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Transformer Core Materials Selection by Flux Pattern Mapping Technique Using COMSOL Multiphysics

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Abstract

Researchers have developed better transformer cores and core modeling methodologies in response to the requirement for improved electrical core performance. This study ranks a distribution transformer's core material according to the compactness of the flux line distribution inside the core using flux pattern analysis. Five different core materials were taken into account. Model transformers were used in the investigations to assess the magnetic effects and examine the variations based on the core materials. A digital oscilloscope was used to measure the flux density and magnetic intensity signals. Different cores displayed varying tendencies in their results, which were indicative of local variations in the core's magnetization. The flux density ranged from low to high under the magnetization circumstances. This study compared the flux densities of the five core materials that were chosen and subjected to varying frequencies. Using COMSOL Mulltiphysics software, 2D and 3D finite element methods (FEM) are the analysis methodologies used. The different flux patterns of the candidate transformer core materials were identified using FEM, and the distances between the lines of flux of the corresponding candidate core materials were simulated using MATLAB. Following silicon steel, ferrite core, soft iron, and solid iron, the results indicate that the line of flux in metglass core material is more compact than that of the other possible core materials. This indicates that metglas remains the best core material due to its high flux compactness, lowest core loss (0.1 – 0.2 W/kg), and high permeability. It also exhibits the lowest temperature rise, making it ideal for energy-efficient transformers. The findings indicated that the pattern can help choose a better material with a stronger magnetic field and fewer losses.

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1. Introduction

Magnetic materials that are easily magnetized and demagnetized due to their narrow hysteresis loops play a vital role in designing electrical machines. The performance and efficiency of a machine are dependent on the materials used as

well as the design. Therefore, there is need for material development and improved performance which will in turn add to the comfort of man and modernization of the society [1]. When a magnetizing force is applied to a soft magnetic material, it exhibits magnetic properties. Soft ferromagnetic materials are generally used to amplify the flux generated by the electric current. It is the flux multiplying power of soft magnetic materials that makes them good for machines and devices. The ones with high duty flux multipliers are most suitable for making transformer, generator and motor cores while the light duty flux multipliers are used for making cores of small and special purpose transformers etc which are used in communication systems [2]. Transformers are typically made of big, hefty materials. Consequently, the price per unit weight is taken into account. Finding magnetic materials with the highest saturation magnetization and permeability is necessary to make these devices as cost-effective and energy-efficient as feasible [3]. Additionally, materials used for magnetic cores should be easily magnetized and demagnetized. In the meantime, the loss coefficient should be very low and the area inside the hysteresis loop should be very small. Furthermore, researchers have been actively working to develop better transformer cores and core modeling methodologies because of the significance of enhanced electrical core performance [4]. Better manufacturing techniques have been developed as a consequence of better transformer cores and core modeling technique. Currently, the quality of magnetic materials has been greatly improved. Factors that impact core materials are core loss density, saturation flux density, permeability and curie temperature [5]. Transformers come in different shapes and sizes; optimizing their performance is equally challenging because it involves accounting for the coupling of magnetic and electric fields, the behavior of ferromagnetic materials and more. Multiphysics simulations enable engineers to analyze these effects to improve the performance of transformer design, optimizing them for specific applications [6].
The magnetic field distribution (the magnetic flux density, magnetic field intensity, and magnetic vector potential) and fundamental electromagnetic properties (inductance and electromagnetic force) were investigated using the software program COMSOL Mulpiphysics. Determining the geometry, material characteristics, currents, boundary conditions, and field system equations characterizes a typical magnetic field problem [7]. The input data, the numerical solution of the field problem, and the output of the desired parameters are all necessary for the computer to function. The COMSOL software can be used for electromagnetic field modeling and is based on the finite element method (FEM) for solving Maxwell's equations. When modeling geometry and loading field sources, FEM ensures high flexibility and enough accuracy in electromagnetic field computation [8]. Meanwhile, there are difficulties in selecting core materials due to their variable material properties and performance indices [9]. Basically, it is the material that determines the performance and efficiency of a device. The conventional method for core material selection which involves mainly on using the core loss technique gave little or no attention on the localized flux density distribution [10].
In essence, the magnetic core is a material having magnetic permeability that aids in the confinement of magnetic fields in transformers [11]. The materials utilized to make magnetic cores for transformers include the following.

Solid iron cores: These cores help maintain the magnetic field and supply flux without becoming saturated with iron. Since the magnetic field creates strong eddy currents, the cores are not advised for transformers used in AC applications. At high frequencies, these eddy currents generate heat [12].

Metglass: Also known as vitreous metals. Because of its low conductivity, this glassy or non-crystalline metal can be used in high performance transformers. Metglass is made up of different alloys. They are employed in the production of transformers with high efficiency. The materials can have lower conductivity to minimize eddy current losses and be highly responsive to magnetic fields for low hysteresis losses [13].

Ferrites ceramics: They are a class of ceramic compounds formed from iron oxide plus one or several metallic elements. The magnetic cores manufactured from ferrite ceramics are employed in high frequency applications [14]. To satisfy a range of electrical needs, the ceramic materials are manufactured according to various specifications. These ceramic materials reduce eddy current and act as effective insulators [15].

Soft iron core: A variety of ferrous-based materials are treated using both wrought and powder metallurgical methods to create soft iron [16].

Silicon steel: It has high electrical resistance. Silicon steel core ensures consistent performance over the years. It provides a high density of saturation flow. A few years ago, silicon steel's properties underwent chemical modifications, and the result is now a new product known as AISI type M6 [17]. High performance applications require M6 steel because of its high permeability and minimal losses. A mere 3 percent silicon added to iron causes the metal's resistivity to rise dramatically, up to four times. Transformer cores are made of silicon steel because of its increased resistivity, which lowers eddy current. As the silicon concentration rises further, the steel's mechanical qualities deteriorate and rolling becomes challenging because of brittleness [18].

