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Numerical modeling of magnetic cores with combined electrical steel grades

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Abstract

Purpose – This paper aims to investigate the impact of combining grain-oriented electrical steel (GOES) grades on specific iron losses and the flux density distribution within a single-phase magnetic core.

Design/methodology/approach – This paper presents the results of finite-element method (FEM) simulations investigating the impact of mixing two different GOES grades on losses of a single-phase magnetic core. The authors used different models: a 3D model with a highly detailed geometry including both saturation and anisotropy, as well as a simplified 2D model to save computation time. The behavior of the flux distribution in the mixed magnetic core is analyzed. Finally, the results from the numerical simulations are compared with experimental results.

Findings – The specific iron losses of a mixed magnetic core exhibit a nonlinear decrease with respect to the GOES grade with the lowest losses. Analyzing the magnetic core behavior using 2D and 3D FEM shows that the rolling direction of the GOES grades plays a critical role on the nonlinearity variation of the specific losses.

Originality/value – The novelty of this research lies in achieving an optimum trade-off between the manufacturing cost and the core efficiency by combining conventional and high-performance GOES grade in a single-phase magnetic core.

Keywords Transformer, Grain-oriented electrical steel, Flux density distribution, Iron losses, Finite element method

Paper type Research paper

1. Introduction

Power transformers are widely recognized for their high efficiency, but the widespread use of transformers in the electric power grid, the rising energy costs and their environmental impact have led both customers and the European Union to establish high requirements on transformer

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efficiency and related costs (European Commission, 2014). The paper contributes to the ongoing effort to achieve a better balance between the magnetic core cost and performance.

The efficiency of power transformers has significantly improved through the latest advances in numerical and analytical modeling for the design of power transformer cores (Valkovic, 1988; Ilo *et al.*, 1996; Nakata *et al.*, 1994; Mechler and Girgis, 2000). However, the investigations on transformers' magnetic cores made with a mix of different material grades still require further attention. Several research works have analyzed mixing different grades of grain-oriented electrical steel (GOES) within a laminated core. Moses and Hamadeh (2014) demonstrated that the magnetic core building factor can be enhanced using certain combination of materials and that it is feasible to reduce operational costs, especially at low or medium flux density levels. In addition, in Snell and Coombs (2003), the authors showed that mixing materials in a 100 kVA three-phase transformer magnetic core can be achieved without any detrimental effects. Magdaleno-Adame *et al.* (2016) demonstrated that combining a conventional and a laser-scribed steel is possible and may lead to a 31% reduction in the core losses of power transformers. Moreover, the study by Kefalas and Kladas (2012) shows that mixing a three-phase transformer core with a conventional GOES grade, which is 19% less cost-effective than a high-permeability GOES grade, leads to a loss increase of less than 5.4% up to 1.6 T and a significant reduction of 8.6% of the transformer core cost. In addition, in Balehosur (2012), the author shows that the specific losses of a mixed three-phase transformer core are dependent on the mixed materials. However, it was observed that these losses do not vary linearly with the proportion of the lower loss material used in a core made entirely with higher loss materials, and vice versa, although the causes for this nonlinearity were not specified.

In this paper, a combination of 2D and 3D finite element analysis (FEA) of a mixed single-phase magnetic core using two different GOES grades is introduced to evaluate the distribution of flux density, as well as the trends in terms of no-load losses in the core. The scientific challenge consists in determining the flux density distribution of the different grades in the core, taking into account the laminated sheets layers and corners geometries, along with the material permeabilities. A simplified mixed single-phase magnetic core has been experimentally analyzed to validate the FEA simulations.

2. Description of the experimental device

2.1 Experimental setup

Measurements of the specific losses P are performed on a simplified laminated single-phase magnetic core with a step-lap joint configuration, as shown in Figure 1. The magnetic core is

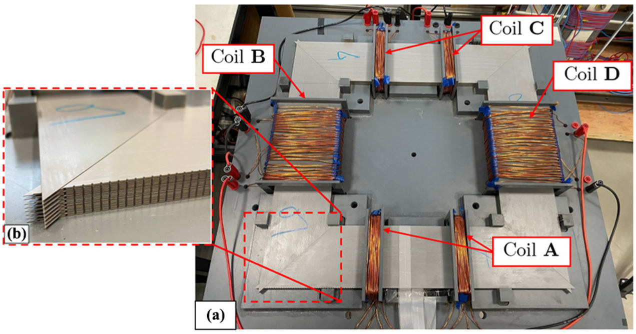

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Figure 1.
(a) The single-phase magnetic core setup and (b) the step-lap joint configuration

made of 40 laminated sheets for each limb; the external dimensions are 500 × 500 mm^2. The used laminated sheets are 100 mm wide and they have a thickness of 0.27 mm. The core is built using a 45° multi-step-lap joint configuration, which consists of five lamination sheets per step and an overlap length of 2.5 mm between the laminations. The core is coiled with four identical primary windings to magnetize it and four secondary windings, each of them has 26 turns, thus a total of 104 turns.

The simplified single-phase magnetic core is magnetized up to 1.7 T with a sinusoidal voltage waveform, 50 Hz, generated by a waveform generator (AWG2005) and amplified with the power amplifier (NF4505). The total power loss of the core is measured using a precision power meter (WT330). The wattmeter current coil is connected in series with the primary winding, and the voltage coil is connected to the secondary winding. A schematic representation of the experimental setup is shown in Figure 2.

