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PERFORMANCE EVALUATION OF VARIANT TRANSFORMER CORE MATERIALS WITH VARIABLE FREQUENCIES

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***Abstract*: This study involves modeling of the transformer core for flux pattern analysis of variant core materials which include metglass, ferrite, soft iron, silicon steel and solid iron under different frequencies and time intervals. The analysis techniques deployed were 2D Finite Element Method (FEM) using Comsol Multiphysics software. FEM was used to determine the various flux pattern of the candidate transformer core materials, while MATLAB was used to simulate the distances between the lines of flux for the respective candidate core materials. The result from the flux pattern mapping shows that the lines of flux in metglass core material are more compact than in the rest candidate materials followed by silicon steel, ferrite core, soft iron and solid iron respectively. The flux pattern mapping was successfully deployed in the selection of a better core material with stronger magnetic field and lower losses. Among the samples considered, metglass gave the least core loss of 0.1 kW, 0.065 kW, 0.14 kW, 0.24 kW, 1.09 kW and 1.36 kW for frequencies of 50 Hz, 100 Hz, 150 Hz, 200 Hz, 500 Hz and 1000 Hz respectively.**

***Keywords:* Core Loss, Core Material, Ferrite, Finite Element Method, Frequency, Metglass, Silicon Steel, Soft Iron, Solid Iron, Transformer.**

I. INTRODUCTION

Power transformers are the most prevalent and significant component of an electric power system, typically employed for transmission and distribution of power. Transformers are employed in a wide range of power system applications, including low voltage machine control, power transmission and distribution over a power grid [1]. For a given application, the transformer can be used to increase or reduce voltage and current in the opposite direction. A step-up transformer is typically used to connect the power plant and transmission lines after the power plant. Its function is to increase the voltage to a very high level and decrease the current at the same time [2]. As a result, that will assist in moving power over great distances through transmission lines while minimizing significant losses while a step-down transformer is used to connect transmission lines to distribution lines [3]. Transformer core which is a structure of thin laminated sheets of ferrous metal stacked together comprises of different material, depending on transformer application. Some examples are soft metal, silicon steel, carbonyl steel, ferrite ceramic and vitreous metal [4]. Typically, cores are made of steel containing high silicone content, specifically to minimize hysteresis losses. By stacking the metal laminations, the core is equivalent to multiple individual circuits as opposed to one large magnetic circuit. Each sheet has only a percentage of the total magnetic flux and since eddy currents flow around those lines of flux, this arrangement greatly prevents eddy current from flowing [5]. As converters become more and more focused on achieving high power density, low profile, light weight, and high efficiency, magnetic components play a major role in making all of these goals possible. With the development of high frequency switching components, researchers were able to reduce the size of magnetic components like transformers and inductors while still achieving great power density by moving toward high operating frequency [6]. This document outlined the development, standard practice, and selection criteria for transformer cores that have been established by the industry. The core's construction takes into account the highest flux that passes through it, the least amount of magnetization, and the eddy current. Since air has a permeability that is 2000 times lower than that of a steel core, silicon steel (0.3–0.5 mm) makes up the majority of cores, with the thickness being determined by the output efficiency [7]. A highly important stage that depends on the transformer's kind, size, rating, efficiency, and utilization location is choosing the core. High switching frequency transformer cores, operating above 20 kHz, are essential to power distribution because they provide galvanic isolation between the input primary and output secondary circuits [8]. The type of core material employed, along with the operating frequency and excitation voltage waveform, have a significant impact on the transformer core losses, thermal behavior, and efficiency. The transformer windings undergo continual magnetization and demagnetization as an alternating current flow through them. The transformer core material's saturation point and rate of magnetization are determined by its magnetic characteristics. The efficiency of a power converter can be increased by utilizing a transformer core material with desired magnetic characteristics [9].

[10] presented a proposed Mo.Me[6] material with enhanced physical properties, resulting in optimal core design and transformer efficiency. Among the requirements are modifications to a few of the core's effective characteristics, which result in an improvement in the transformer's operational efficiency. An overview of magnetic materials suitable for high frequency (MHz) planar transformer applications is given in this paper. Additionally, it compares the temperature rise and losses of planar magnetic cores composed of several magnetic materials labeled F, P, R, and L. The transformer design uses the EE core shape [3]. Furthermore, choosing the right core material for a transformer is essential, particularly for high-frequency transformers where the operating frequency has a big impact on the transformer's efficiency and thermal control needs. Some material properties, such as core loss density, saturation flux density, permeability, and curie temperature, may be taken into account in order to properly pick the core material [11].

