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Performance comparison of core loss in induction motor using non-oriented electrical steels

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ABSTRACT

Induction motor (IM) enjoys certain advantages that include simple design, robust construction, reliable operation, low initial cost, easy operation, and simple maintenance besides offering reasonable efficiency. Modelling and definition of procedures leading to good estimation of core losses in induction motors from material test data is still a challenge and is considered a problem statement. The major objective of this paper is to estimate the core loss in an induction motor (IM) by analyzing a selection of non-grain oriented electrical steel materials and then identifying for each represented whether it can be used both as stator and rotor core material. As core loss is influenced by factors such as air gap, B-H theory, eddy currents and excess loss coefficients, and Steinmetzuhl factor, this study is intended to improve the electromagnetic performance of the motor. Influencing core loss are the amounts of flux density and elasticity of material. This study was accomplished by using three sorts of non oriented electrical steel: DI MAX-M15, DI MAX-M19, and DI MAX-M36. A 5 HP induction motor was the subject for finite element method (FEM) simulations whose results have been verified by empirical relations, which show the merit of using non oriented electrical steel as core material.

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1. INTRODUCTION

Induction motors (IM) find their usage over heap of industrial manufacturing facilities and household appliances owing to their reliability and efficiency. These motors constitute around 67% of worldwide demand of electrical energy, thus energy demand in these motors is an important factor for the environment. With fossil fuels still the dominant source of energy for electricity generation, optimization of motor losses has emerged as a key area of focus. IMs are the most straightforward structure, their performance is consistent, cost-effective, easy to operate and maintain, and highly efficient [1]. However, to enhance their efficiency even further, it is imperative to accurately predict their output characteristics, which will allow for the development of efficient designs. Efficiency is a critical concern—electric motors are responsible for around 69% of electricity consumption in the industrial sector and around 36% in the service sector [2]. The main components of losses in induction motors (IMs) consists at stator and rotor copper loss, core loss as well as friction and windage loss. Because energy saving has become more and more emphasis than ever, people are redesigning high-efficiency electrical machines and appliances [3]. Now, in order to achieve the result, new approaches will be needed. Traditional methods of estimating iron performance may no longer suffice to meet today's efficiency demands [4].

Traditional approaches fail to accurately convey the magnetic properties of electrical machines. The core of the machine simultaneously experiences rotation and alternating magnetization, so that core losses must be estimated more inclusively [5]. Its two-dimensional induction motor requires numerical analysis to take into consideration (2D) magnetic characteristics to truly capture the magnetic phenomena in the motor. While many methods have been written about, assessing the degradation of magnetic properties in electrical steels at the time consumption of processing, and so far, as stator core shapes are concerned, their use is limited [6]. Although studies have indeed covered the influence of machining processes on stater poles in induction motors as far back as the 1950s, this problem remained irrelevant [7]. There are some newly developed core loss evaluation techniques in literature, such as the inner core excitation method and stator winding excitation method [8]. However, the material complex properties result in the hysteresis and eddy current losses on silicon steel sheet cores being more complex than worked out yet. Without in-depth research, how can one be sure of which is best for different field [9]. Simulation results of the core loss performance of the motor are very different from those obtained using silicon steel sheets. Electrical machine designers will often find that incomplete predictions of losses will result in simulation results failing to meet their desired level of accuracy [10]. Many studies have attempted to predict iron core loss more accurately with small errors. They have focused either on the core-loss separation method or on deriving core-loss formulas [11]. However, these projects represent small progress in developing such methods to improve accuracy to achieve the most accurate predictions possible and therefore, the best choice for core material, original methods, and innovative means must be found [12]. Thus, it is critical to the direction and the productivity of electric machine design [13].

2. PROBLEM STATEMENT

This study is intended to recommend the non-oriented electrical steel which is most suitable as an induction motor (IM) core material for both stator and rotor. In this research, core losses are estimated by numerical analysis based on finite element method (FEM). In addition, core losses will be tested experimentally using a test frame, designed to compare the numerical results with actual measurement. The objective is to evaluate the feasibility of recommended process and rate most suitable material for performance enhancements of engines as opposed to those currently under study.

