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Faculty of Electrical and Computer Engineering Institute of Electromechanical and Electronic Design

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

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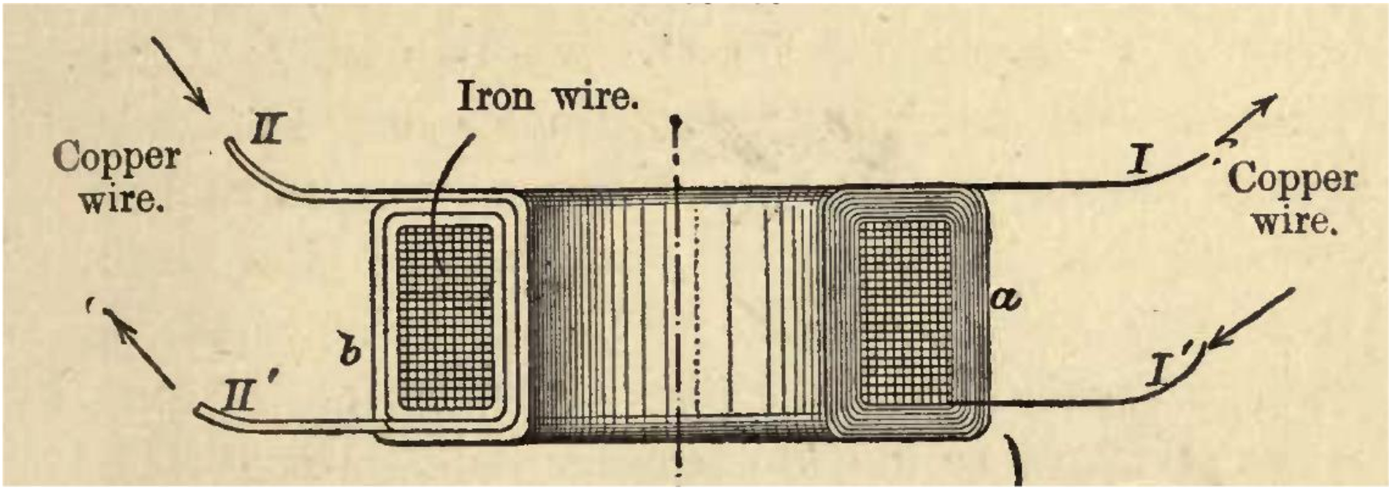
Outline

1. Introduction
2. Homogenization Procedures for Laminated Magnetic Cores
3. Electromagnetic Transformer Model
4. Results from Simulations and Measurements
5. Conclusions

1 Introduction

Laminated magnetic cores

- Stacked electric sheets or strip wound cores
- Used to reduce eddy currents, to minimize the dynamic hysteresis losses in transformers and to improve the dynamics of magnetic actuators



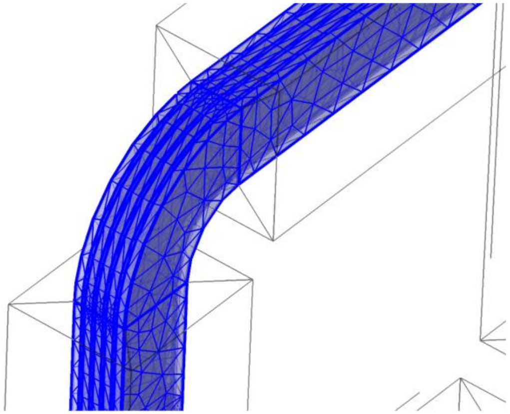
Zipernowsky, Déri, Bláthy, 1885
[F. Uppenborn: History of the transformer 1889]

1 Introduction

Laminated magnetic cores in finite element models

- Thickness of the individual sheets is small as compared to the core thickness
- Modeling explicitly a large number of sheets leads to a large number of elements
- Nonlinear magnetic material or a non-harmonic excitation require simulations in *transient mode*
- *Transition boundary condition* is not applicable between domains in time-dependent studies → insulation layers between the sheets must be modeled