The FEM software packages have been the main methods used in studies on the performance analysis of high-frequency transformer core materials. The goal of this work is to evaluate different transformer core materials with variable frequency for optimum mutual inductance of the transformer, which can swiftly ascertain the true efficiency and output power performance of various comparable transformer core material kinds.

II. METHODOLOGY

The materials used for core flux mapping are soft iron, solid iron, silicon steel, metglass (amorphous metal), and ferrite ceramics with the aid of flux pattern technique deploying finite element analysis solver for the simulation.

The model equations of a three-limb three-phase transformer are stated in [12 – 14] as based in Maxwell's equations is stated as;

$$curl\,(\vec{E}) = -\frac{dB}{dt} \quad \text{Faraday's law of electromagnetic induction} \tag{1}$$

$$div(\vec{B}) = 0 \quad \text{Inexistence of magnetic charge} \tag{2}$$

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

$$curl\,(\vec{E}) = -\frac{1}{\epsilon_0}\rho_T \quad \text{Gauss's law} \tag{4}$$

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

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

The term ρ_f is the density of free charges, $\vec{J_f}$ is the free current density due to the motion of the free charges, $\vec{P}$ is the electric dipole moment density, and $\vec{M}$ is the magnetic dipole density. It is assumed that the total current density, $\vec{J_T}$ and the total charge density, ρ_T, are the given functions of time and position. Because the divergence of any curl is equal to zero, Equations (1) becomes

$$curl\left(\vec{E}\right) = -\frac{\partial}{\partial t}\, curl\left(\vec{A}\right) = -curl\,\frac{\partial\vec{A}}{\partial t} \quad (7)$$

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

$$curl\,\left(curl\,(\vec{A})\right) = \mu_0\overrightarrow{J_T} - \mu_0\,\epsilon_0\frac{\partial}{\partial t}(-\frac{\partial\vec{A}}{\partial t} - grad\ V) \quad (8)$$

$$curl\,\left(curl\,(\vec{A})\right) = \mu_0\overrightarrow{J_T} - \mu_0\,\epsilon_0(-\frac{\partial^2\vec{A}}{\partial^2 t} - \overrightarrow{grad}\frac{\partial^2 V}{\partial t^2}) \quad (9)$$

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

$$curl\ curl = \nabla^2 + gr\vec{a}d\ div \quad (10)$$

Substituting Equation (10) on (9) gives

$$\nabla^2\vec{A} + \mu_0\,\epsilon_0\frac{\partial^2\vec{A}}{\partial^2 t} + gr\vec{a}d\,\left(div\,\vec{A} + \mu_0\,\epsilon_0\frac{\partial V}{\partial t}\right) = \mu_0\overrightarrow{J_T} \quad (11)$$

In order to wholly specify a vector field, it has to give both its divergence and its curl. But at this instant, only that of curl of $\vec{A}$ has been fixed by the condition that $\overrightarrow{B} = curl\,\left(\vec{A}\right)$, on this, one still has to force some limitations on the divergence of $\vec{A}$. It is convenient to select the vector potential so that it meets the condition

$$div\,\vec{A} + \mu_0\,\epsilon_0\frac{\partial V}{\partial t} = 0 \quad (12)$$

This choice of div ($\vec{A}$) is called the Lorentz gauge. In the Lorentz gauge, Equation (11) simplifies to become

$$\nabla^2\vec{A} + \mu_0\,\epsilon_0\frac{\partial^2\vec{A}}{\partial^2 t} = -\mu_0\overrightarrow{J_T} \quad (13)$$

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

$$\vec{A} = Ae^{-j\omega t} \quad (14)$$

Therefore

$$\frac{\partial^2\vec{A}}{\partial^2 t} = j\omega A \quad (15)$$

Refer to Equation (13), by employing the complex form of the magnetic field and when considering the problem of three dimensions in Cartesian coordinate (x, y, z), hence

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_y}{\partial y}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_y}{\partial y}\right) + \epsilon_0 j\omega A = \overrightarrow{J_T} \quad (16)$$

Analytically, there is no simple exact solution of the above equation. Therefore, in this paper the 2-D and 3-D FEM is chosen to be a potential tool for finding approximate magnetic field solutions for the quasi-static partial differential equation described as in Equation (16)

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The dimensions of the case study transformer which comprises of various specifications are given in Table 1.

