OPTIMIZATION OF QUADRUPOLE CORE FOR HOMOGENOUS MAGNETIC FIELD USING NON-ORIENTED SILICON-IRON MATERIALS

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This paper investigates the optimization of quadrupole core configurations designed to generate a homogeneous magnetic field, with emphasis on the performance of non-oriented (NO) Fe–Si electrical steels. Four commercial grades (M330-50A, M400-65A, M700-50A, and M700-65A) were comparatively analyzed by means of numerical modeling in the 50–1000 Hz frequency range. The results show that although M330-50A provides the highest magnetic flux density, the differences among the four materials are minor (below 1%). Consequently, the detailed analysis focused on this grade. Two quadrupole geometries were evaluated. The results indicate that Q_2 yields higher average flux density values (B_{med} = 527 mT compared to 487 mT for Q_1 at 50 Hz), while Q_1 exhibits superior field homogeneity, maintaining at least 98% of the minimum flux value across 77.1% of the target area (versus 68.5% for Q_2). Both configurations follow the same trend of decreasing induction with increasing frequency. These results highlight the trade-off between maximizing magnetic flux density and preserving homogeneity, providing design guidelines for applications requiring controlled and uniform magnetic fields.

Keywords: non-oriented Fe–Si steels, quadrupole core, magnetic flux density, field homogeneity, numerical modeling.

1. Introduction

Soft magnetic materials (SMMs) are essential in electrical engineering applications due to their high magnetic permeability, low coercivity, and minimal hysteresis losses, which facilitate efficient magnetic flux conduction and energy conversion [1]. Conventional alloys, such as non-oriented electrical steels (NO FeSi) and Fe–Ni alloys (e.g., Permalloy), are widely employed in electric motors, transformer cores, generators, and inductive components, where low core losses are

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crucial for performance and efficiency [2]. In power transformers, thin-gauge NO FeSi sheets are used to reduce eddy current losses and improves operational efficiency, particularly at industrial frequencies (50–60 Hz) [3]. In rotating machines (synchronous and induction motors), soft magnetic cores enhance torque density and reduce energy dissipation [4]. Moreover, amorphous and nanocrystalline alloys offer superior performance at medium and high frequencies, making them suitable for modern applications like high-frequency transformers, inductors in switch-mode power supplies, and electric vehicle traction systems [5].

In the magnetic field production equipment industry, FeSi sheets continue to occupy a particularly important place. Non-oriented (NO) and grain-oriented (GO) electrical steels are both soft magnetic materials based on Fe–Si alloys, designed for low core losses and high permeability in electrotechnical applications [1]. With a typically 2–4% Si to reduce hysteresis losses and increase electrical resistivity, they share similar chemical compositions [6]. However, their microstructural and textural characteristics differ significantly. NO steels possess a random crystallographic grain orientation, which results in isotropic magnetic properties, dedicated especially to rotating machinery [3]. In contrast, GO steels are processed through secondary recrystallization to develop a strong Goss texture ({110}⟨001⟩), aligning the easy magnetization axis with the rolling direction; this yields extremely high permeability and very low losses along that direction, which is ideal for transformer cores operating with unidirectional flux [7]. While GO steels offer superior efficiency in static magnetic circuits, NO steels provide balanced performance in dynamic, multidirectional fields.

NO sheets balanced magnetic performance in all directions makes them particularly suitable for rotating or alternating field sources, such as those used in magnetic stimulation devices, magnetic particle imaging (MPI), and targeted drug delivery systems [8]. In these applications, magnetic cores must ensure efficient flux conduction under alternating fields, often in the range of tens to thousands of hertz, to enable precise control of field intensity and uniformity in the biological target zone [9]. Compared to GO steels, NO grades offer uniform permeability and lower anisotropy, allowing for flexible coil and core geometries that produce homogeneous fields in multiple directions—an essential requirement for bioelectromagnetic exposure systems [10]. Furthermore, their relatively low cost and established manufacturing processes facilitate scalable designs for laboratory and clinical devices [11]. Recent developments, the reduced thickness of these sheets leads to decreased eddy currents, which is critical for maintaining biological safety standards [12].

