IMPACT OF NONLINEAR ANISOTROPIC MAGNETIC BEHAVIOR MODELS ON IRON LOSS MODELING IN TRANSFORMERS

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JOËL DRAPPIER,[1] FRÉDÉRIC GUYOMARCH,[1]
RIHEB CHERIF,[2] YVONNICK LE MENACH[1]

[1] University of Lille, Arts et Metiers Institute of Technology, Centrale Lille, Junia, Lille, France
joel.drappier@univ-lille.fr, Frederic.Guyomarch@irisa.fr, yvonnick.le-menach@univ-lille.fr
[2] ESME, ESME Research Lab, Lille, France
rihaab.cherif@gmail.com

This paper explores the implications of nonlinear anisotropic behavior models on the simulation of magnetic losses in a transformer made of a conventional Grain-Oriented Electrical Steel (GOES) within a finite element method (FEM) simulation environment. GO laminations are commonly used to improve the efficiency of electrical machines, but their complex behavior requires accurate modeling. Nonlinear resolutions for different anisotropy models were implemented and compared with isotropic nonlinear and linear anisotropic models. Then, the iron losses were estimated using an anisotropic model developed by Appino *et al.*.

Keywords:
nonlinear anisotropic models,
iron loss modelling
grain-oriented electrical steel (GOES),
finite element method (FEM),
transformer efficiency

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I Introduction

Electrical machines are currently undergoing extensive research to enhance their efficiency by a few percentage points. One solution involves the use of grain oriented (GO) laminations. Renowned for superior magnetic performance in the rolling direction (RD) (high permeability and low magnetic losses), these steels are strategically employed to guide the magnetic flux along this preferred direction.

However, due to their inherent texture, these laminations not only exhibit nonlinear behavior but also strongly anisotropic magnetic characteristics between the RD and the transverse direction (TD). Considering the anisotropic behavior of these materials is essential when examining magnetic properties.

Implemented within the Finite Element Method (FEM) software code_Carmel, this study relies on different anisotropic behavior law models, such as the elliptical model [1] and the modified elliptical model [2]. These models rely solely on measurements in the rolling and transverse directions. A comparative analysis contrasts them with more common approaches, including nonlinear isotropic and linear anisotropic modeling.

Subsequently, an anisotropic iron loss model, proposed in [3], and recently implemented in a FEM simulation environment in [4], has been employed to estimate the iron losses in a quarter of a transformer made of GOES with Epstein frame dimensions. Nonlinear 3D magnetostatic simulations were performed. The iron losses have been computed based on FEM distributions of the **H** and **B** magnetic fields.

II Magnetic anisotropy models

A. Notations and assumptions

Defining our models involves considering the local coordinate system of laminations (RD, TD, ND), with ND representing the normal direction to the laminations. The permeability tensor μ carries the magnetic behavior of materials. It establishes the relation between magnetic induction and magnetic field according to $\mathbf{B} = \mu(\mathbf{H})\mathbf{H}$. As measured in [5], the permeability along ND is assumed to be low and linear. This assumption allows us to decouple the magnetic behavior along ND. We also assume the anhysteretic behavior.

The considered models were originally developed in 2D, and enable us to determine permeabilities in the principal plane. As mentioned in the introduction, models requiring measurements of the magnetic characteristics in the RD and TD directions were chosen. More specifically, we have chosen elliptical-type models, which will be described in detail here.

The permeability tensor μ, can be seen as a norm variation between H and B multiplied by an orientation variation. In the particular context of our models, the relationship between the angles of our fields is given by:

$$\tan\beta = \frac{\mu_{TD}(H)}{\mu_{RD}(H)}\tan\theta \tag{1}$$

μ_{RD} and μ_{TD} being the measured characteristics along the two principal directions and θ and β the respective angles of **H** and **B** with respect to the RD. For brevity, the H dependency is not indicated hereafter. Moreover, as illustrated in [6], μ is expressed as a diagonal tensor, such that:

$$\mu = \mu_{scal}\begin{pmatrix} \frac{\cos\beta}{\cos\theta} & 0 \\ 0 & \frac{\sin\beta}{\sin\theta} \end{pmatrix} \tag{2}$$

with μ_{scal} the factor depending on the studied model.

B. The models

Illustrations in Fig. 1 depict the evolution of induction B according to the applied fields along RD and TD (resp. H_x and H_y). Each model, is defined such as:

- Elliptical model [1]:

$$\mu_{scal} = \left(cos^2(\beta)\ /\ \mu_{RD}^2(H) + sin^2(\beta)/\mu_{TD}^2(H)\right)^{-\frac{1}{2}}. \tag{3}$$

– Modified elliptical model [2]:

$$\mu_{scal} = \left(\cos^n(\beta) \,/\, \mu_{RD}^{n2}(H) + \sin^n(\beta)/\mu_{TD}^{n}(H)\right)^{-\frac{1}{2}}. \tag{4}$$

For our numerical examples, we choose $n = 1.4$ as proposed in [2].

– Nonlinear isotropic model: considers the magnetic characteristic along RD in the lamination, i.e. $\mu = \mu_{RD}$.
– Linear anisotropic model: linear approximations of the characteristics along the principal directions, with $\mu_{RD} = 26281.2\mu_0$ and $\mu_{TD} = 2159.5\mu_0$.

