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CV-8 Power Loss Calculation Using the Parametric Magneto-dynamic Model of SMSSs

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Introduction

To describe the electromagnetic phenomena inside a thin non-oriented (NO) soft magnetic steel sheet (SMSS) with predominately small magnetic domains, eddy currents are modeled parallel to the surface of the SMSS [1]. This problem is usually solved by using the well-known 1-D Maxwell penetration equation, which links the magnetic field strength H and the magnetic flux density B in a homogenous SMSS [1], [2]. Solving the penetration equation is however complicated, limited to certain hysteresis models, and requires numerically intensive solving methods (e.g. finite differences). Alternatively the magnetic field and eddy current distributions inside such a SMSS can be solved using the parametric magneto-dynamic model presented in [3]. The discussed magneto-dynamic model is very promising due its simplicity, parametric basis, flexibility and computational efficiency. The model is voltage driven and can be also used as a part of a circuit and can predict arbitrary transient states. The aim of this work is however to present and evaluate the calculation of eddy current and hysteresis power loss using the discussed magneto-dynamic model.

Parametric Magneto-dynamic model

The influence of eddy currents on the magnetic field distribution in a conducting soft magnetic material is described by dividing the steel sheet into several virtual slices N_s. When dividing the SMSS into an adequate number of slices N_s, the magnetic field inside the individual slices s can be treated as uniform and the magnetic field distribution across the SMSS thickness can be described piece-wise uniformly. Based on Ampere's Law, the equilibriums of magnetomotive forces in the slices of the SMSS can be expressed for all slices in matrix form with (1),

$$\Theta = \mathbf{N}\, i = \mathbf{H}(\Phi)\, l_m + \mathbf{L}_m (\mathrm{d}\Phi/\mathrm{d}t);\ \mathbf{N} = N\,[1]_{Ns\times 1} \quad (1)$$

where $\mathbf{L}_m$ represents the so-called linear magnetic tensor inductance matrix, l_m is the mean magnetic length, N is the vector of excitation winding turns N, Φ is a vector of magnetic fluxes in the slices, $\mathbf{H}$ is a vector of field strengths as nonlinear functions of the fluxes in the slices, and i is current in the excitation winding. The coupling with the external electrical circuit completes the relation (2), where the induced voltage u_i in the excitation winding is calculated and A_{Fe} represents the cross section of the SMSS.

$$u_i = -\mathbf{N}^T (A_{Fe}/N_s)(\mathrm{d}\mathbf{B}/\mathrm{d}t) \quad (2)$$

The nonlinear relationships for individual slices can be calculated using an arbitrary static hysteresis model. In this work the hysteresis model proposed by Tellinen [4] was implemented.

Power loss calculation

With the presented magneto-dynamic model not only arbitrary transient states but also the power loss distribution inside a SMSS can be calculated. The time behavior of power due to hysteresis effects and eddy currents in each individual slice of the SMSS can be calculated. The power losses due to eddy currents p_{es} can be calculated based on the current densities j_s in individual slices s using (3), where a represents the width, b the thickness and σ the specific conductivity of the SMSS.

$$p_{es}(t) = 2 a l_m/\sigma \int_{(s-1)b/(2Ns)}^{sb/(2Ns)} j^2_{es}(x)\,\mathrm{d}x$$

$$= 2\sigma\, a l_m (b/(2N_s))^3 \Big[\Big(\sum_{i=1}^{(s-1)} (\mathrm{dB}_i/\mathrm{d}t)\Big)^2 + \Big(\sum_{i=1}^{(s-1)} (\mathrm{dB}_i/\mathrm{d}t)\Big)(\mathrm{dB}_s/\mathrm{d}t) + 1/3(\mathrm{dB}_s/\mathrm{d}t)^2\Big] \quad (3)$$

The total power losses due to eddy currents P_e in the SMSS from time t_1 to time t_2 can be calculated with (4)

$$P_e = 1/(t_2 - t_1) \int_{t1}^{t2} \sum_{i=1}^{Ns} p_{es}(t)\,\mathrm{d}t \quad (4)$$

The power due to static hysteresis p_{hs} in individual slices s can be calculated with (5)

$$p_{hs}(t) = abl_m H_s (\mathrm{dB}_s/\mathrm{d}t), \quad (5)$$

and the corresponding total power due to hysteresis P_h can be calculated with (6)

$$P_h = 1/(t_2 - t_1) \int_{t1}^{t2} \sum_{i=1}^{Ns} p_{hs}(t)\,\mathrm{d}t\ . \quad (6)$$

Results

The discussed magneto-dynamic model was validated by comparing the calculated and measured major and symmetrical minor dynamic hysteresis loops for various NO steels. 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. In this digest the results for M400-50A SMSS samples are presented. In Fig. 1 the calculated time behavior of powers due to eddy currents and due to static hysteresis in individual slices for frequency f =1000 Hz and B_{max}=1.5 T are presented.

In Fig. 2a the comparison between the calculated and measured total power losses of one period for different frequencies and amplitudes of maximal flux densities B_{max} is shown. The calculated results show good agreement with the measurements. Figures 2b and 2c show calculated components of eddy current losses P_e and hysteresis losses P_h in the discussed SMSS.

In the full paper the basis for the calculation of power losses will be presented and discussed in detail. The calculated results will be evaluated and validated using different samples of NO SMSS.

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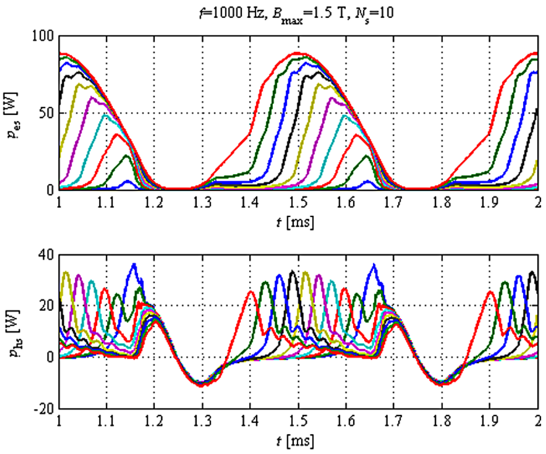

Fig. 1: Calculated time behavior of powers due to eddy currents and due to static hysteresis in individual slices

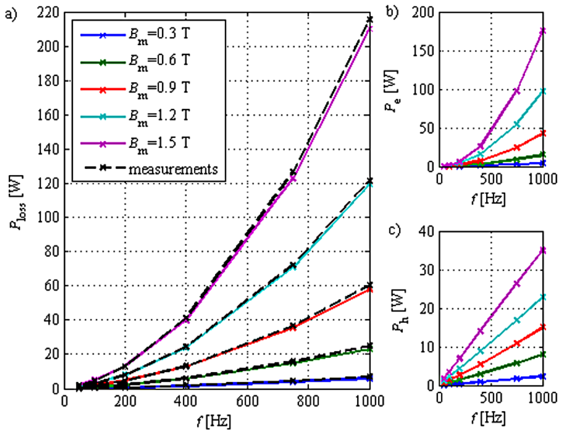

Fig. 2: Measured and calculated power losses for a M400-50A NO SMSS