2. Materials

The most common soft magnetic materials used in industrial applications are ferrimagnetic and ferromagnetic solids characterized by high initial and maximum magnetic permeability, low coercivity, and minimal hysteresis loss, enabling rapid and energy-efficient magnetization and demagnetization cycles [13, 14]. Their functional properties are critically dependent on chemical composition, crystallographic texture, grain size, and impurity content, which influence domain wall motion and magnetic anisotropy [15, 16]. Conventional soft magnetic alloys, such as low-carbon steels and silicon steels, are extensively employed in transformer cores, electrical machines, and magnetic shielding due to their low core losses and cost-effectiveness [17].

With a classical 1-4 wt. % of silicon, non-oriented (NO) Fe–Si electrical steels are soft magnetic alloys designed with a practically isotropic magnetic behavior in the rolling and transverse directions to ensure uniform efficiency under alternating magnetic fields [13, 18]. Their microstructure consists of equiaxed ferrite grains with a random crystallographic texture, which minimizes directional dependence of magnetic properties compared to grain-oriented (GO) steels [19]. NO Fe–Si steels are commonly used in rotating electrical machines, such as motors and generators, but also in devices that have multiple flow concentration directions [20]. Current developments focus on thin-gauge NO-Fe-Si steels with optimized crystallographic textures and refined grain structures to meet the growing demand for high-efficiency electric machines, especially in renewable energy systems [21].

Thus, for the numerical modeling that is an integral part of this work, we used the magnetic characteristics of 4 types of NO type of electrical sheets. They have the form code Mabc-xyA, where M – indicates the magnetic alloys steel, abc – represents the value of the maximum magnetic losses multiplied with 100 for specific thickness of the sheet, accepted for 1.5 T and 50 Hz, xy – represents the thickness of the steel multiplied with 100, A – if the electrical steel is in final production form [22]. These materials exhibit a very good magnetization and a high initial permeability, as evidenced by both the first magnetization curves (Fig. 1) and the corresponding relative permeability curves (Fig. 2). Previous studies have demonstrated the favorable performance of these sheets at frequencies up to 1 kHz [23], which motivated the present work to conduct a comparative analysis over the 50–1000 Hz frequency range.