Table 1: Details of Transformer dimension labels

Specification Description	Value (mm)
T.Length	895
T.Height	833
W.Length	277
W.Height	539
Cross Section Diameter	157
LV ID	184.5
LV OD	197
HV ID	213
HV OD	242

Finite element method (FEM) is a numerical approach for finding approximate solution to boundary value problem. FEM can be used for solving differential equations involving coupling of electromagnetic fields with circuit [14]. With respect to the dimensions of the real transformer and its geometry, the FEM equations have been modeled for 2D simulation of low frequency transient electromagnetic fields. The basic procedure of transient simulation includes spatial and temporal discreteness of the physical equations. The core materials employed in the analysis are soft iron core, solid iron core, metglass core, silicon steel core, and ferrite core. The case study considers a three-phase transformer with a 500 kVA, 11kV/415V, star connection distribution transformer. Fig. 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.

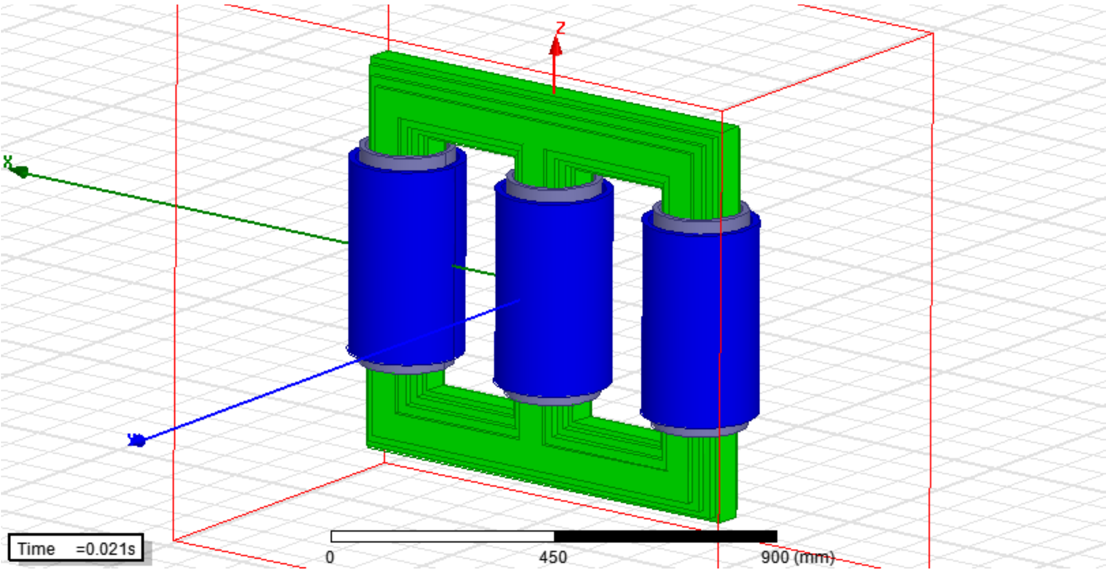

Fig. 1: Distribution transformer

III. RESULT

The magnetic flux of each candidate core material was carried out at frequencies of 50 Hz, 100 Hz, 200 Hz, 500Hz and 1000 Hz. They were done at these frequencies to get their various flux patterns. The soft iron core flux patterns at variable frequencies are shown in Fig. 2. This shows the material properties defining the soft iron.