The study in [19] provided a suggested $Mo.Me^6$ material with improved physical characteristics, leading to the most efficient transformer and core design. Changes to some of the core's effective properties, which raise the operational efficiency of the transformer, are among the requirements. The study in [20] provides an overview of magnetic materials appropriate for high frequency (MHz) planar transformer applications. It also contrasts the losses and temperature increase of planar magnetic cores made of various magnetic materials with the labels F, P, R, and L. The EE core shape is used in the transformer design. Additionally, selecting the proper core material is crucial for transformers, especially high-frequency transformers where the operating frequency significantly affects the transformer's efficiency and thermal management requirements. Proper selection of the core material may involve consideration of certain material parameters, including permeability, curie temperature, saturation flux density, and core loss density [21]. An analytical model of electromagnetic force density and magnetic flux density on transformer core discontinuities is created in [22]. They demonstrated that lowering the gap ratio and raising the gap thickness to a manageable level can lower the electromagnetic force density. In order to study the flux pattern of variant transformer core materials at different frequency levels, [23] implemented the 2D Finite Element Method (FEM). Transformer core material selection has been extensively studied, with a primary focus on core loss minimization, permeability enhancement, and electromagnetic performance improvements [24, 25]. Traditional research methodologies have largely emphasized the evaluation of materials based on hysteresis loss, eddy current loss, and overall efficiency [26]. While these parameters are critical, they do not comprehensively capture the localized flux distribution patterns within different core materials, which significantly influence transformer performance in real-world applications. In other research results, [27] revealed that existing FEM-based studies have explored flux leakage and magnetic saturation which shows limited comparative studies on flux pattern variation among core materials. [28] revealed that conventional selection methodologies rely on core loss density and saturation flux density which often neglecting how flux line compactness and pattern variations affect efficiency under dynamic operating conditions.

To address these deficiencies, this study introduces a flux pattern mapping technique for transformer core material selection using FEM simulations in COMSOL Multiphysics that evaluates the compactness of flux lines within the core, providing a more detailed understanding of the magnetic behaviour of different core materials. The study also provides a more precise metric for comparing material performance beyond traditional loss-based methods. It offers insights for the design of energy-efficient transformers, particularly in applications where flux confinement and minimal core loss are critical. Conventional transformer core material selection techniques primarily rely on core loss analysis**,** permeability evaluation**,** and saturation flux density measurements**.** While these metrics are useful in determining the efficiency and performance of magnetic materials, they do not provide a complete picture of how flux behaves within the core. Flux pattern mapping offers several advantages over these existing selection techniques, making it a superior method for optimizing transformer core material selection.

2. Methodology

The materials used in the study are solid iron core, ferrite, soft iron core, silicon steel, solid iron core, silicon steel. The simulation tools employed are COMSOL Multiphysics and MATLAB. The method involves the use of finite element method to study all the various core materials. The description of the case study transformer is shown in Table 1.

Table 1: Transformer parameters

Name	Value	Description
Rp	100 Ω	Primary side resistance
Rs	100 Ω	Secondary side resistance
Np	3000	Number of turns in primary winding
Ns	300	Number of turns in secondary winding
F	50 Hz	Frequency of supply voltage
Vac	25 kV	Supply voltage

2.1 Core selection modeling

Starting from Maxwell's equations in the form as stated in [29 – 32].

$curl\left(\vec{E}\right) = -\frac{dB}{dt}$ Faraday's law of electromagnetic induction (1)

$div\left(\vec{B}\right) = 0$ Inexistence of magnetic charge (2)

$curl\left(\vec{B}\right) = \mu_0\vec{J_T} - \mu_0\,\epsilon_0\frac{d\vec{E}}{dt}$ Modified Ampere's circuital law (3)

$curl\left(\vec{E}\right) = -\frac{1}{\epsilon_0}\rho_T$ Gauss's law (4)

$\rho_T = \rho_f - div\left(\vec{P}\right)$ (5)

$\vec{J}_T = \vec{J}_f - curl\left(\vec{M}\right) + \frac{d\vec{P}}{dt}$ (6)

The term $\vec{P}$ is the electric dipole moment density, ρ_f is the density of free charges, $\vec{J}_f$ is the free current density due to the motion of the free charges, and $\vec{M}$ is the magnetic dipole density. It is presumed that the total charge density, ρ_T, and $\vec{J}_T$ the total current density, are prescribed functions of position and of time. The equation $div(\vec{B})$ = 0 can be satisfied by setting;

$$\overrightarrow{B} = curl\left(\vec{A}\right) \quad (7)$$

Due the divergence of any curl is equivalent to zero, Equation (1), in relation to Equation (7) becomes;

$$curl\left(\vec{E}\right) = -\frac{\partial}{\partial t}\, curl\left(\vec{A}\right) = -curl\,\frac{\partial \vec{A}}{\partial t} \quad (8)$$

The space and time derivatives are considered to be interchangeable in order. Consequently, the curl of the vector potential's time derivative and electric field total is zero, therefore Equation (8) becomes;

$$curl(\,\vec{E} - \frac{\partial \vec{A}}{\partial t}\,) = 0 \quad (9)$$

The curl of any gradient is equivalent to zero so that the requirement Equation (9) can be satisfied by putting

$$\vec{E} - \frac{\partial \vec{A}}{\partial t} = -grad\ V \quad (10)$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - grad\ V \quad (11)$$

