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3D Electromagnetic and Thermal Behaviour Analysis of Magnetic Flux Leakage Transformers Using Finite Element Method

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Abstract – **This paper focuses on the thermal analysis of the magnetic flux leakage (MFL) transformer, which is a critical and expensive component in microwave power supply systems due to their high-frequency and high-power nature. The purpose of the analysis is to determine the temperature distribution of the transformer, including hot spots and temperature gradients, to improve its design and performance for safe and reliable operation. The finite element analysis (FEA) is used to simulate the thermal behavior of the transformer, considering various factors such as geometry, materials, and external conditions. This method allows for the prediction of the magnetic field distribution, current density, and heat generation within the transformer, and can be used to optimize its design and predict its performance under different conditions. The results of the simulation provide valuable information for improving the design and performance of MFL transformer in microwave power supply systems.**

Keywords – **Microwave Ovens, ANSYS-Workbench, MFL Transformer, Magnetron, Thermal Behavior, FEA.**

I. Introduction

Since its introduction in the early 1960s, microwave ovens have become a standard element in the majority of modern kitchens. Existing power supply functioning and limits regarding size and efficiency are investigated. In the past two decades, there are numerous applications for microwaves, which have been widely used for food preparation at home and in the food service industry [1]. Microwaves are largely utilized in the industrial sector for tempering, defrosting big blocks of frozen meat, and preheating. Microwave sterilization of food products has been the subject of limited research.

The MFL transformer is the most important and expensive component in a microwave's power supply. The high voltage transformer is responsible for stepping up the voltage of the electrical power supplied to the oven, so that it can generate the high voltage needed to produce microwaves [2]. The high voltage is used to create an oscillating electromagnetic field within the oven, which generates the microwaves. The microwaves are then directed into the cooking compartment, where they penetrate the food and cause its molecules to vibrate, producing heat and cooking the food.

The MLF transformer is typically designed to work under sinusoidal excitation and is capable of not just voltage transformation but also voltage stabilization. It provides a variety of voltage stabilizers and continuously variable transmissions (CVT) to maintain optimal voltage across the entire system [3]. They are intended to safeguard magnetrons by supplying a consistent voltage to their output terminals when the input voltage fluctuates. In addition to delivering a constant output voltage, they protect devices from spikes and surges. It can increase productivity and reduce vibration and noise. Additionally, it controls the variable input voltage before feeding it to the voltage-sensitive magnetron.

Excessive eddy currents in the iron core of a transformer can cause abnormal temperature rises and heat generation in the core, leading to losses in the core laminations. The MFL transformer, which is designed to stabilize voltage, often operates in deep saturation, resulting in high currents and increased heat generation. This heat problem is more severe in MFL transformers than in ordinary transformers, leading to copper losses and reduced efficiency. Additionally, MFL transformers generates electromagnetic noise and vibration due to the magneto-strictive action of the iron core material.

Due to the development of traditional transformer structure designs, the basic structural parameters, loss, and temperature increase of transformers are all computed using complicated empirical formulae [4]; however, the actual operating conditions cannot be determined by experimental testing. The results and conclusions derived from these computations are thus empirical and limited. Because empirical methods of conventional design involve the four processes of design, machining, testing, and optimization, the results are frequently inaccurate. Due to the unique roles of MFL transformers, its structures are frequently complicated. The complex transformer cannot be checked separately because it must be coupled to a high voltage capacitor and tested with magnetrons in a circuit. It is widely known that numerical simulations are a type of numerical experiment [5]. Using numerical tests can reduce the cost and duration of research and improve the effectiveness of product development.

In recent years, improved analysis based on computer-aided software and the FEA approach has replaced the old method in electromagnetic modelling [6], particularly for non-sinusoidal excitation voltage or load current situations. Consequently, the power dissipation characteristics and thermal effects of transformers under a nonlinear load can be readily determined during the design phase, and modifications

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can be made without incurring any extra costs. FEA software enables interactive electromagnetic and thermal studies of transformers and other electric devices. Therefore, the transformer may be modeled in three dimensions before it is produced [7]. Thus, the optimization process is shortened and good cost-related findings are attained. In transformer design, the FEA method is very important for figuring out the effects of nonlinear behavior.

In recent years, the development of software using FEA has enabled precise designs, allowing for accurate calculation of magnetic characteristics, power losses, and noise in transformer components [8]. This type of software utilizes mathematical models to simulate transformer behavior under various conditions. With input of transformer dimensions and material properties, the software generates results that more closely match the actual performance of the transformer.

However, it's important to note that FEA results are only as accurate as the mathematical models and assumptions used, and there may still be discrepancies between the software results and the actual transformer performance, especially if there are uncertainties in the input data or if the model does not accurately capture all relevant physical phenomena. Additionally, the accuracy of FEA results can also be influenced by the quality and resolution of the mesh used in the analysis. Transformers can be easily modeled with the finite element approach for any type of nonlinear load or excitation in the virtual environment provided by modern electromagnetic design software. In this study, electromagnetic and thermal three-dimensional modeling of the MFL transformer at a specific rated power level have been performed. However, with the advancement of FEA software and computing power, it has become possible to model increasingly complex nonlinear systems, including transformers, with a high degree of accuracy [9]. The finite element approach remains a useful tool for analyzing transformers under nonlinear conditions, but it is important to consider the limitations and challenges of accurately capturing all relevant nonlinearities.