The overall flux density in the core is sinusoidal, it is determined by measuring the secondary winding voltage. The peak flux density was calculated using the following equation:

$$B_m = \frac{\sqrt{2}}{2\pi} \cdot \frac{V_{rms}}{f.N_s.L.t} \tag{1}$$

where V_{rms} is the rms value of the secondary winding voltage, f is the frequency, N_s is the turn number of the secondary winding, L is the width length of the core and t is the thickness of the core, which is calculated from the density and the masses of the laminated sheets used in the core.

2.2 Selected grain-oriented electrical steel materials

The GOES grades selected for the experiments are M095-27P with specific iron losses of 0.93 W/kg at $B = 1.7$ T, and M120-27P (1.16 W/kg at $B = 1.7$ T). The selection of these grades is based on their distinct characteristics in the rolling direction (RD), which are essential for examining their impact on the magnetic core. Their B-H curves and their specific losses' characteristics at a frequency of 50 Hz in the RD as well as in the transverse direction (TD) were obtained using a standardized Single Sheet Tester (SST), as shown in Figure 3.

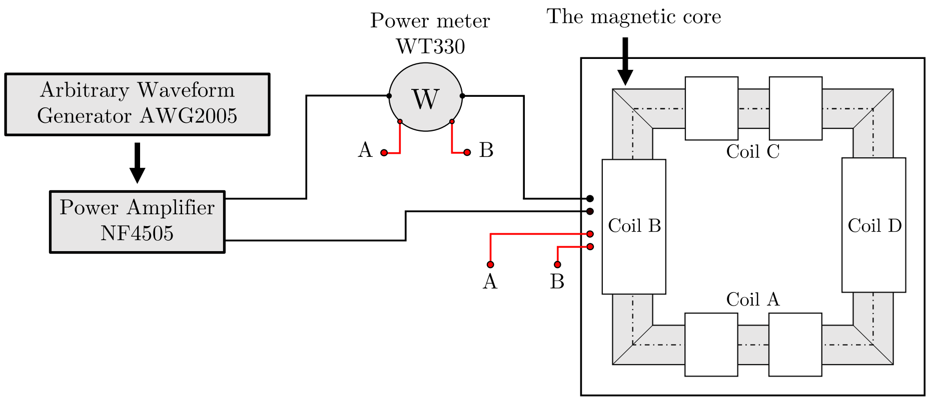

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Figure 2. Experimental setup schematic representation

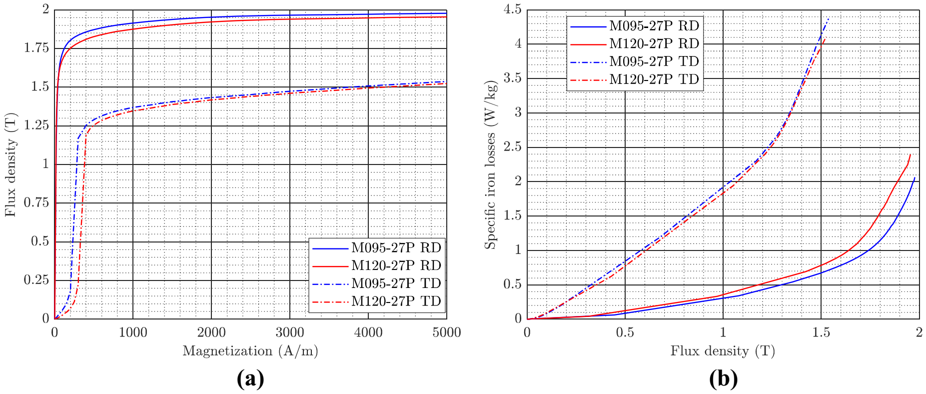

Figure 3. Characteristics of M095-27P and M120-27P at 50 Hz in the RD and TD

Notes: (a) Magnetization curves; (b) specific iron losses
Source: Authors' own creation

2.3 Concept of the grain-oriented electrical steel grade mixing

To investigate the influence of steel grade mixing, the authors carried out a comparative analysis involving various percentages of grades with a chosen magnetic core defined as a reference. Initially, iron losses are measured on a core composed entirely of M120-27P sheets. Thereafter, the lamination situated in the middle of the magnetic core are progressively replaced by sheets of grade M095-27P, keeping the symmetry of the core, and until a core composed solely of the grade M120-27P, as depicted in Figure 4. This choice of grade layout was chosen based on findings from Corin *et al.* (2022), which showed that positioning the high-performance grade in the middle of the core leads to the lowest core losses.

3. Experimental results

The Figure 5(a) shows the specific iron losses behavior for the five magnetic cores as a function of the global flux density. The experimental results indicate a decrease in the specific losses as the proportion of M095-27P in the core increases. Notably, the magnetic core composed entirely of M095-27P has the lowest losses, whereas the core without this grade records the highest losses.