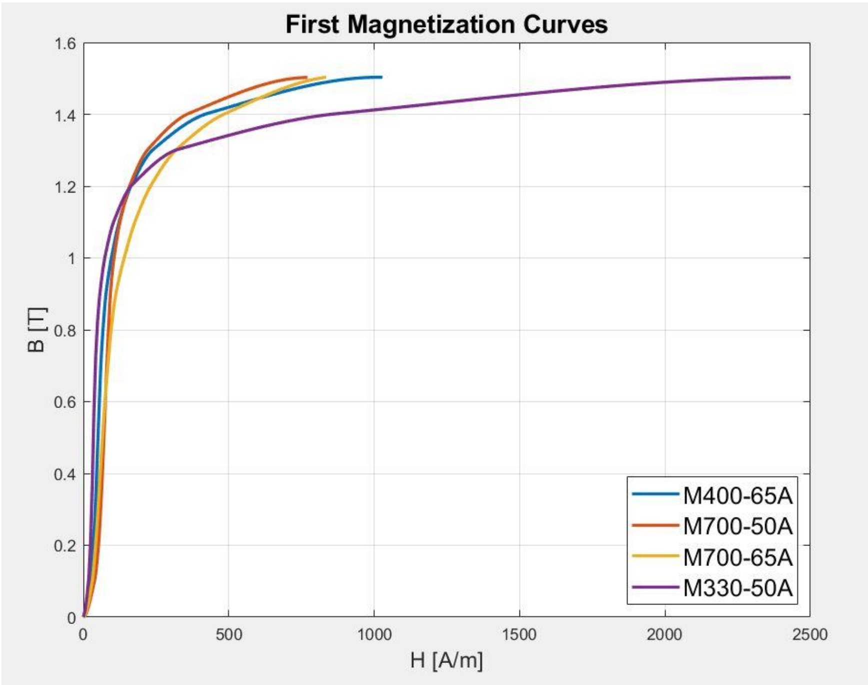

Fig. 1. First magnetization curves for the 4 types of NO electrical sheets

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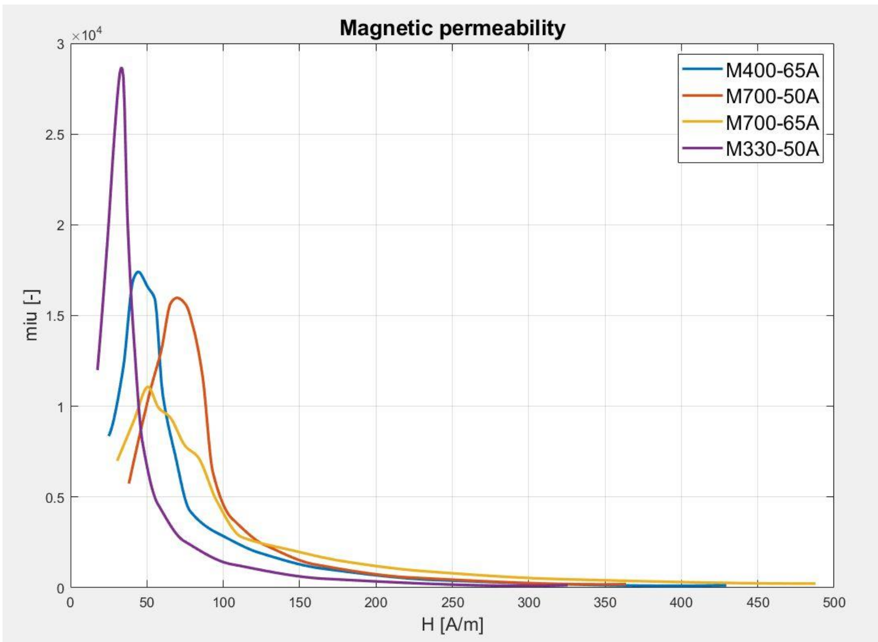

Fig. 2. Relative permeability for the 4 types of NO electrical sheets.

3. Results and discussion

Using the previously described materials as nonlinear core materials, the numerical analysis was conducted to compare the capabilities of two similar configurations (Fig. 3a – Q_1 and Fig. 3b – Q_2) [24] to generate a magnetic field with the highest possible degree of homogeneity. In both cases, the cores were modeled with a diameter of 22 mm, and each winding was supplied with a current of 1800 A. The main distinction between the two designs lies in the core volume, which is approximately 380 cm^3 for Q_1 and 490 cm^3 for Q_2. Additionally, the beveling of the poles represents a critical structural feature differentiating the two configurations. The simulations were performed both in 2D and 3D solvers, considering a variable field regime.

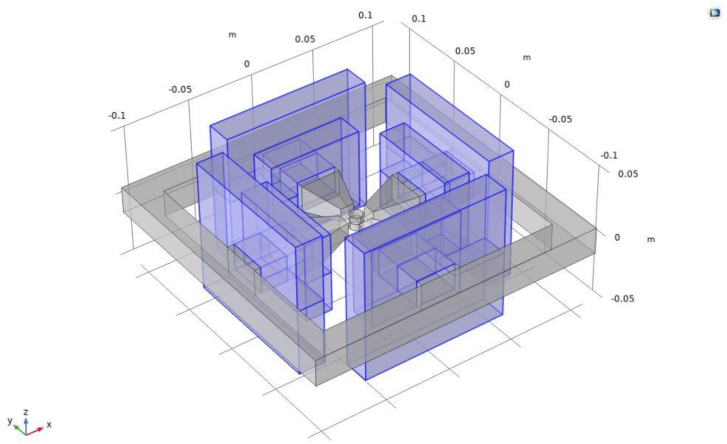

Fig. 3a. Quadruple core configuration Q_1.

