety. The core and winding losses have been used in thermal analysis as heat sources.

Besides, the recent developments and improvements in new magnetic materials have made the core loss an issue that bought an interest in researchers once again. In [18], researchers studied the effect of core material types in three-phase transformers in terms of core loss. M3, M4, and M5 electrical silicon steel materials were used to design a core and analyze Finite Element Analysis (FEA) under the no-load condition to guide manufacturers in comparing efficiency differences [19]. The various thickness of Cold Rolled Grain Oriented (CRGO) material was examined in terms of loss in watts per kg; therefore, the characterizing criteria of core loss and power factor differences were obtained within limits [20]. Researchers used different electrical steel and amorphous material grades to design transformers in simulations. Magnetic analysis of transformers was performed in ANSYS/Maxwell software. The results showed that using materials with a reduced crystal structure, low magnetization, and thickness had better results in reducing losses and increasing efficiency due to their magnetic properties and characteristics of highly effective parameters.

The literature review has shown that analysis and experimental research have been done to reduce or obtain an accurate core loss calculation. In this case, optimization studies also aim at improving efficiency. The purpose of doing such studies is to provide minimal cost while trying to achieve maximum efficiency. However, considering the cost, nanocrystalline and amorphous materials are seen as high-cost solutions for the industry. Also, a dry-type transformer is more expensive to manufacture than an oil-immersed transformer. For this reason, grain-oriented electrical steels are preferred according to cost and performance. These steels are classified according to their thickness. Therefore, a comparison study is important for giving an idea while making transformer designs without causing any loss of time.

This study used ANSYS/Maxwell and Workbench/Mechanical analysis to obtain magnetic flux density distribution, core loss, and thermal difference. A 100 kVA 10/0.4 kV dry-type three-phase transformer is designed with three grades of grain-oriented electrical steel, M3, M4, and M5. Then, the results were compared in terms of efficiency and thermal characteristics.

It is possible to summarize the main purpose of this study as follows:

- to show electromagnetic and thermal analysis of transformer by using time-dependent Maxwell and Workbench at the same time;
- to show the importance of the different grades of electrical silicon steel in transformer performance;
- to compare magnetic and thermal behaviors and examine the effect of the transformer on temperature and efficiency.

The rest of the study is organized as follows: the methodology of FEA electromagnetic and thermal modeling of dry-type power transformer has been explained in Section II. The electromagnetic and thermal analysis results and discussion based on ANSYS simulations are shown in section III. The conclusion is summarized in section IV.

II. FEA ELECTROMAGNETIC AND THERMAL MODELING OF DRY-TYPE POWER TRANSFORMER

In many disciplines, finite element analysis is a numerical method to solve linear and non-linear problems using differential and integration equations. This method is used to solve time-dependent magnetostatics, electric field, and eddy current problems based on frequency or time.

Two categories explain transformer losses: core loss/no-load loss and load losses. The core loss also comprises hysteresis loss and eddy current loss. Both depend on the types of core materials, magnetic flux density, and frequency. Therefore, it is essential to know the flux density distribution at the design step. Moreover, winding or load losses depend on the load current.

When the transformer core is excited under a sinusoidal waveform, the instantaneous alternating variation of flux density is given by [21]:

$$B(\mathrm{t}) = \frac{1}{NA_c} \int e(t) sinwtdt \tag{1}$$

where $B(t)$, N, $A_{c,}$ and $e(t)$ are defined as magnetic flux density in the core legs, the number of turns, the cross-section area of the core legs, and induced voltage, respectively. As it is mentioned above, core loss depends on frequency flux density and core material. Thus, it is expressed by the Steinmetz equation as [22]:

$$P_v = Kf^{a} B_{pk}^{\beta} \tag{2}$$

Equation (2) shows the basic formula and K, f, and B_{pk} are expressed as a specific loss constant related to the magnetic material used in the core, frequency, and the peak value of flux density, respectively; however, these specific parameters are stated as a specification of using material separately; thus, three categories are given as:

