AN INSIGHT INTO FACTORS INFLUENCING CORE PERFORMANCE IN TRANSFORMERS

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ABSTRACT

In this paper, magnetization process of grain-oriented steel and its impact on performance of the core are elaborated. To start with, the magnetization process is explained in terms of domain theory. Reversible and irreversible magnetization processes and their influence on determining the shape of the hysteresis curve are explained. The core losses can be separated into static and dynamic loss components. The effects of anisotropy, frequency of excitation, and mechanical and thermal stresses on the core losses are summarized. Manufacturing processes and techniques for reducing these loss components are highlighted. Finally, an example involving implementation of a hysteresis model in a circuit-coupled finite element simulation is presented.

1 INTRODUCTION

Grain Oriented steel (GO) provides a high permeable path with low losses along its rolling direction (RD) [1]. The magnetization of these materials is a complex multi-scale process which depends predominantly on microstructural parameters [2], [3]. The energy spent in the magnetization process results into core losses. These losses depend on the magnetic excitation [4], [5]. Moreover, mechanical and thermal stresses also affect the magnetic characteristics. The total energy expended during the process can be broadly split into three components: E_{mag} (magneto-static energy and exchange energy), E_{an} (anisotropic energy), and $E_{elastic}$ (magneto-elastic energy). The magnetization of these materials happens through a complicated process of domain magnetization rotation and domain wall movements [6].

Mechanical stresses affect the microstructural parameters of the material and hence its magnetic performance [7]. The loss of GO materials is strongly affected by compressive stresses. Moreover, an increase in the operating temperature of the magnetic circuit of a transformer also affects its core losses [8]. In this paper, a brief description of the physics behind the magnetization process that leads to hysteresis phenomenon is presented and the effects of mechanical and thermal stresses on the magnetic performance are also elaborated.

2 MAGNETIZATION PROCESS IN TERMS OF DOMAIN THEORY

A. Magnetic domains

In earlier days, Ewing tried to explain the demagnetized state of a bulk material using the random distribution of atomic magnetic moments [9]. However, this explanation is not capable to explain local magnetization in a demagnetized state [9]. Magnetic domains can be defined as regions in which magnetic moments align in particular directions. *Exchange energy* tends to align moments along a specific direction to form magnetic domains. Typically 10^{12} to 10^{15} moments are aligned inside a domain leading to its spontaneous saturation [9]. In a magnetic material, domains are aligned in a random direction to obtain zero net magnetization in a demagnetized condition.

B. Domain walls

Inside a domain, the direction of moments does not change suddenly from one domain to another. Magnetic moments gradually change their direction in out of the plane as shown in Fig. 1, which minimizes the net energy of the material in its demagnetized state. This kind of domain wall is known as *Bloch Wall* or 180° domain wall. In GO materials both 180° and 90° domain walls can be found.

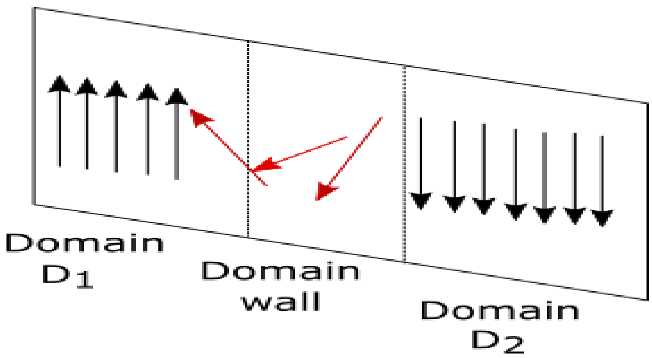


Fig-1: Domain wall

C. Magnetization

In a demagnetized state, all magnetic moments in a domain are aligned in a specific direction but the bulk magnetization is zero because of random orientations of various domains. At low fields, magnetic domains along the direction of magnetization grow at the expense of those along an unfavourable direction and this process is generally completed by domain wall motion. At higher fields, the domain magnetization vectors rotate themselves to align with the direction of the magnetic field. The process of magnetization is shown in Fig. 2. When all domain magnetization vectors are along the field direction, the condition is called saturation.