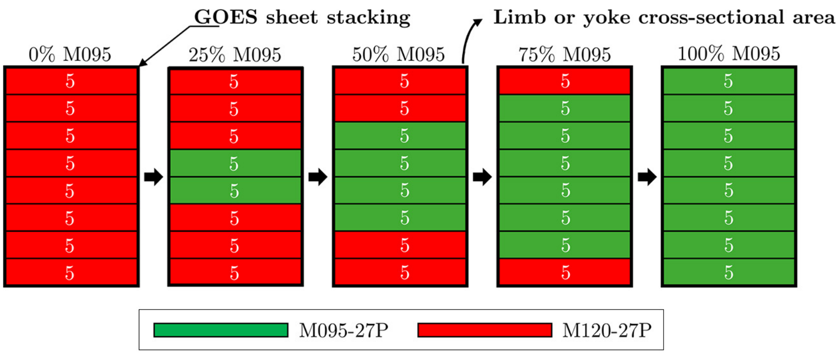

Figure 4. Grade mixing layout in the magnetic core

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In addition, the study reveals that the specific losses decrease follows a nonlinear pattern with respect to the proportion of M095-27P used in the core, particularly for the highest flux density values. However, for the lower flux densities, a less pronounced nonlinearity is observed, as depicted in Figure 5(b).

The fundamental question raised by the measured results consists in determining the factors, which contribute to the nonlinear variation of the specific losses. In pursuit of an answer, the authors developed a 2D and 3D FEA models.

4. Mixed core finite element analysis modeling

4.1 Grain-oriented electrical steel material anisotropy

Accurately modeling the GOES anisotropy remains a challenging task in FEA due to the varying magnetic characteristics associated with different magnetization angles. Most of the commercial FEA software applications currently model the anisotropy using a permeability tensor in three primary directions (using the two-axis anisotropic method) based on measurement data: rolling direction (RD), transverse direction (TD) and normal direction (ND) (Nakata *et al.*, 1994). Consequently, the system for determining the flux density vector $\boldsymbol{B}(\boldsymbol{H})$ can be described as follows:

$$\left\{ \begin{array}{l} B_x = \mu_0 \mu_x (H_x) H_x \\ B_y = \mu_0 \mu_y (H_y) H_y \\ B_z = \mu_0 \mu_z (H_z) H_z \end{array} \right. \quad (2)$$

4.2 Iron losses modeling

JMAG simulation software is used for performing single-phase mixed magnetic core FEA, as it provides the capability to consider both material saturation and the magnetic anisotropy of GOES laminations. The calculation of iron losses in JMAG is based on two methods. First, the classical Steinmetz model approximation which uses a bidirectional coefficient as shown in equation (3), where i is the harmonic rank, N is the highest harmonic, B_{RD} and B_{TD} are the peak magnetic flux density according to the RD and TD, respectively,

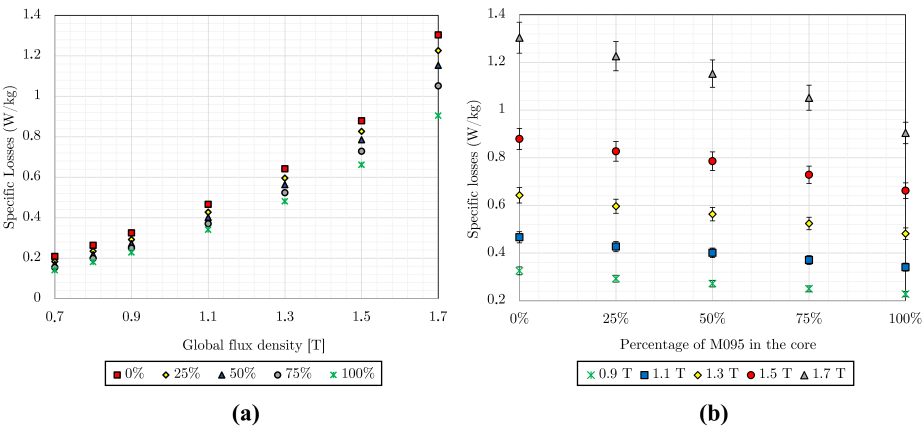

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Figure 5. (a) Specific losses variation across the five magnetic cores as a function of the global flux density and (b) variation of the specific losses as a function of the flux density and the percentage of M095-27P in the core

and f is the operating frequency. The coefficients K_{hRD}, K_{hTD}, K_{eRD}, K_{eTD}, α, β, δ and γ are determined using material SST characteristics data. Second, JMAG can directly use specific iron losses function of flux density to calculate the corresponding iron loss values in each element of the model:

$$P_{core\_loss} = \sum_{i=1}^{N} \left\{ \begin{array}{l} (K_{hRD}.B_{RD}{}^{\alpha} + K_{hTD}.B_{TD}{}^{\alpha}).f^{\beta} \\ (K_{eRD}.B_{RD}{}^{\gamma} + K_{eTD}.B_{TD}{}^{\gamma}).f^{\delta} \end{array} \right. \quad (3)$$

4.3 Model and method of analysis

The accurate modeling is a typical 3D problem. Developing a 2D model serves the dual purpose of reducing the computation time as well as to study the flux distribution in a section across the joints perpendicular to the plane of the laminated sheets. The magnetic vector potential formulation was used to solve the FEA models, represented by the following equation (4), where μ is the permeability (H/m), A is the magnetic vector potential (Wb/m) and J is the current density (A/m^2). The finite element method is used to solve equation (4) in the magnetic core domain:

$$\nabla \times \left(\frac{1}{\mu} (\nabla \times A) \right) = J \quad (4)$$

Figure 6 shows the 3D FEA model, showcasing a mixed magnetic core with the same dimensions as the experimental one. The nonlinearity and anisotropy in RD, TD and ND are taken into account and, to enhance computational efficiency and account for core symmetry, only one-quarter of the core is modeled, as illustrated by the red dashed lines in Figure 6. The joints of the core follow the same configuration of the experimental single-phase magnetic core.