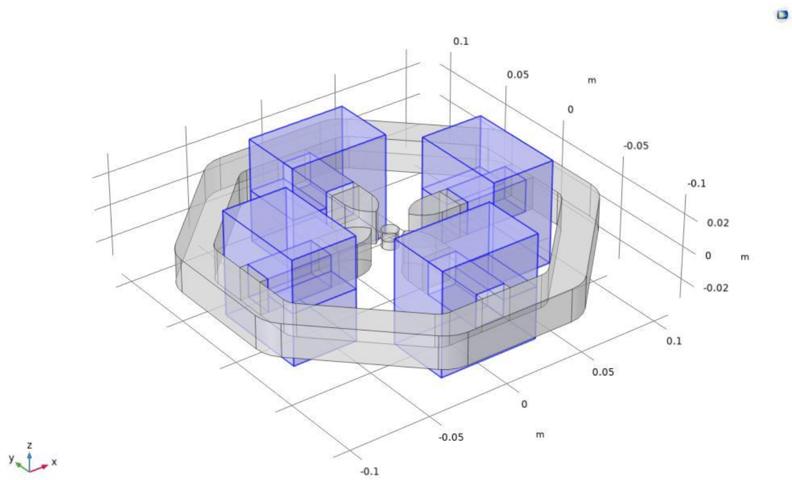

Fig. 3b. Quadruple core configuration Q_2.

The objective of this study was to identify the most suitable material in terms of magnetic field intensity and homogeneity within the region of interest (a 1 cm diameter cylinder). The analysis demonstrated that M330-50A exhibits the highest magnetic flux density values; however, the differences among the four investigated materials remain negligible (below 1%). Consequently, the subsequent analysis focuses on M330-50A. Furthermore, the comparison of magnetic field homogeneity revealed no significant variations among the four materials for either configuration (Q_1 or Q_2). A key finding of this investigation is that, for the same core material (M330-50A) and identical excitation frequency in the windings, configuration Q_2 provides superior magnetic flux density values (B_{med} = 527 mT) compared to Q_1 (B_{med} = 487 mT), as illustrated in Fig. 4 (for 50 Hz).

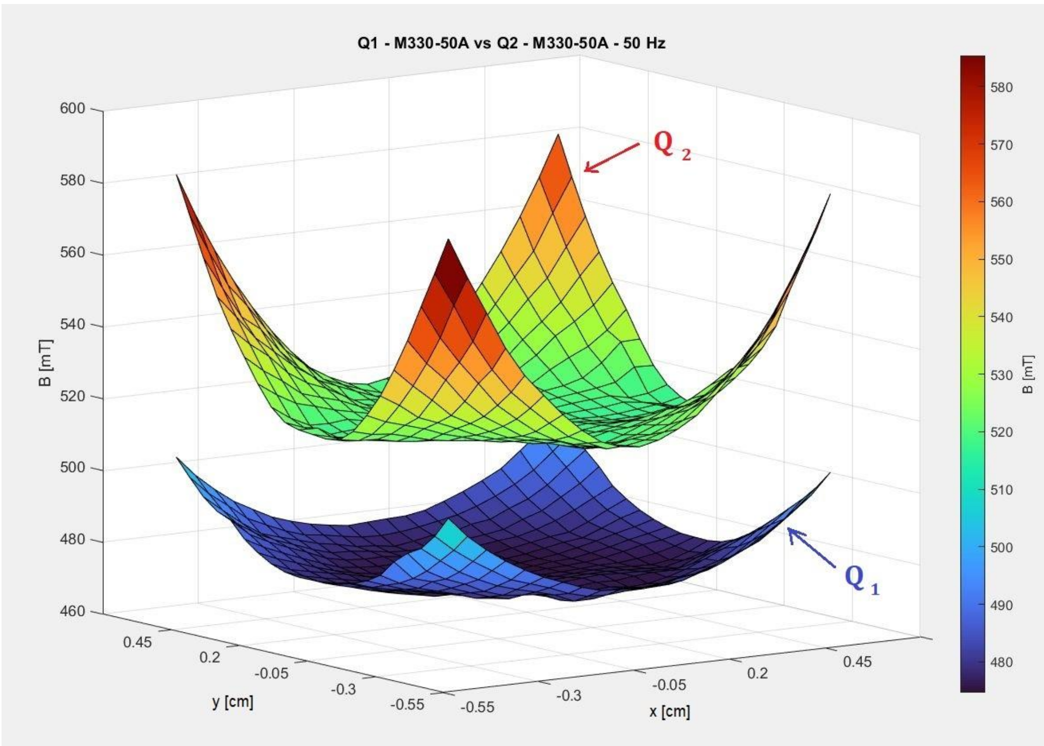

Fig. 4. Comparison between the map of magnetic flux density for both configurations using M330-50A core material at 50 Hz.