In considering the above issues, this work proposes an improved 3D magnetic and temperature field coupling analysis approach for an MFL transformer based on FEA that takes into account the effect of air movement. Transformer electromagnetic modeling was accomplished with Ansys-Maxwell 3D and co-simulated with Ansys-Simplorer [3]. Using the ANSYS-Workbench tool, the thermal impacts of the transformer losses were subsequently simulated, revealing the thermal behavior of the transformers in response to the load circumstances. Thus, comparative simulations of the thermal behavior of a dry-type isolation transformer have been conducted. For the related MFL transformer design, simulation is performed in an electronic environment.

II. Power Supply Design for a Magnetron Drive

The power supply circuit for a microwave oven typically includes a transformer, rectifier, filter, and voltage regulator are shown in Fig. 1. The transformer steps down the incoming AC voltage to a lower AC voltage, the rectifier converts it to DC voltage, the filter removes any remaining AC components and the voltage regulator stabilizes the DC voltage to the required level for the microwave's components. The secondary winding of the transformer takes electrical power from the primary winding and steps up or steps down the voltage to the desired level. This voltage is then regulated using a rectifier, which converts the alternating current to direct current, and a voltage regulator, which maintains a constant output voltage. The output is then filtered to remove any remaining ripple or fluctuations, providing a stable DC voltage to the load.

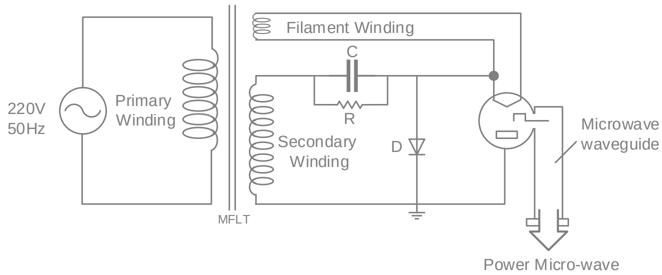


Fig. 1. Scheme of the three-phase HV power supply of a magnetron per phase [1]

A magnetron comprises a cathode, an anode, and a magnetic field. The cathode is a heated filament that emits electrons, the anode is a cylindrical metal structure that attracts the electrons, and the magnetic field is generated by a surrounding coil and helps control the movement of the electrons. The interaction of these components produces high-frequency electromagnetic waves that are used to cook food in a microwave oven.

A. Electrical Model of High Voltage Power Supply

Fig. 2 shows the various components and their connections that are used to convert AC power into the DC power required to operate the microwave. It includes components such as a transformer, rectifier, filter, and regulator. The primary winding is directly linked to the source of alternating current electricity. In combination with the diode, the high voltage capacitor creates a voltage doubler rectifier circuit, which increases the magnetron's voltage to over 4000V DC, and ensures a steady supply of voltage to the magnetron, which is the heart of the microwave oven and generates microwave energy for cooking food.

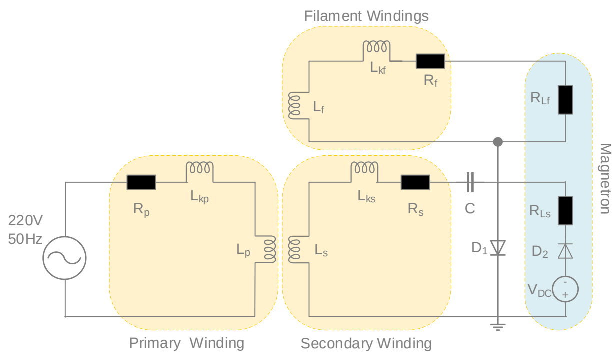


Fig. 2. Field-circuit coupled model of the stable power supply

The filter smoothens the rectified voltage and removes any residual AC components. The regulator maintains the output voltage at a constant level, regardless of changes in the input voltage or load conditions. This helps in ensuring the stability and reliability of the power supply.

The design of the magnetron power supply includes two separate components: a filament supply with a low voltage 3.3 V/12A AC power source to heat the filament, and a separate high voltage -4kV/0.66A DC power source to provide bias to the cathode. The secondary winding of the transformer is designed to provide high voltage to the magnetron anode, which helps to stabilize the average anode current (I_{averg}= 300mA). This stability is important for the proper functioning of the magnetron, as changes in the anode voltage can result in noticeable changes in the anode current and cause the magnetron to stop working. Thus, it is crucial for the power supply to have some form of management to stabilize the magnetron's power output.

The field-circuit coupled model of the stable power supply refers to a model that integrates electrical and magnetic field analysis to study the behavior of the power supply system. This model takes into account the interactions between the electrical components, such as the windings and diodes, and the magnetic field produced by the current flowing through the conductors. The field-circuit coupled model provides a more comprehensive and accurate representation of the power supply system compared to traditional models that only consider the electrical components.

The power supply circuit from the source to the magnetron uses the MFL transformer finite element model, as shown in Fig. 2. Field and circuit are connected through L_p, L_s, and L_f, which represent the primary, filament, and secondary windings. End-winding leakage inductances L_{kp}, L_{ks} and L_{kf} are constant. R_p, R_s and R_f are winding constant resistances. The magnetron's filament is R_{Lf}. The load characteristic between a magnetron's anode and antenna is complex. The cutoff voltage and voltage applied between the anode and cathode determine its volt-ampere characteristic curve's two linear modes. When the applied voltage is below the cutoff voltage, the magnetron runs without oscillation. As current increases, it acts as a large resistor to quickly raise voltage. When the applied voltage exceeds the cutoff voltage, the magnetron oscillates. A little voltage change causes large current variations due to its low dynamic resistance. To equalize the section between the anode and the antenna in this research, a tiny dynamic resistor (RLs) is connected in series with a diode (D_2) and a cutoff voltage (VDC).

B. Construction Details of the MFL transformer

The transformer cross section shown in Fig. 3 is a rectangular armored design with a single-phase, two-column core construction that is ideal for stable power supply applications. The core is made of glazed M125-027 silicon steel sheets, while the conductors are made of copper. The primary and secondary windings are wound around the centers of the columns. Both phases have vertical silicon steel rolling shunts with air gaps at each end.