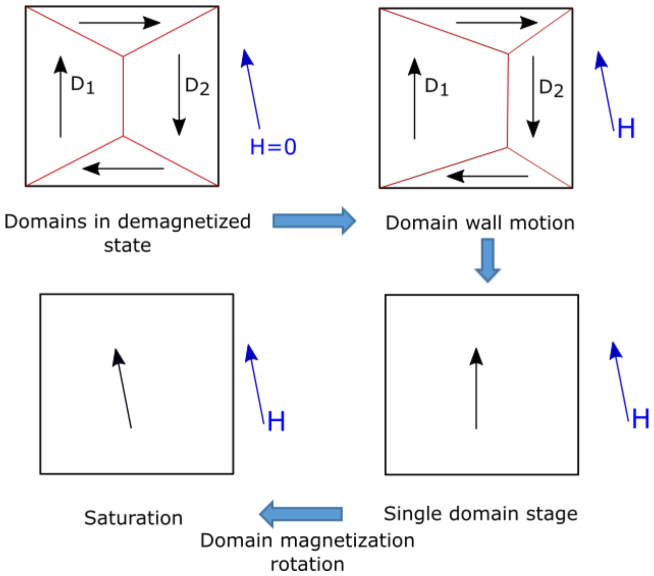


Fig-2: Magnetization process

D. Reversible and irreversible magnetization processes

The changes in magnetization arising from the application of the magnetic field are reversible and irreversible, which often cannot be separated for quantification. In a typical reversible process, domain walls come back to their original position after removal of the applied field. With reference to a typical BH loop shown in Fig. 3a, in the very low field regions, domain wall motion would not generally cross the defects (pinning sites) and hence they can come back to their original positions and there would be zero energy loss; this is a reversible process. This results in domain wall bowing as shown in Fig. 3b. For higher fields, beyond ‘a’ in Fig. 3a, domain wall movements will generally pass through the pinning sites and if the source direction is reversed, because of pinning sites, M (and B) lags H (representing source current), and therefore there is an irreversible component and the corresponding contribution to the hysteresis loss. Thus, beyond ‘a’, both reversible and irreversible magnetizations occur. Beyond ‘b’, there is domain magnetization rotation for aligning along the field direction, up to the peak saturation point ‘c’. From b to c and then from c to b (when the field is reversed), the rotation magnetization is dominant.

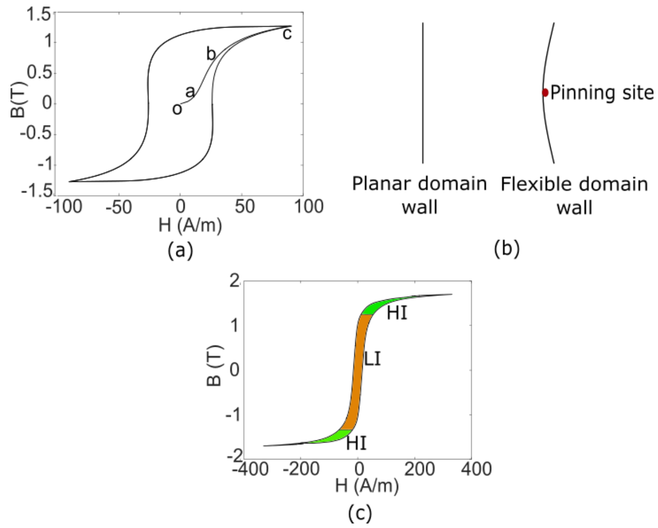
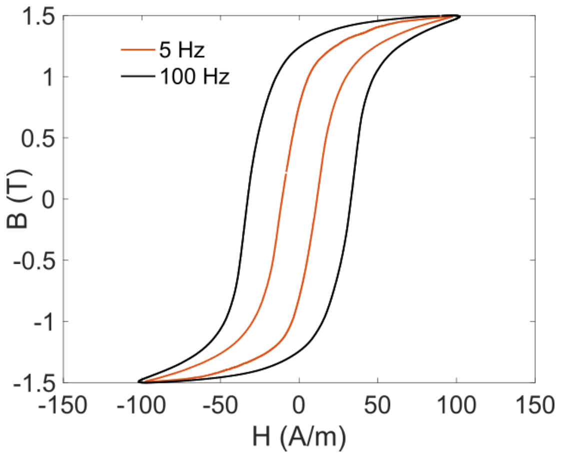


