



HAL
open science

Anisotropic Models of Nonlinear Magnetic Behavior Laws for Finite Element Modeling of Iron Losses in a Toroidal Core

Joël Drappier, Frédéric Guyomarch, R. Cherif, Yvonnick Le Menach, Oualid Messal, Loïc Chevallier, Abdelkader Benabou

► To cite this version:

Joël Drappier, Frédéric Guyomarch, R. Cherif, Yvonnick Le Menach, Oualid Messal, et al.. Anisotropic Models of Nonlinear Magnetic Behavior Laws for Finite Element Modeling of Iron Losses in a Toroidal Core. 2024 IEEE International Magnetic Conference - Short Papers (INTERMAG Short Papers), May 2024, Rio de Janeiro, France. pp.1-2, <10.1109/INTERMAGShortPapers61879.2024.10577022>. <hal-04879330>

HAL Id: hal-04879330

<https://hal.science/hal-04879330v1>

Submitted on 10 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Anisotropic Models of Nonlinear Magnetic Behavior Laws for Finite Element Modeling of Iron Losses in a Toroidal Core

J. Drappier¹, F. Guyomarch¹, R. Cherif², Y. Le Menach¹, O. Messal¹, L. Chevallier¹ and A. Benabou¹

¹Univ. Lille, Arts et Metiers Institute of Technology, Centrale Lille, Junia, ULR 2697 - L2EP, F-59000 Lille, France

²ESME, ESME Research Lab Lille, France

This paper explores the implications of nonlinear anisotropic behavior models on the simulation of magnetic losses in a toroidal core 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 a measurement-based model. Then, an anisotropic iron loss model from Appino *et al.* has been applied to evaluate the iron losses. This method provides a decisive way to qualitatively assess various models directly, relying on measurable quantities of interest.

Index Terms—Grain-oriented materials, iron losses, magnetic anisotropy, nonlinear magnetics.

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 (e.g. iron losses).

Implemented within the Finite Element Method (FEM) software code_Carmel [1], this study examines various anisotropic behavior law models: the elliptical model, the rocked elliptical model [2] and the modified elliptical model [3]. These models rely solely on measurements in the rolling and transverse directions. A comparative analysis is conducted, including a model exclusively based on measurements.

Subsequently, an anisotropic iron loss model, proposed in [4], and recently implemented in a FEM simulation environment in [5], has been employed to estimate the iron losses in a toroidal core made of GOES commonly used in turbogenerators. Nonlinear 3D magnetostatic simulations were performed. The iron losses have been computed based on FEM distributions of the \mathbf{H} and \mathbf{B} magnetic fields.

This approach enables existing anisotropic models to be evaluated qualitatively and opens the perspective to a better understanding of magnetic losses in electrical machines.

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 [6], the permeability along ND is assumed to be low and linear. This assumption, holds until around 40 000 A/m, 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:

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

μ_{RD} and μ_{TD} being the measured characteristics along the two principal directions and θ and β the respective angles of \mathbf{H} and \mathbf{B} with respect to the RD. For brevity, the H dependency is not indicated hereafter. Moreover, as illustrated in [7], μ is expressed as a diagonal tensor, such that:

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

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). For each model, the μ_{scal} factor is defined as:

- Elliptical model [2]:

$$\mu_{scal} = (\cos^2(\beta)/\mu_{RD}^2 + \sin^2(\beta)/\mu_{TD}^2)^{-1/2}. \quad (3)$$

- Rocked elliptical model [2]:

$$\mu_{scal} = (a \cos^2(\beta + \zeta) + b \sin^2(\beta + \zeta))^{-1/2} \quad (4)$$

with $a = 2/\mu_{RD}^2 - 1/\mu_{TD}^2$, $b = 2/\mu_{TD}^2 - 1/\mu_{RD}^2$, and $\zeta = 90^\circ - 54.7^\circ$, the difficult magnetisation angle being 54.7° .

- Modified elliptical model [3]:

$$\mu_{scal} = (\cos^n(\beta)/\mu_{RD}^n + \sin^n(\beta)/\mu_{TD}^n)^{-1/n} \quad (5)$$

for a heuristic choice of $n = 1.4$ as proposed in [3].

- Measurement-based Model: utilizes bicubic spline interpolation for different angles of applied fields on GO laminations, and then provides access to norm variation.

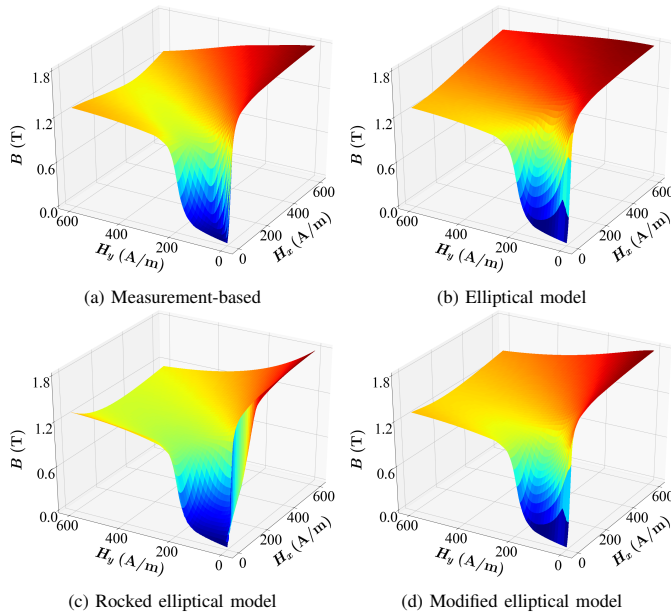


Fig. 1. Induction level according to applied field components.

