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Broadband magnetic losses in Fe-Si and Fe-Co laminations

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We discuss comprehensive broadband (DC – 10 kHz) investigations on magnetic losses in Fe-(3 wt%)Si and Fe-Co laminations. In this range of frequencies, the prediction of loss is not easy, because skin effect can be quite important. The theoretical approach generally relies on a dynamic hysteresis model in association with a diffusion equation, but it imposes heavy computational burden. We present here a computationally efficient dynamic hysteresis model based on the Dynamic Preisach Model (DPM), by which one can achieve fast and precise solution of the diffusion equation taking into account the hysteretic constitutive equation of the material. This is achieved at a greatly reduced computational cost with respect to the standard DPM. The loss results provided by this simplified model are at all frequencies in very good agreement with the prediction by the full DPM and with the experiments.

Index Terms—Magnetic losses, Fe-Si and Fe-Co laminations, Dynamic Preisach Model, Skin effect.

I. INTRODUCTION

THE PREDICTION of power losses in magnetic laminations up to high frequencies is an important issue in the design of high-speed high-torque density machines [1]. It is, however, a challenging task, because skin effect cannot be neglected and an accurate and computationally efficient model is required for a satisfactory treatment of the losses at high frequencies. Some authors have tried empirical approaches, derived from the Steinmetz equation corrected by appropriate frequency dependent coefficients, to take into account the skin effect [2]. The dependence of these coefficients from frequency is obtained through a linear skin effect formulation, assuming constant material permeability. This approximation proves effective only at low induction levels, far from magnetic saturation. At technically relevant inductions the non-linear hysteretic material behavior must be considered, as put in evidence in [3].

To address the whole problem, significant work has been performed in the literature, aimed at a physically based model, taking into account both skin effect and the non-linear hysteretic constitutive law of the material. The solution of the diffusion equation using a finite element approach, and the modeling of the material constitutive law given by the Static Preisach Model (SPM) has been considered in [4]. The hysteretic $B(H)$ relationship is dealt with using the fixed point method and an iterative algorithm is applied in [5]. Although computationally efficient, thanks to the Everett formalism [6], the SPM has the drawback of not taking into account the role of the domain walls in the magnetization dynamics (i.e. the excess loss contribution). This has been then addressed by means of a dynamic hysteretic relationship, like the viscous-type model [7], or Bertotti's Dynamic Preisach Model (DPM) [8]. Because of its solid physical basis and the fact that it only requires the experimental identification of a single material constant (i.e. the dynamic constant k_d [9]), the DPM has become very popular [10]. The implementation of the DPM into a numerical scheme for solving the diffusion equation of the magnetic field can well take into account skin effect, as discussed in [11] [12], where the fixed point method is used to deal with the non-linearity. Although accurate, this procedure

is computationally cumbersome, because the state of every hysteron must be evaluated at each time step [8] on every finite element, until convergence of the iterative scheme is attained.

The purpose of this work is to derive a simplified dynamic hysteresis model based on the DPM and its physical framework. It requires greatly reduced computation time, (the computational burden being approximately that of the SPM). This model and the full DPM are compared with the experimental magnetic energy losses in 0.2 mm thick Fe-Si and Fe-Co laminations, measured in the frequency range DC-10 kHz. It is shown that the prediction by the simplified DPM closely agrees with the experiments and the full DPM simulations, at a drastically reduced computational cost.

II. MODELING

A. Computational scheme

The concept of static magnetic field H_{stat} is first introduced. It is the field that would give, under quasi-static excitation, the same irreversible polarization $J_{\text{irr}}(t)$ obtained under dynamic conditions through the applied field $H(t)$. Once the static field H_{stat} is known, the irreversible polarization J_{irr} can be efficiently computed by application of the SPM. The main question is how to derive the static field H_{stat} from knowledge of the dynamic magnetic field $H(t)$. In the following, it is shown that a simplified relationship between H and H_{stat} can be derived in terms of a non-linear first order differential equation in H_{stat} , whose solution can provide the static field H_{stat} for any given field H . This model is summed up in Fig. 1, where the dynamic operator $\mathbf{F}$ takes into account the dynamic properties of the hysteretic model. Once J_{irr} is known, it is added to the reversible component J_{rev} to obtain the total polarization $J(t)$. The irreversible and reversible density functions are identified using the same technique as in [10].

B. Differential relation between H and H_{stat}

The dynamic operator $\mathbf{F}$ is derived from the DPM under appropriate simplifying assumptions. In the following, the dynamic constant k_d of the DPM is assumed to be known (it is identified according to [9]).

