Hybrid Magnetic Field Formulation Based on the Losses Separation Method for Modified Dynamic Inverse Jiles-Atherton Model

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Abstract —**Dynamic formulation based on the losses separation method in conducting media for the inverse Jiles-Atherton model is proposed. This formulation is based on the concept of the Hybrid Magnetic Field model (HMF). The HMF consists on the modification of the effective field by introducing two counter-fields associated, respectively, with the eddy current and excess losses. Such a formulation is characterized by seven parameters with five parameters coming from the quasi-static Jiles-Atherton model. Thus, two new parameters related to these fields are added to that defined in the quasi-static model. The identification of these new parameters is based on the measurements of the volumetric energy density. To validate this formulation, measurements are carried out on grain non-oriented FeSi 3% electrical sheets.**

I. Introduction

Most of electromagnetic devices operate in dynamic regime where the frequency of the supply voltages is an essential parameter in their operations. However, the hysteresis losses in these devices increase with the frequency and the precise determination of these losses is an important parameter for suitable operating mode. In the present work, the separation losses formulation for a modified dynamic inverse Jiles-Atherton model is proposed. Such formulation is based on the statistical theory of iron losses separation developed by Bertotti in the conducting magnetic materials [1]. In this proposed formulation, the effective field is modified by introducing two counter-fields associated with eddy current and excess losses. The modified effective field or hybrid magnetic field HMF is introduced in the modified inverse Jiles-Atterton model and it needs two new parameters to be evaluated. The identification of these new parameters is carried out from the measurements of the energy density dissipated by cycle for three different frequency values. The seven parameters are kept unchanged whatever the frequency used. Thus, this model permits to avoid the identification of the five model parameters at each frequency. The obtained results, using this formulation for dynamic Inverse Jiles-Atherton model, are compared with measurements. The Epstein-framework is used to obtain the measurements.

II. Inverse Jiles-Atherton Model

A. Modified Inverse Quasi-Static Model

The modified inverse quasi-static Jiles-Atherton model considers the magnetic flux density B as an independent variable and it is based on the modified direct model [2]:

$$\frac{dM}{dB}=\frac{M_{an}-M+kc\delta\dfrac{dM_{an}}{dH_e}}{\mu_0\left(k\delta+(1-\alpha)\left(M_{an}-M+kc\delta\dfrac{dM_{an}}{dH_e}\right)\right)} \qquad (1)$$

with the following complementary relationships :

$$M_{an}=M_s\left(\coth\frac{H_e}{a}-\frac{a}{H_e}\right) \qquad (2.a)$$

$$H_e=H+\alpha M \qquad (2.b)$$

$$\frac{dM_{an}}{dH_e}=\frac{M_s}{a}\left(1-\coth^2\frac{H_e}{a}+\left(\frac{a}{H_e}\right)^2\right). \qquad (2.c)$$

H_e, M_{an} and M_s are, respectively, the effective field, the anhysteresic magnetization and the saturation magnetization. The model parameters a, α, c, k are determined from the measured loops in the quasi-static case. δ is a directional parameter taking the value +1 for $dB/dt > 0$ and -1 for $dB/dt < 0$. This inverse model keeps the advantages of the direct model.

B. HMF Dynamic Model

The main idea of the HMF dynamic model is based on the losses separation method. It consists on modifying the effective field by adding two counter-fields related to the eddy currents and excess losses. The new expression of the effective field or the HMF is given by:

$$H_e=H+\alpha M-H_{edd}-H_{exc}. \qquad (3)$$

H_{edd} and H_{exc} are, respectively, the magnetic field produced by eddy currents and the magnetic field related to the excess losses. They are given by [3]:

$$H_{edd}=C_{edd}\frac{\Delta B}{\Delta t} \qquad (4)$$

$$H_{exc} = C_{exc} \left| \frac{\Delta B}{\Delta t} \right|^{-1/2} \frac{\Delta B}{\Delta t} \quad (5)$$

C_{edd} and C_{exc} are parameters related to the physical and the geometrical properties of the material [4,5]. These parameters are identified by using the losses separation method expressing that the volumetric energy density is defined by three terms [1].

