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Dynamic hysteresis modeling including skin effect using diffusion equation model

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ABSTRACT

An improved dynamic hysteresis model is proposed for the prediction of hysteresis loop of electrical steel up to mean frequencies, taking into account the skin effect. In previous works, the analytical solution of the diffusion equation for low frequency (**DELF**) was coupled with the inverse static Jiles-Atherton (**JA**) model in order to represent the hysteresis behavior for a lamination. In the present paper, this approach is improved to ensure the reproducibility of measured hysteresis loops at mean frequency. The results of simulation are compared with the experimental ones. The selected results for frequencies 50 Hz, 100 Hz, 200 Hz and 400 Hz are presented and discussed.

1. Introduction

The modeling of electromagnetic devices containing laminated iron cores requires an adequate description of the magnetic material properties. For instance, the accuracy of the iron loss calculation depends on how well the shape of the dynamic hysteresis loop is modeled [1]. Besides, the ferromagnetic hysteresis affects the dynamic behavior of magnetic circuits, thus it should be taken into account in engineering calculations [2].

Most of the electromagnetic devices operate in dynamic regime where the frequency of the supply voltages is an essential parameter for their operation. Nevertheless, a time varying magnetic field that magnetizes the core is at the origin of eddy currents induced in the conducting core material. These currents produce an additional magnetic field that can be interpreted in terms of the effective field change. As a result, the resultant hysteresis loop in dynamic conditions differs from the quasi-static one. Moreover, these eddy currents flow in the core at different scales: in the macro scale, that covers the whole bulk core material and in the micro scale along moving domain walls [2]. The experimentally observed hysteresis loop surface (the hysteresis losses) of the laminations increases with the frequency [3–5] due to these eddy currents.

Moreover, above a given frequency, in association with the electromagnetic and geometric characteristics of the lamination, the skin effect can also be observed (the magnetic field is less penetrating in the lamination with increasing frequency). Therefore, a difficult problem arises in the prediction and assessment of the magnetization process, because of these dynamic effects (eddy currents and skin effect) that are combined with the nonlinear hysteretic response of the material.

The development of a model able to describe correctly this behavior and its variation depending on the operating system is always a question that inspires the researchers [6] in the domain of magnetic materials for energy conversion. Most of the used methods for modeling the dynamic hysteresis loop are linked to the dynamic Preisach model and various differential models: Jiles-Atherton model, Chua model, Hodgdon model, Duhem model [7–8].

The formalism developed by D.C. Jiles et al. [9–12] is based on physical premises concerning domain wall movement in soft magnetic materials. It is interesting from both the theoretical and practical points of view, as it will be further presented.

With the aim to improve the hysteresis modelling with the diffusion equation for low frequency model (**DELF**) [13], we introduce new formulations which take into account the correction of dynamic loop's shape and the counter field associated with eddy current and excess losses.

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In the present work, and in order to deal with the inhomogeneous profile of the magnetic flux density over the sheet thickness, the magnetic field is computed by solving the diffusion equation coupled with the inverse static **JA** hysteresis model for the material constitutive law. The proposed model can be applied in both quasi-static and dynamic regime.

First, the description of the inverse static **JA** model is presented in Section 2. Secondly, the modeling of the hysteresis by the diffusion-equation model for low frequency (**DELF**) is elaborated in Section 3.The detailed description of the proposed diffusion equation model for mean frequency (**DEMF**) is presented in Section 4. Then, the simulation results and analysis are provided in Section 5 and the conclusion is given in Section 6.

2. Inverse static Jiles-Atherton hysteresis model

The **JA** model is a physical model that simulates hysteresis effects based on the various mechanisms (domain wall motion with pinning effect) in the magnetization process of a ferromagnetic material [7–10]. The original **JA** model [9] gives the magnetization M versus the external magnetic field H.

The total differential susceptibility of the system is given by the following expression [8,14].

$$\frac{dM}{dH} = \frac{(1-c)\frac{dM_{irr}}{dH_e} + c\frac{dM_{an}}{dH_e}}{1 - \alpha c\frac{dM_{an}}{dH_e} - \alpha(1-c)\frac{dM_{irr}}{dH_e}} \tag{1}$$

