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Homogenization Approaches for Laminated Magnetic Cores using the Example of Transient 3D Transformer Modeling

Holger Neubert[1]*, Johannes Ziske[1], Tobias Heimpold[1], Rolf Disselnkötter[2]

1 - TU Dresden, Institute of Electromechanical and Electronic Design, Dresden, Germany
2 – ABB AG, Corporate Research Center Germany, Ladenburg, Germany

*** Corresponding author: TU Dresden, IFTE, 01062 Dresden, Germany, holger.neubert@tu-dresden.de**

1 INTRODUCTION

A specific issue in transformer modeling using the finite element method is the consideration of **electric sheets** or other **laminated core materials** which are used to reduce eddy currents (**Figure 1.a**). It would be impractical to explicitly model a large number of sheets as this would lead to unacceptable computational costs. **Homogenization procedures** overcome this problem. They substitute the laminated structure by a solid having nearly the same electro-magnetical behavior (**Figure 1.b**). In our study, we have implemented several of them in a transformer model. Simulation results obtained with the different homogenization approaches are compared to those from models having explicitely modeled sheets and experimental test results as well.

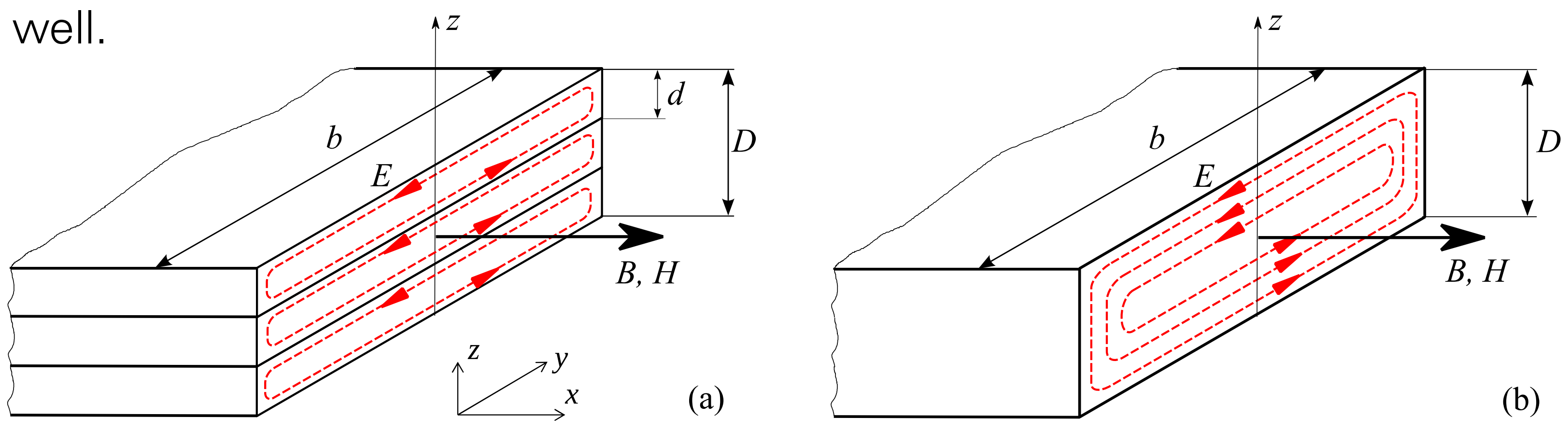

Figure 1: Eddy currents in a laminated magnetic core (a) and in an equivalent homogenized core (b); B, H – magnetic field, E – electric field

2 ELECTROMAGNETIC TRANSFORMER MODEL

Figure 2 depicts the transformer samples which were both experimentally investigated and simulated. The core consists of stacked electric sheets which wear a closely wound secondary coil at one leg and a primary coil equally distributed over all legs of the ring core.