3. CORE LOSS EQUATION AND COEFFICIENTS

In recent years, the advancement of loss models has received far more attention than in the past because existing ones have changed out of all recognition [14]. Though core losses in silicon steel laminations may be estimated with high precision, this is decidedly not the case for electric machinery and transformers [15]. This deviation is due to various reasons, including the rotating flux density, harmonic components, and uneven distribution of flux within the motor core. While these factors make calculating core losses for electrical machines more difficult than with silicon steel laminations, this is easily plagued. Core losses mainly occur in the stator and rotor cores of an induction motor due to the distribution of magnetic flux [16]. These losses can be modeled using empirical equations derived from experimental data. According to the Steinmetz equation, core losses of induction motors can be quickly estimated by the use of loss separation models. The core total losses are usually given in (1) and they comprise two main elements: hysteresis losses (Ph) and eddy current losses (Pe). The movement of the magnetic domain walls within the core consumes energy, which results in hysteresis losses. On the other hand, the changing magnetic flux induces circulation currents in the core, which results in eddy current losses. These two factors are the key components in determining core losses in electrical machines.

$$p_c = p_h + p_e \tag{1}$$

Where P_c is the total core loss, P_h is the hysteresis loss, and P_e is the eddy current loss. The eddy current loss can be calculated using Maxwell's equations, as shown in (2).

$$p_e = \frac{\sigma.\pi^2.d^2}{6.\rho}.{B_m}^2.f^2 \tag{2}$$

The parameters explained in the preceding equation are defined as follows: σ is the volumetric conductivity, d is the steel lamination thickness, ρ is the mass density of the steel lamination, f is the supply voltage’s frequency, and Bm is the maximum value of the magnetic flux density [17]. Eddy current and hysteresis losses, which are core losses, interefere with the interaction of rotor current and rotor flux. This results in a mismatch between the output torque and the reference torque; hence the system performance is affected negatively [18]. Therefore, looking at the losses in a different way in terms of the compensation needed comes into focus.

In the same way that core losses are compensated for in (3) and (4), core losses should also be compensated for in rotor torque output. With proper compensation, rotor flux and rotor current can be used independently, and the accuracy of torque output can be improved.

$$p_c = p_h + p_e + p_{ex} \tag{3}$$

$$p_c = k_h(B_m)^2 + k_e(fB_m)^2 + k_{ex}(fB_m) \tag{4}$$

Where k_h stands for hysteresis loss, k_e represents eddy current loss, and k_{ex} denotes excess loss. In (4) can be rewritten as (5) [19].

$$p_c = k_1 {B_m}^2 + k_2 {B_m}^{1.5} \tag{5}$$

The (4) and (5) can be combined or reformulated as (6).

$$k_1 = k_h f + k_e f^2 \text{ and } k_2 = k_{ex} f^{1.5} \tag{6}$$

The eddy current loss coefficient can be determined directly using (6).

$$k_e = \pi^2 \sigma \frac{d^2}{6} \tag{7}$$

The values of K_1 and K_2 can be determined by minimizing the quadratic form presented in (8).

$$f(k_1, k_2) = \Sigma[w_{ci} - (k_1 {B_{mi}}^2 + k_2 {B_{mi}}^{1.5})]^2 = min \tag{8}$$

Where W_{ci} and B_{mi} correspond to the i-th point on the measured loss characteristic curve. The remaining two loss coefficients can be determined as follows:

$$k_h = \frac{k_1 - k_e {f_0}^2}{f_0} \text{ and } k_{ex} = \frac{k_2}{{f_0}^{1.5}}$$

In the case of the loss curve, "f_0" represents the testing frequency. The parameters "Kh" and "Kex" are the coefficients that can be estimated by curve fitting on the core loss coefficient data. As shown in Table 1, the core loss is in W/kg at the magnetic flux density of 1.2 Tesla, the material density is in kg/m^3, and the maximum looking absolute permeability is for three non-oriented electrical steel grades of equal thickness at 50 Hz.