III. ANISOTROPIC LOSS MODEL OF APPINO

Concerning the iron loss model of Appino *et al.* [4], the study is based on previous work [5], performing for a linear behavior the simulation of losses in a similar toroidal core. This model separates total losses into three components: hysteresis losses, classical losses, and excess losses. Hysteresis losses, representing quasi-static losses per magnetization cycle, are notably calculated using the peak polarization level \hat{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 loss simulations were performed for a period at 50 Hz, with an excitation current of 50 A. The peak induction level did not exceed 1.7 T, corresponding to a resulting field below 400 A/m. Table I and Fig. 2, reveal substantial variations in total and specific iron losses across the models. Notably, the rocked elliptical model exhibits significant differences.

Explained by his natural reduction of induction levels to simulate difficult magnetisation (Fig. 1c), and considering that losses exhibit a roughly quadratic dependence on induction, we can observe the deviation on the B-H curve compared to the measurement-based model in the table of losses.

TABLE I
COMPUTED TOTAL LOSSES FOR DIFFERENT MODELS.

Models	Measure-based	Ell.	Rocked Ell.	Mod. Ell.
Losses (W/kg)	1.3911	1.9239	0.8134	1.5836

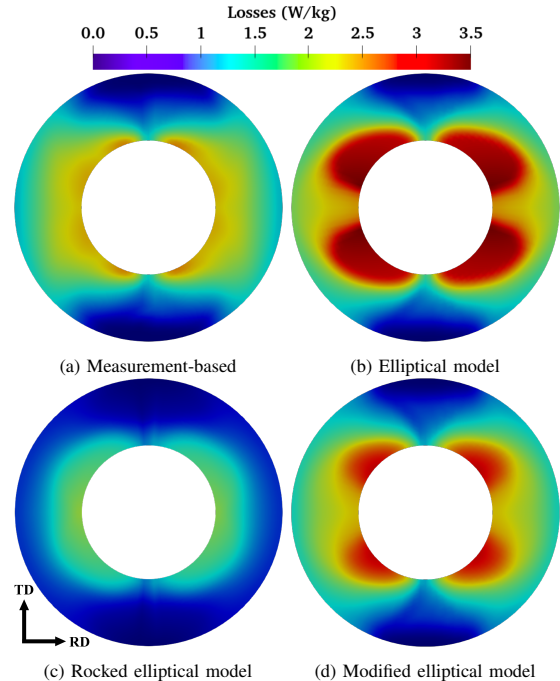


Fig. 2. Specific iron losses (W/kg) by model.

V. CONCLUSION

This study effectively identifies models requiring improvement in future nonlinear FEM codes. Specifically, the evaluation of anisotropy models on iron losses reveals that, the rocked elliptical model, with a substantial error in losses, should be abandoned in favor of models closer to material physics. Our next step involves validating these findings through actual measurements on the toroidal device to confirm observed trends. Another potential solution is thermal imaging during excitation to characterize loss shapes.

REFERENCES

- [1] LAMEL, "Principles of the time-based and multi-harmonic versions of code_Carmel," 2022. [Online]. Available: <https://code-carmel.univ-lille.fr/codeCarmelEn.pdf>
- [2] A. Di Napoli and R. Paggi, "A model of anisotropic grain-oriented steel," *IEEE Trans. Magn.*, vol. 19, no. 4, pp. 1557–1561, 1983.
- [3] O. Bíró, S. Außerhofer, K. Preis, and Y. Chen, "A modified elliptic model of anisotropy in nonlinear magnetic materials," *COMPEL*, vol. 29, no. 6, pp. 1482–1492, 2010.
- [4] C. Appino, E. Ferrara, F. Fiorillo, C. Ragusa, and O. de la Barrière, "Static and dynamic energy losses along different directions in GO steel sheets," *J. Magn. Magn. Mater.*, vol. 500, p. 166281, 2020.
- [5] L. A. Millan Mirabal, O. Messal, A. Benabou, Y. Le Menach, L. Chevalier, J. Korecki, J.-Y. Roger, and J.-P. Ducreux, "Iron loss modeling of grain-oriented electrical steels in fem simulation environment," *IEEE Trans. Magn.*, vol. 58, no. 2, pp. 1–5, 2022.
- [6] N. Hihat, J.-P. Lecoq, O. Ninet, S. Duchesne, E. Napieralska, and S. Wiak, "Normal permeability of grain non-oriented, grain oriented and amorphous electrical steel sheets," *Int. J. Appl. Electromagn. Mech.*, vol. 46, no. 2, pp. 349–354, 2014.
- [7] D. Huttenloher, H. Lorenzen, and R. Nuscheler, "Investigation of the importance of the anisotropy of cold-rolled electrical steel sheet," *IEEE Trans. Magn.*, vol. 20, no. 5, pp. 1968–1970, 1984.