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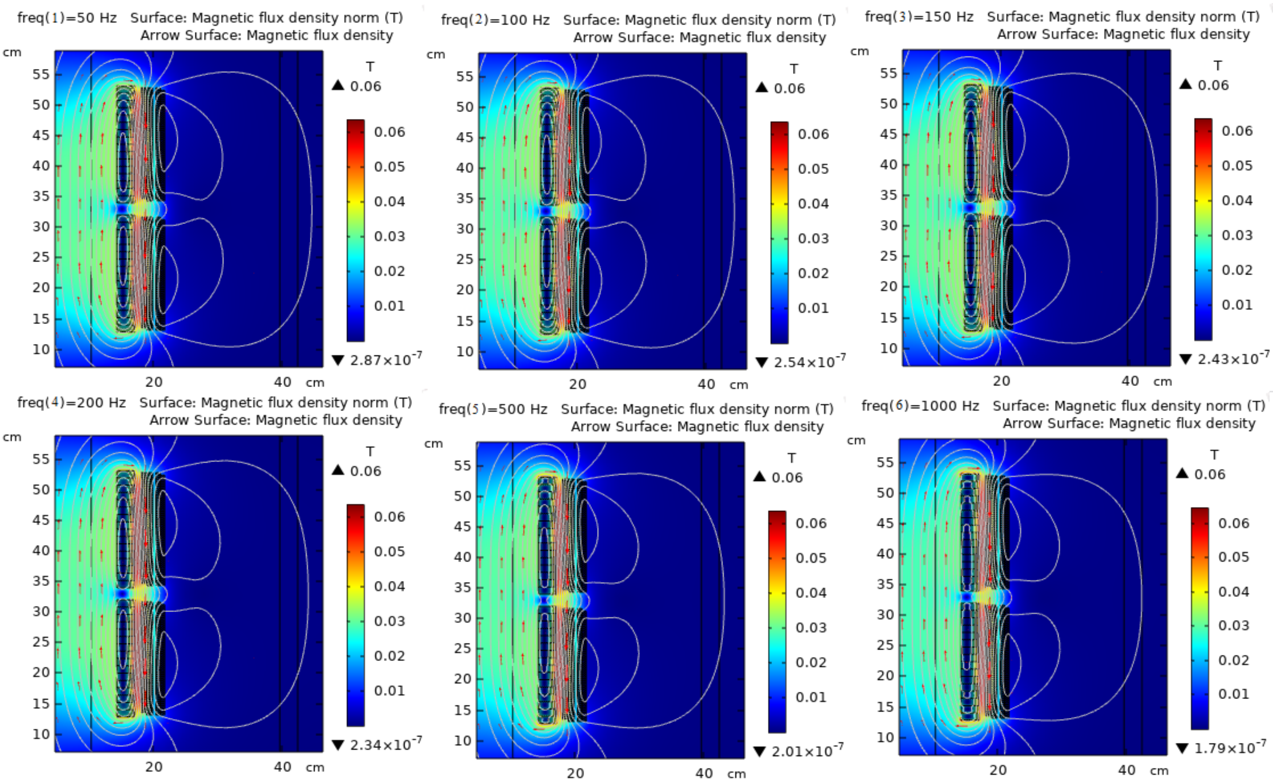

Fig. 2: Comparison of magnetic flux of soft iron at variable frequencies

The solid iron core flux patterns at variable frequencies are shown in Fig. 3. In this section, the material for the transformer core modeling is Solid iron core. This shows the material properties defining the solid iron.