$$P_v = K_h B_{pk}^{x} f + K_c B_{pk}^{2} f^{2} + K_e B_{pk}^{1.5} f^{1.5} \tag{3}$$

where K_h, $K_{c,}$ and K_e are defined as a hysteresis loss constant, eddy current loss constant, and anomalous loss constant, respectively. Localized power losses on the core lamination under one dimension can be expressed, and it is possible to show average power loss over one cycle as [23]:

$$P_{average} = \frac{1}{T} \int_0^T \left(\int H(t) \frac{\partial B(t)}{dt} dv + \frac{1}{\sigma} \int \left(\frac{\partial H(t)}{\partial z} \right)^2 dv \right) dt \text{ [W]} \tag{4}$$

By rearranging (2), averaged total loss can be expressed as:

$$P_{average} = \frac{1}{T} \int_0^T \int H(t) \frac{\partial B(t)}{dt} dvdt + \frac{1}{T} \int_0^T \int \frac{1}{\sigma} \left(\frac{\partial H(t)}{\partial z} \right)^2 dvdt \text{ [W]} \tag{5}$$

When magnetic field strength and magnetic flux density change depending on time dependency and are uniform within the volume, then $\frac{\partial H(t)}{\partial z}$ can be zero and $\frac{\partial B(t)}{dt}$ is defined as $\frac{dB(t)}{dt}$. Thus, averaged total power loss can be expressed as:

$$P_{total}=\frac{v}{m}\frac{1}{T}\int_0^T\left[H(t)\frac{dB(t)}{dt}\right]dt\ [\text{W/kg}] \tag{6}$$

There are two primary heat sources in transformers. These heat sources occur due to the losses in the core and windings and increase depending on these parameters.

The heat source in the thermal model of the transformer in terms of the volumes of the inner (V_{cc}) and the outer part (V_{ce}) of the core is given in (7) and (8), respectively [24].

$$P_{cc}=P_vV_{cc} \tag{7}$$

$$P_{ce}=P_vV_{ce} \tag{8}$$

Thermal modeling determines the heat released by the losses occurring in core windings. The simple thermal equivalent circuit of the transformer, whose temperature rise values are analyzed, is shown in Fig. 1 [24].

The behavior of the materials in nature toward the energy transferred by radiation differs. Some of the materials reflect the energy transferred by radiation. Some of them transmit or absorb it into their structure. Therefore, heat transfer with different properties occurs between the transformer winding, insulation, core, and other transformer parts. Mathematical expressions for heat transfer by radiation, conduction, and convection can be defined by (9)-(11) separately [22].

$$C\frac{\partial T}{\partial t}+\nabla\left(-k\nabla T\right)=Q \tag{9}$$

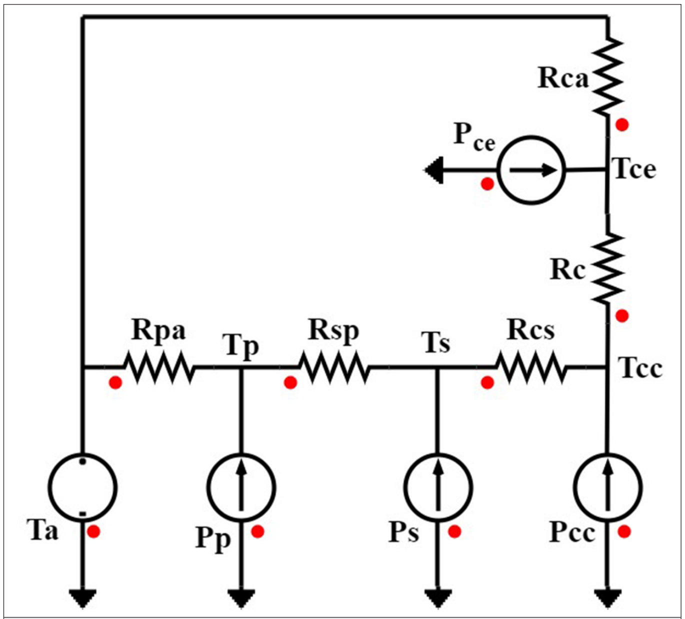

Fig. 1. Basic thermal equivalent circuit.