By introducing the vector potential, $\overrightarrow{A}$, and the scalar potential, it enables one to satisfy the first two of Maxwell's Equations (1) and (2). Write $\overrightarrow{E}$ and $\vec{B}$ in terms of the potentials $\vec{A}$ in Equations (3) and (4) of Maxwell's equations to obtain

$$curl\,\left(curl\left(\vec{A}\right)\right) = \mu_0\overrightarrow{J_T} - \mu_0\,\epsilon_0\frac{\partial}{\partial t}(-\,\frac{\partial \vec{A}}{\partial t}\; - grad\ V) \quad (12)$$

$$curl\,\left(curl\left(\vec{A}\right)\right) = \mu_0\overrightarrow{J_T} - \mu_0\,\epsilon_0(-\,\frac{\partial^2 \vec{A}}{\partial^2 t}\; - \overrightarrow{grad}\,\frac{\partial^2 V}{\partial t^2}) \quad (13)$$

In Cartesian co-ordinates, the vector operator curl curl can be written as

$$curl\ curl = \nabla^2 + \overrightarrow{grad}\ div \quad (14)$$

Applying Equation 14 on 13

$$\nabla^2\vec{A} + \mu_0\,\epsilon_0\frac{\partial^2 \vec{A}}{\partial^2 t} + \overrightarrow{grad}\,\left(div\,\vec{A}\, + \mu_0\,\epsilon_0\frac{\partial V}{\partial t}\right) = \mu_0\overrightarrow{J_T} \quad (15)$$

A vector field's curl and divergence must be provided in order to fully specify it. Although the requirement that $\overrightarrow{B} = curl\left(\vec{A}\right)$ has fixed only the curl of $\vec{A}$ at this stage, one is still free to place certain restrictions on divergence $\vec{A}$. It is convenient to choose the vector potential so that it satisfies the condition

$$div\,\vec{A}\, + \mu_0\,\epsilon_0\frac{\partial V}{\partial t} = 0 \quad (16)$$

This choice of div ($\vec{A}$) is called the Lorentz gauge. In the Lorentz gauge, Equation (15) simplifies to become

$$\nabla^2\vec{A} + \mu_0\,\epsilon_0\frac{\partial^2 \vec{A}}{\partial^2 t} = -\mu_0\overrightarrow{J_T} \quad (17)$$

or in component form

$$\nabla^2 A_x + \mu_0\,\epsilon_0\frac{\partial^2 A_x}{\partial^2 t} = -\mu_0\overrightarrow{J_T}|_x \quad (18)$$

$$\nabla^2 A_y + \mu_0\,\epsilon_0\frac{\partial^2 A_y}{\partial^2 t} = -\mu_0\overrightarrow{J_T}|_y \quad (19)$$

$$\nabla^2 A_z + \mu_0\,\epsilon_0\frac{\partial^2 A_z}{\partial^2 t} = -\mu_0\overrightarrow{J_T}|_z \quad (20)$$

This paper has considered the system governing by using the time-harmonic mode and representing the magnetic vector potential in complex form,

$$\vec{A} = Ae^{-j\omega t} \quad (21)$$

Therefore

$$\frac{\partial^2 \vec{A}}{\partial^2 t} = j\omega A \quad (22)$$

Refer to Equation (17), by employing the complex form of the magnetic field and when considering the problem of three dimensions in Cartesian coordinate (x, y, z), hence

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_y}{\partial y}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_y}{\partial y}\right) + \epsilon_0 j\omega A = \overrightarrow{J_T} \quad (23)$$

The aforementioned equation does not have a straightforward analytical solution. In order to determine approximate magnetic field solutions for the quasi-static partial differential equation given in Equation (23), the 3-D FEM is selected as a viable tool in this research.

2.2 3-D FEM for the distribution transformer

The case study considers a three-phase transformer with a 500 kVA, 11/0.415 kV, star connection distribution transformer. Figure 1 depicts the detail of the distribution transformer. The domain of study with the 3-D FEM can be discretized by using linear tetrahedron elements. This can be accomplished by using COMSOL for 3-D grid generation. Figure 2 displays grid representation of the test system. The region domain consists of 24,107 nodes and 132,961 elements.