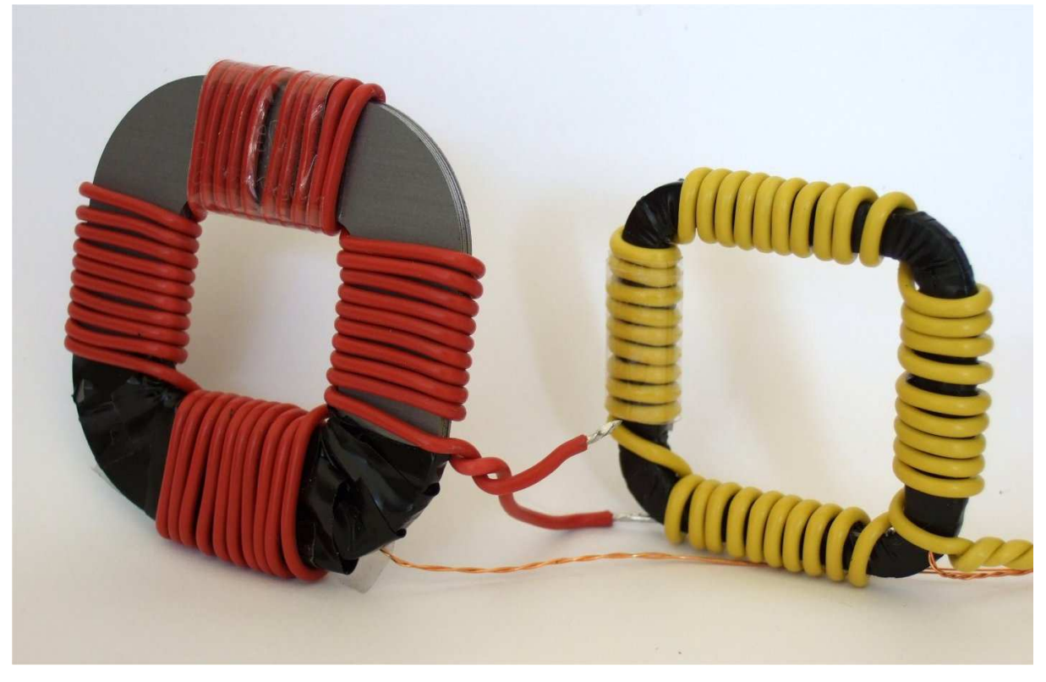

Figure 2: *Transformers with laminated ring core for hysteresis measurements.*

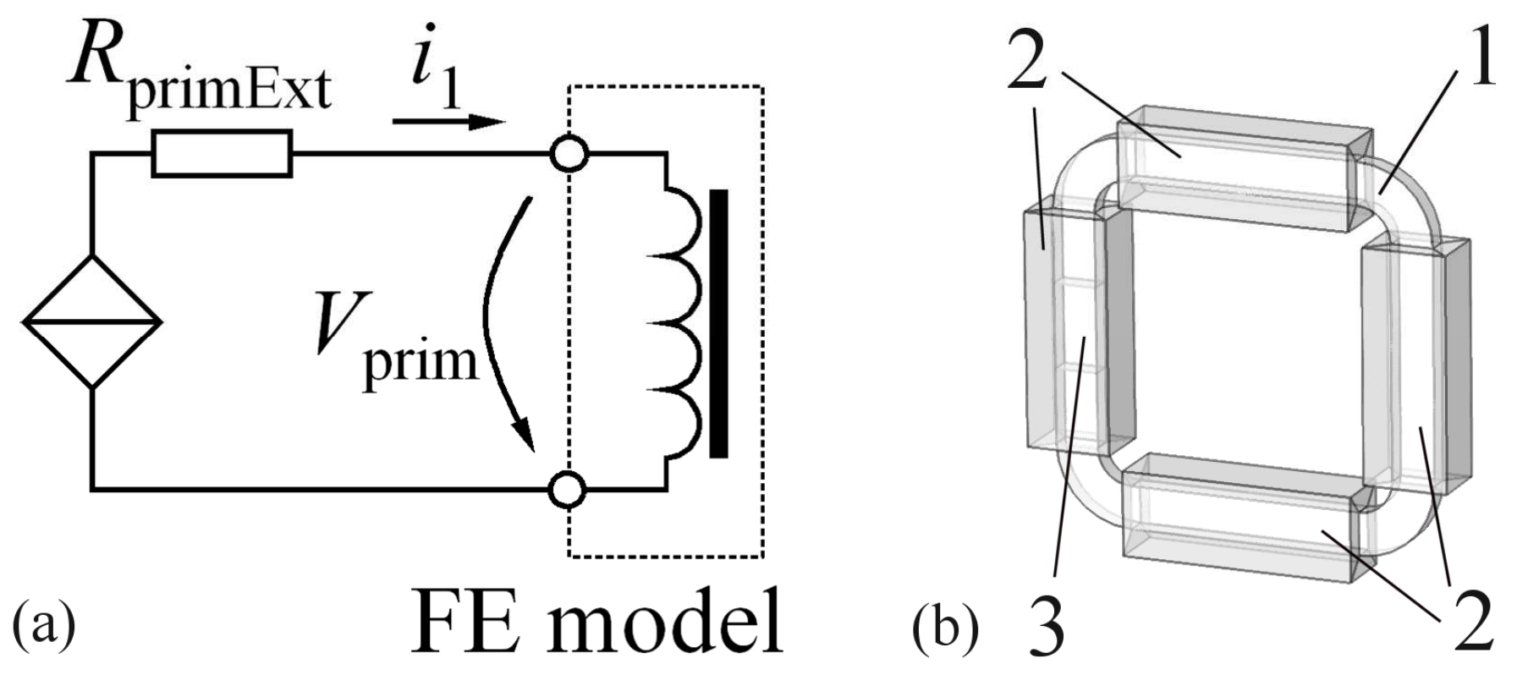

Figure 3: *Transformer model with external circuitry (a) and 3D finite element core model (b)*

Figures 3 and **4** show the parametric 3D and 2D transformer models [1, 2]. An external circuit (a) feeds the finite element model by i_1 (b). For a closed core with a constant cross section area A_c and a mean length of the ferromagnetic path l_c Eqs. (1) and (2) are used to measure the static and dynamic hysteresis between field strength $H(t)$ and flux density $B(t)$:

$$H(t)=\frac{i_1(t)\cdot N_1}{l_c} \qquad (1) \qquad\qquad \Delta B=\frac{1}{N_2 A_c}\int_{t_1}^{t_2} u_2(t)\,\mathrm{d}t \qquad (2)$$

In contrast to measurements, $B(t)$ can directly be derived from the model solution. Therefore, the secondary winding is not modeled.