TABLE I. GENERAL SPECIFICATIONS OF THREE PHASE DRY-TYPE TRANSFORMERS

	Values
Quantity	**TRF**
Power level	100 kVA
Voltages	10/0.4 kV
Connection type	Δ/Y
Turns	1819/42
Core material	Electrical silicon steel
Winding material	Aluminum
Lamination thickness	0.30, 0.27, 0.23 mm (M5, M4, M3)
Impedance	4%
Pcoreloss	400 ± %10 W
Pcu	2000 ± %10 W
Core volume	0.05498 m^3

Pcu, Winding loss or copper loss.

$$k\frac{dT}{ds}\underset{n}{\rightarrow}=-h_c\left(T-T_a\right) \tag{10}$$

$$k\frac{dT}{ds}\underset{n}{\rightarrow}=\varepsilon\gamma\left(T^4-T_a^4\right) \tag{11}$$

where C, Q, h_c, T_a [°C], T [°C], ε, and γ are defined as the thermal capacity, the volumetric density of the heat source, the actual heat transfer coefficient by convection, the temperature at a point far from the surface, the temperature of the surface heating, the thermal radiation coefficient, and the Stefan-Boltzman coefficient, respectively.

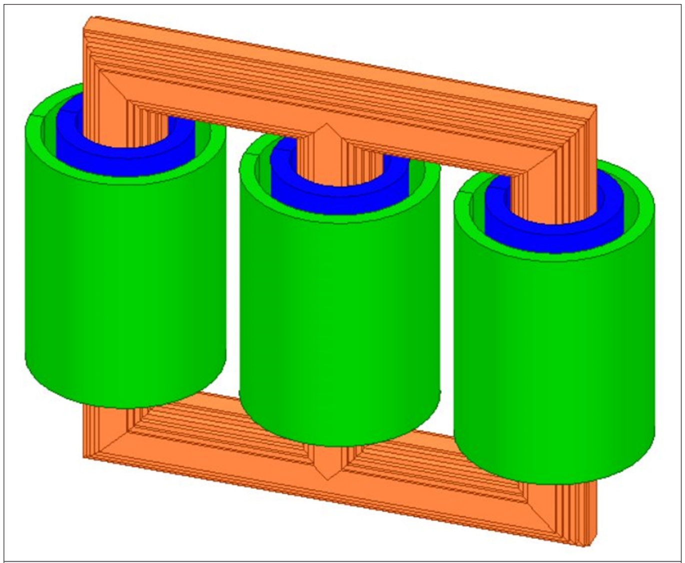

Fig. 2. Transformer ANSYS/Maxwell model.