As seen in Fig. 3, the majority of magnetic cores, particularly in power transformers, are constructed using interleaved sheets of shapes E and I, respectively. Transformer dimensions can vary greatly depending on the type and size of the transformer. Factors that influence transformer dimensions include:

- Power rating: A larger transformer will typically have larger dimensions than a smaller transformer with a lower power rating.
- Voltage class: High-voltage transformers may require larger dimensions to accommodate the necessary insulation and spacing between windings.
- Cooling method: Transformers can be air-cooled or liquid-cooled, and the cooling system can impact the overall dimensions of the transformer.
- Core material: Transformers with laminated iron cores will typically have smaller dimensions than transformers with solid cores.
- Winding configuration: The number and arrangement of windings can affect the dimensions of the transformer.

In general, transformers can range in size from small, handheld devices to large, multi-ton installations.

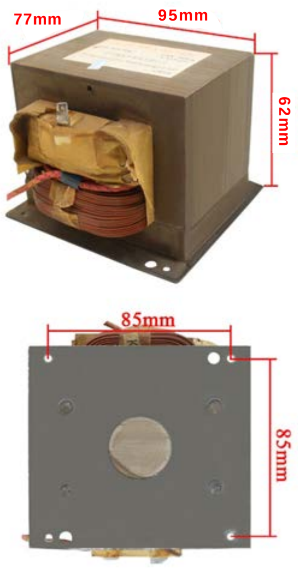


Fig. 3. Simplified view of the MFL model

III. Thermal Modelling of the MFL Transformer

Thermal modeling of a transformer involves predicting the temperature distribution and behavior of the device under various operating conditions. This can be done using numerical simulations such as FEA or computational fluid dynamics (CFD) to determine the thermal resistance and heat dissipation of the components. The input parameters for the simulation can include electrical loads, ambient temperature, and cooling mechanisms. The output provides insight into the thermal behavior of the transformer, which can help in identifying potential hotspots and cooling requirements to ensure reliable and safe operation. In our research, the transformer topology is divided into a finite number of elements, and the FEA is used to determine the flux density in each element, composing the thermal model for the complete transformer shape by combining the thermal behavior of its components.

A. Core and Winding Losses

Frequency effects on core losses in transformers can have a significant impact on the efficiency and performance of power converters. Several mathematical models have been proposed in the literature to account for these effects, including the Steinmetz mode, Jiles-Atherton model, Preisach model [10], and others. These models typically involve the use of complex equations and parameters, such as magnetic permeability, saturation, and hysteresis, to predict the core losses as a function of frequency and magnetic field strength. The accuracy of the models depends on the quality of the data and the validity of the assumptions made in their derivation. The Steinmetz equation, which is defined based on the transformer volume (V_c) as indicated, is the most practical formulation.

$$P_v = Kf^{\alpha}B_m^{\beta} \tag{1}$$

Where K, α and β are defined by the parameters of the core material, f is the frequency of the waveform, and Bm is the amplitude of the magnetic flux density in the case of bidirectional magnetization. Due to the rise in power electronics-based systems in recent years, the Steinmetz equation for nonsinusoidal excitation has been modified. This expression takes into consideration the losses that occur in the magnetic core based on the fluctuation frequency of the magnetic flux density. The Steinmetz equation for nonsinusoidal waveforms is provided in Eq. (1) according to the rate of change of magnetic flux density per unit volume (P_v). The modified Steinmetz coefficient (k_i) in this equation varies according to the core material parameters as given in Eq. (2) [10].

$$\begin{aligned} P_v &= \frac{1}{T}\int_0^T k_i \left|\frac{dB(t)}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt \\ k_i &= \frac{K}{(2\pi)^{\alpha-1}\int_0^{2\pi} |\cos\theta|^{\alpha}\ 2^{\beta-\alpha}\, d\theta} \end{aligned} \tag{2}$$

Then, the core losses are determined according to the core volume (V_c) using Eq. (3).

$$P_{core} = P_v V_c \tag{3}$$

The magnetic flux density waveform is an additional crucial factor that influences core losses. The core losses of a transformer are provided by Eq. (4) for rectangular wave excitation [10].

$$P_v = 2^{\alpha+\beta} k_i K f^{\alpha} B_m^{\beta} \tag{4}$$

Equations (5) and (6) represent the heat sources used in the thermal model for the transformer's interior core (V_{cc}) and external core (V_{ce}), respectively [11]. This state is only true when the interior and exterior temperatures differ.

$$P_{cc} = P_v V_{cc} \tag{5}$$

$$P_{ce} = P_v V_{ce} \tag{6}$$

Solid enameled copper wire is used for conductors in line frequency transformer windings. In MFL transformers, skin and proximity effects influence the AC resistance of the conductor. As a result, multiple-stranded Litz wire or foil conductors are recommended for medium- to high-frequency applications in order to reduce the consequences of these phenomena. In Eq. (7), Dowell's equation [11] expresses the AC resistance of the conductor foil.

$$RF = \frac{R_{ac}}{R_{dc}} \tag{7}$$

RF stands for the resistance factor. Current harmonics also affect winding losses, and Eq. (8) can be derived for transformer winding losses by taking these current harmonic components into consideration [10],[11].

$$P_w = \sum_{v=1}^{n} {}^{v}R_{ac-p}^{v} I_p^2 + \sum_{v=1}^{n} {}^{v}R_{ac-s}^{v} I_s^2 \tag{8}$$

In this case, each transformer winding is defined as an independent heat source. Eqs. (9) and (10) represents the heat sources (P_p and P_s) used in the thermal model for the main and secondary windings, respectively [10], [11].

$$P_p = \frac{N_p \rho l_p}{A_{pr}} RF \cdot I_p^2 \tag{9}$$

$$P_s = \frac{N_s \rho l_s}{A_{sc}} RF \cdot I_s^2 \tag{10}$$

Where A_{pr} and A_{sc} are the cross-sectional areas of the primary and secondary conductors, respectively. ρ is the conductivity, which varies by conductor material type. l_p and ls are the mean turns of the primary and secondary windings, respectively. In addition, N_p and N_s represent the number of turns on the primary and secondary windings, respectively.