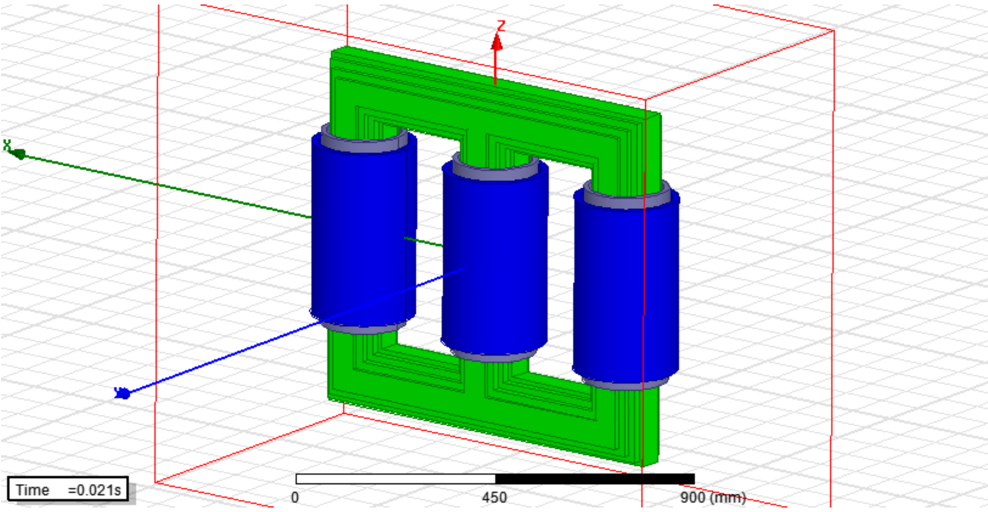

Figure 1: Distribution transformer

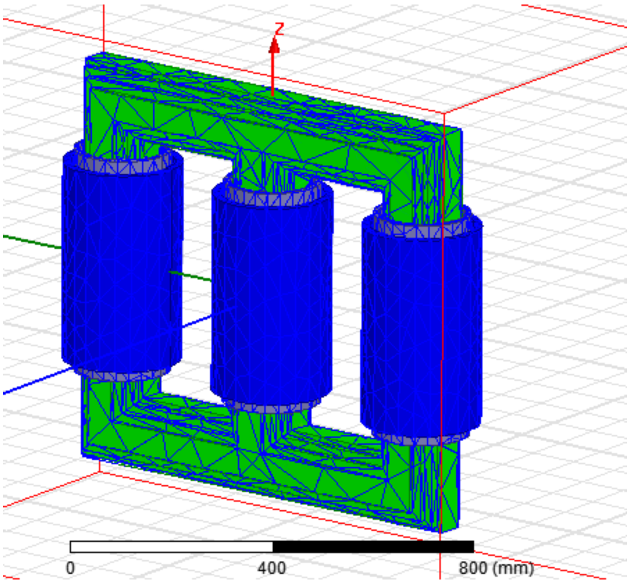

Figure 2: Discretized grid representation

The procedure for determining distances between flux patterns in transformer is shown in Figure 3.

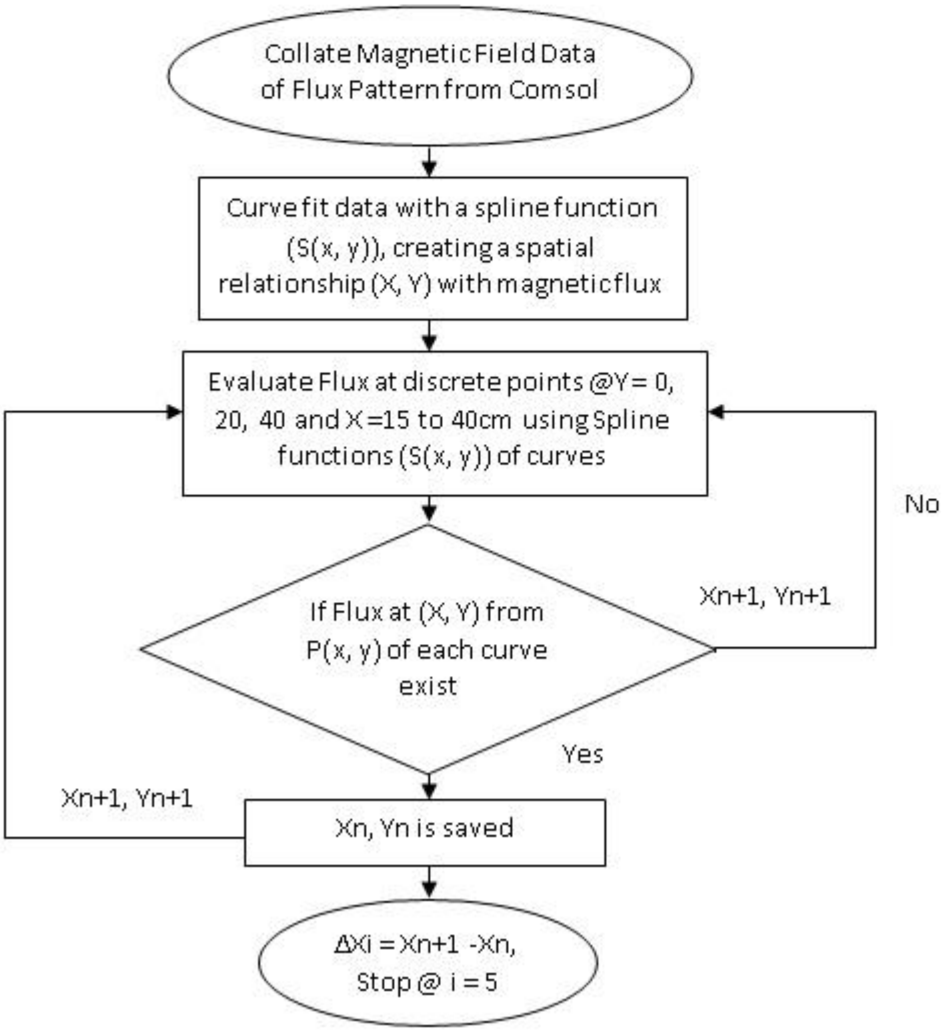

Figure 3: Algorithm for determining distances between flux patterns

3. Results and Discussion

This section discusses the results of the modeling and simulation of the variant core materials.

3.1 2-D of variant core materials

The modeling of transformer was done to analyze the pattern and direction of flux density vectors at different time intervals. The simulations of the variant transformer cores were carried out at the time intervals of 40 ms to 48 ms. The time was varied to get the direction of the flux.

