Comparison of Different 1-D Models for the Calculation of Magnetization Dynamics in Non-Oriented Soft Magnetic Steel Sheets

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This paper presents the comparison of different 1-D nonlinear dynamic models of non-oriented soft magnetic steel sheets (SMSSs). The discussed models take into account dynamic effects on magnetization due to eddy currents and hysteresis inside such sheets and differ in the way the coupled Maxwell equations with hysteresis are solved. Finite-difference and finite-element approaches are used to solve the strongly coupled problem. In contrast to this, an alternative modelling approach is based on Ampere's and Faraday's laws, where a system of ordinary differential equations is obtained when using adequate discretization. The different modelling approaches are analysed and compared in terms of mathematical structure, implementation work, spatial discretization and accuracy.

***Index Terms*— dynamic modeling, eddy currents, finite-differences method, finite-element method, magnetic hysteresis, power loss**

I. Introduction

Non-oriented soft magnetic materials are widely used as a basic constituent of rotating electrical machines and exhibit complex properties such as saturation and dynamic hysteresis. Modelling of iron losses and transients in laminated structure is of critical importance for designers of electrical machines and transformers. The behaviour of ferromagnetic cores that are operating under distorted flux waveforms is the result of several intertwined phenomena: eddy currents, skin effect, saturation and hysteresis. This interdependence cannot be solved without a strongly coupled model of diffusion equation. First numerical solutions to the penetration equation have been obtained using the finite-difference (FD) method using compact or non-compact stencils [1-3]. In contrast to this, the finite-element (FE) method allows to consider the distributed nature of the time derivative over some spatial domain [3, 4]. However, solving the fully coupled problem using FD- or FE-scheme considering rate-dependent or rate-independent hysteresis requires tedious implementation work. Furthermore, its direct coupling to external circuits is an intricate task. Alternatively the magnetic field and eddy current distributions inside a lamination can be solved using the parametric magneto-dynamic model (PMD) [5, 6], where the diffusion phenomena are effectively solved based on a simple matrix differential equation.

This paper presents a comparative analysis of the PMD model and the FE- and FD-solutions in terms of mathematical structure, implementation, computational performance, accuracy and spatial discretization. To couple the magnetic field and magnetic flux density an inverse static hysteresis model is used [7, 8].

II. Theoretical Background

Measured quantities in Epstein frames are currents and fluxes related to the magnetic field at the surface of the lamination and the average magnetic flux density across the lamination thickness. Symmetries of the measurement tools and the geometry of the sample facilitate to work with a 1-D formulation of the eddy current problem (1).

$$\sigma \frac{\partial \mathbf{B}}{\partial t} = \frac{\partial^2 \mathbf{H}}{\partial z^2} \qquad (1)$$

Considering a lamination of thickness d with an upper surface normal vector $\mathbf{n} = (0, 0, 1)$, the domain of analysis is a line parallel to $\mathbf{n}$, across half the thickness. A static hysteresis model yields the constitutive relation between $\mathbf{B}$ and $\mathbf{H}$.

A. Static Hysteresis Model

The considered description is an inverse modified Jiles-Atherton static, rate-independent hysteresis model. The model is formulated in terms of an ODE supplemented with a number of auxiliary non-linear relationships [7, 8].

B. Finite-Differences Modelling Approach

The simplest FD-scheme to solve (1) is a second-order scheme based on the central difference approximation [1, 2] linking the magnetic field and flux density of the internal nodes of the FD-grid along the line. Together with the required boundary conditions this leads to the FD approximation of the diffusion problem, which is compatible with the ODEs of an external electrical circuit. Voltage- or current-driven versions can be introduced using prescribed Dirichlet or Neumann boundary conditions [2].

C. Finite-Element Modelling Approach

Using the FE method (1) can be formulated in terms of the magnetic field intensity or in terms of the magnetic vector potential to cover different types of excitation (voltage- or current-driven) [4]. Resulting PDEs with appropriate boundary conditions can be solved by the Galerkin method and a time-stepping scheme. The boundary value problem originating from the **A**-field formulation inherits one major difficulty, namely that the hysteresis is considered in terms of the magnetic reluctivity and hence in the stiffness matrix exacerbating the introduction of the differential reluctivity.