IV. STUDIED TRANSFORMER

The FEA method is widely used in transformer design to study the power loss behavior under nonlinear loads [12]. FEA allows engineers to model the complex electrical and magnetic behavior of a transformer, including nonlinear effects such as saturation and hysteresis. By simulating different operating scenarios, the FEA can provide a comprehensive understanding of the power losses, temperature distribution, and other performance characteristics of the transformer. This information can then be used to optimize the design, improve efficiency, and ensure reliable operation under various conditions. The use of this software in transformer design has become increasingly important as the demand for high-performance, high-efficiency electrical systems continue to grow.

A. Construction Details of the Shell-Type Transformer Finite Element Mesh

As shown in Fig. 4, it is possible to determine the temperature distribution of the local heating element in a microwave oven using a quarter model approach. This is due to the symmetrical nature of the MFL transformer, which allows only a quarter of the full model to be used to represent the entire heating element [18]. By using this quarter model approach, the temperature distribution can be simulated and studied, allowing for a better understanding of the heating performance of the MFL transformer and the microwave oven as a whole. The simulation of a quarter of a transformer with the symmetry and anti-symmetry planes can be performed using numerical simulation tools. The simulation involves modeling the electromagnetic properties of the transformer components, including the winding and core, and analyzing the behavior of the magnetic fields under various conditions. The symmetry and anti-symmetry planes are taken into account in the simulation to ensure an accurate representation of the transformer's geometry.

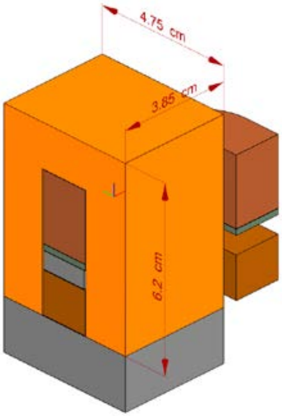


Fig. 4. A quarter of the MFLT with the symmetry and anti-symmetry planes

The FEM mesh of the magnetic core of the distribution transformer is presented in Fig. 5. The FEM mesh of the magnetic core of a distribution transformer refers to the finite element analysis mesh, which divides the core into small interconnected elements to simulate its behavior in a magnetic field [13]. The mesh helps to predict the magnetic flux distribution, current density, and inductance of the core, providing valuable information for the design and optimization of the transformer.

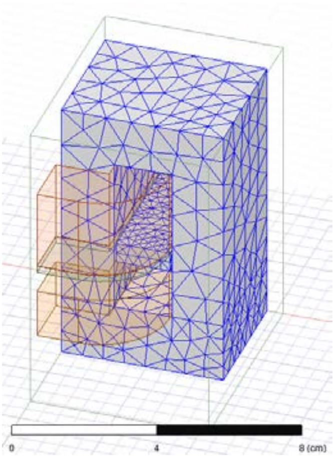
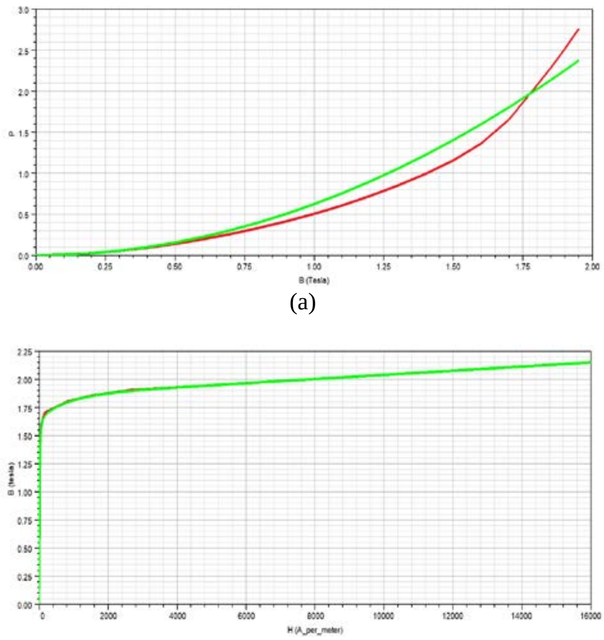


Fig. 5. Transformer 3D model with meshes

B. B-H Curve of the Core Material M125-027

Modeling the magnetic behavior of a magnetic core can be accomplished by utilizing either the magnetic hysteresis loop or the B-H curve. The B-H curve characterizes the correlation between the magnetic flux density (B) and magnetic field strength (H) in a material, and can be obtained through experimental measurements of the material's response to varying magnetic fields [1], [14], [15]. Fig. 6 depicts the B-H curve of core material M125-027 in the magnetic core simulation, which serves as a basis for modeling the core's magnetic behavior under different magnetic fields. To account for the hysteresis and magnetic nonlinearities exhibited by the core material, a nonlinear magnetic model such as the Preisach or Jiles-Atherton model [10], [11] can be utilized.