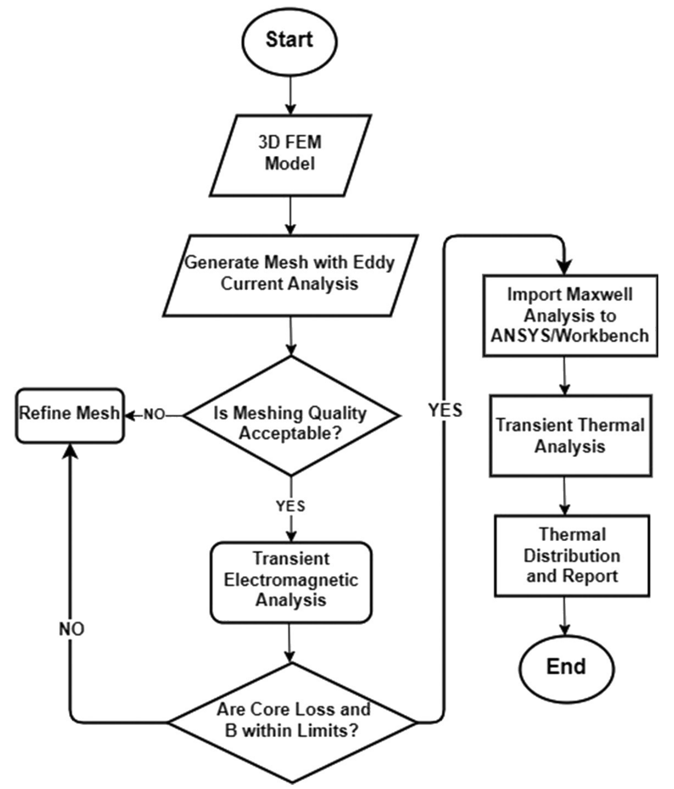

Fig. 3. Block diagram of the FEA model coupled with thermal analysis.

Natural convection heat transfer can be expressed in a three-dimensional thermal model as:

$$\frac{\partial(pu)}{\partial x}+\frac{\partial(pv)}{\partial y}+\frac{\partial(pw)}{\partial z}=0 \tag{12}$$

where *p*, *u*, *v*, and *w* are the air pressure in Pascal, the fluid velocity in the *x*, *y*, and *z* axes.

In this study, a three-limb three-phase transformer with a power rating of 100 kVA was performed using ANSYS/Maxwell software 3D modeling based on time to obtain core loss, winding loss, and magnetic flux density within the core and coils. The transformer model and transformer specifications are shown in Table I and Fig. 2, respectively.

Then, after the transformer is analyzed with a transient solver, it is coupled with transient thermalto investigate the temperature distribution in terms of time dependency. The core and winding losses are heat sources for thermal analysis.

Electromagnetic transient analysis is performed to obtain the distribution flux density, core loss, and winding losses with M5, M4, and M3 electrical silicon steels to compare the differences between magnetic behaviors and core loss. Finally, ANSYS/Workbench was used to analyze the thermal behavior of the transformer based on electromagnetic analysis as heat sources. Figure 3 shows the modeling and the flow chart of the analysis steps performed in the software.

III. RESULTS AND DISCUSSIONS

Transformer analysis was performed using FEA over time. These non-linear analyses obtained magnetic and design values such as core loss, magnetic flux density, and core volume. The time-based analysis is advantageous and preferred as it allows simultaneous display and acquisition of simulation values. Sinusoidal voltage is used for transformer excitation. Equation (13) shows the mathematical expression of the excitation voltage. In this way, an excitation voltage is preferred to ignore the inrush currents that occur during the first operation of the transformers. Figure 4 and 5 show the primary current and voltage plots over time. The primary windings are delta connected; therefore, the current in Fig. 4 represents the RMS value of the line currents.

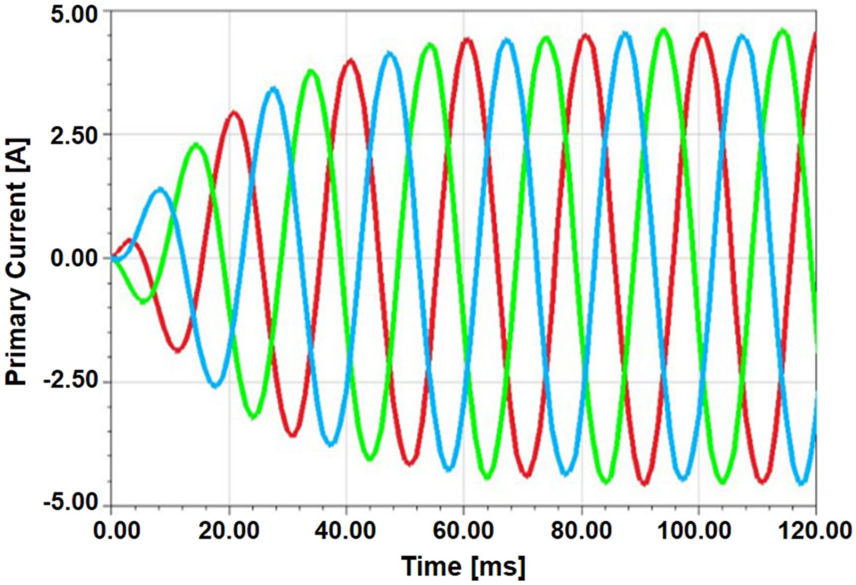

Fig. 4. Three phase 100 kVA 10/04 kV transformer primary currents.