D. Parametric Magneto-Dynamic Model

Based on average values of magnetic variables inside individual slices of the SMSS and Faraday's law, induced eddy currents i_{es} inside all the slices can be calculated, which directly affect the excitation of magnetic field inside the SMSS. Considering this fact by expressing the equilibriums of magneto-motive forces (mmfs) in all the slices of the SMSS using Ampere's law, the eddy currents calculation can be eliminated [5, 6]. Finally, the PMD is expressed in form of a simple matrix differential equation (2)

$$\mathbf{\Theta} = \mathbf{N} i_{\mathrm{p}} = \bar{\mathbf{H}}\left(\bar{\mathbf{\Phi}}\right) l_{\mathrm{m}} + \mathbf{L}_{\mathrm{m}} \frac{\mathrm{d}\bar{\mathbf{\Phi}}}{\mathrm{d}t} = \mathbf{R}_{\mathrm{m}} \bar{\mathbf{\Phi}} + \mathbf{L}_{\mathrm{m}} \frac{\mathrm{d}\bar{\mathbf{\Phi}}}{\mathrm{d}t}. \quad (2)$$

In (4) $\mathbf{\Theta}$ represents a vector of the mmfs generated by the applied current i_{p} in the excitation winding, $\bar{\mathbf{H}}\left(\bar{\mathbf{\Phi}}\right)$ is a vector of average magnetic field strengths as hysteretic functions of the average magnetic fluxes in the slices and l_{m} is magnetic path length. $\mathbf{N}$ is a vector with number of turns of the excitation winding, $\mathbf{R}_{\mathrm{m}}$ is a vector of non-linear reluctances due to the static hysteresis and $\mathbf{L}_{\mathrm{m}}$ is the linear magnetic inductance matrix due to induced eddy currents inside each slice [5, 6]. The presented PMD can be both current and voltage driven, where the magnetic equation (2) can be coupled with an external excitation circuit calculating induced voltage u_{i} in the excitation winding by (3)

$$u_{\mathrm{i}} = -N \frac{\mathrm{d}\Phi_{\mathrm{m}}(\Theta)}{\mathrm{d}t} = -\frac{A_{\mathrm{Fe}}}{N_{\mathrm{s}}} \mathbf{N}^{\mathrm{T}} \frac{\mathrm{d}\bar{\mathbf{B}}}{\mathrm{d}t}. \quad (3)$$

III. Results

Discussed models were implemented, evaluated and compared using the software package Matlab/Simulink. Due to spatial limitations only results for the PMD model are shown. Fig. 1 and Fig. 2 show the time dependence of magnetic flux densities B_{s} and magnetic field strengths H_{s} for a coarse ($N_{\mathrm{s}} = 3$, Fig. 1) and fine discretization ($N_{\mathrm{s}} = 7$, Fig. 2) for sinusoidal voltage excitation of 1000 Hz. Corresponding dynamic hysteresis loops along with measured and static hysteresis loops are presented in Fig. 3.

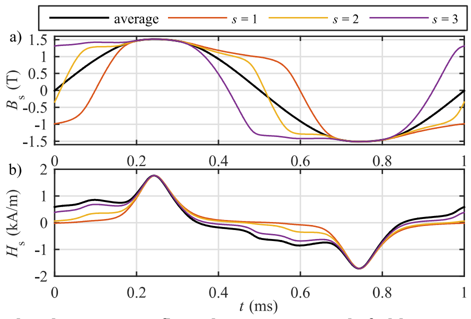

Fig. 1. Calculated magnetic flux densities B_{s} and field strengths H_{s} in individual slices along with the average magnetic flux density B_{m} and surface magnetic field strengths H_0 using $N_{\mathrm{s}} = 3$ slices.

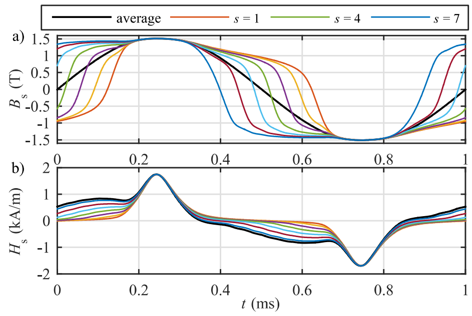

Fig. 2. Calculated magnetic flux densities B_{s} and field strengths H_{s} in individual slices along with the average magnetic flux density B_{m} and surface magnetic field strengths H_0 using $N_{\mathrm{s}} = 7$ slices.

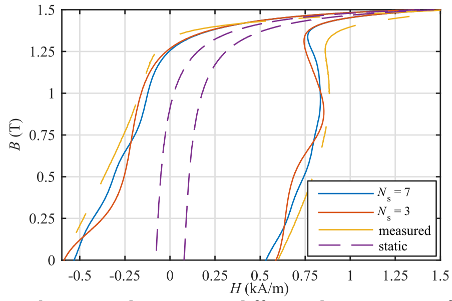

Fig. 3. Dynamic hysteresis loops using different discretization of the SMSS ($N_{\mathrm{s}} = 3$ and $N_{\mathrm{s}} = 7$ slices) along with measured and static hysteresis loops for sinusoidal voltage excitation.

IV. Conclusion

This paper presents a profound insight in the various methods to solve the strongly coupled diffusion problem and gives comparisons to measured data. The full paper will present the details of the implementation and the comprehensive analysis of the different methods. The PMD model offers the sought for flexibility to include various hysteresis models and simplifies the intricate task coupling the lamination model to external circuits.

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