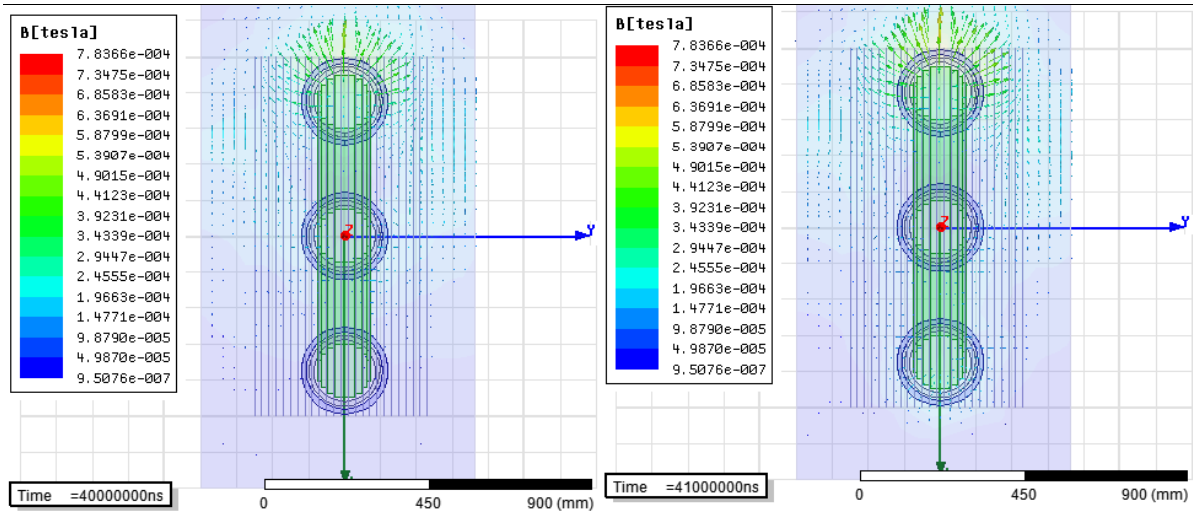

Figure 4: Flux density vectors showing pattern and direction of flux at 40 and 41 ms for silicon steel core

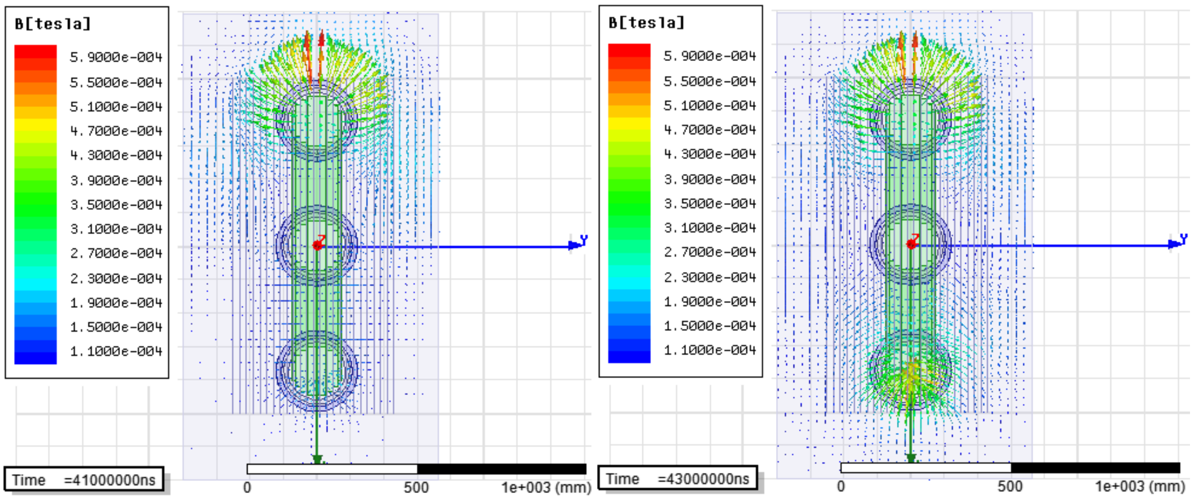

Figure 5: Flux density vectors showing pattern and direction of flux at 42 and 43 ms for metglass core

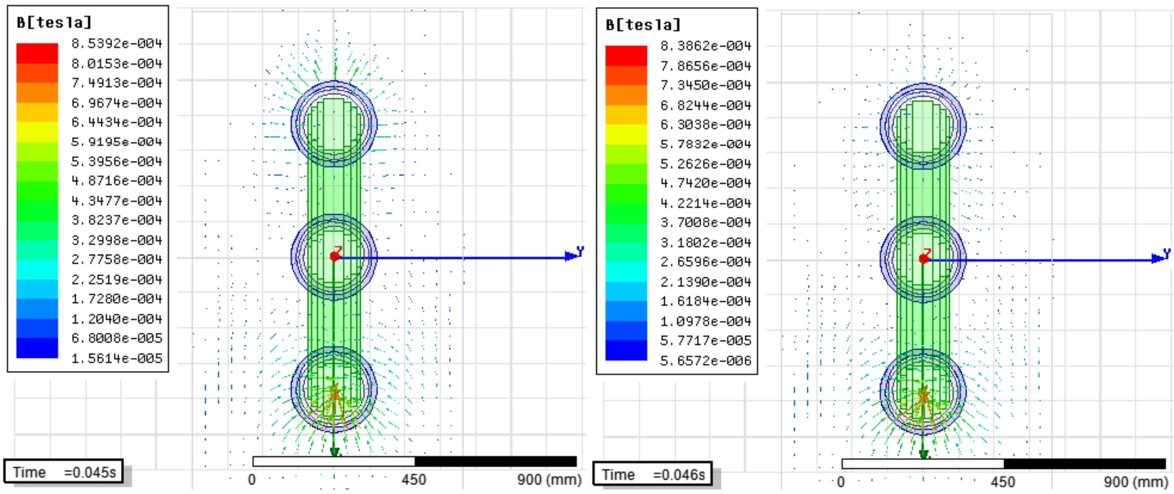

Figure 6: Flux density vectors showing pattern and direction of flux at 45 and 46 ms for ferrite core