The B-H curves for three different non-oriented electrical steel grades, DI-MAX-M-15, DI-MAX-M-19, and DI-MAX-M-36, are shown in Figures 1 to 3. The corresponding magnetic field intensities at which the flux density achieves 1.2 T are 135 A/m, 137 A/m, and 150 A/m for DI-MAX-M-15, DI-MAX-M-19, and DI-MAX-M-36, respectively. DI-MAX-M-15 has the lowest field requirement among these grades, so it is more permeable. These discrepancies demonstrate the impact of material characteristics on magnetic performance [20]. These properties are important when determining the efficiency and effectiveness of the magnetic saturation and the material quality for the intended device. This difference indicates how important it is to control the grades of steels in proportion to the required functioning of electromagnetic devices. Material optimization enables to maximize energy efficiency of the system while minimizing the losses and enhancing the performance of the electrical and magnetic components [21]. Figure 4 shows the core loss characteristics of 0.36 mm non-oriented steel, DI-MAX-M15.

The core loss characteristics on the electrical non-oriented steel grades DI-MAX-M15, DI-MAX-M19, and DI-MAX-M36 with a thickness of 0.36 mm are presented in Figures 5 and 6. When core loss, measured in W/kg, is plotted against magnetic flux density in T, the core loss values increase exponentially as flux density increases. Among the three groups, DI-MAX-M15 has the best core loss performance at all levels of flux density, while DI-MAX-M19 and DI-MAX-M36 follow. These indicate core losses are very different, indicating energy loss is very different among the materials [22]. Differences in core losses show the significance of choosing the correct grade of steel to maintain energy efficiency and loss minimization in electromagnetic devices that work with alternating and different ranged flux densities. This also helps in improving performance and reliability in systems electrical and magnetic systems [23].

