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EFFECTS OF SATURATION AND HYSTERESIS ON MAGNETIZATION DYNAMICS: ANALYSIS OF DIFFERENT MATERIAL MODELS

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***Abstract* – In this paper effects of material saturation and magnetic hysteresis on magnetization dynamics in non-oriented soft magnetic steel sheets are analysed. In the analysis four different models for description of the static material characteristic are used, which describe the material with increasing accuracy. The resulting magneto-dynamic model using different static models is analysed over a wide frequency range from quasi-static to $f = 1000$ Hz and for different induction levels up to $B_{max} = 1.5$ T. The adequacy of use of different static material models at different frequency and magnetic flux density levels are discussed in detail, whereas the influence on the dynamic behaviour and power losses are analysed.**

I. INTRODUCTION

The magnetization dynamics in long and thin non-oriented (NO) soft magnetic steel sheets (SMSS) with predominately small domains can be in many cases adequately described using an 1-D quasi static approximation of the magnetic phenomena inside the SMSS [1], [2]. Traditionally, this approximation is described by the well-known 1-D Maxwell penetration equation, which links the magnetic field strength H and the magnetic flux density B in a homogeneous SMSS [1], [2]. This equation is, however, rather cumbersome to numerically implement. Alternatively the magnetization dynamics can be described using the magneto-dynamic model of SMSS presented in [3].

The aim of this paper is to analyse the effects of different static material models on the behaviour and accuracy of the magneto-dynamic model presented in [3]. Four different static material models are evaluated over a wide range from quasi-static to $f = 1000$ Hz at different magnetic flux density levels up to $B_{max} = 1.5$ T, where the effects of saturation, non-linearity and magnetic hysteresis on dynamic magnetization are studied.

II. THEORETICAL BACKGROUND

Using the magneto-dynamic model, the magnetic field distribution inside an SMSS is described piece-wise uniformly across the SMSS thickness by dividing the SMSS into several slices s. The magnetic field inside individual slices can be treated as uniform when the SMSS is divided into adequate number of slices N_s. The first slice ($s = 1$) is assumed to be in the center and last slice ($s = N_s$) close to the surface of the SMMS [3]. The magnetic field inside the SMSS is descibed with a coupled system of differential equations for all slices s in matrix form (1), where $\mathbf{N} = N\left[1\right]_{N_s \times 1}$ represents a vector composed of N the number of excitation winding turns, i is the current in the excitation winding, $\bar{\mathbf{H}}(\bar{\mathbf{\Phi}})$ is a vector of magnetic field strengths as, e.g., linear, non-linear or hysteresis functions of the magnetic flux of individual slices, l_m is the mean magnetic path length and $\mathbf{L}_m$ represents the so called linear magnetic inductance matrix of the SMSS.

$$\mathbf{N}i = \bar{\mathbf{H}}(\bar{\mathbf{\Phi}})l_m + \mathbf{L}_m \frac{\mathrm{d}\bar{\mathbf{\Phi}}}{\mathrm{d}t} \qquad (1)$$

The coupling with the external excitation winding completes the average magnetic flux Φ_m inside the SMSS according to (2), where u_i is the induced voltage in the excitation winding, A_{Fe} is the effective cross section of the SMSS and $\bar{\mathbf{\Phi}}$ represents a vector of average values of magnetic fluxes inside individual slices in the SMSS.

$$u_i = -N\frac{\mathrm{d}\Phi_m\left(\Theta\right)}{\mathrm{d}t} = -\mathbf{N}^T\frac{\mathrm{d}\bar{\mathbf{\Phi}}}{\mathrm{d}t} \qquad (2)$$

The relationships $H(B)$ for individual slices s can be calculated using an arbitrary material model. In this work four different material models with increasing accuracy are used and evaluated:

1. linear, purely reversible material model, where $H(B) = B/(\mu_0\mu_r)$ with μ_r = const.,
2. piecewise linear material model based on linear model including saturation region with $\mu_r = 1$,
3. non-linear $H(B)$ characteristic based on measurements, and
4. hysteresis model proposed by Tellinen [4], based on measurements.

III. RESULTS

The discussed magneto-dynamic model was validated by comparing calculated and measured major and symmetrical minor dynamic hysteresis loops for a M400-50A NO steel. The experimental results for the presented evaluation were carried out on an Epstein frame, which was incorporated into an accurate computer controlled system. The SMSS sample was characterized using controlled sinusoidal magnetic flux density with a form factor error of less than 1% in the frequency range from quasi-static to 1000 Hz. The static material models were characterised using measurements results for the M400-50A NO steel.

Dynamic magnetizations were calculated dividing the SMSS into 10 slices ($N_s = 10$) with the specific electrical conductivity $\sigma = 2.16 \cdot 10^6$ S/m. Fig. 1 shows the comparison of magnetization dynamics in the magneto-dynamic model when using different static material models. In the full paper the adequacy of use of different static material models at different frequency and magnetic flux density levels are discussed in detail, whereas also power losses for each case are analysed.