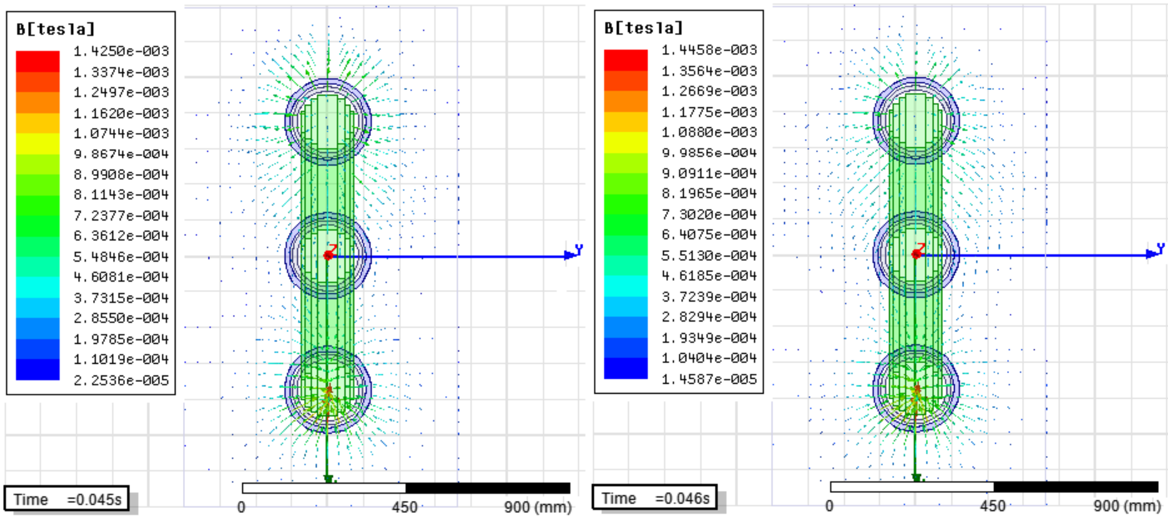

Figure 7: Flux density vectors showing pattern and direction of flux at 48 and 47 ms for soft-iron core

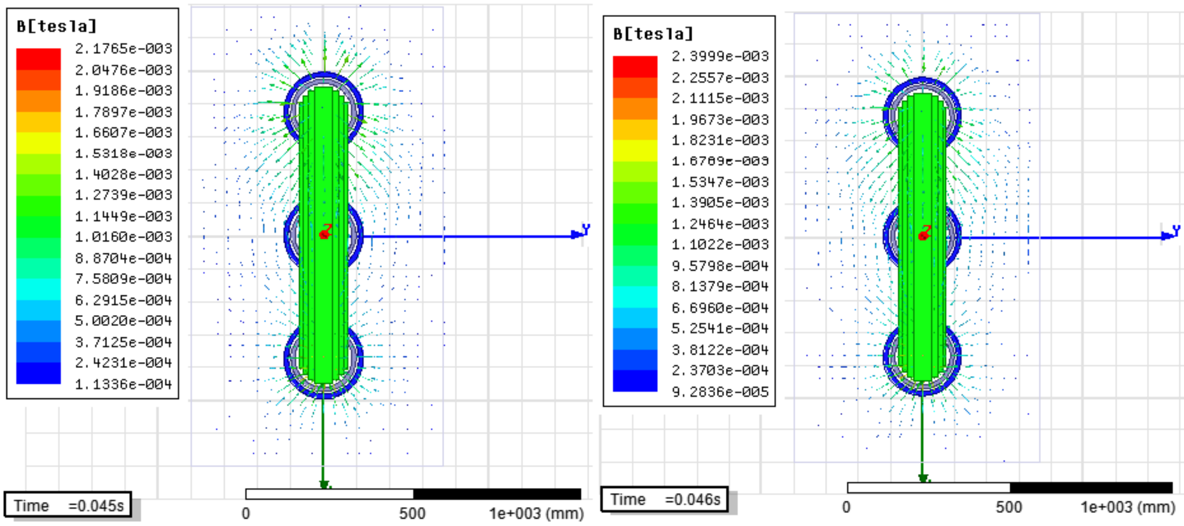

Figure 8: Flux density vectors showing pattern and direction of flux at 48 and 47 ms for solid-iron core

Figure 4 shows the pattern and direction of silicon steel. This shows the momentary flux lines interactions of silicon which indicates low residual magnetic flux density. Figure 5 shows the pattern and direction of metglass core. The magnetic flux lines interactions are likely to be similar to the ones of ferrite core and soft iron cores in Figures 6 and 7 respectively. The flux interactions of solid iron in Figure 8 appears to be more prominent which shows high saturation flux density.

3.2 Comparison of core loss with relation to flux pattern profile

The various profile plots of flux pattern profile around the core which were generated with MATLAB from the individual flux density along the sensor lines within the magnetization region. The 3D mesh plots of the variant core materials are shown in Figures 9 to 13.

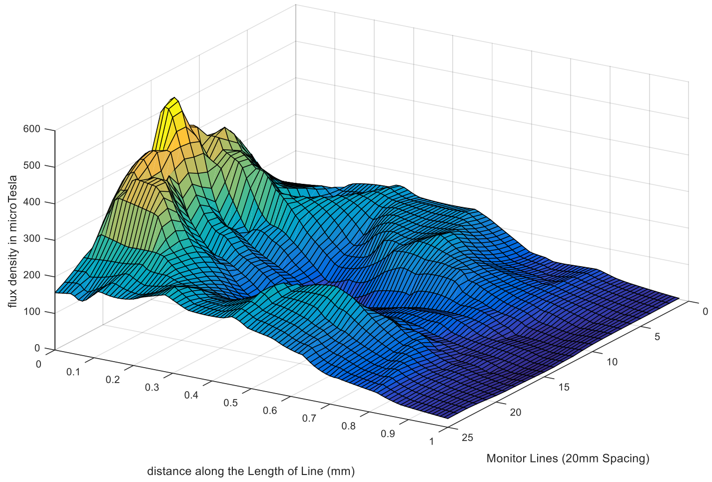

Figure 9: 3-dimensional mesh plot showing the profile of flux density along the 25 monitoring lines for metglass material