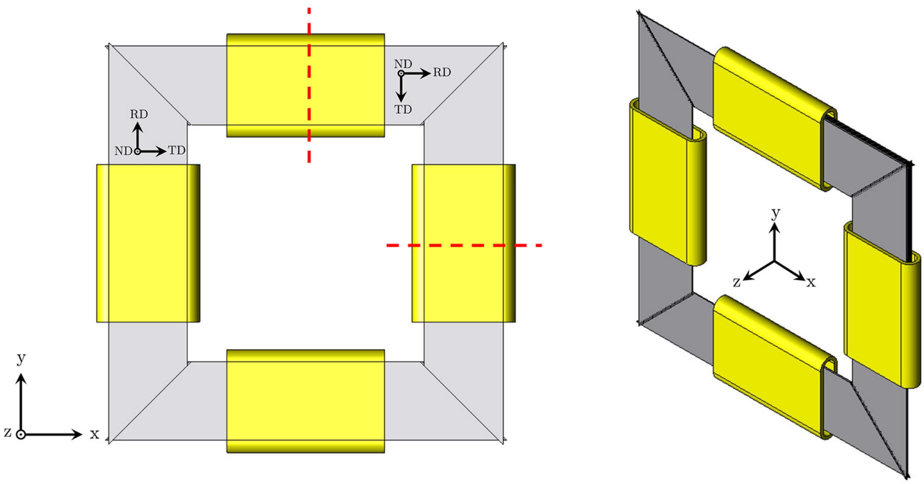

Figure 6.
The single-phase magnetic core FEA model

Source: Authors' own creation

4.4 Magnetic core 2D finite element analysis model

To analyze the flux density distribution in the joints of the mixed core, it is essential to examine the flux distribution in a cross-sectional area across the joints perpendicular to the plane of the lamination sheets. Figure 7 shows the 2D model used for this purpose.

This 2D model is characterized by the step-lap joint configuration, where air gap between lamination sheets is 0.15 mm and the interlaminar gap between layers is taken to be 0.01 mm. Due to a lack of information for the magnetization curve in the ND, a linear relative permeability of $\mu_Z = 30$ was used. This choice was based on a previous study (Hihat *et al.*, 2010) involving similar GOES materials, which identified that the ND permeability can range between 28.6 and 34.2. In addition, this study demonstrated that at a magnetic field strength of 945 A/m, the flux density only varied from 1.5 to 1.525 T, staying within 1%, thus justifying the linear approximation.

The magneto-harmonic simulation in steps from 0.7 to 1.7 T with a frequency of 50 Hz was performed. The global flux density of the core is controlled by the voltage applied to the excitation coil, as described in equation (1). A fine mesh is made of 1,690,415 elements for this simulation.

4.4.1 Flux density behavior in the joint area. Figure 8 shows the flux density behavior in the joint area of the core for global flux densities of 1.3 and 1.7 T. The results indicate that, in a step-lap joint configuration, the flux density increases as it gets closer to the gap region, reaching around 2 T. This change in interlaminar flux causes localized iron losses in the joint. Furthermore, the critical role played by the step-lap joint configuration is evident in reducing the concentration of high-magnetic flux density values in the joint area, thus reducing iron losses.

4.4.2 Results of the distribution of the magnetic flux density. The computed flux density distribution within the core for two different magnetization levels, 1 and 1.7 T is shown in

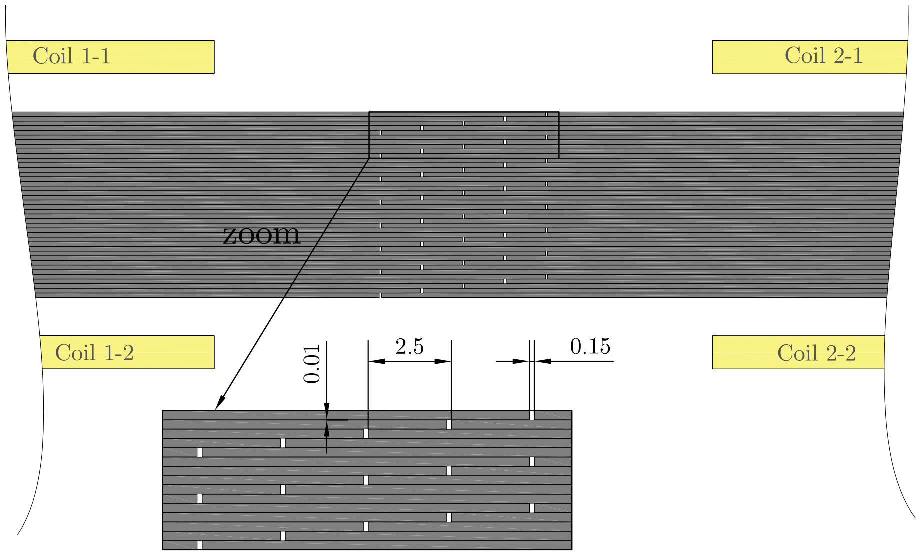

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Figure 7. The magnetic core 2D FEA model