However, the comparative analysis of field homogeneity between the two configurations shows that, regardless of the material or excitation frequency, configuration Q_1 ensures the preservation of at least 98% of the minimum field value over approximately 77.1% of the region of interest. In contrast, configuration Q_2 maintains the same degree of homogeneity over only 68.5% of the corresponding area, as illustrated in Fig. 5a for Q_1 and Fig. 5b for Q_2.

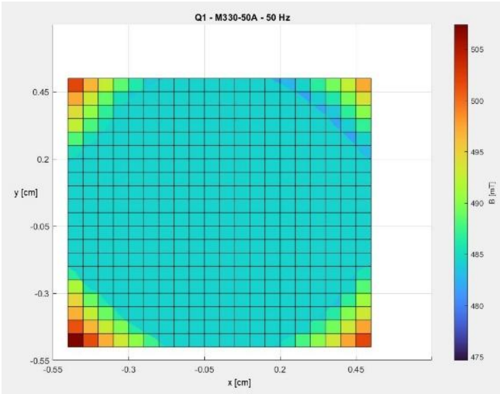

Fig. 5a. Q_1 configuration - 77.1% homogeneity.

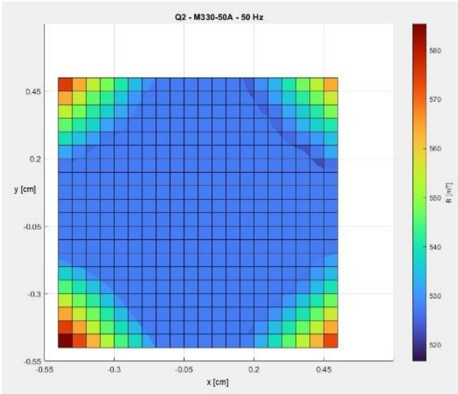

Fig. 5b. Q_2 configuration - 66.4% homogeneity.

Fig. 6a presents the magnetic flux density spectrum of configuration Q_1 at 400 Hz with an M330-50A core, while Fig. 6b illustrates the corresponding spectrum for configuration Q_2 under the same conditions.

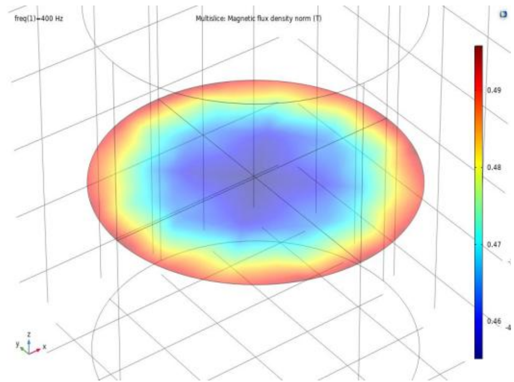

Fig. 6a. 3D magnetic flux density spectrum for Q_1.

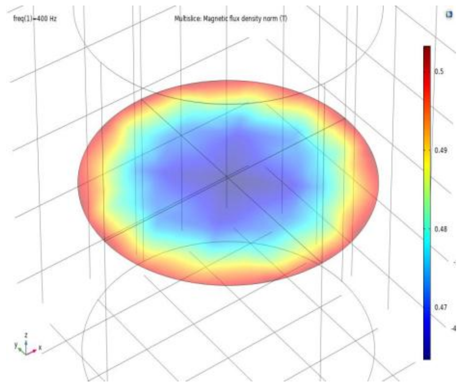

Fig. 6b. 3D magnetic flux density spectrum for Q_2.

It is further observed that, across the 50–1000 Hz frequency range, configuration Q_1 yields lower average magnetic induction values compared to Q_2; however, Q_1 provides slightly higher field homogeneity.