(a)

(b)

Fig. 6. Specific core losses at 50 Hz frequency of the M125-027 type laminating material (a) PB curve, (b) B-H curve

The magnetic behavior of a magnetic core can also be modeled using the Permeance-Based (PB) method. In this method, the magnetic behavior of the core is represented using the permeance characteristics of the core, which are derived from the core's geometry and magnetic properties.

C. The Circuit Diagram of the Joint Simulation Of Maxwell and Simplorer

Fig. 7 presents a general flowchart of the process being depicted in the figure. The flowchart outlines the steps and decisions involved in the process being depicted, providing a clear and concise overview of the process. The different shapes and arrows in the flowchart are used to represent different stages and actions, making it easy to follow the progression of the process and understand the relationships between the different steps [16]. Also, the specific steps involved in a thermal analysis may vary depending on the complexity of the system being analyzed and the specific requirements of the analysis.

In this section, in the first phase of the thermal analysis, as seen in the flowchart, the thermal analysis process in ANSYS Maxwell typically involves the following steps:

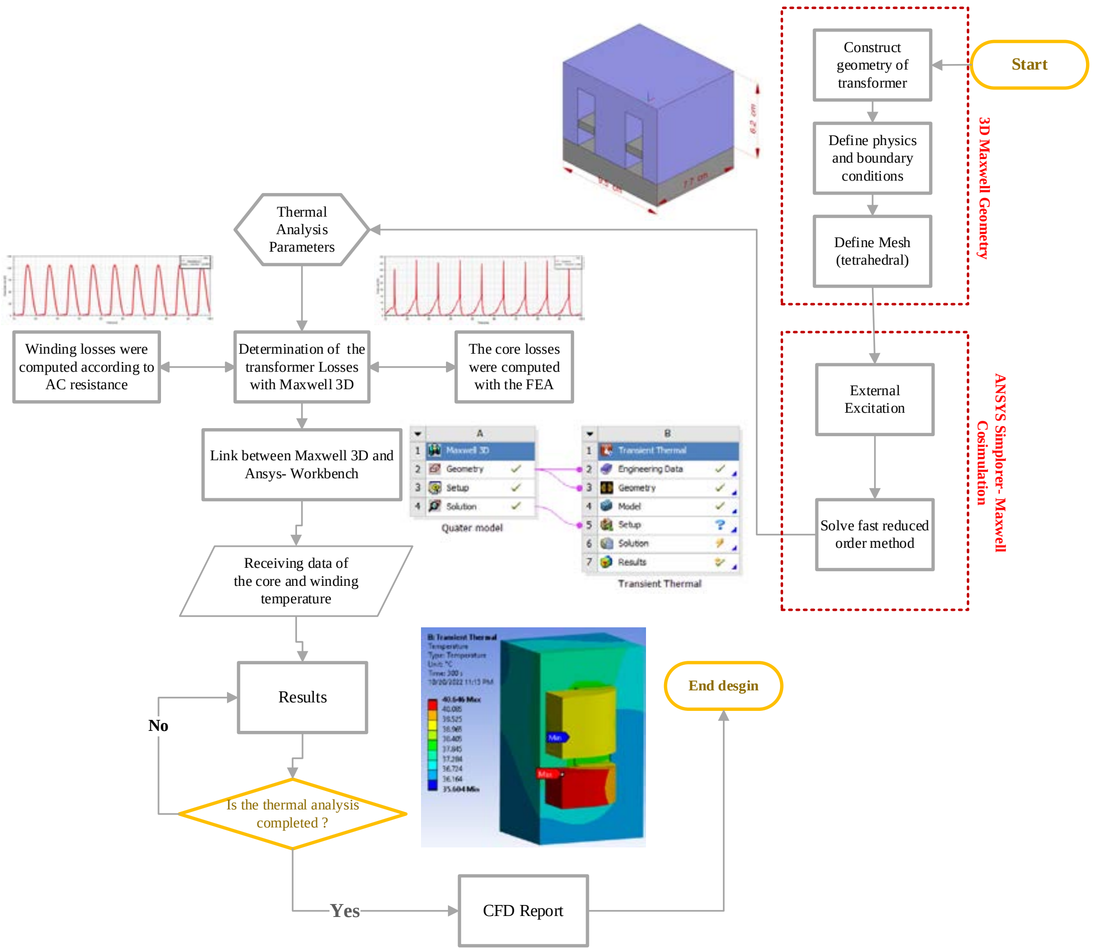


Fig. 7. Flowchart of thermal analysis process

- Model creation: Creating a 3D model of the system to be analyzed, including material properties and boundary conditions.
- Meshing: Creating a finite element mesh of the model to discretize it for analysis.
- Thermal analysis setup: Setting up the thermal analysis, including selecting the type of analysis, defining heat sources and loads, and specifying any initial temperature conditions.
- Solving: Running the thermal analysis, which involves solving the system of equations defined by the model and boundary conditions.
- Post-processing: Analyzing the results of the thermal analysis, including plotting temperature distributions and calculating heat fluxes, heat transfer coefficients, and other relevant quantities.
- Validation and optimization: Comparing the results of the analysis to experimental data, if available, and making changes to the model or analysis setup as needed to improve the accuracy of the results.

The following are the technical parameters of the transformer: 700 VA rated power, 50 Hz operating frequency, 220V voltage ratio. In the modeling investigations, M125-027 core material and copper conductors are employed for the windings [1],[17].

Before constructing a 3D model of transformers for simulation, the transformer design procedure must be completed. Calculating the area product and then selecting a suitable transformer core, finding the area of the primary and secondary windings, calculating the number of turns on the primary and secondary sides, and calculating the copper and core losses comprise the fundamental design.