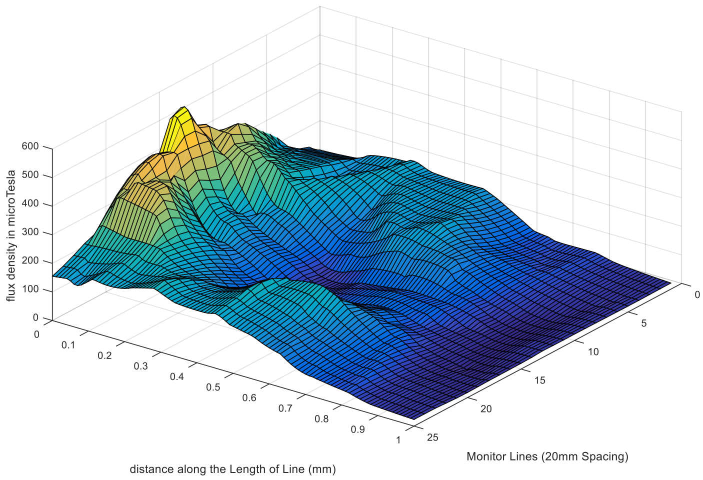

Figure 10: 3-dimensional mesh plot showing the profile of flux density along the 25 monitoring lines for silicon steel material

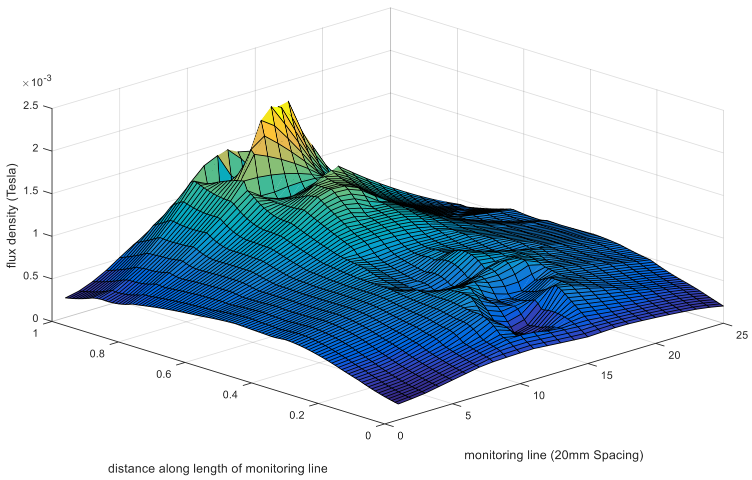

Figure 11: 3-dimensional mesh plot showing the profile of flux density along the 25 monitoring lines for solid-iron material

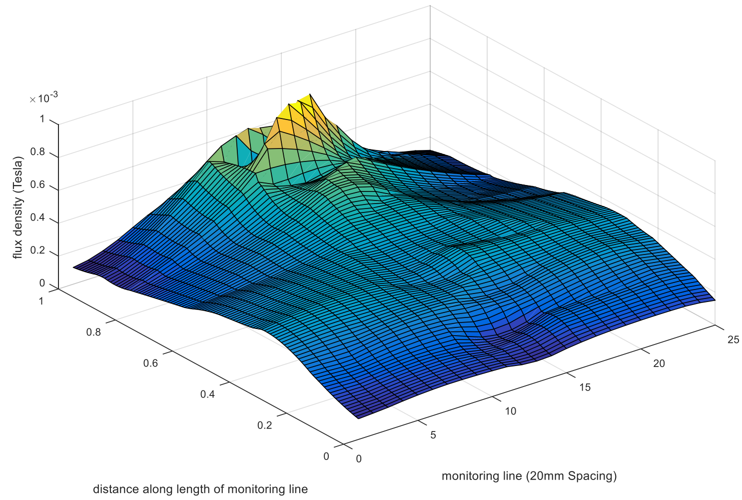

Figure 12: 3-dimensional mesh plot showing the profile of flux density along the 25 monitoring lines for soft-iron material

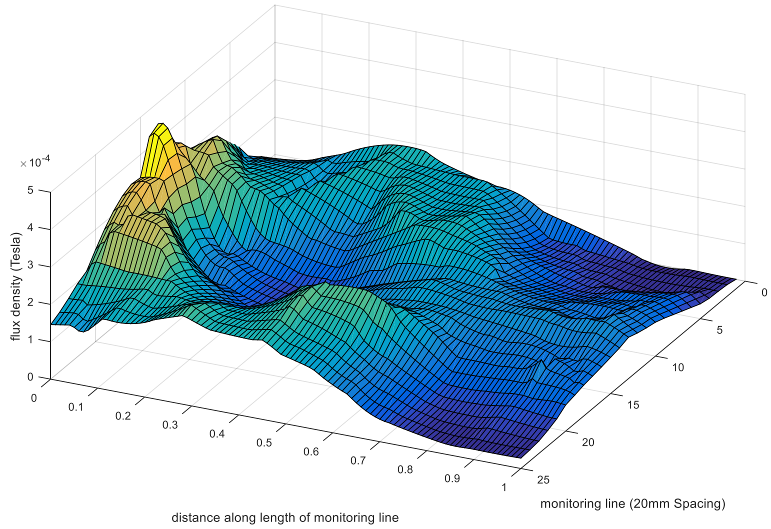

Figure 13: 3-dimensional mesh plot showing the profile of flux density along the 25 monitoring lines for ferrite material

The values of the dimensional profiles of the variant core materials are shown in Table 2.