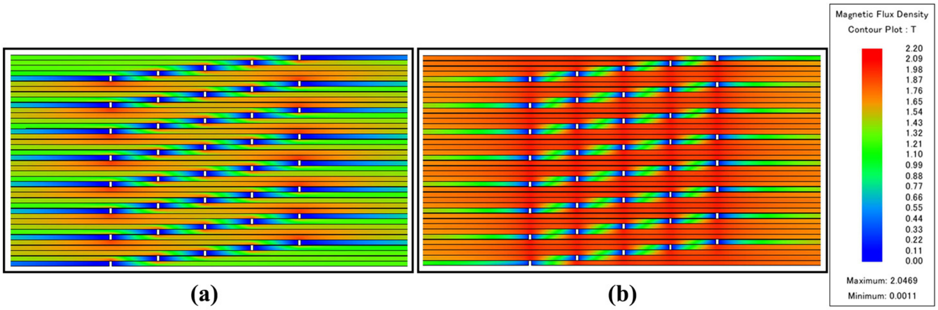

Figure 8.
Flux density behavior in the magnetic core joint area

Notes: (a) 1.3 T; (b) 1.7 T
Source: Authors' own creation

Figure 9. These distributions show clearly that the flux density follows the B-H curves of the grades used in the core. Notably, the permeability of M120-27P is higher than that of M095-27P at 1 T, but this relationship reverses at higher flux densities, as observed at 1.7 T. Furthermore, a nonlinearity of the flux density distribution is observed.

4.4.3 Results of the specific iron losses. Figure 10(a) shows the specific iron losses as a function of the percentage of M095-27P used in the core and global flux density level, offering a comparison of the five magnetic cores. It is evident that the magnetic core composed entirely of M095-27P presents the lowest losses, while the magnetic core with 100% M120-27P presents the highest losses. The Figure 10(b) shows the nonlinear nature of the iron loss decrease and the trends are consistent with the experimental results.

However, the iron losses calculated using the 2D FEA model are higher than the measured losses. This disparity arises because the 2D model assumes uniform flux density in the lamination sheets, which is not the case, as the magnetic flux is concentrated near the inner rectangle of the magnetic core rather than the exterior, resulting in lower values of flux density at the exterior of the core and thus lower iron losses.

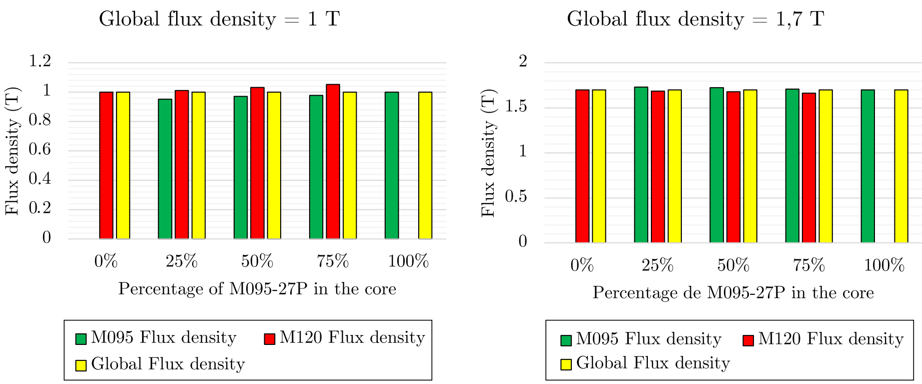

Figure 9.
2D model results of the flux density distribution in the core

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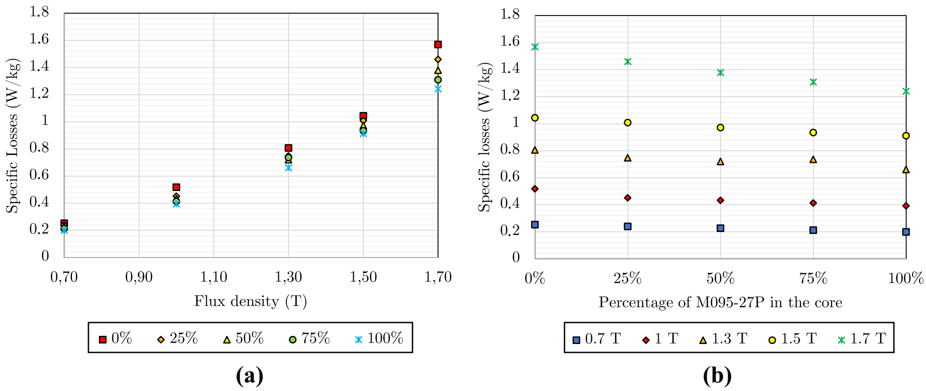

Notes: (a) Across the five magnetic cores as a function of the global flux density; (b) as a function of the flux density and the percentage of M095-27P in the core
Source: Authors' own creation

Figure 10. 2D FEA model specific losses variation

4.5 Magnetic core 3D finite element analysis model

Due to the anisotropic nature of GOES materials and the complexity introduced by the mixing of grades within the single-phase magnetic core, a 3D modeling approach with individual laminated sheets is required. However, using a highly detailed 3D single-phase core model with 40 in each limb of thin (0.27 mm) laminated sheets separated by an interlaminar gap of less than 10 μm sheets would be impractical due to the extensive computation time required.