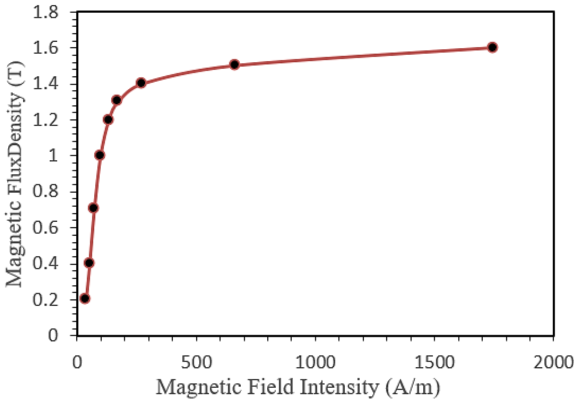

Figure 1. B-H relationship for 0.36 mm non-oriented steel, DI-MAX-M-15

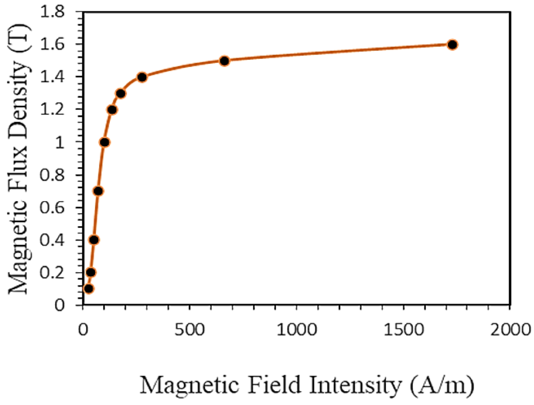

Figure 2. B-H relationship for 0.36 mm non-oriented steel, DI-MAX-M-19

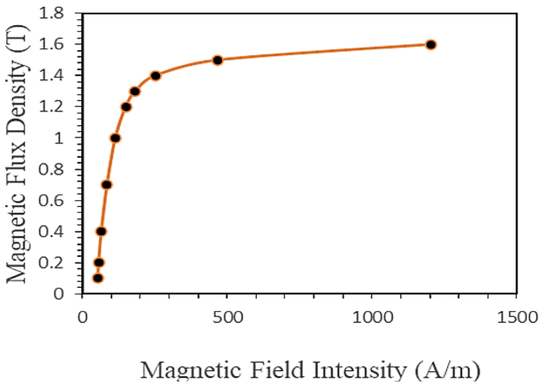

Figure 3. B-H relationship for 0.36 mm non-oriented steel, DI-MAX-M-36

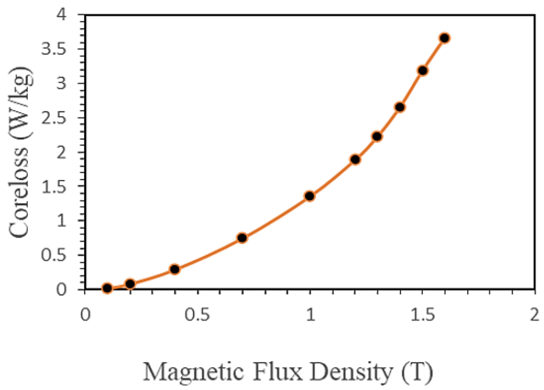

Figure 4. Core loss characteristics for 0.36 mm non-oriented steel, DI-MAX-M15

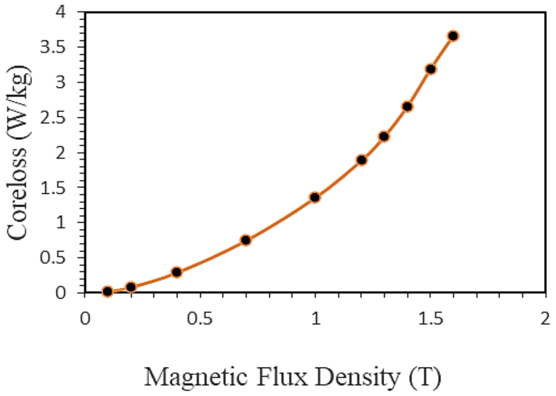

Figure 5. Core loss characteristics for 0.36 mm non-oriented steel, DI-MAX-M19

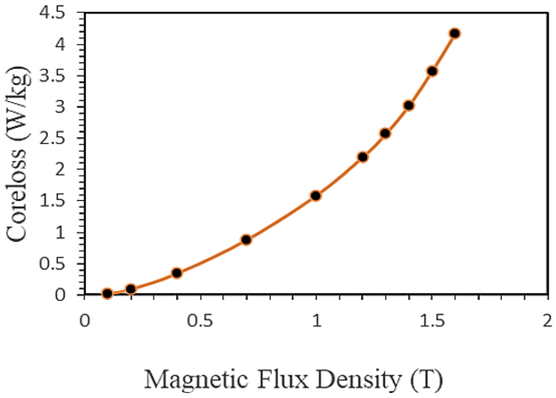

Figure 6. Core loss characteristics for 0.36 mm non-oriented steel, DI-MAX-M36

Table 1. Properties of core magnetic materials utilized

Type of material	Thickness (mm)	Coreless (W/kg) @1.2 T	Density (kg/m^3)	Max. relative permeability
DI-MAX-M-15	0.36	1.83	7650	7077.14
DI-MAX-M-19	0.36	1.89	7650	6973.82
DI-MAX-M-36	0.36	2.2	7700	6369.42

4. SIMULATION RESULTS

The main goal of the present methodology is to emphasize three non-oriented electrical steels for induction motor cores and, analogously, the investigation of its magnetic properties for a proper selection of material. Considering different numerical approaches, the most popular is the development of FEM by obtaining an appropriate model [24]. In this research, ANSOFT Maxwell 2D is employed to simulate the performance of a 5HP induction motor. The process involves the solution of Maxwell's equations for all elements at each time step and recording flux density values, which are later used in further calculations of core losses. Since 2D time-stepping FEM simulations involve large numbers of time steps and immense computational resources, calculation accuracy is highly influenced by mesh quality [25]. It is also observed that the core losses are critical at the vicinity of rotor and stator pole corners. These may be explained with differences in peak flux level and LTI of flux or dB/dt. Figure 7 shows the core loss distribution for the non-oriented electrical steel grades DI-MAX-M15, DI-MAX-M19, and DI-MAX-M36, respectively. Figure 7(a) shows the simulation results of the core loss in the DI-MAX-M15, where Figure 7(b) gives the results of the core loss DI-MAX-M19 and Figure 7(c) shows the simulation results of the DI-MAX-M36. The therotical and practical core loss calculation is carried out for the chosen non oriented electrical steel. Out of these three choosen magnetic material DI-MAX-M15 has low core loss when compared to the remaining two materials.