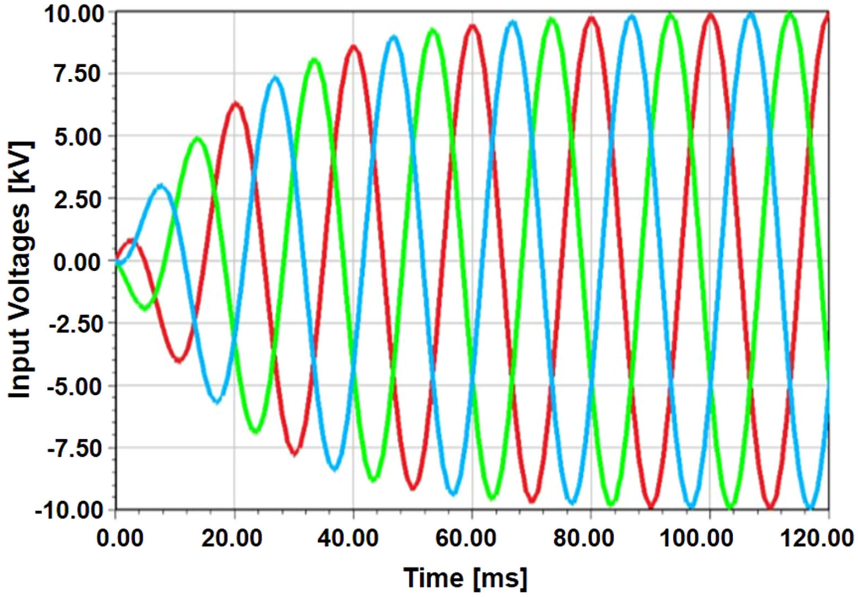

Fig. 5. Three phase 100 kVA 10/04 kV transformer excitation voltages.

$$U_p = V_p\left(1-\exp\left(-50t\right)*\cos\left(2\pi ft\right)\right) \tag{13}$$

Simulation studies were repeated separately for different classes, M3, M4, and M5. Also, the power loss was calculated mathematically with the help of the magnetic flux density-loss (B-P) curve shown in Fig. 6. However, this calculation gives the result that would be obtained when the magnetic flux density is homogeneous throughout the transformer. The average loss values obtained in these two cases and the percentage differences between the two cases are shown in Table II.

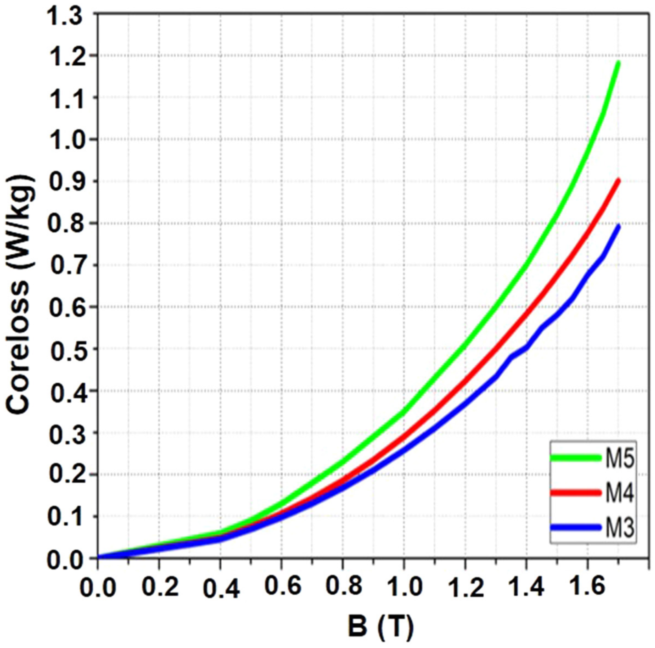

Fig. 6. B-P curves at 50 Hz for different grain-oriented electrical steel.