V. Resultants and Discussion

A. *Flux Distribution in MFL Transformer*

The flux distribution in a transformer refers to the distribution of magnetic flux within the transformer's core and windings. The magnetic flux pattern shown in Fig. 8 is what allows energy to move from one winding to the next and is a result of the current flow in the transformer's windings.

In a transformer, the magnetic flux passes through the core and is concentrated in the regions between the primary and secondary windings. The shape and distribution of the magnetic flux are largely determined by the geometry of the core and windings, as well as by the properties of the magnetic core material. The flux distribution in a transformer is affected by several factors, including the number of turns in

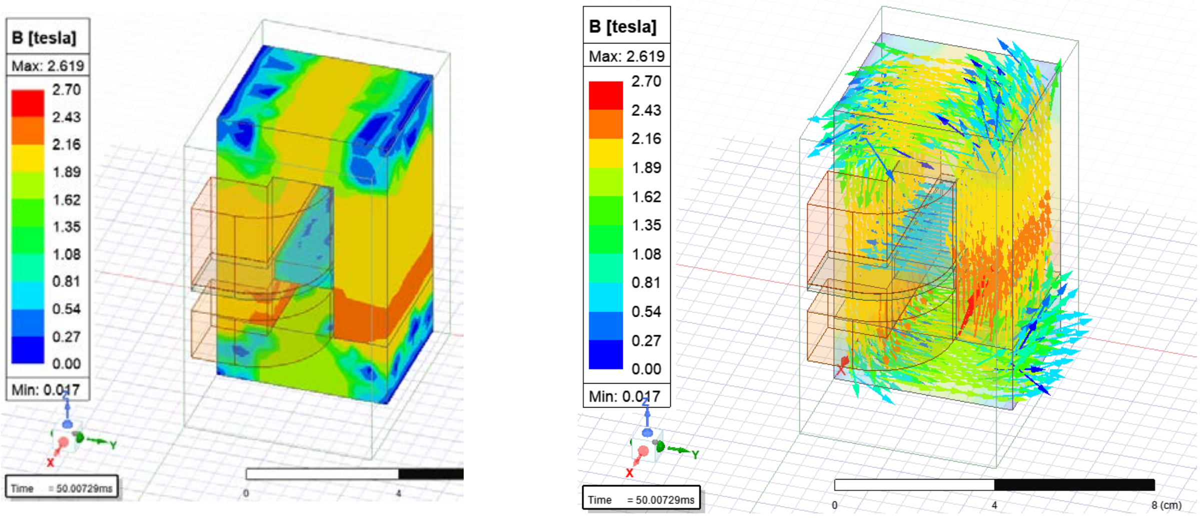


Fig. 8. Flux density distribution for the maximum 2.7 T

the primary and secondary windings, the dimensions of the core, the material properties of the core, and the frequency of the alternating current. In general, the flux distribution in a transformer is optimized to achieve maximum coupling between the primary and secondary windings, which results in maximum power transfer and minimum losses. The flux distribution can be analyzed and optimized using computer simulations, such as finite element analysis, to study the magnetic field distribution and evaluate the performance of the transformer under various operating conditions.

Transient analysis is performed for the calculation of the no-load losses and flux distribution in a transformer, which is an electrical component used to transfer electrical energy from one circuit to another. Transient analysis is a useful tool for determining the behavior of a transformer under changing conditions, such as changes in load, voltage, and frequency. The results of transient analysis can provide information about the response of the transformer to these changes, including the no-load losses, which are losses incurred when the transformer is operating without any load, and the flux distribution, which is the distribution of magnetic flux within the transformer.

B. Core Losses in Transformer

Core losses in a distribution transformer are caused by magnetic hysteresis and eddy currents [18]. These losses are inherent in all magnetic materials and increase with increasing frequency and temperature. The core losses can be reduced by using high-quality magnetic materials, such as grain-oriented steel, and by keeping the transformer operating temperature low. In addition, core losses waveform for nonlinear loads refers to the magnetic losses that occur in the core of an electrical device or transformer due to the non-sinusoidal waveform of the current flowing through it. Unlike stranded losses, core losses are independent of the load impedance and are a function of the amplitude and frequency of the current waveform. Nonlinear loads typically generate high levels of harmonics, which result in increased core losses in the electrical system components. These losses reduce the efficiency of the system and can lead to overheating, reduced performance, and reduced lifespan of the components.

FEM (Finite Element Method) uses the magnetic field distributions and the loss to calculate the losses in the core of a distribution transformer [19]. It is a numerical technique for solving complex electromagnetic problems, which is widely used for transformer design and analysis. By modeling the magnetic fields and losses, FEM can accurately predict the performance of the transformer and identify areas for improvement.