The final aspect addressed in this study concerns the variation of the average magnetic induction in the two configurations as a function of the excitation frequency applied to the coils. As illustrated in Fig. 7, both configurations exhibit a similar trend, with the induction values decreasing as the frequency increases.

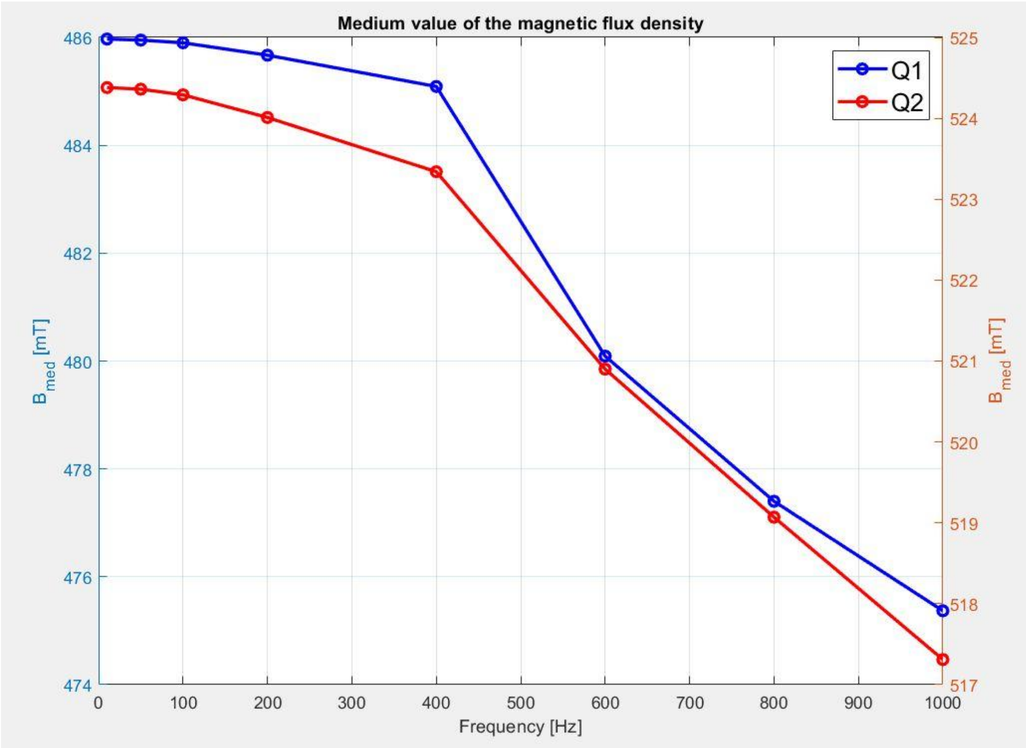

Fig. 7. Variation of the medium magnetic flux density for both configurations with frequency.

4. Conclusions

The comparative evaluation of four non-oriented electrical steels demonstrated that M330-50A offers the highest magnetic flux density across the analyzed frequency spectrum. However, the differences between the grades investigated remain negligible (under 1%), suggesting that the selection of material within this class may be guided by availability and cost efficiency rather than performance. The study of the two quadrupole core geometries revealed a distinct trade-off: configuration Q_2 provides higher average induction values, whereas configuration Q_1 ensures improved homogeneity of the magnetic field in the area of interest. This balance highlights the importance of adapting the core design to the specific requirements of the intended application.

The analysis of frequency-dependent behavior indicated that both configurations exhibit similar decreasing trends in flux density with increasing excitation frequency, confirming the predictable response of NO Fe–Si cores under alternating field conditions. The results obtained underline the potential of optimized quadrupole cores for use in electrotechnical and bioengineering applications, where uniform field distribution is critical. By selecting the appropriate combination of material and geometry, designers can tailor magnetic systems either towards maximizing field strength or enhancing homogeneity.

Overall, this work contributes to the understanding of how NO Fe–Si materials and structural design influence the performance of quadrupole magnetic cores, offering practical insights for the development of efficient and application-oriented magnetic field generation systems.

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