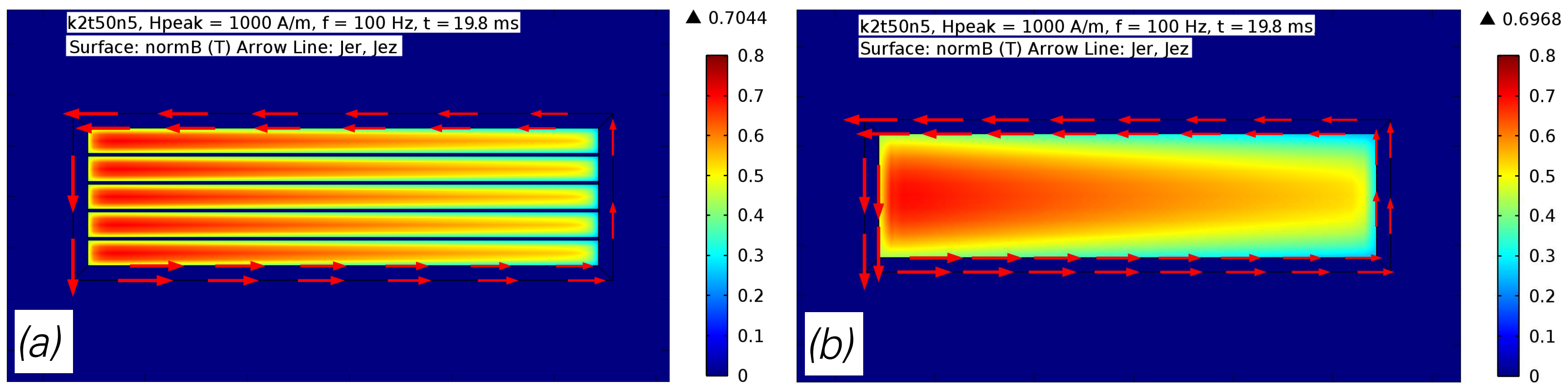

Figure 4: *2D model of a transformer, (a) explicitely modeled sheets and (b) homogenized core using the* K*IWITT approach* [5], *b* = 10 mm, *d* = 0.5 mm, *n* = 5

3 HOMOGENIZATION APPROACHES

In each of the approaches listed in **Table 1**, an orthogonal electrical conductivity $\sigma = [\sigma_x\ \sigma_y\ \sigma_z]$ is proposed to adapt the behavior as desired. The magnetic material behavior is considered in $H(|B|)$ form by piecewise cubic interpolation of the measured static commutation curve.

Table 1: *Homogenization procedures for laminated magnetic cores;* σ_b *isotropic conductivity of the basic material,* n *number of stacked sheets*

SILVA [3] $\sigma_x=\sigma_y=\sigma_b \qquad \sigma_z=0$	HAHNE [4] $\sigma_x=\sigma_y=\sigma_b \qquad \delta_L=\frac{1}{\sqrt{\pi f \sigma \mu}}$ $\sigma_z=\sigma_b\left[\frac{D-2\delta_L}{n(b+d-2\delta_L)-b}\right]$
KIWITT [5] $\sigma_x=\sigma_y=\frac{1}{n^2}\sigma_b \qquad \sigma_z=\sigma_b$	KÜHNER [6] $\sigma_x=\sigma_y=\sigma_b \qquad \sigma_z=\frac{1}{n^2}\sigma_b$
WANG [7] $\sigma_x=\sigma_y=\sigma_b \qquad \sigma_z=\left(\frac{b}{d}\right)^2\sigma_b$	Basic material of the sheets $\sigma_x=\sigma_y=\sigma_z=\sigma_b$

4 SIMULATION RESULTS AND MEASUREMENTS

Figure 5 depicts exemplarily simulated **dynamic hysteresis loops**. The measured dynamic loops were reduced by the static portion of hysteresis for better comparability to simulation results.