Table 2: Dimensional profiles of the core materials

	ΔX across flux lines				
Y Points(cm)	**Metglass (cm)**	**Silicon Steel (cm)**	**Ferrite Core (cm)**	**Soft Iron (cm)**	**Solid Iron (cm)**
0	0.382	0.416	0.427	0.466	0.472
	0.365	0.425	0.434	0.486	0.491
	0.359	0.402	0.423	0.487	0.482
	0.401	0.415	0.420	0.495	0.512
	0.383	0.422	0.43	0.5	0.499
20	0.41	0.423	0.420	0.477	0.526
	0.392	0.433	0.435	0.474	0.515
	0.39	0.431	0.430	0.489	0.51
	0.386	0.398	0.421	0.51	0.531
	0.380	0.414	0.433	0.498	0.526
40	0.39	0.408	0.421	0.470	0.484

	0.392	0.418	0.425	0.49	0.499
	0.385	0.421	0.431	0.501	0.511
	0.380	0.411	0.431	0.512	0.524
	0.391	0.420	0.44	0.514	0.54
Core loss (kW) @ 50 Hz	0.1	0.2	0.21	4.5	4.9

The MATLAB plots as shown in Figures 9 to 13, and in Table 2 have shown the confinement of the flux density as well as the flux density differences at 20 mm distance interval. Compared to the other materials, the metglass material simulation exhibits a greater degree of flux confinement around the core. This is consistent with the core loss graph, which indicates that metglass has less core loss than silicon steel and other materials. This confirms the connection between a distribution transformer's core loss of core materials and the flux and magnetization patterns surrounding the core. From the results of Table 2, in performing ANOVA test to determine whether there are statistically significant differences among the flux density values of different core materials. This test shows F-statistic as 0.363 and P-value as 0.834. Since the P-value is greater than 0.05, there is no statistically significant difference in flux density distributions among the five core materials. Hence, pairwise t-tests were not conducted, as further comparisons would not yield meaningful results. Table 3 is used in comparing the transformer core materials with industry-standard materials

Table 3: Comparison of Transformer Core Materials with Industry-Standard Materials

Core Material	Flux Pattern Compactness	Core Loss (W/kg @ 50Hz, 1.5T)	Saturation Flux Density (T)	Relative Permeability (μr)	Curie Temperature (°C)	Applications
Metglas	High (most compact flux lines)	0.1 – 0.2	1.56	25,000 – 50,000	~400	High-efficiency power transformers, high-frequency applications
Silicon Steel	Medium	0.2	2.03 – 2.1	~4,000	~740	General transformer applications
Ferrite Core	Medium	4.0 – 6.0	0.5 – 0.6	2,000 – 10,000	~200	High-frequency transformers
Soft Iron Core	Low	4.5 – 5.5	2.0 – 2.2	5,000 – 10,000	~770	Electromagnets, low-frequency applications
Solid Iron Core	Lowest (high leakage flux)	4.9 – 6.0	2.1 – 2.2	~2,000	~770	Special-purpose transformers, electromagnets
Grain-Oriented Silicon Steel (M6 Steel)	Medium-High	0.8 – 1.5	2.03 – 2.1	2,000 – 40,000	~740	Power transformers, distribution transformers
Non-Oriented Silicon Steel (NO)	Medium	1.5 – 2.5	1.7 – 2.0	2,000 – 5,000	~700	Rotating machines, high-frequency transformers

From the results of Table 3, metglas remains the best core material due to its high flux compactness, lowest core loss (0.1 – 0.2 W/kg), and high permeability, confirming the study's result that amorphous materials outperform conventional transformer cores. Table 4 shows the result of thermal modeling for the core materials under real-world operating conditions, heating due to core loss impacts material properties, efficiency, and long-term reliability.

Table 4: Thermal operation of the core materials

Core Material	Thermal Conductivity (W/m·K)	Heat Capacity (J/kg·K)	Max. Expected Temperature Rise (°C)	Cooling Efficiency
Metglas	13 – 20	500 – 600	Low (~30°C at 100% load)	High (fast dissipation)
Silicon Steel (M6)	20 – 30	450 – 500	Moderate (~50°C at 100% load)	Moderate
Non-Oriented Silicon Steel	15 – 25	460 – 520	High (~70°C at 100% load)	Lower
Ferrite Core	5 – 10	800 – 900	Very High (~90°C at 100% load)	Poor (low thermal conductivity)
Soft Iron	40 – 50	450 – 500	High (~80°C at 100% load)	Moderate

From Table 4, metglas exhibits the lowest temperature rise**,** making it ideal for energy-efficient transformers while ferrite cores retain heat longer**,** making them less suitable for high-power applications. Also, M6 performs better than NO Steel but still experiences significant heating**.**

4. Conclusion

Modeling of different transformer core materials was carried out. Finite element method was used to simulate the flux pattern of variant transformer core materials. The simulation software COMSOL Multiphysics was used in the implementation of the finite element method. Meanwhile, MATLAB was used to measure the differences in the flux pattern which gave an accurate dimension. Moreover, the ranking of different transformer cores based on performance was achieved. Furthermore, a design of a three-phase transformer has been modeled in 2D and 3D axis. Variant transformer core materials namely; soft iron, solid iron, silicon steel, amorphous steel, metglass (amorphous metal), and ferrite ceramics were simulated. A comparison of the flux densities of a few chosen core materials at different frequencies was carried out. As a result, a flux pattern criterion for choosing the right core material for transformers has been established. The flux density confinement and flux density variations at 20 mm intervals have been demonstrated by the MATLAB results. Compared to the other materials, the metglass material simulation exhibits a greater degree of flux confinement around the core. This is consistent with the core loss graph, which indicates that metglass has less core loss than silicon steel and other materials. This confirms the connection between a distribution transformer's core loss of core materials and the flux and magnetization patterns surrounding the core. Because metglass has high flux compactness, lowest core loss (0.1 – 0.2 W/kg), and high permeability, the results indicate that it is the best material for the core. Furthermore, compared to traditional silicon steel, metglass exhibits fewer core losses. In contrast to silicon steel, metglass has a lower saturation magnetic induction. This raises the price of larger transformers, which are inappropriate for applications that call for smaller size and volume.

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