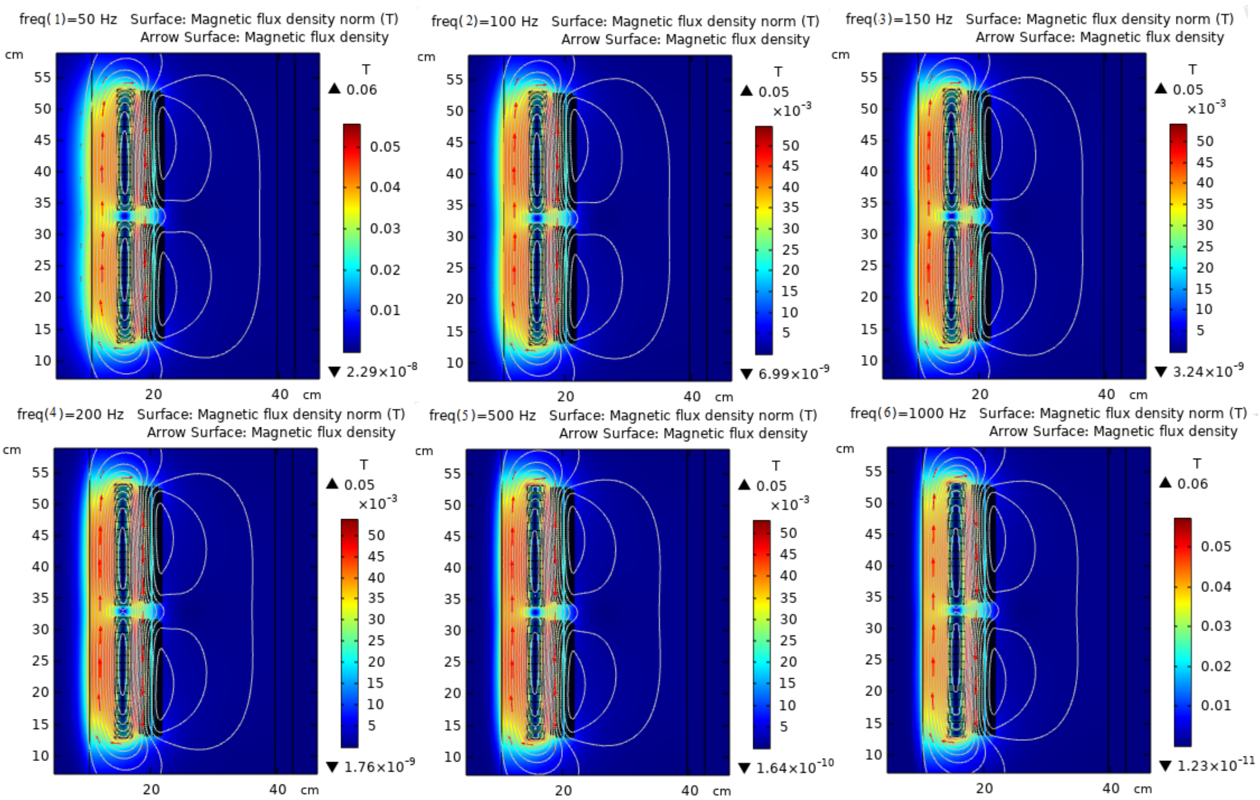

Fig. 3: Comparison of magnetic flux of solid iron at variable frequencies

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The metglass core flux patterns at variable frequencies are shown in Fig. 4**.** In this section, the material for the transformer core modeling is metglass core. This shows the material properties defining the metglass core.

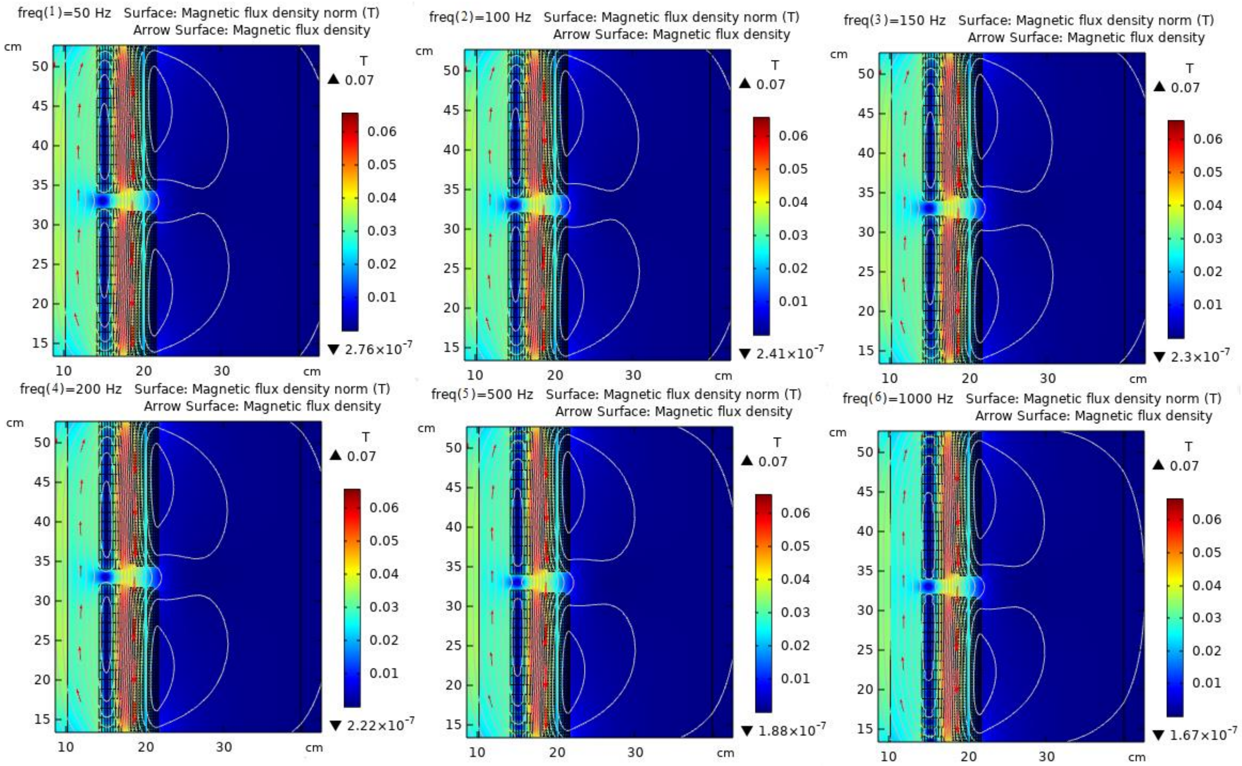

Fig. 4: Comparison of magnetic flux of metglass at variable frequencies

The silicon steel flux patterns at variable frequencies are shown in Fig. 5. In this section, the material for the transformer core modeling is silicon steel core. This shows the material properties defining the silicon steel.