However, the model can also be adapted with the magnetic induction B as entry [14–17]

$$\frac{dM}{dB} = \frac{(1-c)\frac{dM_{irr}}{dB_e} + c\frac{dM_{an}}{dB_e}}{1 + \mu_0(1-c)(1-\alpha)\frac{dM_{irr}}{dB_e} + \mu_0 c(1-\alpha)\frac{dM_{an}}{dB_e}} \tag{2}$$

with the following complementary relationships:

$$H_e = H + \alpha M \tag{3-a}$$

$$B_e = \mu_0 H_e \tag{3-b}$$

$$M_{an}(H_e) = M_s\left[\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right)\right] \tag{3-c}$$

$$\frac{dM_{an}}{dB_e} = \frac{M_s}{\mu_0 a}\left[1 - \coth^2\left(\frac{H_e}{a}\right) + \left(\frac{a}{H_e}\right)^2\right] \tag{3-d}$$

$$M_{irr} = \frac{M - cM_{an}}{1-c} \tag{3-e}$$

$$\frac{dM_{irr}}{dB_e} = \frac{M_{an} - M_{irr}}{\mu_0 k\delta} \tag{3-f}$$

in which $\delta = +1$ for $dB \rangle 0$ and $\delta = -1$ for $dB \langle 0$.

H_e, M_{an}, M_s and M_{irr} are respectively, the effective field, the anhysteretic magnetization, the saturation magnetization and the irreversible magnetization. The model parameters M_s, α, a, c, k are determined from the measured loops in the quasi-static case. This inverse model keeps the same features as the original **JA** model.

3. Model of the diffusion equation for low frequency (DELF)

We consider the lamination in Fig. 1 with the dimensions L and l much higher than e the thickness of the sheet. The lamination is placed in a time varying magnetic field that is perpendicular to its section (along the z axis). The field frequency is sufficiently low so that the field amplitude in the thickness of the sheet $H(x, t)$ decreases slightly compared to the surface [7].

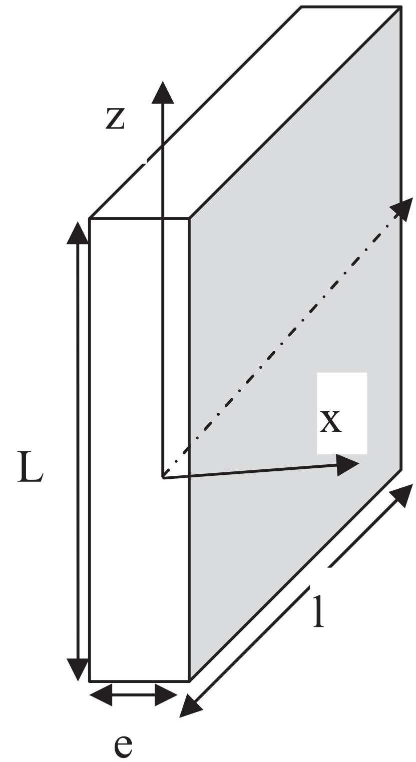

Fig. 1. Geometry of lamination.

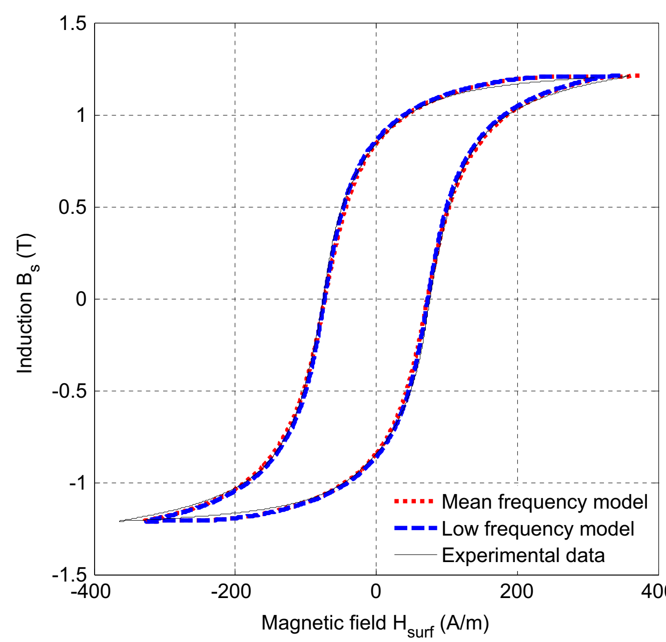

Fig. 2. Measured and simulated hysteresis loops at f=50 Hz and $B_m = 1.2$T.

The induction $B(x, t)$ and its time derivative $\frac{dB(x,t)}{dt}$, that can be considered quasi-homogeneous in the thickness of the lamination, are given by:

$$B(x, t) = B_{ave}(t) \tag{4}$$