Fig-3: (a) A sample hysteresis loop (b) Reversible domain wall motion (c) Loss subdivision

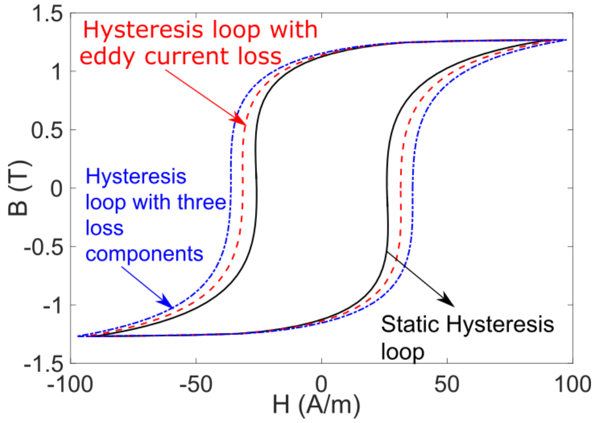
In Fig. 3c, the two horizontal lines divide the hysteresis loop at knee points in both positive and negative going loops. The regions marked as HI are the high induction hysteresis loss regions, and the energy dissipated is associated with irreversible domain magnetization rotation [10]. The region marked with LI is the low induction hysteresis loss region, and the corresponding loss is associated with irreversible domain wall movement (during which pinning sites are usually encountered).

3 SEPARATION OF THE CORE LOSSES

Core losses in a transformer correspond to the energy spent due to hysteretic, dynamic and anisotropic properties of its GO steel laminations. Time-varying magnetic fields induce the classical eddy current loss in ferromagnetic materials because of their finite conductivity. In [11], it has been reported that computed eddy current loss (using the classical formula derived from Maxwell’s equations) is less than the measured loss (after subtracting the static hysteresis loss). The extra loss is attributed to the spatial eddy current loss induced due to change in the local magnetization when domain wall movements occur [12]. This loss component of the dynamic core losses is called *excess loss* or *anomalous loss* [11], [12]. This loss increases with grain size, contrary to the hysteresis loss since the wall movements would be faster because of less number of domains, and the corresponding induced loss would be higher. The effect of frequency on the hysteresis loss is shown in Fig. 4 [4].



(a)



(b)

Fig-4: (a) Typical hysteresis loops of GO material at different frequencies (b) Hysteresis loops considering different loss components

Therefore, the excess and hysteresis loss components depend on the microstructure and domain configurations of the material. The three components of the core losses can be calculated, for example, by using the loss separation approach reported in [4].

4 ANISOTROPIC BEHAVIOUR OF CORE LOSS COMPONENTS

GO steel exhibits anisotropic behaviour in its magnetic properties including losses [13]. The directions of the hard and easy axes depend on its crystal structure. In iron, which is a body-centred cubic lattice, the hard axis is <111>, because of a higher density of atomic moments in this direction [14]. An easy axis means a direction in which the material can be magnetized by applying a small amount of applied magnetic field energy. Whereas, magnetization along its hard axis requires a much higher field to magnetize as shown in Fig. 5.