$$W = W_{hys} + W_{edd} + W_{exc} \quad (6)$$

W_{hys} (J/m^3) is equal to the area of the hysteresis loop totally independent of frequency, W_{edd} is called the classical density loss (J/m^3) caused by eddy current induced in the material and W_{exc} is called the density of excess losses (J/m^3). The expression (6) can be written as:

$$W = W_{hys} + C_{edd} \int \frac{\Delta B}{\Delta t} dB + C_{exc} \int \left| \frac{\Delta B}{\Delta t} \right|^{-1/2} \frac{\Delta B}{\Delta t} dB \quad (7)$$

By measuring W for three different frequencies, the parameters W_{hys}, C_{edd} *and* C_{exc} are immediately determined:

$$[C] = [A]^{-1} [W] \quad (8)$$

where:

$$[C] = \begin{bmatrix} W_{hys} \\ C_{edd} \\ C_{exc} \end{bmatrix}, \ [W] = \begin{bmatrix} W_{f_1} \\ W_{f_2} \\ W_{f_3} \end{bmatrix}$$ and $[A]$ is 3x3 matrix defined

by the following vector lines $[A_i]$ (for i=1, 2, 3) :

$$[A_i] = \left[1 \quad \left(\int \frac{\Delta B}{\Delta t} dB \right)_{f_i} \quad \left(\int \left| \frac{\Delta B}{\Delta t} \right|^{-1/2} \frac{\Delta B}{\Delta t} dB \right)_{fi} \right]$$

III. RESULTS AND DISCUSSION

3% Fe-Si non-oriented magnetic sheets are used in this work. These sheets are characterized by 0.35 mm thickness, 15 mm width and 7650 kg/m^3 mass density. The five parameters of the quasi-static Jilles-Atherton model are presented in Table I. They are obtained by the same procedure given in [2].

TABLE I
QUASI-STATIC PARAMETERS

J-A model parameters	Quasi-static values
M_s (A/m)	$1.18 \cdot 10^6$
a (A/m)	45.14
k (A/m)	60.1
α	$1.5 \cdot 10^{-4}$
c	$1.3 \cdot 10^{-2}$

When measuring the volumetric energy density dissipated for three arbitrary frequencies 10, 50 and 100 Hz for a maximum induction equal to 1.4 T, the parameters W_{hys}, C_{edd} and C_{exc} are determined using the equation (7). Table II presents the three parameters values.

TABLE II
NEW DYNAMIC PARAMETERS

W_{hys} (J/m^3)	C_{edd} (m/Ω)	C_{exc} (A/m)$^{1/2}$
314.62	$26.8 \cdot 10^{-3}$	$611.5 \cdot 10^{-3}$

To validate the HMF model, calculated and measured hysteresis loops for an arbitrarily frequency 200 Hz are presented in Figure 1. This figure shows also the results for 10 Hz and as expected, the width of the hysteresis loops increases with the frequency. Iron losses calculations are carried out for various frequencies with the same maximum induction 1.4 T and Figure 2 shows the comparisons of these calculations with the measured ones. The formulation gives very satisfactory results.

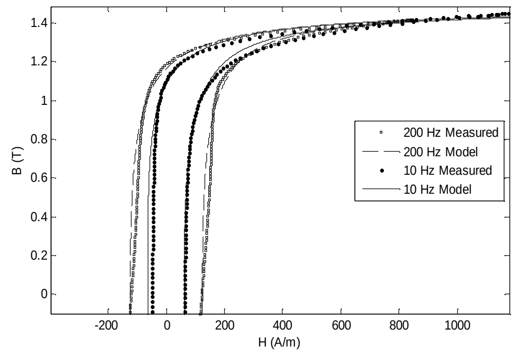

Fig. 1. Measured and calculated hysteresis loops

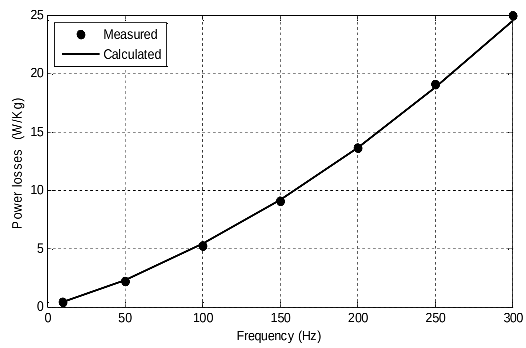

Fig. 2. Measured and calculated power losses

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