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Rate-dependent extensions of the parametric magneto-dynamic model with magnetic hysteresis

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This paper extends the parametric magneto-dynamic model of soft magnetic steel sheets to account for the phase shift between local magnetic flux density and magnetic field strength. This phase shift originates from the damped motion of domain walls and is strongly dependent on the microstructure of the material. In this regard, two different approaches to include the rate-dependent effects are investigated: a purely phenomenological, mathematical approach and a physical-based one. [http://dx.doi.org/10.1063/1.4975996]

I. INTRODUCTION

Soft magnetic steel sheets (SMSSs) are due to their technical as well as economical properties indispensable in many contemporary electrical devices. Their widespread use requires adequate modelling of magnetization processes inside SMSSs. Especially for the use in applied engineering, such models should be adequately simple, whereas the magnetization processes should be described as accurate as possible. These two goals are in general very difficult to realize in the modelling process due to complex magnetization processes inside SMSSs. Such processes include hysteresis and non-linear skin effect due to macro- and microscopic eddy currents. Therefore, the accurate description of magnetization processes in SMSSs remains a largely unsolved physical and engineering problem.[1]

Contemporary models for applied engineering are mostly based on a simplified one-dimensional description that takes into account the macroscopic eddy currents. Such description is suitable for thin and long SMSSs, where the simulation of the magnetization process is reduced to the solution of the well-known diffusion equation. This description links the magnitudes of the magnetic field strength **H** and magnetic flux density **B** in a material with conductivity σ. Due to highly non-linear and hysteretic relation between **H** and **B**, the discussed description can be solved by applying various approaches, whereas most require spatial discretization of the observed SMSS.[2] One of the recent approaches is represented by the parametric magneto-dynamic (PMD) model. Using the PMD model in combination with a static, rate-independent hysteresis model the diffusion problem can be solved effectively, whereas the model is based on sound physical background.[2–4] The PMD is especially convenient when the lamination model has to be incorporated into an electric circuit such as, e.g., for the simulation of dc-dc converters. Both field- and flux-driven versions exist.[2–4]

However, all approaches that solve the discussed diffusion problem underestimate the magnetization dynamics and consequently the total power loss, especially when modeling materials with a coarser-grained structure. This underestimation originates from not considering microscopic eddy currents around moving domain walls in the original problem description. These eddy currents can become unacceptably large and lead to a lag in the flux density **B** behind the applied field **H**.[5] This phenomenon can be taken into account by extending the PMD model using two different approaches. As the discussed process resembles a viscous-like friction, it can be accounted for in the PMD model by introducing the notion of the "fast" magnetic viscosity similar to the Landau-Lifshitz-Gilbert equation for magnetic viscosity.[6,7] Alternatively also the rate-dependent model[8] can be applied.

The aim of this paper is to present and analyze both versions of the upgraded PMD model that appear to be more versatile than existing models. Both discussed extended model versions significantly increase the prediction of the dynamic magnetization as well as total losses under arbitrary magnetizing conditions. The model parameters are thought to be material dependent so it is reasoned that the model can be used to accurately predict losses in a wide range of materials magnetized under sinusoidal as well as non-sinusoidal flux waveforms.

II. THEORETICAL BACKGROUND

The PMD model bases on the average values of magnetic variables inside individual slices (flux tubes) of the SMSS, which allows taking into account the distribution of the induced eddy currents inside all the slices and their influence on the excitation of magnetic field inside the SMSS. The PMD is expressed in the form of a matrix differential equation (1), where $\mathbf{\Theta}$ represents a vector of the magneto-motive forces 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 $\mathbf{N}$ is a vector with the number of turns n_p of the excitation winding.

$$\mathbf{\Theta} = \mathbf{N} i_\mathrm{p} = \bar{\mathbf{H}}(\bar{\mathbf{\Phi}}) l_\mathrm{m} + \mathbf{L}_\mathrm{m} \frac{\mathrm{d}\bar{\mathbf{\Phi}}}{\mathrm{d}t}. \tag{1}$$

The matrix of magnetic inductance $\mathbf{L}_\mathrm{m}$ depends only on the geometric, material properties and on the discretization of the observed SMSS, i.e., the number of slices N. Magnetic hysteresis enters into the PMD in the constitutive relation. In this paper the static hysteresis is considered using the Tellinen hysteresis model.