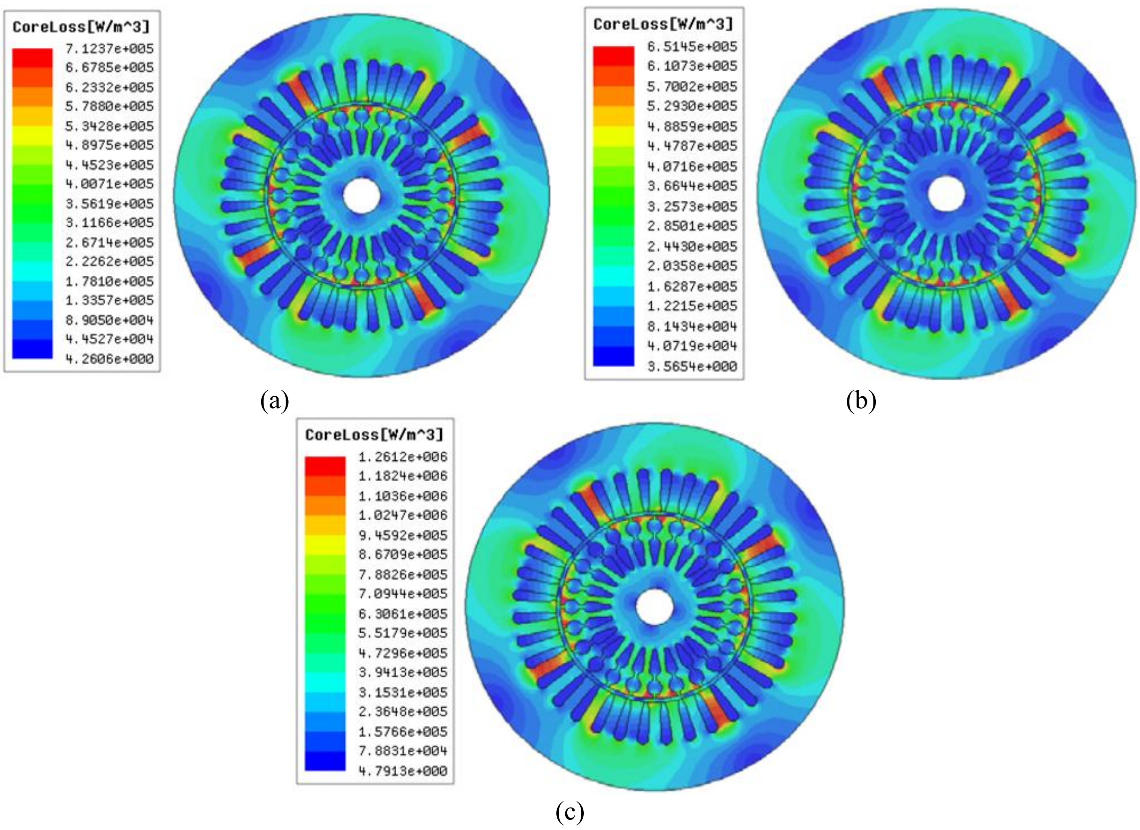

Figure 7. Core loss distribution: (a) IM of DI-MAX-M-15, (b) IM of DI-MAX-M-19, and (c) IM of DI-MAX-M-36

5. CONCLUSION

The study investigates the effect of non-oriented electrical steel on the stator and rotor cores of induction motors (IM) using empirical relations and finite element method (FEM) analysis. Three specific grades of non-oriented electrical steel were selected as candidate materials for the cores. Core loss values obtained from empirical equations were compared with those calculated through FEM simulations. The analysis revealed that DI MAX-M15 exhibits lower core losses compared to DI MAX-M19 and DI MAX-M36. The findings suggest that DI MAX-M15 is the most suitable core material for both the stator and rotor of induction motors. The study emphasizes the importance of selecting the appropriate material to minimize core losses and enhance the efficiency of induction motors.

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AUTHOR CONTRIBUTIONS STATEMENT

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Ezhilarasi Arivukkannu	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓		
Kartigeyan Jayaraman			✓	✓	✓	✓	✓	✓	✓					

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest regarding this manuscript.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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