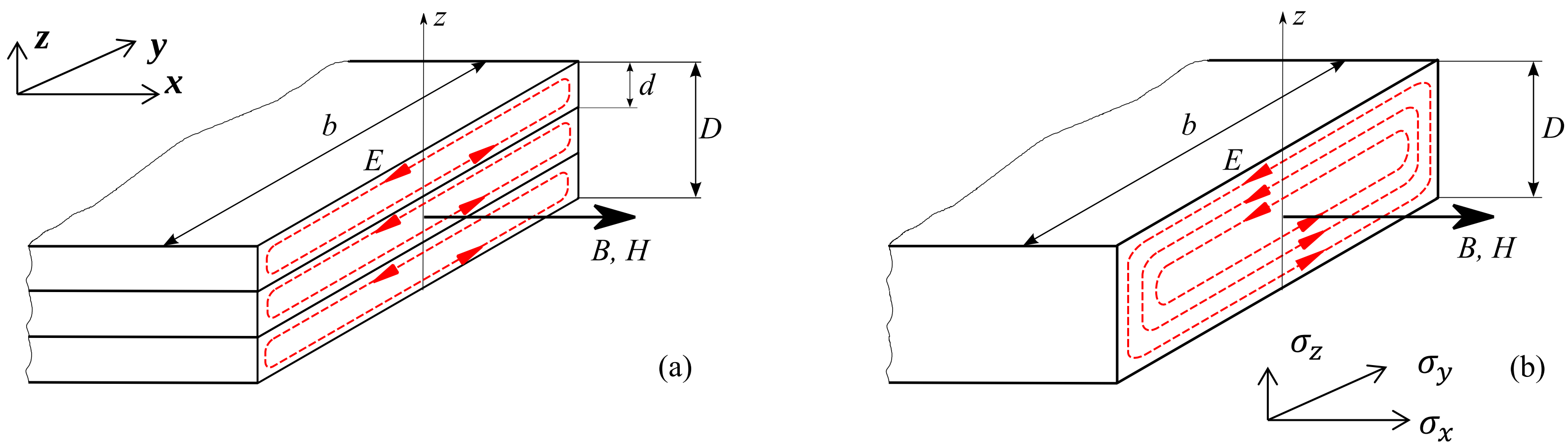
Typical sheet thickness	0.35, 0.5, 0.65, 1.00 mm
Typical insulation thickness	1 … 10 µm



2 Homogenization Procedures

Approach

- Replacing the laminated structure (a) by a single domain of an electrically orthotropic material (b) which exhibits the same macroscopic behavior
- Computational effort can be significantly reduced



2 Homogenization Procedures

σ_b isotropic conductivity of the basic material, n number of stacked sheets

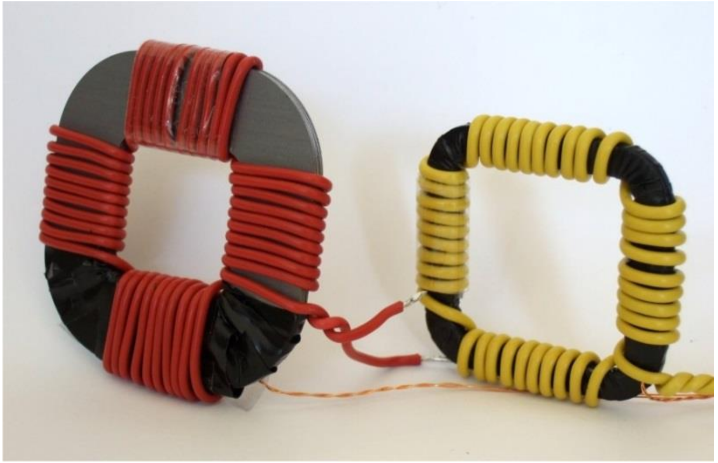
SILVA [1] $\sigma_x = \sigma_y = \sigma_b \qquad \sigma_z = 0$	HAHNE [2] $\sigma_x = \sigma_y = \sigma_b \qquad \delta_L = \frac{1}{\sqrt{\pi f \sigma \mu}}$ $\sigma_z = \sigma_b \left[\frac{D - 2\delta_L}{n(b + d - 2\delta_L) - b}\right]$
KIWITT [3] $\sigma_x = \sigma_y = \frac{1}{n^2}\sigma_b \qquad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