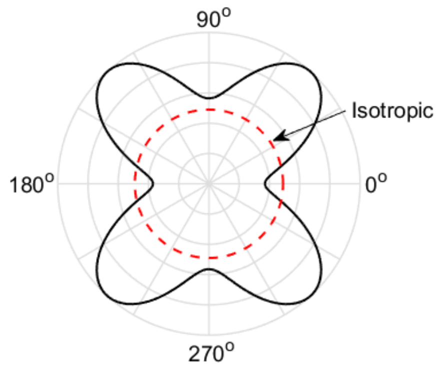


Fig-5: Anisotropic behaviour of magnetic properties

The physical origin of crystal anisotropy can be explained by using interactions between magnetic moments [2]. Different kinds of interactions exist in a crystal, viz. spin-spin interaction, orbit-lattice interaction, and spin-orbit interaction. The spin-spin interaction corresponds to the exchange energy that keeps neighbouring magnetic moments either parallel or anti-parallel. This is independent of the direction of magnetic moments. The orbit-lattice interaction is very strong because orientations of orbits are strongly fixed to the lattice and even high fields may not be able to change the direction of any orbit. The spin-orbit interaction resists the rotation of spins since the direction of orbits are strongly influenced and determined by the lattice. Even though this coupling is relatively weak compared to the orbit-lattice interaction, high fields are required to rotate spin moments. Thus, rotation of domain magnetization is strongly influenced by the crystal lattice.

The difference between magnetization along RD and transverse direction (TD) can be explained in terms of 180° and 90° domain wall motions [6]. In GO materials, 180° domain walls are dominant. However, in the case of magnetization along TD, the 180° domain walls transform into 90° domain walls with nucleation of domains along with the other easy direction (along TD), and by increasing magnetic field further, the motion of the two types of domain walls begins. Thus, in the case of magnetization along TD, the process involves motion of both 90° and 180° domain walls, and these motions lead to a complex shape of the hysteresis loop as shown in Fig. 6 (bending of the loop is indicative of higher energy due to the magnetization rotation).

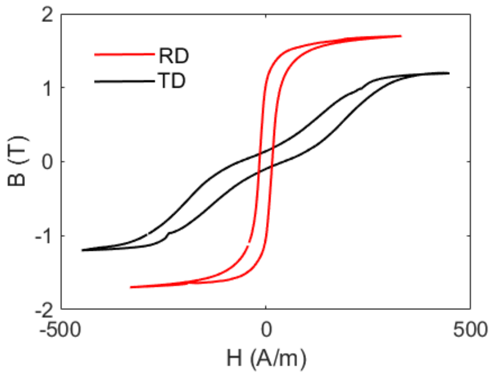


Fig-6: Hysteresis loops of GO material along RD and TD

Thus the anisotropic behaviour of the static hysteresis loss can be attributed to crystallographic orientations. On the other hand, the anisotropic behaviour of the excess loss component can be explained in terms of variations in domain spacings. Since the classical eddy current loss depends only on the conductivity and dimensions of the material, it can be assumed as being independent of the direction of magnetization.

5 EFFECT OF MECHANICAL STRESSES ON STATIC HYSTERESIS LOSS

Depending on the response to mechanical stresses, magnetic materials are classified into positive magnetostrictive materials and negative magnetostrictive materials. For the former ones, under compressive stresses, the domains along RD [1 0 0] will disappear and domains along TD [0 1 0] will nucleate, and under tensile stresses, there will be a similar transition from domains along [0 1 0] to [1 0 0]. GO laminations fall into the category of positive magnetostrictive materials. Thus the magnetic and mechanical behaviour are strongly coupled since the applied stress modifies the magnetic properties of these materials. The effect of mechanical stresses on the hysteresis loss can be accounted in terms of elastic energy. Considering linear elastic behaviour for these materials, the energy can be expressed as [15]

$$W_{elastic} = \frac{1}{2}\varepsilon_\mu : \mathbb{C} : \varepsilon_\mu \qquad (1)$$

Here, $\mathbb{C}$ is the material stiffness tensor and ε_μ is magnetostriction strain tensor which in the crystallographic frame can be written as:

$$\varepsilon_\mu = \frac{3}{2}\begin{pmatrix} \lambda_{100}\left(\alpha_1^2 - \frac{1}{3}\right) & \lambda_{111}\alpha_1\alpha_2 & \lambda_{111}\alpha_1\alpha_3 \\ \lambda_{111}\alpha_1\alpha_2 & \lambda_{100}\left(\alpha_2^2 - \frac{1}{3}\right) & \lambda_{111}\alpha_2\alpha_3 \\ \lambda_{111}\alpha_1\alpha_3 & \lambda_{111}\alpha_2\alpha_3 & \lambda_{100}\left(\alpha_3^2 - \frac{1}{3}\right) \end{pmatrix}$$

Here, λ_{100} and λ_{111} are the magnetostriction strains along <100> and <111> respectively for a single crystal, and α_i (i = 1 to 3) are directional cosines. The effect of mechanical stresses on the static hysteresis loss component is shown in Fig. 7.

