

A Dynamic Hysteresis Model Based on Vector Play Model for Iron Loss Calculation Taking the Rotating Magnetic Fields into Account

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This paper proposes a simple dynamic three-term hysteresis model which is based on vector play model to estimate iron loss of non-oriented (NO) electrical steel sheet (ESS) taking account of the rotating magnetic fields. The dynamic three-term hysteresis model is consists of static hysteresis field part, frequency-dependent eddy current part and excess field part. In this paper, the static hysteresis part is based on the vector play model, and a novel and simple vector shape function identification method is proposed by using a set of symmetric hysteresis minor loops are measured by one-dimensional (1-D) steel sheet tester (SST) under 1 Hz. In addition, some parameters in the proposed model will be identified by particle swarm optimization (PSO) method though fitting the measured hysteresis loops. The validity of the proposed hysteresis model will be investigated through comparisons with experimental results under various magnetic field conditions.

Index Terms—Vector play model, hysteresis property, iron loss, electrical steel sheet

I. INTRODUCTION

IRON LOSS and other performance analyses of electrical motors and transformers require accurate description of the vector hysteretic property of an electrical steel sheet (ESS). It is because most electric machines have rotating magnetic fields as well as alternating magnetic fields, and combination of them always results vector hysteretic behaviors. The play model is one of the most efficient and accurate models to describe the vector hysteretic behaviors. Its vector versions can be classified into two: one is the superposition of scalar play models along the azimuthal direction [1], and another is geometric extension of the scalar model [2]. Though based on the geometric extension which is known to be more efficient [3], amount of measured data is needed for identification, and the data is very difficult to measure under 1 Hz magnet field. On the other hand, a lot of experimental results, however, show the non-oriented ESS also has anisotropic properties when rotating magnetic field is applied. For this reason, some anisotropic versions of the vector play model have been proposed [4]. However, comparisons of their outputs with experimentally measured data show that the accuracy of the anisotropic versions is still not satisfactory to be applied to electric machines such as motors and generators.

In this paper, an anisotropic vector dynamic hysteresis model based on vector play model is proposed. The vector play model is based on the superposition of scalar play models along the azimuthal direction, and a novel and simple identification method for vector shape function is proposed by using a set of symmetric hysteresis minor loops are measured by one-dimensional (1-D) steel sheet tester (SST) under 1 Hz alternating magnetic fields. In additional, the parameters of the dynamic three-term hysteresis model will be identified by particle swarm optimization (PSO) method though fitting the measured hysteresis loops. The validity of the proposed hysteresis model will be investigated through comparisons with experimental results under various magnetic field conditions.

II. SCALAR PLAY MODEL AND ITS IDENTIFICATION

In this paper, the vector play model is based on the superposition of scalar play models along the azimuthal direction, so scalar play model should be constructed firstly. An inverted version of scalar play model, which provides its output magnetic field strength (H) from the input magnetic flux density (B), is expressed as follows [4]:

$$H = P(B) = \int_0^{B_s} f_\zeta(p_\zeta(B)) d\zeta \quad (1)$$

where B_s is saturation value of magnetic flux density, f_ζ is an input-independent shape function. The play operator having its height ζ , and given as:

$$p_\zeta(B) = \max\left(\min(p_\zeta^0, B + \zeta), B - \zeta\right) \quad (2)$$

where p_ζ^0 is the value at previous time.

The discretized form of the scalar play model (1) can be written as:

$$H = P(B) = \sum_{m=1}^M f_m(p_{\zeta_m}(B)) \quad (3-a)$$

$$\zeta_m = (m-1)B_s/M \quad (3-b)$$

where M is the number of play operators.

The identification of the shape function f_m is based on the Everett function of the Preisach model [5]. The Everett function $E(\alpha, \beta)$ is defined from experimentally measured symmetric B-H loops as:

$$E(\alpha, \beta) = \begin{cases} h^-(\alpha, \alpha) - h^-(\alpha, \beta) & (\alpha + \beta \geq 0) \\ h^+(|\beta|, \alpha) - h^+(|\beta|, \beta) & (\alpha + \beta \leq 0) \end{cases} \quad (4)$$

where $h^+(B_a, B)$ and $h^-(B_a, B)$ are, respectively, the ascending and descending branches of the symmetric B - H loop with maximum amplitude B_a .

Based on the equivalence relation between the scalar play model and the scalar Preisach model [5], the shape function is identified from the distribution function, $\mu(\cdot, \cdot)$, as follows:

$$f_m(p) = \int_{\zeta_m}^{\zeta_{m+1}} \int_{\zeta - B_s}^{p + \zeta_m - \zeta} \mu(p, \zeta) dp d\zeta. \quad (5)$$

and it physically corresponds to the area of the filled region in Fig. 1.