[1] V Silva, G Meunier, A Foggia, IEEE Trans. on Magn. 31 2139-2141 (1995)
[2] P Hahne, R Dietz, B Rieth, T Weiland., IEEE Trans. on Magn. 32 1184-1187 (1996)
[3] JE Kiwitt, A Huber, K Reiß, Electrical Engineering (Archiv für Elektrotechnik) 81 369-374 (1999)
[4] A Kühner, Diss. Univ. Fridericiana Karlsruhe, Fakultät für Elektrotechnik (1999)
[5] J Wang, SL Ho, W Fu, Ch T Kit, M Sun, IEEE Trans. on Magn. 47 1378 -1381 (2011)

3 Electromagnetic Transformer Model

Investigated Transformer Cores

- Overall core dimensions □ 45 … 57 mm
- Core sheet width of 5 … 15 mm
- Core sheet thickness 0.35, 0.5, 0.65 mm
- Closed ferromagnetic path with a mean length of 150 mm
- Core Material M330 and M400
- Secondary coil is closely wound at one leg
- Primary coil is equally distributed over all four legs of the core



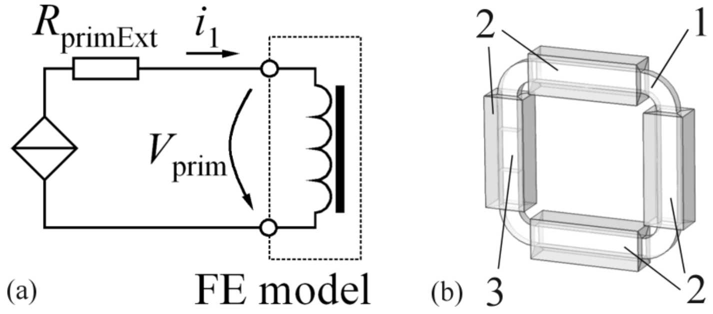
3 Electromagnetic Transformer Model

Finite Element Model

- Parametric 3D and axisymmetric 2D geometries
- *mf* mode used for the transformer model (b)
- Core as sheets with insulating layers between or as solid core
- Coils modeled as homogenized, electrically poorly conductive domains

Circuitry Model

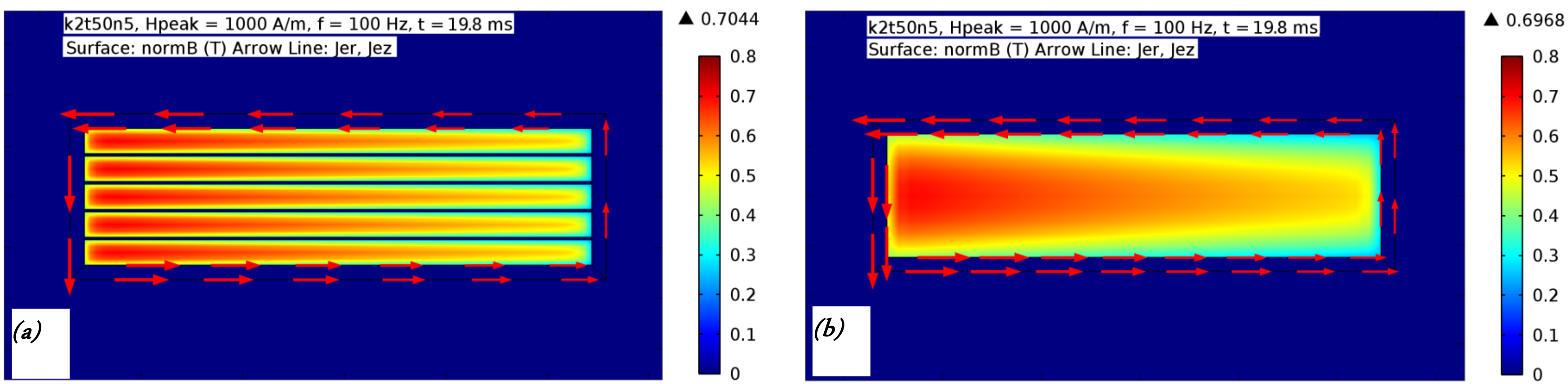
- *cir* mode for the external circuitry
- Bi-directional coupling between transformer model and circuit by using *IvsU* elements