The microscopic eddy currents are, however, generated by movement of domain walls when SMSSs are exposed to dynamic magnetizing fields. These currents generate additional losses as well as influence the dynamic magnetization processes inside SMSSs. Additionally, there are a number of other mechanisms responsible for the excess loss. As a result, the observed dynamic hysteresis loops are additionally inflated. Consequently all adequate classical eddy current models typically underestimate the dynamic loops as well as total power loss inside SMSSs. This deficit is therefore addressed using one of the so called excess field extension of the discussed classical eddy current models.

A. Magnetic viscosity

The lag in the flux density B behind the applied field H caused by the discussed microscopic phenomena can be effectively solved by adding the so-called magnetic viscosity, described by (2),

$$H(t) = H_\mathrm{h}(B) + \delta \left| \left(R_\mathrm{m} \left(1 + \frac{B^2}{B_\mathrm{s}^2} \right) \right)^{-1} \frac{\mathrm{d}B(t)}{\mathrm{d}t} \right|^{1/\alpha} \tag{2}$$

where $H_\mathrm{h}(B)$ represents the magnetic field strength due to the static hysteresis, $\mathrm{d}B/\mathrm{d}t$ is the change rate of the magnetic flux density B, δ is a directional variable, whereas R_m, B_s and α are model parameters.[6,7] The presented description is similar to the Landau-Lifshitz-Gilbert equation for magnetic viscosity.[6,7] Main advantages of the proposed model are that it provides an integral description of the complex phenomena of underlying excess loss and does not contradict their complex underlying physics. Furthermore, it is also very flexible and can adequately describe the excess component in non-oriented as well as grain oriented SMSSs.

B. Rate-dependent extension

The rate-dependent extension was originally developed for homogenized and comprehensive description of all dynamic effects inside SMSSs.[9] In this way, impacts of both micro- and macroscopic eddy currents as well as other effects were taken into account simultaneously. The dynamic effects are described based on an intuitive differential equation (3), which delays its input (supplementary) variable H_h with respect to the actual field strength H. The discussed extension depends additionally also on the change rate of the magnetic flux density dB/dt, whereas a, b and c are the model parameters.

$$\frac{dH_h(t)}{dt} = a(H(t) - H_h(t)) - b\frac{dB(t)}{dt} + c\frac{dH(t)}{dt}. \tag{3}$$

Regardless the original intention of the presented model, such model can be also used to extend classical eddy current models like the PMD. In this way, the discussed extension is used to describe only the excess component of the field produced, whereas the macroscopic eddy currents are calculated with the PMD. Such an approach is also more consistent with underlying physics and with the commonly accepted loss separation theory of SMSSs.

III. RESULTS

For this comparison the original voltage-driven PMD model is extended by the two rate-dependent extensions (2) and (3) and implemented using MATLAB/Simulink software. Different versions of the PMD model by applying the discussed rate-dependent extensions are evaluated and compared, where experimental data (measured voltages) are used directly as the PMD model input. The data of the evaluated NO soft magnetic steel sheets M400-50A, the experimental setup and the PMD model are presented in Refs. 3, 4, 9. The classical model without rate-dependent effects is abbreviated in the figures as "cl.", whereas the viscosity based extension is abbreviated as "cl. + visc." and the mathematic approach as "cl.+ r.d." The parameters of the viscous-like friction term in (2) R_m and α are identified from the frequency dependence of the excess loss whereas B_s is given by the saturation magnetic polarization of the material. More complicated expressions for (2) can be found in Ref. 6. The parameters of the mathematic model are identified by matching the ascending branch of the major hysteresis loop measured at 50 Hz, i.e., minimizing the least square error. The obtained parameter sets are depicted in Table I.

The obtained PMD models are tested for different sinusoidal excitation waveforms for frequencies up to f = 1000 Hz and magnetic flux densities up to B_{max} = 1:5T. Different rate-dependent models are evaluated by comparing the calculated and measured major and minor dynamic hysteresis loops for the NO steel grade M400-50A. In order to provide a comprehensive analysis, in addition the classical model without inclusion of rate-dependent effects is evaluated. At 50 Hz (Fig. 1 (left)) the effect of magnetic viscosity is not significant. This can be observed comparing the three models. The viscosity-based extension overestimates the loop width, whereas the rate-dependent matches the

TABLE I. Parameters of the Rate-Dependent Extensions.