After the number of play operators is decided, identification of the shape function f_m is linearized as follows:

$$f_m(p) = f_m(p_{m,j-1}) + \mu_{m,j}(p - p_{m,j-1}) / \Delta p, \quad (6)$$

$$p_{m,j-1} \leq p \leq p_{m,j}, \quad j=1, \dots, M - m + 1$$

where

$$\mu_{m,1} = \frac{1}{2}(E(b_0, b_k) - E(b_0, b_{k-1}) - E(b_1, b_k) + E(b_1, b_{k-1})) \quad (7-a)$$

$$\mu_{m,j} = E(b_{j-1}, b_k) - E(b_{j-1}, b_{k-1}) - E(b_j, b_k) + E(b_j, b_{k-1}), \quad j \neq 1 \quad (7-b)$$

$$p_{m,j} = -B_s + \zeta_m + j\Delta p, \quad \Delta p = 2B_s / M$$

$$\mu_{m,j} = f_m(p_{m,j}) - f_m(p_{m,j-1}), \quad k = m + j - 1$$

$$b_k = 2kB_s / M - B_s, \quad k = 0, 1, \dots, M$$

$$E(b_j, b_{j-1}) = 0 \quad (7-c)$$

The unknown $E(b_j, b_k)$ in (7) are calculated from the known Everett function values though two-dimensional linear interpolation.

The proposed identification algorithm is applied to a Non-oriented ESS 35PN440 specimen. Totally 16 symmetric B - H loops are measured along the rolling direction for the range of $0.1 \leq B \leq 1.6$ (T) by using 2-dimensional single sheet tester, and then the shape function is identified.

Fig. 2 shows the application results to minor loops under alternating magnetic fields along rolling direction where modeling results match well with the measured ones.

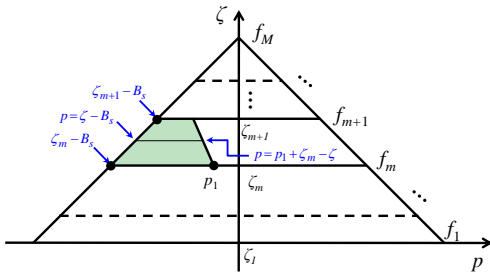


Fig. 1. Physical meaning of shape function $f(\cdot)$ of scalar play model.

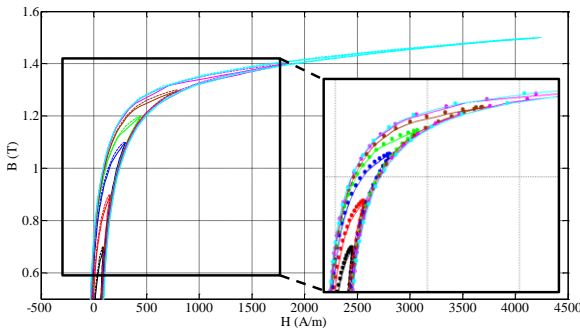


Fig. 2. Comparison of the measured (dot line) and modeled (solid line) loops under alternating magnetic field along rolling direction.

III. DYNAMIC VECTOR HYSTERESIS MODEL

A magneto-dynamic vector hysteresis model which separates H into static field, classical eddy current field and excess fields is proposed as follows:

$$\mathbf{H}(t) = \sum_{i=1}^N \omega_i H_{\varphi_i}(t) \mathbf{e}_{\varphi_i} \quad (8-a)$$

$$H_{\varphi_i}(t) = H_{st}(B_{\varphi_i}(t)) + \delta_e \frac{\sigma d^2}{12} \left| \frac{dB_{\varphi_i}(t)}{dt} \right|^v + \delta_e \left| \frac{1}{r} \frac{dB_{\varphi_i}(t)}{dt} \right|^{1/w} \quad (8-b)$$

$$B_{\varphi_i}(t) = \delta |\mathbf{B}(t)| |\cos(\theta_B - \varphi_i + \psi)|^{1/w}, \quad w \geq 1, \quad i = 1, 2, \dots, N \quad (8-c)$$

$$v(B) = a_0 + a_1 \delta_e \left(\frac{B}{B_s} \right) + a_2 \left(\frac{B}{B_s} \right)^2 \quad (8-d)$$

where $\delta_e = \text{sign}(dB/dt)$, $\delta = \text{sign}\{\cos(\theta_B - \varphi_i + \psi)\}$ and ω_i is the weighting factor for the direction \mathbf{e}_{φ_i} . The phase shift ψ and coefficients w , a_0 , a_1 and a_2 are experimentally identified. In this paper, PSO method will be used to decide the above parameters though fitting measured data. The static hysteresis field of \mathbf{H} in (8) is calculated by vector play model with vector shape function, which is calculated as follows:

Step 1 Calculate the vector Everett function $F(\alpha, \beta)$ from scalar Everett function $E(\alpha, \beta)$ as follows [6]:

$$E(\alpha, \beta) = \sum_{i=1}^N \omega_i \cos \varphi_i F\left\{(\alpha \cos \varphi_i)^{1/w}, (\beta \cos \varphi_i)^{1/w}\right\} \quad (9)$$

Step 2 Calculate the vector distribution function $\lambda(\alpha, \beta)$ as follows:

$$\lambda(\alpha, \beta) = \frac{\partial^2 F(\alpha, \beta)}{\partial \alpha \partial \beta} \quad (10)$$

Step 3 Calculate the vector shape function g as follows:

$$g_m(p) = \int_{\zeta_m}^{\zeta_{m+1}} \int_{\zeta - B_s}^{p + \zeta_m - \zeta} \lambda(p, \zeta) dp d\zeta. \quad (11)$$

In the version of full paper, overall analysis algorithm and will be explained in detail. The scalar and vector shape functions will also be constructed and fully investigated by using symmetric minor loops. This algorithm will be applied on a non-oriented material 35PN440. Meanwhile, iron loss will be calculated and investigated through comparisons with experimental results.

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