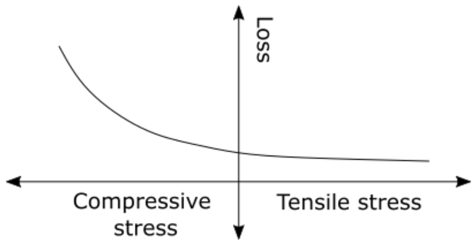


Fig-7: Effect of mechanical stresses on hysteresis loss

Compressive stresses deform the crystallographic structure which in turn change the anisotropic energy and the exchange energy of the material. Thus the core losses increase and the shape of the hysteresis loop also changes because of the induced anisotropy. From Fig. 7, one can infer an asymmetry in magnetic properties under the action of the two types of stresses, because of different domain responses to them [2]. In elastic range, tensile stresses are beneficial in improving magnetic properties.

6 EFFECT OF TEMPERATURE ON MAGNETIZATION

Dependencies of different magnetic properties of ferromagnetic materials on temperature are different. Magnetic properties like residual magnetization (B_r), saturation magnetization (B_s) and coercive force (H_c) decrease with temperature [8], [16] as shown in Fig. 8 and Fig. 9, which could be detrimental to the performance of the transformer. It has been observed experimentally that the total core losses decrease slightly with an increase in temperature [8] for a specific induction level over a range of temperature in which saturation magnetization does not change. Among the three core loss components, for a certain magnetic induction level, the static hysteresis loss (P_{hyst}) and excess loss components remain almost constant, whereas, the eddy current loss decreases with an increase in resistivity with temperature [8], as shown in Fig. 10.

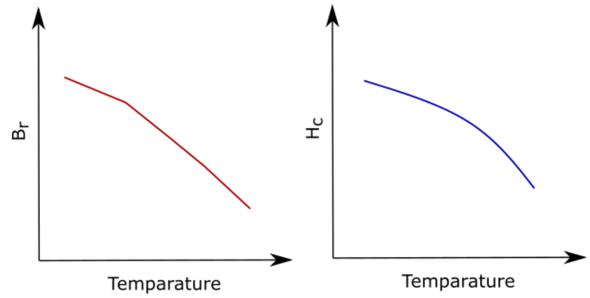


Fig-8: Effect of temperature on residual flux density and coercive field

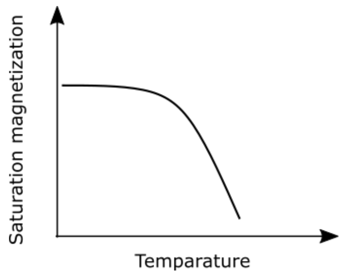


Fig-9: Variation of saturation magnetization with temperature

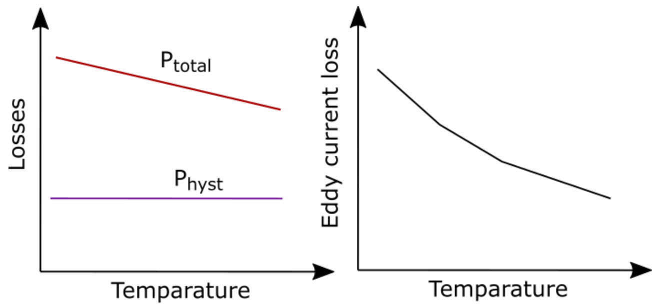


Fig-10: Effect of temperature on hysteresis loss

7 LOSS REDUCTION IN GO MATERIALS

From the above discussion, one can infer that the core losses in a transformer are strongly linked to dimensions, properties and crystallographic structure of the material.

Mean misorientation of domains and the static hysteresis loss can be reduced by following certain process technologies. Even though it is possible to suppress supplementary domains completely (and increase the effective grain size), this may increase the anomalous or excess loss component as mentioned previously [17].