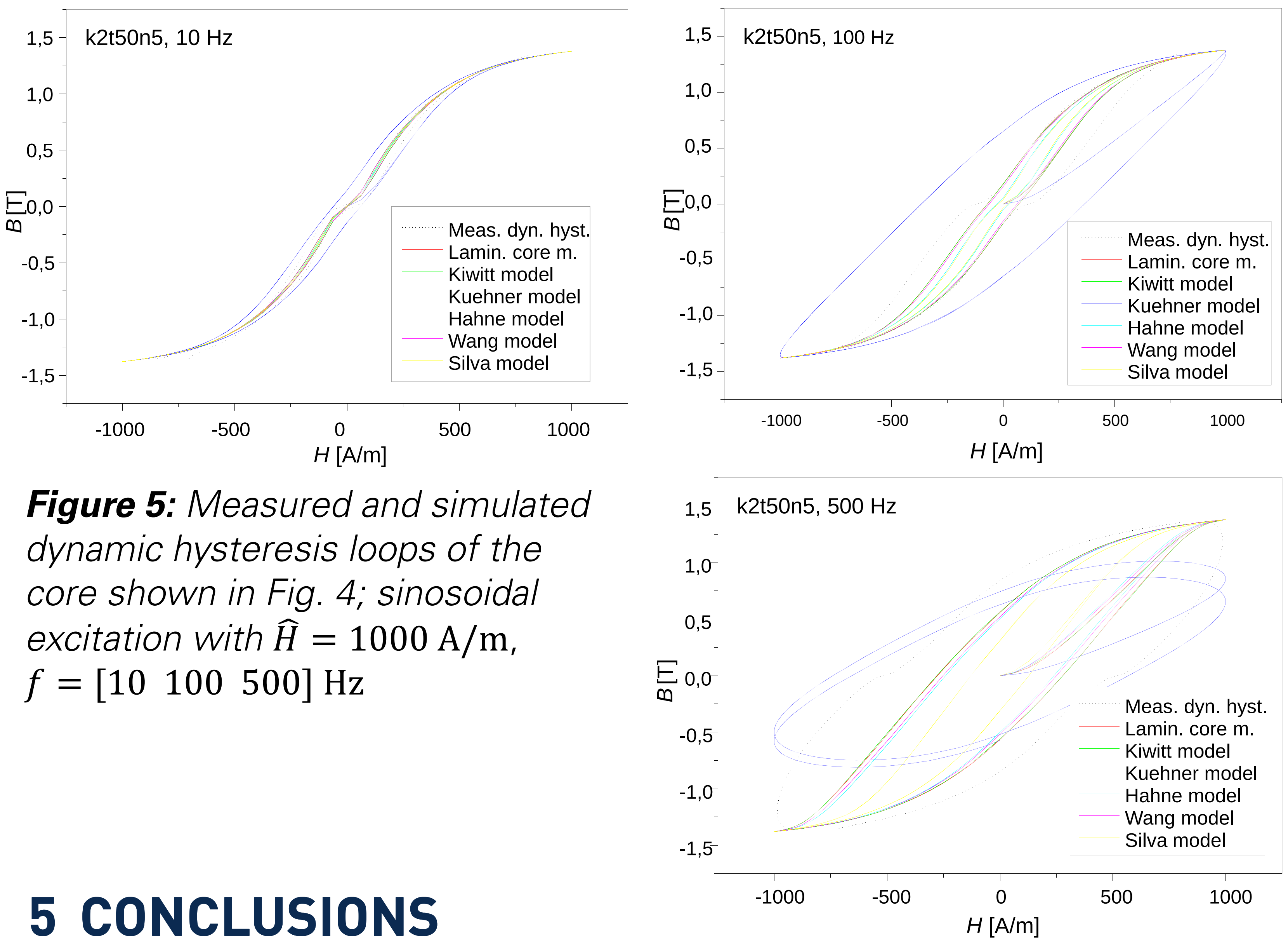

Figure 5: *Measured and simulated dynamic hysteresis loops of the core shown in Fig. 4; sinosoidal excitation with* $\hat{H} = 1000\ \mathrm{A/m}$, $f = [10\ \ 100\ \ 500]\ \mathrm{Hz}$

5 CONCLUSIONS

The KIWITT, HAHNE and WANG model fit best the **dynamic hysteresis loops** calculated with explicitely modeled sheets, even above the critical frequency when the penetration depth falls below the half sheet thickness. The KIWITT model meets best the **dynamic power loss**. The measured dynamic loops are wider than those found with explicitely modeled lamination even if reduced by the static portion of the hysteresis. This is probably caused by considerable residual losses which are not modeled.

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Technische Universität Dresden
Institute of Electromechanical and Electronic Design
D-01062 Dresden
Germany
www.ifte.de

ABB AG
Corporate Research Center Germany
Wallstadter Straße 59
D-68526 Ladenburg
Germany

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