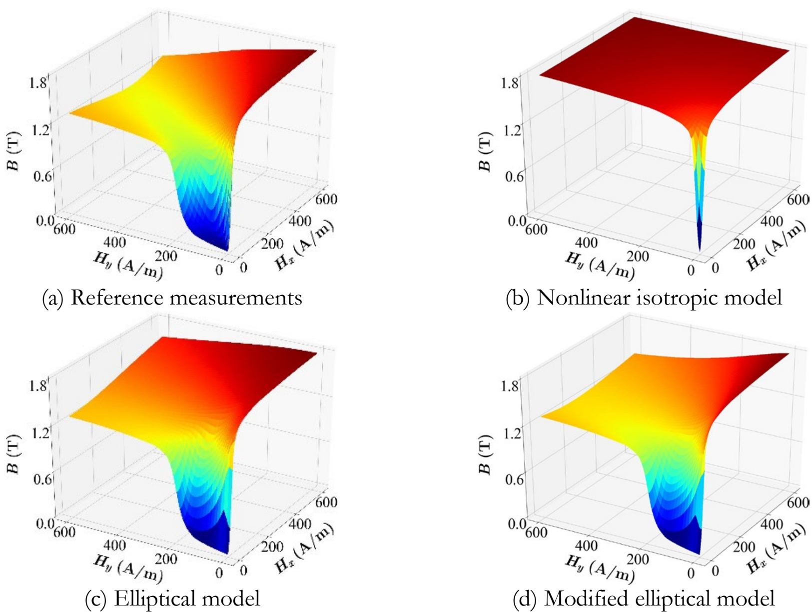


Figure 1: Induction level as a function of the field components.

III Anisotropic loss model of appino

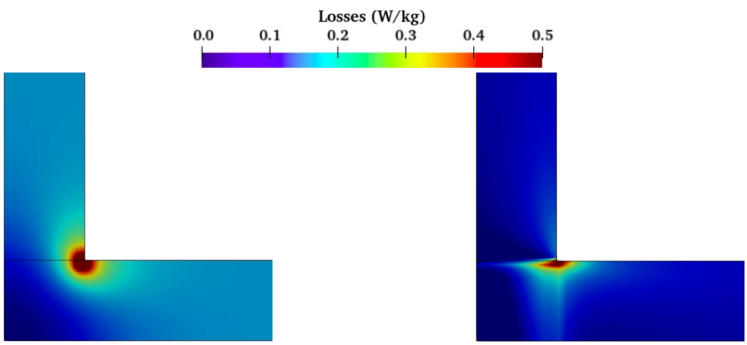
Concerning the iron loss model of Appino *et al.* [3], the study is based on previous work [4], performing for a linear behavior the simulation of losses in a toroidal core. This model separates total losses into three components: hysteresis losses, classical losses, and excess losses. Hysteresis losses, representing quasistatic losses per magnetization cycle, are notably calculated using the peak polarization level $\hat{\mathbf{J}}$ and the angle θ_a of the applied field $\mathbf{H}_a$. During simulation, the effects of the demagnetizing field $\mathbf{H}_d$ arising from anisotropy were carefully considered. The numerical simulation provides the distribution of the resulting field $\mathbf{H}$, such that $\mathbf{H} = \mathbf{H}_a + \mathbf{H}_d$.

IV Results

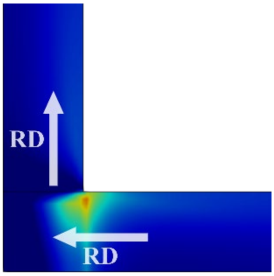
The 3D simulations of losses were carried out over a period at 50Hz, with an excitation current of 22.5mA passing through two coils of 88 turns each, positioned on a straight section of the transformer. The transformer itself consists of four laminations, similar to those in an Epstein frame, arranged in two layers, stacked so that the upper lamination in the frame corner has a horizontally oriented grain, while the lower one is vertically oriented. The maximum induction level does not exceed 1.7T, corresponding to a resulting field below 450A/m. The results in Table I and Fig. 2 show significant variations in total and local iron losses among the models. A more accurate consideration of anisotropy, as with the modified elliptical model, closer to measurements, leads to a reduction in total losses, with a loss shape markedly different from isotropic modeling. Note that linear modeling is relevant here, as we remain below the saturation point.

Table 1: Computed losses for different models.

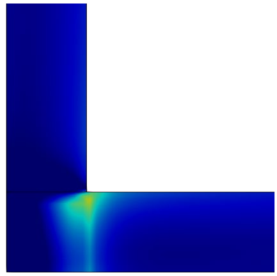
Models	Iso. non-lin.	Aniso. lin.	Ell.	Ell. mod.
Total losses (W/kg)	0.1414	0.1183	0.1254	0.1099
Max. losses (W/kg)	3.2347	0.9602	0.3891	0.3280



(a) Non-linear isotropic (b) Linear anisotropic



(c) Elliptical model



(d) Modified elliptical model

Figure 2: Specific iron losses (W/kg) of the upper laminations per model.

V Conclusion

This study emphasizes the importance of considering anisotropy in iron loss calculations, especially in the practical context of transformer modeling. Notably, it is observed that nonlinear isotropic modeling provides limited relevant information in predicting losses compared to other models that considering anisotropy, even in simpler forms. Our next step involves exploring models that are closer to material physics, requiring improvements in the robustness of the nonlinear solver.

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