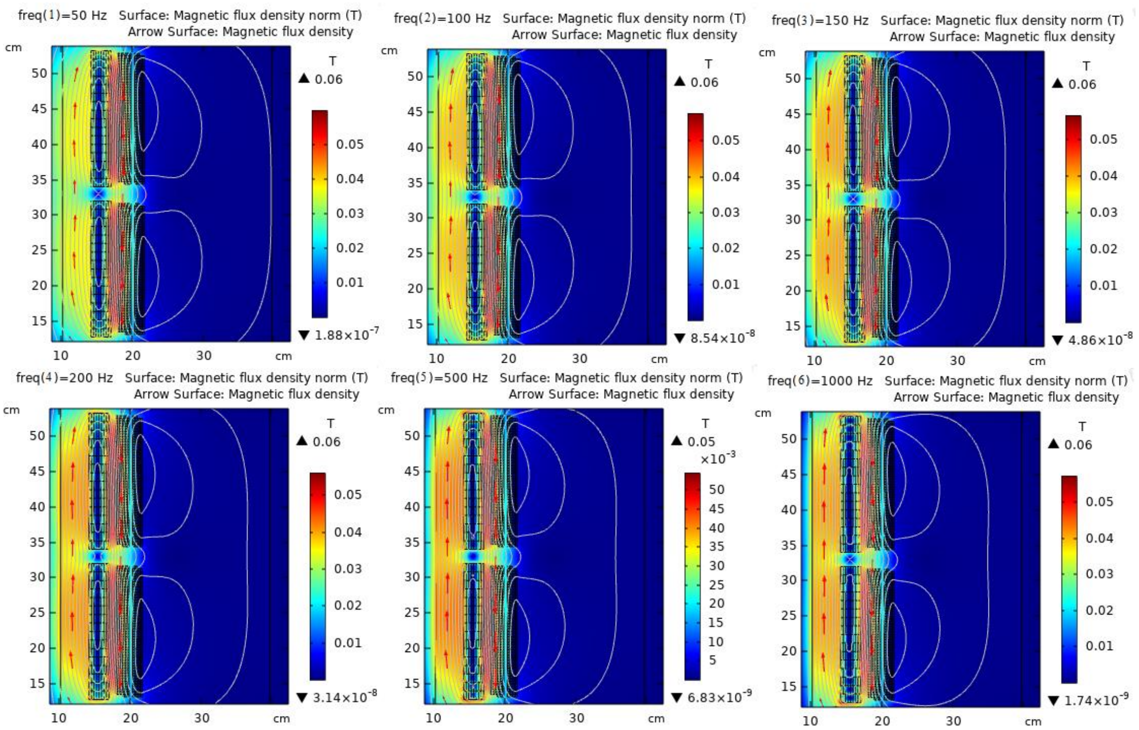

Fig. 5: Comparison of magnetic flux of silicon at variable frequencies

The ferrite core flux patterns at variable frequencies are shown in Fig. 6. In this section, the material for the transformer core modeling is ferrite core. This shows the material properties defining the ferrite.