To address this challenge, the authors tried to simplify the model. Specifically, they have consolidated the five laminated sheets that constitute the five steps of the step-lap joint configuration into a single block, as illustrated in Figure 11. This technique, always considering a quarter of the core as previously explained in Section 4.3, plays a significant

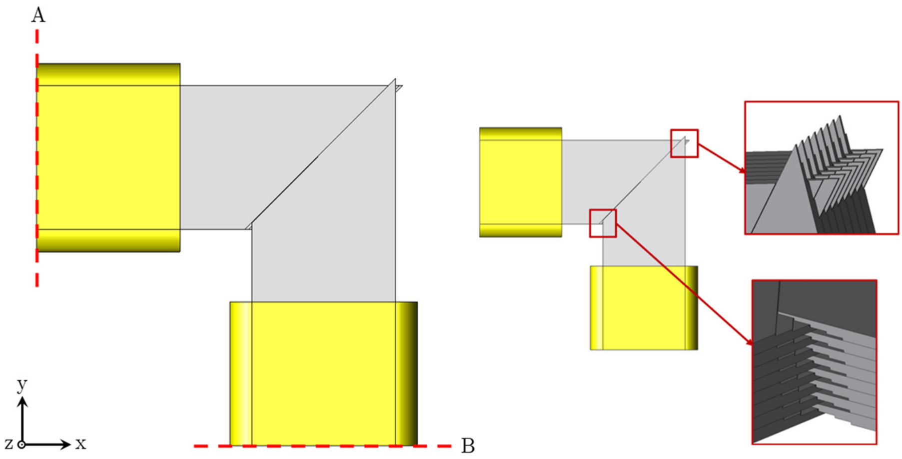

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Figure 11. The 3D model of the magnetic core

role in reducing the number of meshing elements. As a result, a reasonable computational time was obtained while preserving the accuracy of our results.

Figure 12 shows the mesh used in the 3D model, with a very fine mesh in the joint area when the flux is rotational, resulting in a total of 5,590,415 elements. Boundary conditions stipulate that flux flows perpendicularly through boundaries A and B due to the unidirectional nature of the flux in the middle of the core limbs. These boundaries are treated as natural boundaries.

4.5.1 Flux density behavior in the core. The flux density behavior of magnetic core under global flux densities of 0.7 and 1.7 T is shown in Figures 13 and 14. These results show a nonuniformity of the flux density across the width of the core. For low-to-medium global flux densities applied to the core, the flux density is higher in the inner parts of the core, gradually decreasing toward the outer parts of the core as shown in Figure 13. However, for the highest values of flux density, the behavior of the flux density becomes

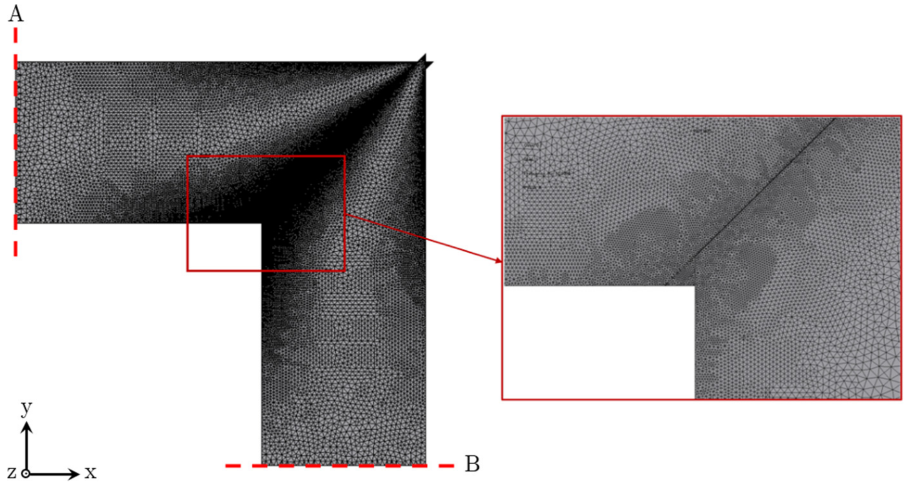

Figure 12. Applied mesh of the 3D model

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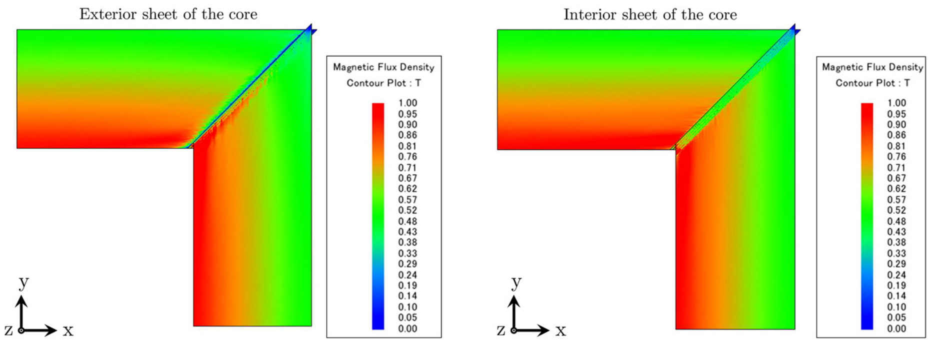