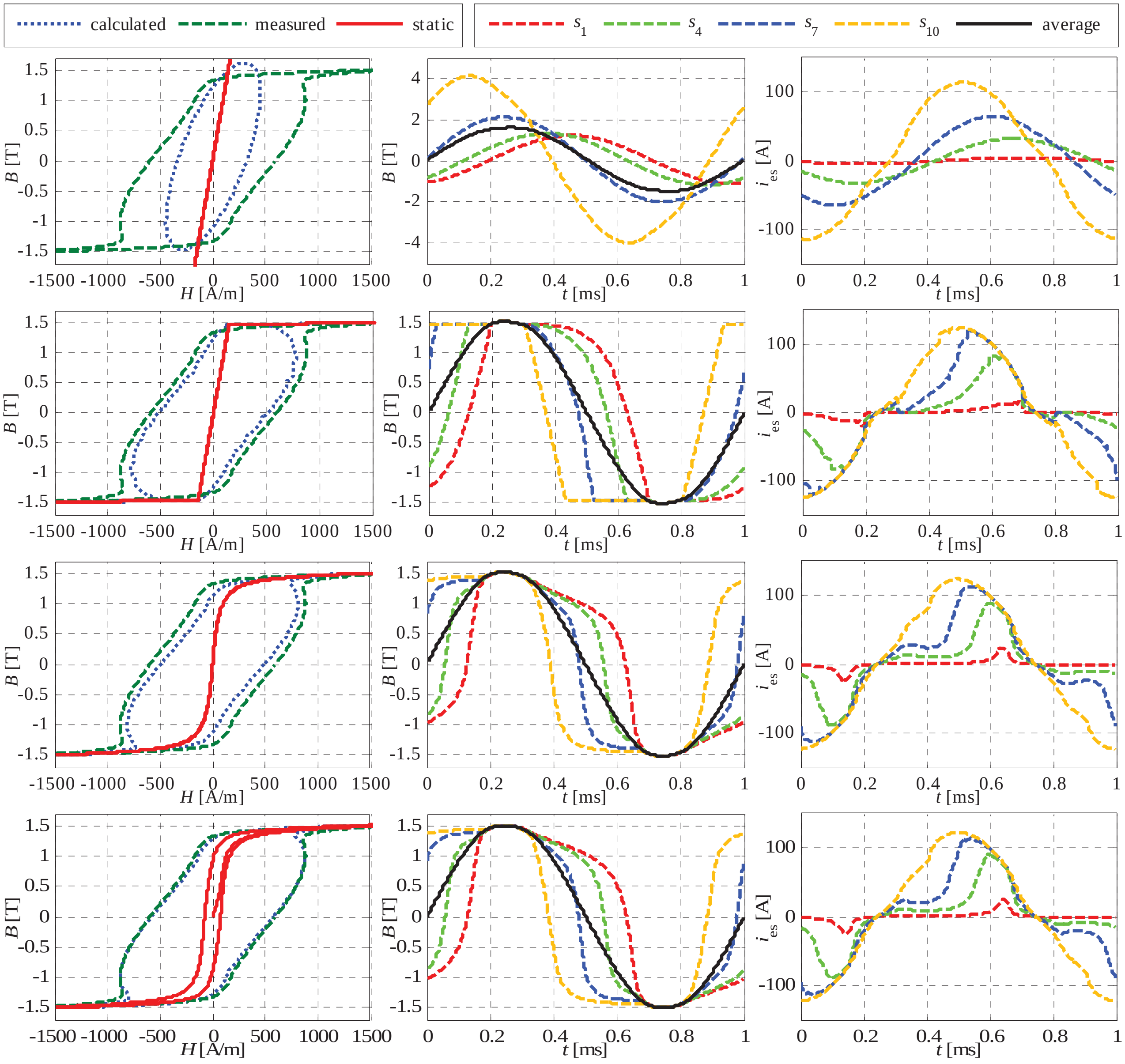

Fig.1. Comparison of influence of different material models on magnetization dynamics in a M400-50A NO SMSS for $f = 1000$ Hz and $B_{max} = 1.5$ T: first row – linear $H(B)$ characteristic, second row – piecewise linear $H(B)$ characteristic including saturation, third row – non-linear $H(B)$ characteristic, and fourth row – hysteretic $H(B)$ characteristic. First column shows the comparison between the measured and calculated dynamic hysteresis loops and used static $H(B)$ characteristic, whereas second and third columns show corresponding flux densities B_s and eddy currents i_{es} in slices $s = 1, 4, 7$, and 10.

REFERENCES

[1] S.E. Zirka, Y.I. Moroz, P. Marketos, A.J. Moses, D.C. Jiles, and T. Matsuo, "Generalization of the Classical Method for Calculating Dynamic Hysteresis Loops in Grain-Oriented Electrical Steels," *IEEE Trans. Magn.*, vol.44, no.9, pp.2113-2126, Sept. 2008

[2] S.E. Zirka, Y.I. Moroz, P. Marketos, and A.J. Moses, "Viscosity-based magnetodynamic model of soft magnetic materials," *IEEE Trans. Magn.*, vol.42, no.9, pp.2121-2132, Sept. 2006

[3] M. Petrun, V. Podlogar, S. Steentjes, K. Hameyer, and D. Dolinar, " A Parametric Magneto-Dynamic Model of Soft Magnetic Steel Sheets," *IEEE Trans. Magn.*, vol.50, no.4, to be published, April 2014

[4] J. Tellinen, "A Simple Scalar Model for Magnetic Hysteresis," *IEEE Trans. Magn.*, vol.34, no.4, pp.2200-2206, Jul. 1998