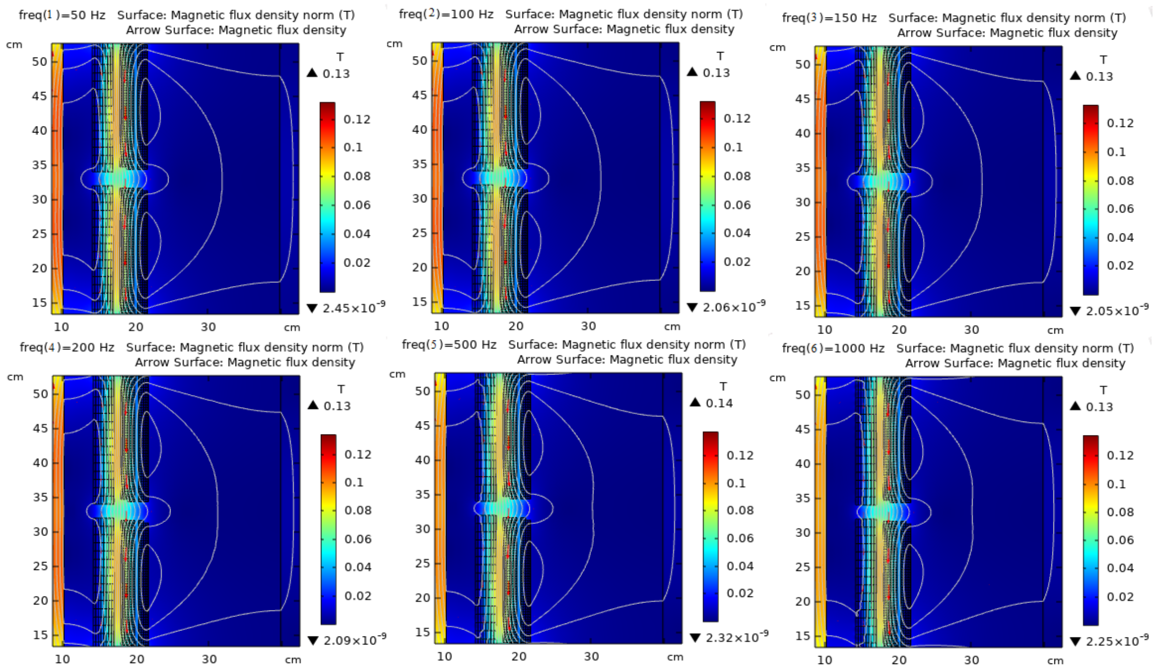

Fig. 6: Comparison of magnetic flux of ferrite at variable frequencies

The core loss results for the variant core materials are shown in Table 2 while the chart for the core losses for different core materials are shown in Fig. 7 to Fig. 9.

Table 2: Core Loss of Variant Core Materials at different Frequencies

Frequency (Hz)	Core Loss (kW)				
	Metglass	Silicon Steel	Ferrite core	Soft Iron	Solid Iron
50	0.1	0.2	0.21	4.5	4.9
100	0.065	1.25	0.65	12.14	13.94
150	0.14	1.42	1.2	23.13	25.73
200	0.24	1.56	1.96	30.73	39.73
500	1.09	2.09	8.4	144.4	158.4
1000	1.36	2.6	26	401.4	451.4

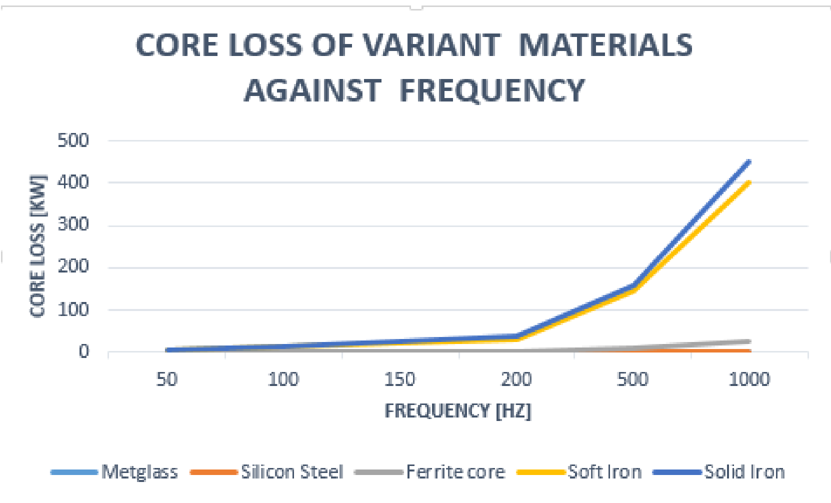

Fig. 7: Core loss of variant core materials against frequency

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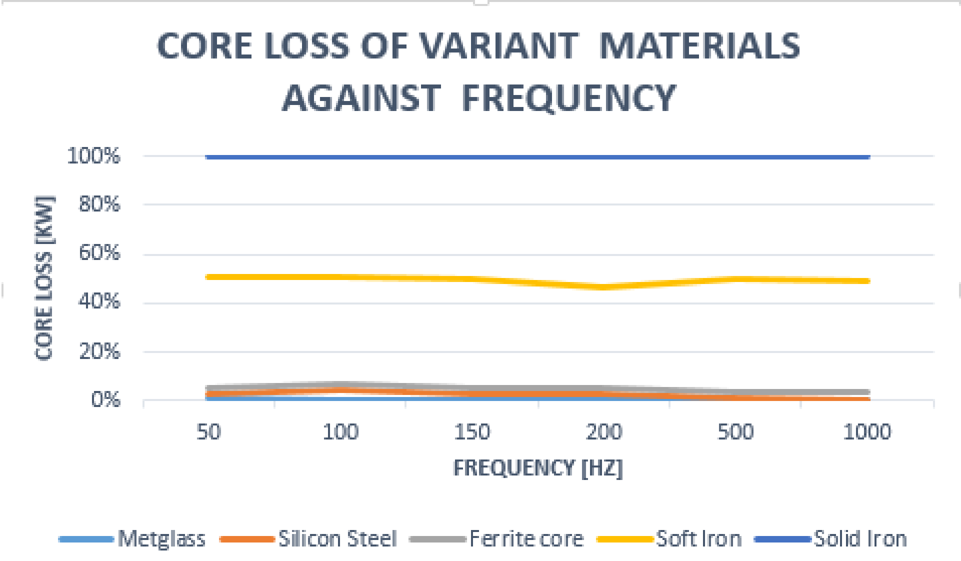