Figure 13. Flux density behavior in the magnetic core for a global flux density of 0.7 T

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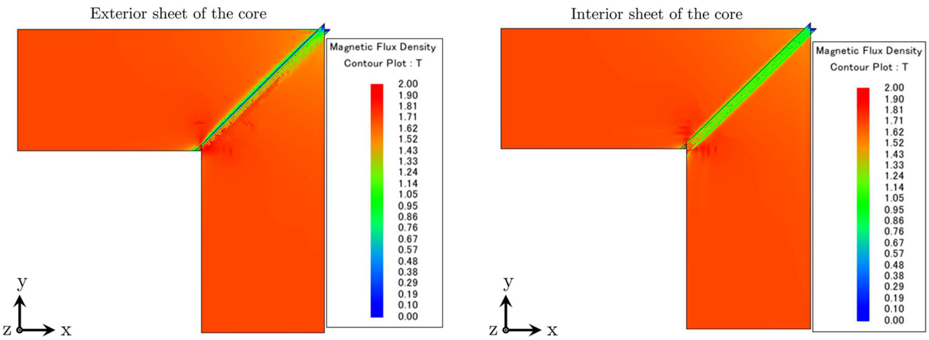

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Figure 14. Flux density behavior in the magnetic core for a global flux density of 1.7 T

nearly uniform, as depicted in Figure 14. In addition, these results indicate a significant solicitation of the TD in the joint area.

These results contradict the 2D model assumptions. It is supposed that the flux density has a uniform distribution across the entire width of the laminated sheet, which is not the case. This nonuniformity in flux density leads to lower calculated iron losses.

4.5.2 Results of the magnetic flux density distribution. Figure 15 presents the computed magnetic flux density distribution for two different magnetization levels, 1 and 1.7 T. These results are consistent with the conclusions drawn from the 2D model. However, they demonstrate more pronounced differences in flux density values between the two grades, including the reversal in the tendencies of the flux density distribution in the core seen in the 2D model.

4.5.3 Results of the specific iron losses. The simulated specific iron losses results are shown in Figure 16 and compared to experimental measurements. The simulated results exhibit similar tendencies to the experimental measurements precisely in 25% and 50% cases.

However, small discrepancies emerge in other results especially for higher flux densities, because of the difficulty of the FEA model to accurately represent the material anisotropy, especially the angle of difficult magnetization of 55°.

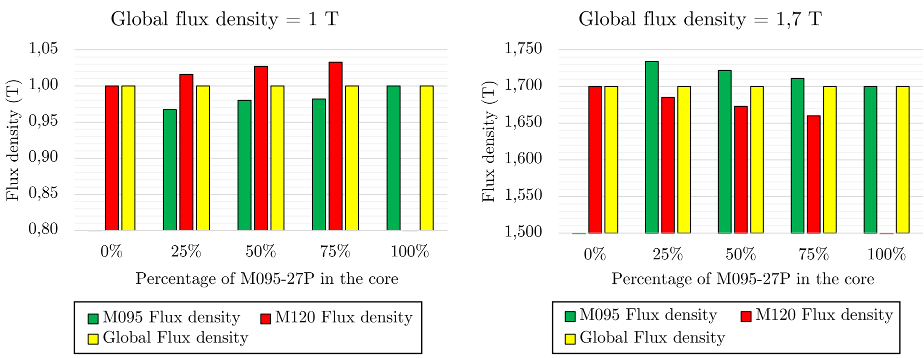

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Figure 15. 3D model results of the flux density distribution in the core

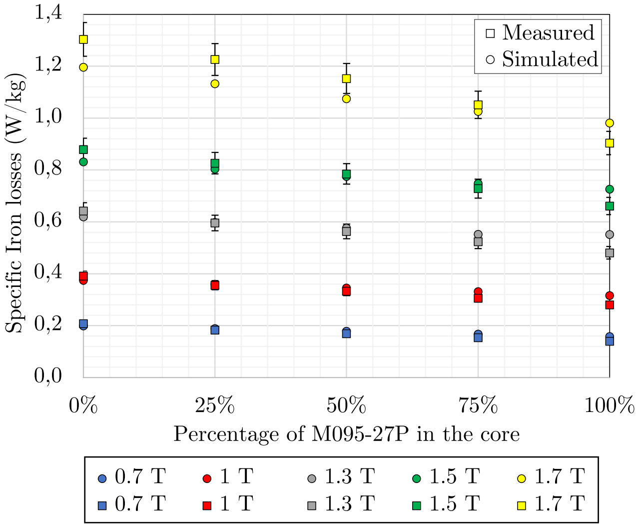

Figure 16.
Comparison of 3D FEA simulated specific losses in the core with experimental results