Magnetic flux density is the most critical point in loss calculations and evaluation of magnetic characteristics. The maximum flux density values obtained by taking the middle leg as a reference as a result of the analysis are given in Table III.

TABLE II. CORE LOSS VALUE IN TERMS OF DIFFERENT GRADES OF ELECTRICAL STEEL IN THREE PHASE DRY-TYPE TRANSFORMERS

Materials	No-Load Losses (W) FEA	No-Load Losses (W) Mathematical	Error (%)
M3 GOES	298	289.2	2.95
M4 GOES	340	336	1.1
M5 GOES	402	424	5.4

TABLE III. MAX FLUX DENSITY IN THE MIDDLE LEG OF TRANSFORMERS

Materials	Magnetic Flux Density (B)
M3 GOES	1.61 T
M4 GOES	1.63 T
M5 GOES	1.74 T

TABLE IV. TEMPERATURE VALUE IN THE SURFACE CENTER OF THE MIDDLE LEG FOR EACH TRANSFORMER

Materials	Max Temperature (°C)
M3 GOES	70.71
M4 GOES	74.724
M5 GOES	80.619

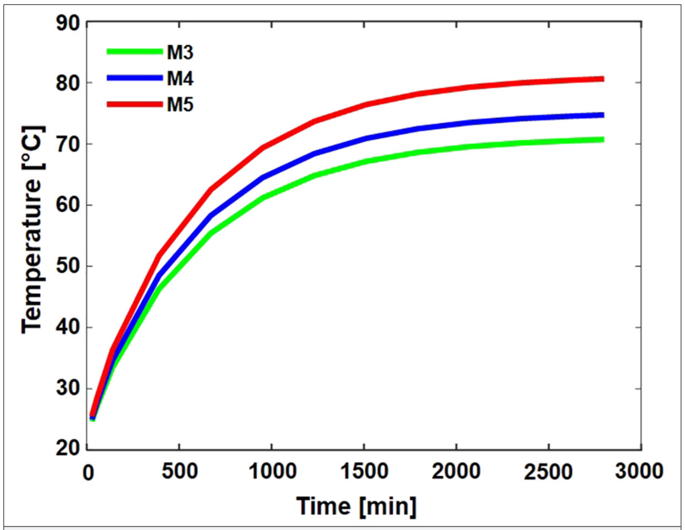

Fig. 7. The time-dependent maximum temperature change of the middle limb.

Thus, the change of material grade in the analysis is a factor that directly affects the core loss without changing the volume or any design parameters. This core material is given explicitly in the datasheets. Before the prototype has been built, the determination of the designed temperature rise behavior of the transformer may not be done entirely with classical methods due to the non-linear behavior of the core. However, experimental studies can fully see temperature behavior after producing a prototype transformer. This method has effectively been used in recent years to reach the most appropriate design before the prototype with modeling and simulation studies with FEA software in the modern transformer design approach due to cost and time loss.

All values such as magnetic parameters, flux distribution, core losses, and winding losses obtained from FEA simulation studies were used as heat sources in transient thermal analysis. The temporal thermal analysis results performed in ANYSY/Workbench with these values are also shown in Table IV.