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Fig. 1: General scheme of the model

We consider the case of an increasing magnetic field. It has been shown in [13] that the set of switching hysterons in the dynamic Preisach plane α - β (α and β being the up and down switching fields, respectively) can be represented as a *strip* of width ΔH (Fig. 2), in the interval $[H-\Delta H, H]$. This relates to the fact that under dynamic conditions hysteron switching takes time. On the contrary, in the Static Preisach Model, the state of each hysteron is assumed to instantaneously switch from -1 to 1. All *hysterons* in the S^+ area are positively saturated, whereas the ones in the S^- area are negatively saturated. A function ϕ , defined in [8], represents the state of each hysteron in the interval $[-1, 1]$. An example is reported in Fig. 2 where the ϕ function depends only on α , because we are on the ascending branch of the field H . Since the hysterons in the interval $[H-\Delta H, H]$ are commuting and display an intermediate state, Φ makes a smooth transition between -1 and +1.

Fig. 2: Representation of the dynamic and static Preisach planes providing the same irreversible polarization contribution J_{irr}

In the SPM the boundary between the positively and negatively saturated hysterons is instead a horizontal line of coordinate H_{stat} , and the function ϕ is therefore a step like one (Fig. 2). Assuming H is increasing, the following function $\mu(\alpha)$ is introduced [13]:

$$\mu(\alpha) = J_s \int_{\beta_{LM}}^{\alpha} p_{irr}(\alpha, \beta) d\beta, \quad (1)$$

where $p_{irr}(\alpha, \beta)$ is the normalized irreversible part of the Preisach density function, and J_s is the saturation polarization. According to the definition of H_{stat} , the following relation holds

$$\int_{H-\Delta H}^H \mu(\alpha) \phi(\alpha, t) d\alpha = \int_{H-\Delta H}^{H_{stat}} \mu(\alpha) d\alpha - \int_{H_{stat}}^H \mu(\alpha) d\alpha. \quad (2)$$

Equation (2) defines the static field at each instant of time, given the state function ϕ and the width ΔH . According to the DPM theory [8], we express the flux derivative as

$\dot{\phi} = k_d \cdot (H - \alpha)$. From the time derivative of (2) we consequently obtain

$$\dot{H}_{stat} = \frac{k_d}{2\mu(H_{stat})} \int_{H-\Delta H}^H (H - \alpha) \mu(\alpha) d\alpha, \quad (3)$$

representing the dynamical part of the model. The solution of (3) requires some simplifying assumptions, as explained in the following.

Assumption of constant μ function on the strip. On the interval $[H-\Delta H, H]$, the function μ is assumed to be constant, equal to its mean value (the validity of this hypothesis is discussed later). Equation (2) therefore becomes

$$\int_{H-\Delta H}^H [1 + \phi(\alpha, t)] d\alpha = 2 \cdot (H_{stat} - H + \Delta H) \quad (4)$$

and (3) provides

$$\dot{H}_{stat} = \frac{k_d}{4} \Delta H^2. \quad (5)$$

Assumption of local constant time derivative of the magnetic field. In this case, as shown in [13], the ϕ function is given by the parabolic function

$$\phi(\alpha, t) = -1 + \frac{2}{\Delta H^2} (H - \alpha)^2, \quad (6)$$

where the strip width ΔH has been introduced by taking into account that $\phi(H-\Delta H, t) = 1$. Introducing (6) in (4), the width ΔH is obtained:

$$\Delta H = \frac{3}{2} (H - H_{stat}). \quad (7)$$

Eq. (7) is further introduced in (5) providing the following differential equation

$$\dot{H}_{stat} = \text{sign}[H(t) - H_{stat}(t)] \frac{9}{16} k_d [H(t) - H_{stat}(t)]^2, \quad (8)$$

where $\text{sign} = \pm 1$ according to the ascending or descending direction of the magnetic field. Equation (8) eventually defines the dynamic operator F of Fig. 1. This equation can be numerically solved by a Crank-Nicholson method, applying periodic conditions on the static field H_{stat} . The involved computational burden of the model is around that required by SPM.

We have introduced this simplified DPM in a numerical scheme for the computation of the magnetic field and flux distribution in the lamination. The results are compared with those provided by the full DPM and the DC 10 kHz experiments.

III. EXPERIMENTAL

The measurements were performed on commercial non-oriented Fe-(3 wt%)Si and Fe₅₀Co₅₀ sheets. Their thickness d is equal to 0.194 mm and 0.201 mm, respectively. The measurements were performed up to 10 kHz using the 200-turn Epstein frame, with the test strips cut half along and half transverse to the rolling direction, according to the measuring standard IEC 60404-10 [14]. The DC normal magnetization curve was obtained up to magnetic saturation by means of the

point-by-point method (calibrated fluxmeter Lake-Shore mod. 480). The hysteresis loops and losses were measured versus frequency for several defined peak polarization values J_p by means of a hysteresisgraph-wattmeter with digital control of the flux waveform. The form factor of the secondary voltage was kept at all frequencies within the interval $FF = 1.1107 \pm 0.4\%$. The primary winding was supplied, depending on J_p , and frequency either by a 200 W NF HSA4101 or a 1 kW NF 4510 power amplifier, driven by an Agilent 33210A function generator.

For each material, the constant of the DPM k_d has been obtained measuring hysteresis loops at 50 Hz, 100 Hz and 200 Hz, for peak inductions of 0.5 T, 1 T, and 1.5 T, and by fitting the related excess loss values. It is provided, together with the main physical parameters of the investigated laminations, in Table I.