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5. Conclusion

The paper analyzes, experimentally and numerically using 2D and 3D FEA simulations, the impact of combining two different GOES grades in a single-phase magnetic core. The authors conclude that the variation of the specific iron losses with respect to the percentage of the grade with lower iron losses used in the magnetic core is nonlinear. Furthermore, analyzing the magnetic core using a 2D FEA model allowed for a rapid initial assessment of the iron losses decrease trends within the core. However, the iron losses obtained from the 2D model are higher than the measured losses experimentally. This discrepancy can be attributed to the assumption of a uniform flux density across all the width of the lamination sheets, a condition inconsistent with the observed magnetic flux distribution in the detailed 3D model. In the 3D model, the flux density is higher in the inner regions of the core, gradually decreasing toward the outer regions, resulting in lower calculated iron losses. Moreover, the 2D finite element analysis of the flux density behavior in the core shows that, in a step-lap joint configuration, the change of interlaminar flux causes localized iron losses in the joint. The step-lap joint configuration is essential to avoid concentrating the flux density in the joint area, thus allowing to decrease the associated iron losses.

In addition, the 3D FEA model allows considering the GOES anisotropic properties in RD, TD and ND. This impacts the accuracy, as the 3D FEA model simulated results show closer tendencies with the experimental measurements, precisely in 25% and 50% cases, with small discrepancies emerging in other results, especially for higher flux densities. And these slight differences can be attributed to the difficulty of the FEA model to accurately represent the material anisotropy in all the directions, especially the angle of difficult magnetization of 55°.

Furthermore, analyzing the core using 2D and 3D FEA models shows that the RD permeability of the grades has a major role in the nonlinear variation of the specific losses.

Indeed, in the 2D model and specifically considering only the RD and ND, specific losses obtained from numerical results show similar nonlinear tendencies. Moreover, the flux density behavior in the core exhibits a nonlinear pattern and it corresponds to the permeabilities of the grades used in the core.

Lastly, the paper highlights that using a conventional GOES grade for the outer laminated sheets of the core, and a high performance GOES grade for the inner laminated sheets, is the best configuration to obtain the optimal reduction of the specific iron losses and, that way, to maintain an attractive cost of single-phase magnetic cores with improved performance.

References

Balehosur, M.B. (2012), "Prediction of no-load losses of stacked 3-phase, 3-Limb transformer cores", PhD Thesis, Cardiff University, available at: https://orca.cf.ac.uk/51925/1/2013BalehosurPhD.pdf

Corin, R., Lecointe, J.P., Demian, C. and Blaszkowski, J. (2022), "Grades layout impact on performance of mixed grade magnetic cores", *2022 International Conference on Electrical Machines (ICEM), Valencia, Spain*, pp. 2176-2180, doi: 10.1109/ICEM51905.2022.9910663.

European Commission (2014), "Commission regulation (EU) no 548/2014 of 21 May 2014 on implementing directive 2009/125/EC of the European parliament and of the council with regard to small, medium and large power transformers", *Official Journal of the European Union*, Vol. L 152 No. 2, pp. 1-15.

Hihat, N., Lecointe, J.P., Duchesne, S., Napieralska, E. and Belgrand, T. (2010), "Experimental method for characterizing electrical steel sheets in the normal direction", *Sensors*, Vol. 10 No. 10, pp. 9053-9064, doi: 10.3390/s101009053.

Ilo, A., Weiser, B., Booth, T. and Pfützner, H. (1996), "Influence of geometric parameters on the magnetic properties of model transformer cores", *Journal of Magnetism and Magnetic Materials*, Vol. 160, pp. 38-40, doi: 10.1016/0304-8853(96)00099-6.

Kefalas, T.D. and Kladas, A.G. (2012), "Mixed Si-Fe wound cores five legged transformer: Losses and flux distribution analysis", *IEEE Transactions on Magnetics*, Vol. 48 No. 4, pp. 1609-1612.

Magdaleno-Adame, S., Melgoza-Vazquez, E., Olivares-Galvan, J.C. and Escarela-Perez, R. (2016), "Loss reduction by combining electrical steels in the core of power transformers", *International Transactions on Electrical Energy Systems*, Vol. 26 No. 8, pp. 1737-1751.

Mechler, G.F. and Girgis, R.S. (2000), "Magnetic flux distributions in transformer core joints", *IEEE Transactions on Power Delivery*, Vol. 15 No. 1, pp. 198-203, doi: 10.1109/61.847251.

Moses, A.J. and Hamadeh, S. (2014), "Effects of mixing materials on losses and cost of operation of three-phase transformer cores", *Journal of Applied Physics*, Vol. 64 No. 10, pp. 2012-2015, doi: 10.1063/1.342376.

Nakata, T., Fujiwara, K., Takahashi, N., Nakano, M. and Okamoto, N. (1994), "An improved numerical analysis of flux distributions in anisotropic materials", *IEEE Transactions on Magnetics*, Vol. 30 No. 5, pp. 3395-3398, doi: 10.1109/20.312667.

Snell, D. and Coombs, A. (2003), "The influence of core materials and mix on the performance of a 100 kVA three-phase transformer core", *Journal of Magnetism and Magnetic Materials*, Vols 244/245, pp. 349-351.

Valkovic, Z. (1988), "Recent problems of transformer core design", *Physica Scripta*, Vol. T24, pp. 71-74, doi: 10.1088/0031-8949/1988/T24/010.

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