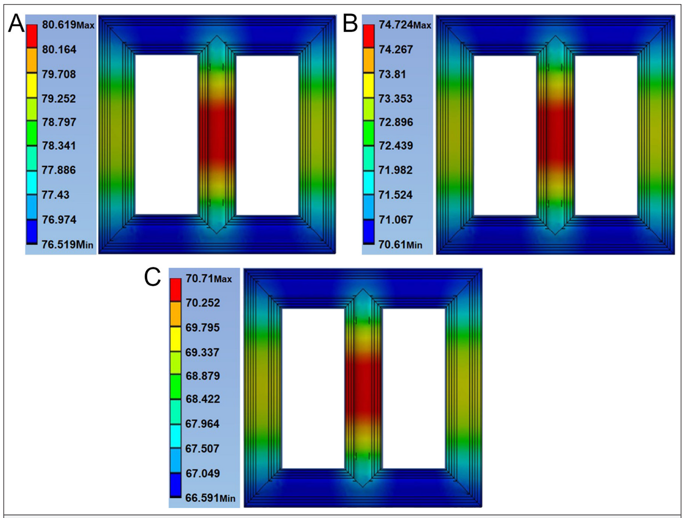

Fig. 8. Thermal distribution of the transformer core depends on A) M5, B) M4, C) M3 materials.

Comparing Tables III and IV, it is seen that the core temperature is higher when losses and magnetic flux density are high. However, it is not possible to accept the temperature changes in the core as linear. Figure 7 shows the maximum temperature variation of the thermal analysis with reference to the middle leg over time. Looking at this figure, it is seen that the heat dissipation on the transformer is not linear. Figure 8 shows the thermal distributions at the maximum temperature on the core according to the materials. Instead of steady-state thermal analysis, the time-dependent thermal analysis also gives an idea to see the temperature distribution characteristic of the transformer.

IV. CONCLUSIONS

In the design of dry-type power distribution transformers, 0.30 mm thick 3% Si-Fe alloy M5 grain-oriented lamination is widely used. As it is known, core losses vary depending on the lamination thickness and decrease as the core packaging materials get thinner. In recent years, innovations in cutting and stacking core laminations and laser cutting techniques have made it possible to use thinner core material. In this study, the temperature behavior of the transformer is given comparatively according to three different degrees of core lamination, M3, M4, and M5, to attract researchers and transformer manufacturers. In this context, electromagnetic and thermal analyses of the transformer are combined and presented simultaneously using FEA transient simulation and thermal coupling software. When M5 and M3 loss values are compared, a 25% reduction in core loss is seen. This reduction in losses increases productivity by 2.25%. When the same evaluation is made for M4 and M3, core loss and efficiency reductions are 12.35% and 2.1%, respectively. Thus, the importance and performance of silicon steel grades in transformer design have been revealed, and a modern method has been presented in the design approach. He also compared the magnetic and thermal behavior of the transformer and examined its contribution to efficiency. The thermal analyses were carried out depending on time and allowed the change in heat distribution on the core to be seen. As a result of the analysis, the maximum temperatures obtained for M3, M4, and M5 are 70.71°C, 74.724°C, and 80.619°C, respectively. Finally, in future studies, the amorphous core material can be compared with silicon steel sheet materials in size and electrical and thermal performances.

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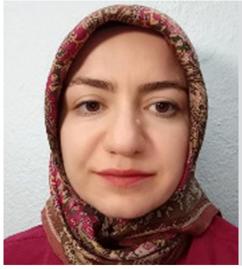

Seda Kul has been working as a Research Assistant in the Electrical and Electronics Engineering Department at Karamanoglu Mehmetbey University. She received her B.S. and M.S degrees in Electrical Electronics Engineering from Selcuk University in 2011 and 2015. She is a Ph.D. student in Electrical Electronics Engineering Department at Gazi University. Her current research interests include electric machines, power transformers, optimization.

Suleyman Sungur Tezcan is an assistant professor in Gazi University Faculty of Engineering, Electrical Electronics Engineering Department. He has completed his undergraduate at Yıldız Technical University Electrical Engineering Department and graduate education (Master of Science and Doctor of Philosophy) at Gazi University Faculty of Engineering, Electrical Electronics Engineering Department. His research areas are high voltage technique and power system analysis.