The static hysteresis loss mainly depends on crystallographic orientations and pinning densities in the material. As pinning defects increase, the energy spent on domain wall movements increases. Pinning sites can be reduced by chemical polishing [18].

The eddy current loss can be controlled by reducing the sheet thickness. However, there is a lower limit for reducing the thickness. It may also be noted that the manufacturing process of reducing thickness should not result in an increase in the other two components of the core losses. It is noted that an optimum sheet thickness can be computed for minimizing core losses [2], [9].

8 AVAILABLE TECHNIQUES FOR HYSTERESIS MODELING

From the above discussion, one can infer that the magnetic properties of GO materials depend on magnetic excitation and thermal/ mechanical stresses. To determine the steady-state and transient performance of transformers in the predesign stage, an accurate modelling approach is required.

Deriving a mathematical formalism for the hysteresis phenomenon is one of the complicated and classical problems. A large number of researchers have published different approaches and modifications to existing models to build a comprehensive model for the hysteresis phenomenon considering different complexities that are discussed earlier. The phenomenon can be modelled using two approaches. Models based on the theory of micro-magnetics fall into the first category. Methods based on domain wall motion [19] and crystalline anisotropy [20] are some of the popular models in this category. The second approach is completely mathematical and is based on curve fitting. Models based on mathematical functions like exponential functions [21], polynomials [22], hyperbolas [23], noninteger power series [24], differential equations [25], and a piecewise linear approximation [26] are some examples of the second category.

9 IMPLEMENTATION OF HYSTERESIS MODELS

The above-discussed models can be used to predict the performance of transformers. Here, the dynamic Jiles-Atherton hysteresis model reported in [4] is implemented in a 2D-coupled circuit-field Finite element analysis of a three-phase three-limb transformer. The inrush currents are calculated using non-linear transient analysis. The flux distribution and inrush currents are shown in Figs. 11 and 12, respectively.

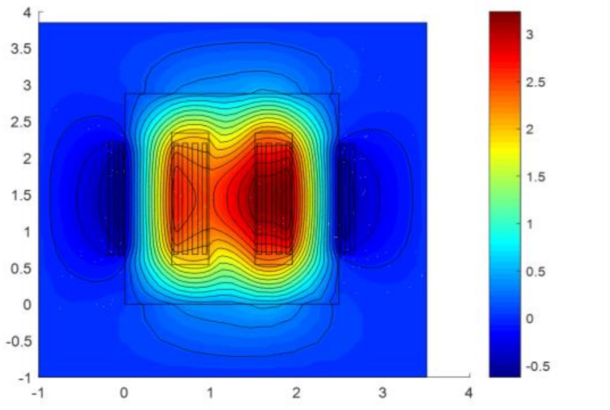


Fig-11: Flux distribution in a three-phase three-limb transformer under transient conditions

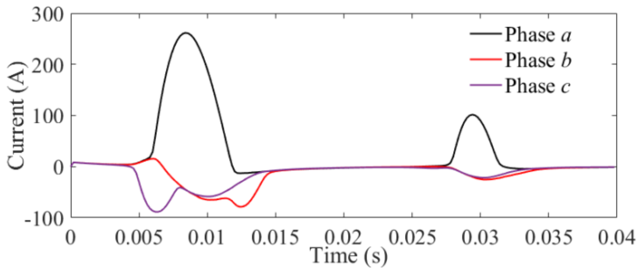


Fig-12: Inrush current computed using FEM [27]

10 CONCLUSION

The core losses of a transformer are composed of hysteresis loss, eddy current loss, and excess loss. The core performance can be improved by choosing a better grade of core material. For this, clear understanding of magnetization process in ferromagnetic materials used in transformers is required. In this paper, an insight into the magnetization process in terms of magnetic domains is provided. Also, effects of anisotropy and frequency of excitation on the three loss components are elaborated. Further, effects of mechanical and thermal stresses on the performance are highlighted. Based on the explained theory of the magnetization process, techniques to reduce the losses are given. Different formulations available in literature for modeling hysteresis are briefly introduced. Finally, an example of implementation of a hysteresis model in a transient coupled circuit–Finite Element Method simulation is presented.

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