Modeling of Anisotropic Laminated Magnetic Cores Using Homogenization Approaches

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Abstract

3D-modeling and simulation of inductors and transformers with finite element methods is a challenge due to the involved nonlinearities and coupling effects between different physical domains. Primarily, there are the non-linear magnetic characteristics of the core materials including ferromagnetic hysteresis and eddy currents. With non-linear magnetic material or a non-harmonic excitation, simulations need to be performed in transient rather than in time-harmonic mode.

A specific issue in transformer modeling is the proper consideration of laminated core materials which are used to reduce eddy currents and thus to minimize dynamic hysteresis losses. Normally, the thickness of the individual sheets is small as compared to the core thickness. Therefore, it would be impractical to explicitly model a large number of sheets with a high dimensional aspect ratio, as this would lead to a large number of elements and hence to unacceptable computational effort. Therefore, several material homogenization approaches for laminated cores have been proposed in the past. They replace the laminated structure with a single domain of an electrically and magnetically orthotropic material which exhibits the same macroscopic behavior in a certain range of conditions. Thus, the computational effort is significantly reduced.

In a former study, we investigated several homogenization approaches for laminated toroidal cores in a 3D transformer model [1] by simulating the influence of the core eddy currents on the dynamic hysteresis losses. The example revealed significant differences between the results of the approaches, however, they could not be directly compared to simulations with explicitly modeled lamination or to test results as there was a remarkable static hysteresis which was not included in our models. In the current publication we now present improved models together with the experimental validation.

We implemented the electrical conductivity of the core material in a linear orthotropic form according to the respective homogenization approach, while the non-linear magnetic characteristic is based on an orthotropic $\mu(|B|)$ relationship. Thus, the reduced effective permeability perpendicular to the lamination plane can be taken into account. Both characteristics are described in a curvilinear coordinate system which is aligned according to the local

lamination direction.

Simulation results obtained on the different homogenization approaches are compared to those on explicitly modeled laminations in axisymmetric 2D and 3D models and further to experimental results.

The comparisons have been made in terms of the shape, coercivity, and losses of the dynamic hysteresis. In our test case the approach according to [2] showed the smallest deviations from the explicitly modeled cores (dynamic losses < 0.5 %, coercivity < 6 %). Moreover, this approach is robust with respect to variations of the sheet dimensions and the frequency as long as the sheet thickness is smaller than double the skin depth. Homogenization approach [3] also leads to reasonable accuracy (deviations of dynamic losses < 5 %, coercivity < 15 %).

A good agreement with experimental results was also found for Permalloy cores. This comparison was made for toroidal core shapes which are used for magnetic material characterization according to DIN EN 60404-6.

Reference

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[2] J. E. Kiwitt, A. Huber, K. Reiß: Modellierung geblechter Eisenkerne durch homogene anisotrope Kerne für dynamische Magnetfeldberechnungen. Electrical Engineering (Archiv fur Elektrotechnik), Springer Berlin / Heidelberg, 81 (1999) 369-374

[3] J. Wang, H. Lin, Y. Huang, X. Sun: A New Formulation of Anisotropic Equivalent Conductivity in Laminations. IEEE Transactions on Magnetics, 47 (2011) 1378 -1381

Figures used in the abstract

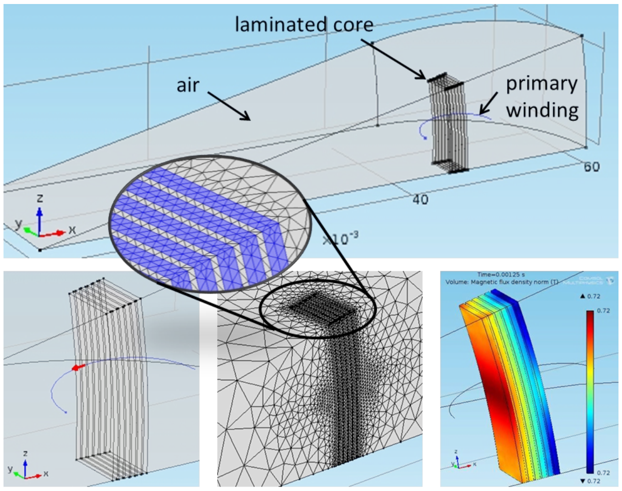

Figure 1: Comsol model of the closed toroidal Permalloy core with explicitly modeled lamination taking advantage of the 1/2·1/32 symmetry

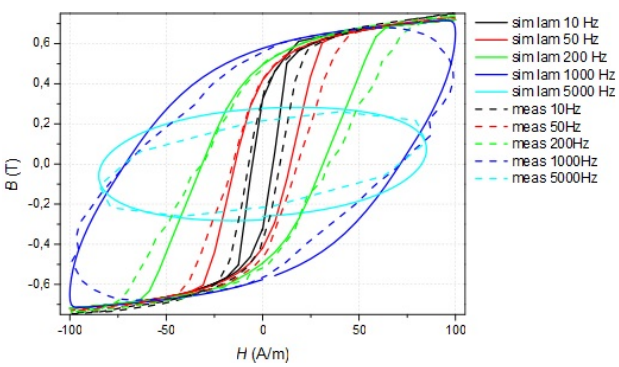

Figure 2: Direct comparison of the dynamic hysteresis loops of a toroidal Permalloy core as obtained from simulations with explicitly modelled lamination (sim lam) and from measurements (meas) for sinusoidal current and different frequencies

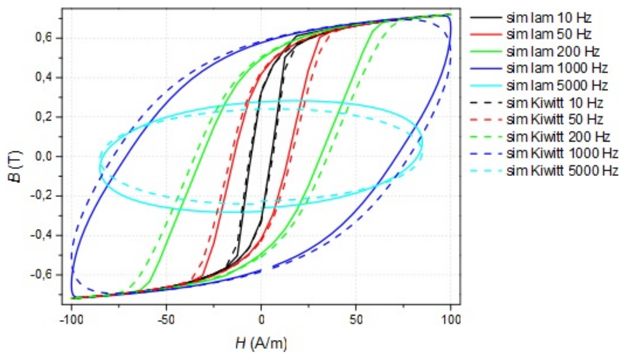

Figure 3: Comparison of simulation results obtained on the model with explicitly modelled lamination (sim lam) and the model based on a homogenization approach according to [2] (sim Kiwitt) for a sinusoidal current and different frequencies

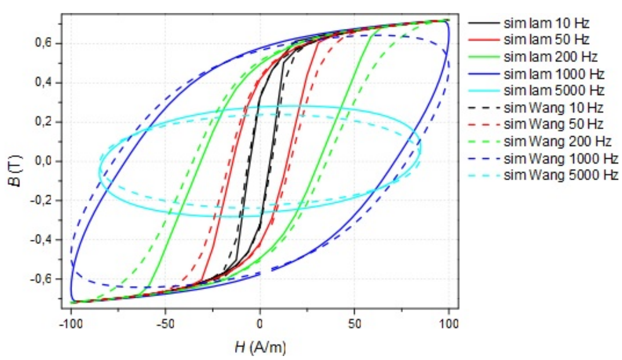

Figure 4: Comparison of simulation results obtained on the model with explicitly modelled lamination (sim lam) and the model based on a homogenization approach according to [3] (sim Wang) for sinusoidal current and different frequencies