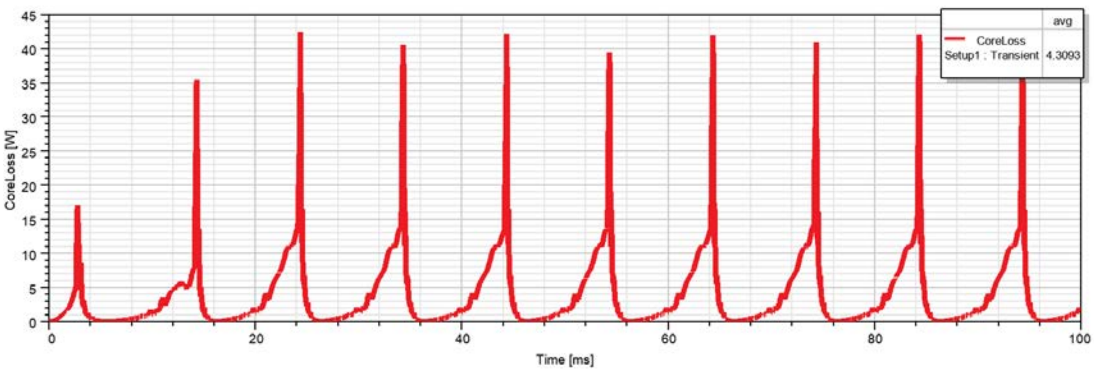


Fig. 9. Core losses waveform for nonlinear load

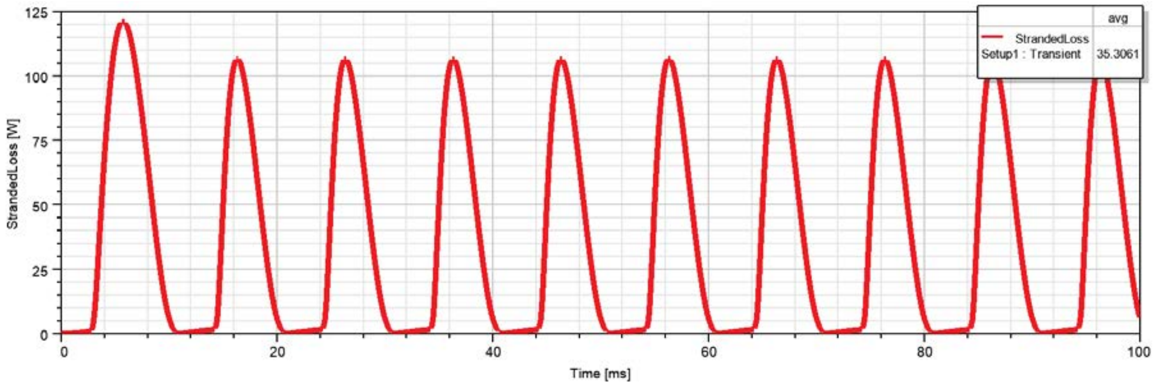


Fig. 10. Stranded losses waveform for nonlinear load

The instantaneous iron loss curves for 220 V input voltage are depicted in Fig. 9. The average iron loss of 4.4 watts indicates that there is some energy being lost as heat in the iron components of an electrical system of the transformer. This energy loss can have an impact on the overall efficiency of the system and can result in higher operating costs. To reduce iron loss and improve efficiency, various approaches can be taken such as using high-quality magnetic materials, reducing the operating frequency, and optimizing the design of the electrical system.

Fig. 10 displays the instantaneous copper loss curves when the MFL transformer input voltage is 220 V. Observably, the average copper loss of 35.30 W indicates that there is a significant amount of energy being lost as heat in the copper components of an electrical system. This energy loss can have an impact on the overall efficiency of the system and can result in higher operating costs. To reduce copper loss and improve efficiency, various approaches can be taken such as using low-resistance conductors, reducing the current flowing through the wires, and improving the overall design of the electrical system. Additionally, those values can be used as a baseline to compare against other systems and assess the effectiveness of optimization efforts. When MFL transformer is utilized in a microwave oven, it can only transmit heat by natural convection of air, and iron loss and copper loss might result in an increase in MFL transformer temperature.

C. The Temperature Field Simulation

The temperature field simulation is a computational technique used to model and predict the distribution of temperature in a specific system or environment. This simulation can be used in various fields, including thermal engineering, climate science, and material science, to study the behavior of heat transfer, thermal conduction, and energy exchange [20], [21]. The simulation is typically done using mathematical models and computer algorithms, which can take into account various factors that affect temperature, such as boundary conditions, material properties, and external heat sources.

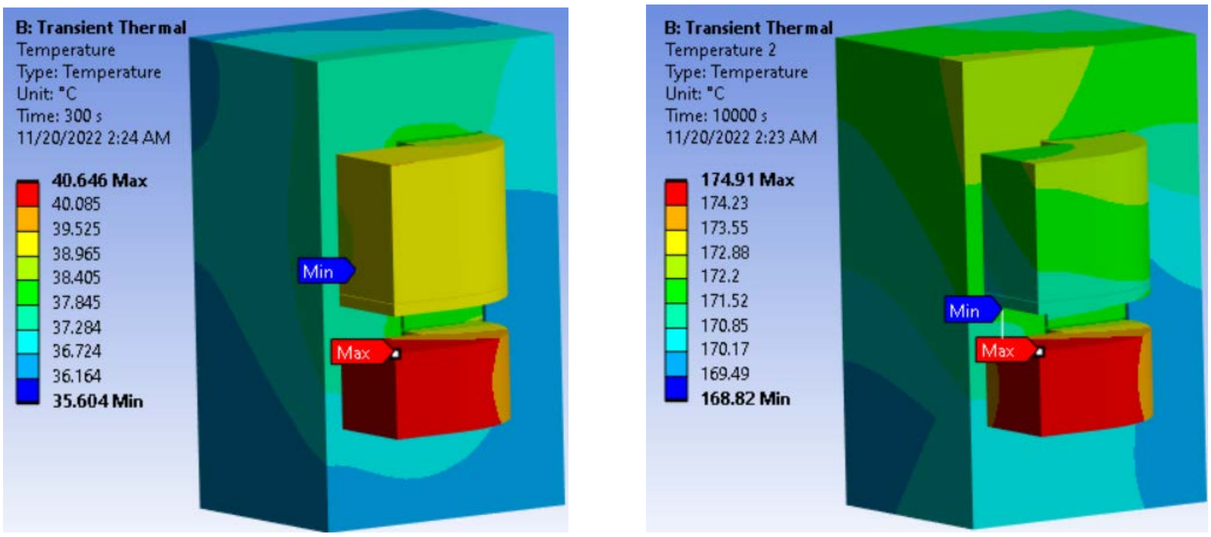
Due to the symmetry of the MFL Transformer, a quarter model was utilized to calculate the temperature distribution of transformer within microwave ovens. After determining the power losses of the transformer, a connection between Maxwell and Ansys-Workbench software for coupled steady-state thermal analysis has been built. The importation of the transformer geometry from electromagnetic FEA software is a common practice in the design and simulation of transformers. This software allows for the creation of a detailed 3D model of the transformer, including its magnetic core, windings, and external components. The FEA software can then be used to perform electromagnetic simulations and analyze the behavior of the magnetic fields within the transformer. The imported geometry can then be used in thermal simulation software to predict the temperature distribution within the transformer under different operating conditions.