3 Electromagnetic Transformer Model

Time-dependent simulations

- Sinusoidal current excitation with a peak field strength $\hat{H} = 1000\ \mathrm{A/m}$
- Simulation of two periods in a frequency range $f = 10\ \ldots 2000\ \mathrm{Hz}$
- Simulations with
  - a) Explicitely modeled core sheets
  - b) Homogenized core material



4 Results from Simulations and Measurements

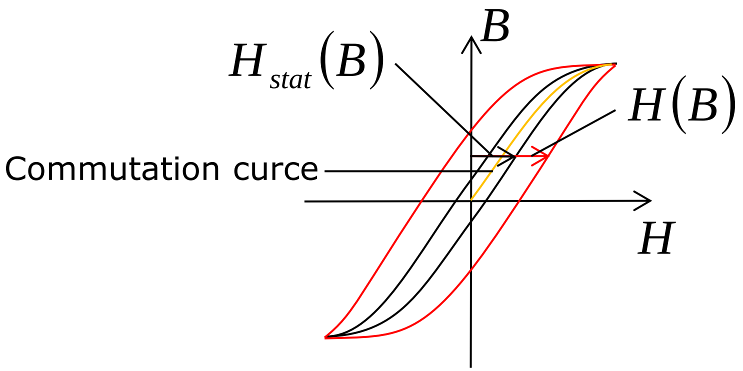
Comparison to simulation results

- Measurement of the static hysteresis and commutation curve
- Flux density $B(t)$ is found by integration of the secondary induced voltage u_2

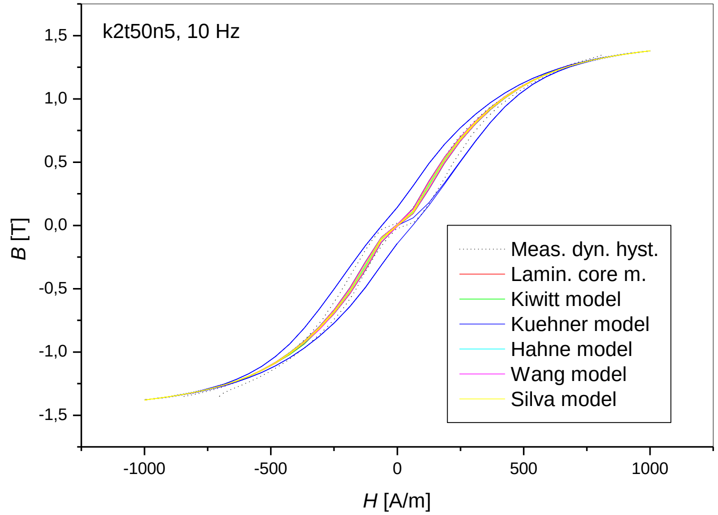
$$\Delta B = \frac{1}{N_2 A_c} \int_{t_1}^{t_2} u_2(t)\,\mathrm{d}t$$

- Consideration of the dynamic part $H_{dyn}(B)$ of the hysteresis from the measured dynamic loops $H(B)$