TABLE I
DATA ON THE TWO MATERIALS USED FOR MEASUREMENTS

	Fe-Si	Fe-Co
Composition	Fe-(3 wt%)Si	Fe ₄₉ Co ₄₉ V ₂
Annealing	780°C, 2 hours	820°C, 10 hours
Thickness d (mm)	0.194	0.201
Density δ (kg/m ³)	7650	8120
Conductivity σ (S/m)	$1.92 \cdot 10^6$	$2.27 \cdot 10^6$
Constant k_d of the DPM (m·s ⁻¹ ·A ⁻¹)	700	1100

Fig. 3 – Energy loss versus frequency at different polarization values J_p (full symbols: experiments, solid line: full DPM, open triangle: simplified DPM, a) case of Fe-Si laminations, and b) case of Fe-Co laminations.

A. Loss results

Application of simplified and full DPMs to the energy loss measurements in the Fe-Si laminations are shown in Fig. 3a. The results obtained in the Fe-Co sheets are presented in Fig. 3b. Fe-Co, with its high saturation polarization ($J_s = 2.35$ T), permits one to perform broadband measurements up to pretty high inductions. Remarkably, the measured losses are excellently described by the abovementioned models, including the high-frequency results, which are considerably influenced by the skin effect.

B. Measured and computed cycles

Hysteresis cycles, experimentally obtained and computed by the DPM and the simplified model, are compared in Fig. 4.

Fig. 4 - Dynamic cycles in Fe-Si ($J_p = 1.0$ T) and Fe-Co ($J_p = 1.7$ T) sheets at 1 kHz and 10 kHz. The experimental loops (symbols) are compared with the prediction by the full (solid line) and simplified (line plus symbols) DPMs.

The dynamic loops are accurately reproduced at the frequency $f = 1$ kHz in both materials. Minor discrepancies are found at $f = 10$ kHz, where the induction profile in the lamination becomes highly inhomogeneous. This is understood as due to the fact that at the highest frequencies, the dynamic strip of the DPM (Fig. 2) can be quite large, and the assumption of constant μ function becomes untenable. But the loop area is still predicted with acceptable accuracy.

B. Influence of the skin effect

In the absence of appreciable skin effect, we assume that the mean polarization $J(t)$ and the local one are the same, and the classical loss is simply obtained, for sinusoidal induction of peak value B_p

$$W_{\text{class}}(J_p, f) = \frac{\pi^2}{6} \cdot \sigma d^2 B_p^2 f. \quad (9)$$

In this case, the hysteresis and excess loss contributions can be found by direct inversion of the hysteresis model presented in this paper. Energy loss calculations in Fe-Co using the model with and without skin effect are compared in Fig. 5 with the experimental values. While the need for considering the skin effect in loss modeling is apparent, we see that when this is ignored, different kinds of discrepancies arise at low and high inductions. Thus, for $J_p = 0.5$ T the conventional loss model, where uniform induction is assumed in the lamination cross-section, overestimates the actual loss, while the opposite occurs at high inductions (e.g. $J_p = 1.7$ T).

Fig. 5 – The prediction of energy losses by the standard model ignoring skin effect overestimates the actual figures at low inductions and underestimates them at high inductions.

Fig. 6 – Calculated profile of the peak induction $B_{p,LOC}(x)$ across the lamination thickness ($-d/2 \leq x \leq d/2$, $d = 0.201$ mm) in Fe-Co ($f = 10$ kHz). Low and high average peak polarization values ($J_p = 0.5$ T and $J_p = 1.7$ T) are considered.

It turns then out that no differences arise at intermediate inductions, as shown for $J_p = 1.5$ T in Fig. 6. This evolution follows from the progressively increasing depth of the magnetically saturated layer on increasing the J_p value. This imposes a corresponding evolution of the induction profile across the lamination thickness, as illustrated in Fig. 6 for $J_p = 0.5$ T and $J_p = 1.7$ T ($f = 10$ kHz). We see here that for $J_p = 1.7$ T the saturated region penetrates a fraction of the sample cross-sectional area while for $J_p = 0.5$ T, the profile has the freedom to adjust close to the predictable behavior of the local peak induction $B_{p,LOC}(x)$ ($-d/2 \leq x \leq d/2$) in a constant permeability material.

IV. CONCLUSIONS

We have discussed DC-10 kHz loss measurements carried out for several peak polarization values in 0.2 mm thick Fe-Si and Fe-Co laminations. They are assessed by means of a computationally efficient dynamic hysteresis model based on the Dynamic Preisach Modeling (DPM), here proposed and implemented. This model has been introduced in a fixed point iterative procedure taking into account magnetic field diffusion across the lamination depth. The calculated energy losses and dynamic hysteresis loops and their evolution with

frequency are in excellent agreement with the experiments and with the full DPM prediction, while showing strongly reduced computation time.

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