This integration of electromagnetic and thermal simulations provides a more complete and accurate understanding of the transformer's behavior and performance, allowing for optimized design and improved reliability. After verifying the accuracy of the mesh in the thermal simulation, the next step would be to import the heat sources of the transformer core and windings. This allows the simulation to accurately model the temperature distribution within the transformer. The heat sources can include various factors such as electrical losses, resistance heating, and Joule heating.

In this case, the thermal behavior of the transformer is being studied under natural convection (NC) conditions. Natural convection refers to heat transfer caused by the buoyant forces created by the density differences in a fluid, such as air, due to temperature differences. This type of heat transfer is important to consider in the thermal behavior of transformers, as it can significantly affect the cooling of the transformer components and the overall temperature distribution within the transformer.

By importing the heat sources and considering natural convection, the thermal simulation can provide a comprehensive and accurate prediction of the temperature distribution within the transformer under different operating conditions, allowing for the optimization of its design and improved reliability.

The coefficient of convective heat transfer was fixed to 20 W/mK. The temperature was set at 22 degrees Celsius. The iron loss and copper loss created heat that was transported directly through air and the iron core. Fig. 11(a) shows how temperatures are distributed in the transformer after it has been operating for 300 seconds. The figure represents the results of measuring the temperatures at various points in the transformer after 300 seconds of operation. It is evident that, Under the natural convection heat transfer circumstances of microwave ovens, the temperature of the primary side



(a) (b)

Fig. 11. Heat distribution on the transformer: (a) for maximum 40.646 °C with air convection, (b) for maximum 174.91 °C with air convection

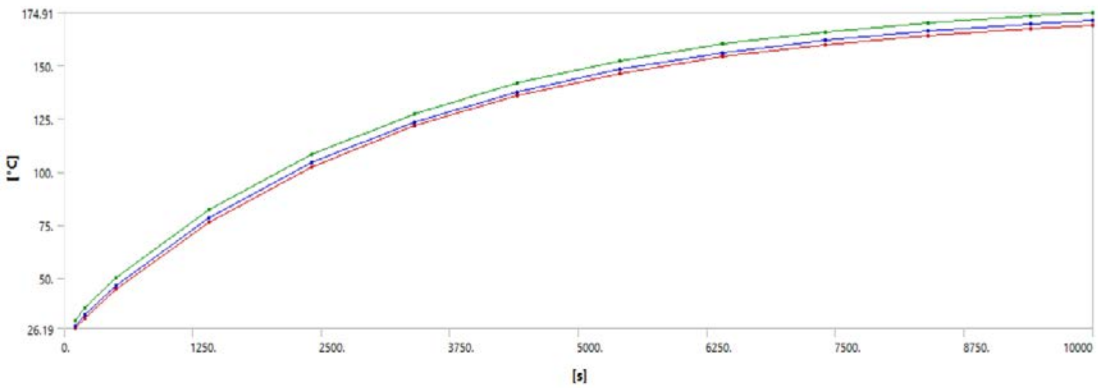


Fig. 12. Highest temperature and lowest temperature of the MFF transformer

windings reaches 40.646 degrees Celsius, while the maximum temperature rises of the MFL transformer is 12.59 degrees Celsius. While Fig. 11(b) presents the distribution of temperatures in the MFLT when it is in a state of balance. The figure demonstrates that the highest temperature recorded was 174.91°C.Fig. 12 presents the curves of the highest and lowest temperatures of an operating MFLT. The graph indicates that when the MFL transformer is in a balanced state, the temperature is approximately 174°C. It is important to monitor the temperature of a transformer to ensure that it is operating within safe temperature limits, as excessive heat can damage the transformer and reduce its lifespan. It can be seen that the temperature of the balanced state was roughly 174 °C. The high temperature will reduce efficiency and increase electromagnetic interference. Simulation and experimental results of transformers can be compared based on power losses and solution time. Power losses refer to the amount of energy that is lost as heat during the operation of a transformer. Solution time refers to the amount of time it takes to solve a problem or perform a task.

In general, simulation results tend to be faster and more efficient than experimental results, as simulations can be run on high-performance computers with faster processing speeds and greater memory capabilities. However, simulation results may not always accurately reflect real-world conditions, and experimental results may provide more accurate results. The comparison of simulation and experimental results will depend on the specific application and the accuracy required.

V. Conclusion

The paper discusses the transformer model used to represent transformers in power systems simulations, including the equivalent circuit models and the magnetic core models. The paper also covers the implementation and validation of the transformer model in simulation software, including the choice of parameters and the verification of simulation results. The paper also discusses the potential for improvement and further development of the transformer model, including the integration of new technologies and the consideration of non-linear effects.

The objective is to design a compact high voltage magnetic flux leakage transformer for a single-phase current transformer, with the aim of improving efficiency and reducing size. The design involves balancing various parameters such as magnetic performance, power density, and material selection, and may require the use of computer simulations and optimization algorithms. The end goal is to create a transformer that provides improved performance and reduced size for use in various power industry applications.

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