$$H(B) = H_{stat}(B) + H_{dyn}\left(\frac{\partial B}{\partial t}\right)$$

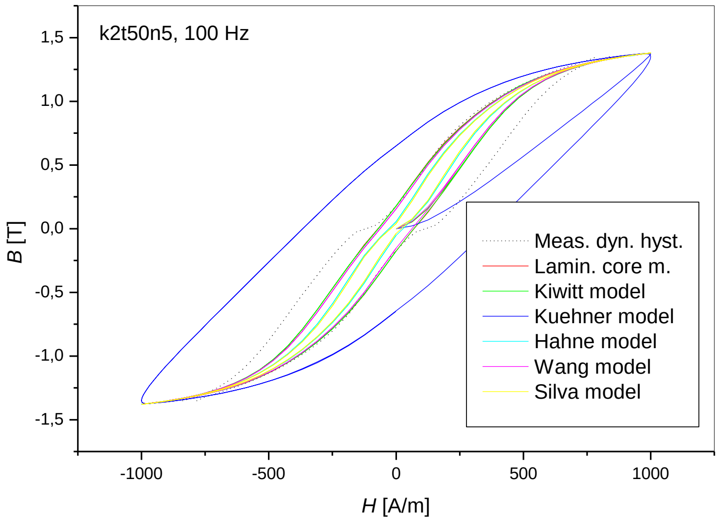


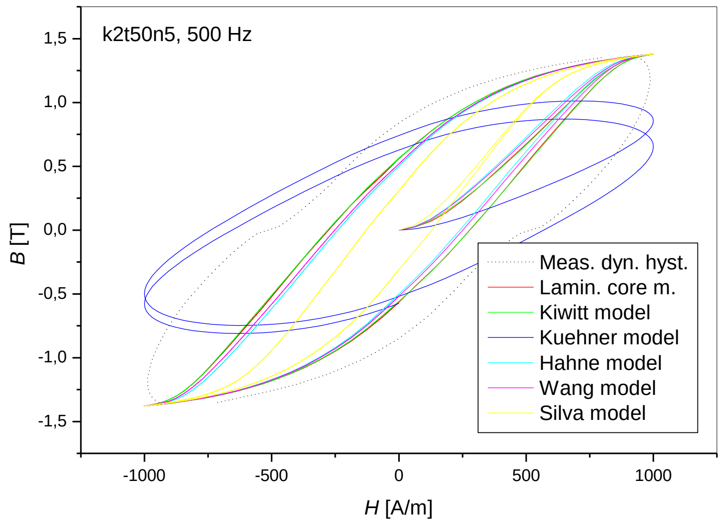
4 Results from Simulations and Measurements



Dynamic hysteresis loops

- Kiwitt, Hahne and Wang model fit best the dynamic hysteresis loops
- Even above the critical frequency when the penetration depth falls below the half sheet thickness
- Measured hysteresises are wider
- Residuel losses not modeled

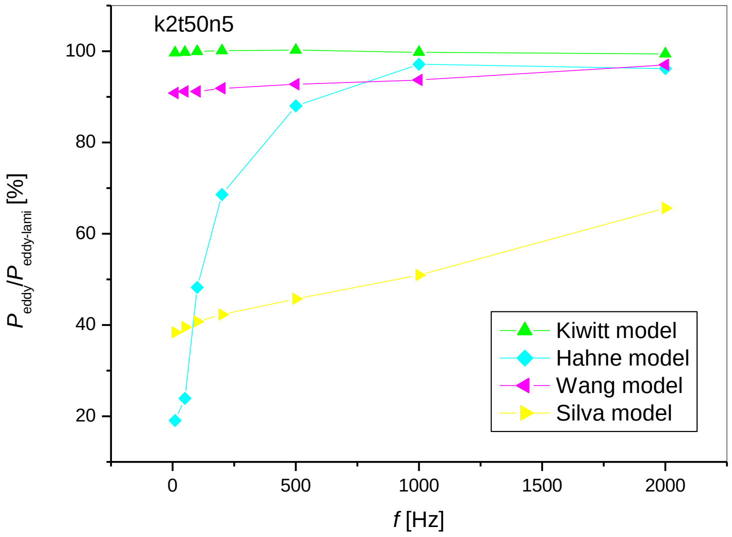




4 Results from Simulations and Measurements

Dynamic losses

- KIWITT model is in good agreement with simulation results from laminated cores



5 Conclusions

- Homogenization approaches for laminated magnetic cores are easy to use in finite element models
- Significant reduction of DoF and allow to analyse laminated magnetic cores in 3D models
- The KIWITT homogenization approach fits best the results from models with laminated cores in the investigated parameter range
- The measurements are in sufficient agreement with the laminated models
- For a final evaluation, a larger parameter space has to be involved
- Alternative modeling approaches using a flux rate dependent term will be investigated in the future

Thank you very much
for your attention.