Fig. 8: Percentage core loss against frequency

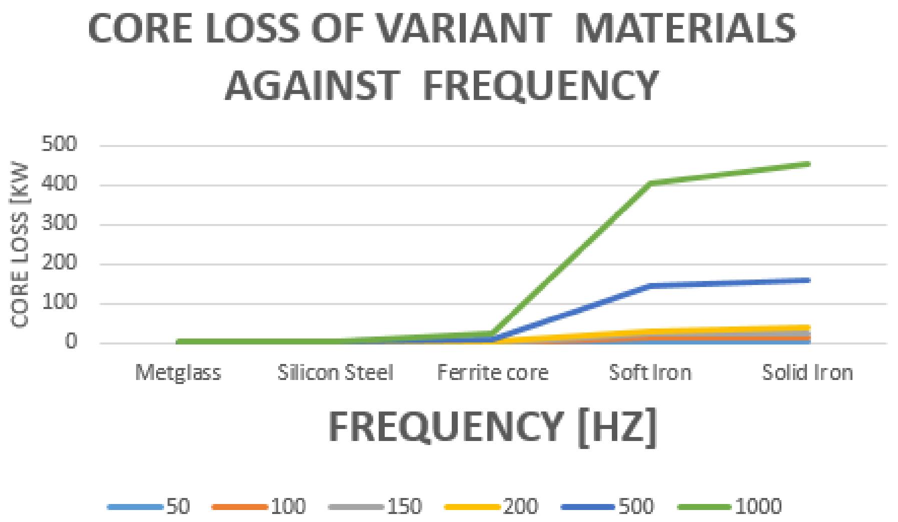

Fig. 9: Core loss against frequency

IV. DISCUSSION

As can be seen from Fig. 7 to Fig. 9, at 50 Hz operating frequency, metglass, silicon steel and ferrite had very slight differences in their core losses of 0.1 kW, 0.2 kW and 0.21 kW respectively, other than soft iron and solid iron of 4.5 kW and 4.9 kW respectively. Meanwhile, metglass has the smallest core loss of 0.1 kW. Likewise, when the frequency is increased, metglass core maintained the smallest core loss as the highest applied frequency of 1000 Hz led to core loss of 1.36 kW. However, solid iron had the highest core loss of 451.4 kW at the highest frequency. This also proves the results from Fig. 2 to Fig. 6 as the confinement of flux around the core is shown to be more in the metglass core material than that of the other core materials. In Fig. 7, as the frequency is increasing, there is a slight rise on the core loss of metglass, silicon and ferrite but a sharp rise from soft iron down to solid iron which shows the highest core loss. In Fig. 8, as the frequency is increasing, the core loss values of metglass, silicon steel and ferrite appear to be almost the same but at a very high frequency, there is a sudden rise in soft iron and solid iron core as well. In Fig. 9, at lower frequencies, there is a moderate rise in the core loss values of metglass, silicon steel and ferrite cores and a considerable rise in the core loss of soft iron and solid iron.

V. CONCLUSION

Modeling of different transformer core materials was carried out using finite element method for simulating the flux pattern. Variant transformer core materials namely; soft iron, solid iron, silicon steel, metglass (amorphous metal), and ferrite ceramics were simulated. A flux density comparison between selected core materials under variable frequencies was performed. This has established a flux pattern criterion for proper core material selection in transformers. The measurements have shown the flux density differences at 20 mm distance interval. This confinement of flux around the core can be seen to be more in the metglass material simulation than that of the other materials. This agrees with the core loss graph that shows lesser core loss in metglass than silicon steel and other materials. This validates the relationship between core loss of core materials to the behavioral pattern of flux and magnetization around the core of a distribution transformer. The results show that metglass is the ideal core material because it has the lowest core loss of 0.1kV. Moreover, metglass presents lower core losses than the conventional silicon steel. This implies that the use of metglass as core material in distribution transformer for optimal/improved performance is recommended.

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