	R_m	α	B_s in T
Visc. (2)	1	2	1.98
	a	b	c
R.d. (3)	5500	64	0.81

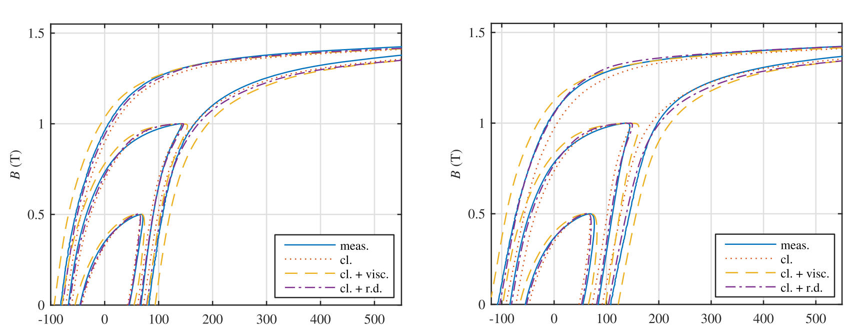

FIG. 1. Comparison of measured and modelled hysteresis loops at 50 Hz (left) and 100 Hz (right) for magnetic flux densities of 0.5 T, 1.0 T and 1.5 T in M400-50A.

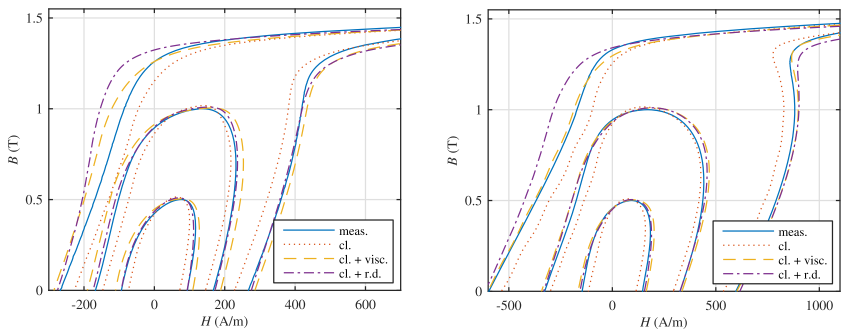

FIG. 2. Comparison of measured and modelled hysteresis loops at 400 Hz (left) and 1000 Hz (right) for magnetic flux densities of 0.5 T, 1.0 T and 1.5 T in M400-50A.

measured curve very well with small deviations approaching material saturation. Increasing the frequency to 100 Hz increases the importance of rate-dependent effects. The classical solution underestimates the loop width, i.e., the energy loss. Again the rate-dependent model (3) describes the hysteresis loop shape accurately.

A further increase in frequency leads to an improved accuracy of the viscosity-based model (Fig. 2). In contrast, the mathematical model, which was identified at 50 Hz, obeys a completely different shape at 400 and 1000 Hz near the boots of the hysteresis loops. In general, by introducing a rate-dependent term in the constitutive law of the PMD it is possible to improve the prediction of the loop shape, i.e., energy loss significantly, in particular at higher frequencies. The viscosity-based model allows a good estimation of the loop shape without any additional parameter identification procedure just using the parameters obtained from the classical excess loss theory in combination with the saturation polarization. In contrast, the mathematical model performs better at those frequencies where it was identified. Therefore, it has a smaller predictive value and needs some re-parameterization or dedicated identification scheme.

IV. CONCLUSION

This paper compares and analyzes two rate-dependent extensions of the PMD model under sinusoidal magnetization waveforms. The models are compared in terms of identification procedure and accuracy of the hysteresis loop shape prediction at frequencies from 50 Hz to 1000 Hz and different magnetic flux densities. The application of the coupled approach (lamination model plus rate-dependent hysteresis model) allows improving the loss calculation as well as the prediction of magnetization dynamics without increasing the computational burden or the need for any additional measurements for parameter identification purposes.

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