# Parametric Homogenized Model for Inclusion of Eddy Currents and Hysteresis in 2-D Finite Element Simulation of Electrical Machines

Christian Krüttgen, Simon Steentjes, Gregor Glehn, and Kay Hameyer, *Senior Member, IEEE*
Institute of Electrical Machines (IEM), RWTH Aachen University, Aachen NRW, Germany
e-mail: christian.kruettgen@iem.rwth-aachen.de and simon.steentjes@iem.rwth-aachen.de

***Abstract*—Consideration of a fully coupled lamination model with eddy currents and magnetic hysteresis in standard finite element (FE) models is prohibitively expensive in terms of implementation effort, memory requirements and computation time. Hence this paper utilizes an algebraic approximation of the lamination model as a conventional constitutive relationship in two-dimensional FE simulations of rotating electrical machines. Extraction of model structure and parameters of the parametric model as well as iterative adaption of the homogenized FE characteristic are presented. This pragmatic approach turns out to be quite accurate and efficient simultaneously allowing for refinement of the pre-determined parametric expression by iterating between the fully coupled lamination model and the macroscopic model.**

***Index Terms*—Eddy Currents, Electrical Machines, Homogenization, Magnetic Hysteresis, System Identification.**

## I. Introduction and Methods

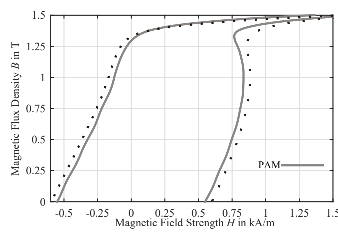
Soft magnetic cores of rotating electrical machines are laminated for reduction of eddy current losses and exhibit magnetic hysteresis when subjected to a time-varying magnetic field strength. These closely intertwined phenomena alter the overall behavior and performance of the rotating electrical machine, i.e., iron losses and magnetizability. Accounting for these is a critical problem to the accurate electrical machine design. A fine discretization of each single lamination and application of a dynamic hysteresis model [1], [2] as a constitutive relationship in standard finite element (FE) models is prohibitively expensive in terms of implementation effort, memory requirements and computation time. The heterogeneous multiscale method (HMM) allows connecting the lamination model (mesoscale) with the macroscopic model of the rotating electrical machine. However, a monolithic implementation of the HMM, such as in [3], leads to models one or two orders of magnitude larger than the initial non-homogenized model, not to mention the significant implementation work. Instead of this, in this paper the method proposed in [4] that separates the HMM approach into two independent steps is utilized to deliver the vectorial macroscopic constitutive relationship region by region accounting for the intricate coupling of magnetic hysteresis and eddy currents at the lamination level. The parametric algebraic model (PAM) utilized is given in (1) and detailed in [4]. Parameters $p_k$ are identified in order to minimize the least square approximation error for adequate excitation signals of the lamination model [1], [2].

$$\mathbf{H}(\mathbf{B}, \dot{\mathbf{B}}, p_k) = \left(p_0 + p_1 |\mathbf{B}|^{2p_2}\right) \mathbf{B} + p_3 \dot{\mathbf{B}} + \frac{p_4 \dot{\mathbf{B}}}{\sqrt{p_5^2 + |\dot{\mathbf{B}}|^2}} \quad (1)$$

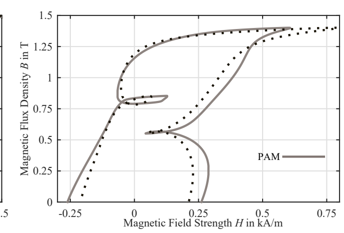
The accuracy of these region dependent PAMs can be controlled at any time adapting the model parameters and/or model structure by iteration between the local lamination model and the global homogenized model, i.e., the PAM. This means that the field waveforms obtained by the FE simulation with a first version of the PAM are fed back into the lamination model in order to identify a more accurate PAM matching a sufficient accuracy bound, e.g., when the operating characteristics of the electrical machine change.

## II. Results

Fig. 1 shows a comparison of measured and simulated major hysteresis loops using the PAM for time-varying sinusoidal magnetic flux densities of 1.5 T amplitude at 1000 Hz excitation frequency (Fig. 1a) and sinusoidal excitation of 200 Hz with added 5th harmonic with a phase angle of 45° (Fig. 1b). Measured results were obtained for a non-oriented soft magnetic material, classified as M400-50A, on a standardized Epstein frame. It is apparent that the model structure (1) is capable to predict hysteresis loop shapes with sufficient accuracy and is well-suited to serve as a region dependent constitutive material model in combination with a re-parametrization scheme in the simulation of rotating electrical machines.




(a) Sinusoidal Waveform




(b) Arbitrary Waveform

Fig. 1: Comparison of measured data (dots) and model prediction (dashed lines).

## III. Conclusion

This paper utilizes a parametric homogenized model to simulate a macroscale 2-D FE machine model. Comparisons to measured data are given. The full paper will include details about the models of each scale as well as the used methods for error estimation (change of magnetic energy, field continuity, ...) and the re-parameterization strategies. Results of the homogenized model will be compared to the fully coupled 1-D-2-D FE reference model in terms of accuracy, computation time and convergence.

## References

[1] S. Steentjes, F. Henrotte, C. Geuzaine, and K. Hameyer, "A dynamical energy-based hysteresis model for iron loss calculation in laminated cores," *International Journal of Numerical Modeling*, vol. 27, no. 3, pp. 433443, 2014.
[2] F. Henrotte, S. Steentjes, K. Hameyer, C. Geuzaine, "Iron loss calculation in steel laminations at high frequencies," *IEEE Transactions on Magnetics*, vol. 50, no. 2, pp. 333336, 2014.
[3] I. Niyonzima, R.V. Sabariego, P. Dular, F. Henrotte, C. Geuzaine, "Computational homogenization for laminated ferromagnetic cores in magnetodynamics," *IEEE Transactions on Magnetics*, vol. 49, no. 5, pp. 20492052, 2013.
[4] F. Henrotte, S. Steentjes, K. Hameyer, and C. Geuzaine, "Pragmatic two-step homogenization technique for ferromagnetic laminated cores," *IET Science, Measurement & Technology*, vol. 9, no. 2, pp. 152-159, 2015.

978-1-5090-1032-5/16/$31.00 