A New Vector Hysteresis Model Based on Series-Distributed Play Hysterons

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This paper proposes a new vector hysteresis model based on series-distributed play hysterons. First, a new vector play operator is developed to satisfy the rotation loss property beyond saturation, which the ordinary vector hysteresis model fails to obey. Second, a variable recoil-line slope algorithm is introduced to more accurately represent individual minor loop behavior and to best match the measured minor loop. Then, to accommodate the proposed vector play operator and the variable slope algorithm, a series-distributed hysteron model is put forward. Finally, a detailed parameter identification procedure which is not only practical, but also computationally efficient is established. The presented model has been successfully implemented in 2-dimensional (2D) and 3-dimensional (3D) transient finite element analysis (FEA). Some application results are presented.

***Index Terms*—Finite element methods, hysteresis, magnetic materials, modeling.**

I. INTRODUCTION

THE PHENOMENON of magnetic hysteresis has been observed for a long time in various magnetic materials which are widely used in electrical devices. To simulate the magnetic hysteresis behavior, a hysteresis model is required to be coded in FEA software. One of the most widely used models for magnetic hysteresis is the Preisach model [1] or extensions of the original model. Although the scalar Preisach model can accurately predict the hysteresis behavior when a magnetic field is applied in a fixed direction, the vector Preisach model fails to match the measured data for large rotating fields [2]-[3].

Some extensions of the original vector Preisach model [2] were proposed [4]-[6], but they still have certain limitations which include: unable to fulfill all essential properties that a vector hysteresis model should possess, or difficult in parameter identification, or computationally intensive.

To predict the magnetization behavior for isotropic magnetic materials with hysteresis in 2D or 3D transient finite element analysis (FEA), it has been recognized that the vector play model [7]-[11] is more computationally efficient than various vector Preisach models. However, the ordinary vector play model does not obey the rotational loss property. Some modified vector play models have been developed to satisfy the loss property, but their applications are still limited due to the difficulty in parameter identification [7]-[8], or over simplistic minor loop behavior [11].

This paper presents a new vector hysteresis model based on series-distributed play hysterons for isotropic magnetic materials. All required parameters of the model can be conveniently identified from the major hysteresis loop and loss curve. This model not only satisfies the rotational loss property, but also improves the accuracy for minor hysteresis loops.

II. THE MODEL

A. Ordinary Vector Play Model

In the ordinary vector play model, the magnetization **m** is computed from the applied field **h** as

$$\mathbf{m} = m_{an}(h_{re}) \cdot \mathbf{h}_{re}(\mathbf{h}) / h_{re} \tag{1}$$

where $m_{an}(h_{re})$ is an anhysteretic curve, and h_{re} is the absolute value of $\mathbf{h}_{re}(\mathbf{h})$, which is the vector play operator, representing the reversible field component, and is expressed by

$$\mathbf{h}_{re} = \begin{cases} \mathbf{h}_{re0} & \text{if } \left|\mathbf{h} - \mathbf{h}_{re0}\right| < r \\ \mathbf{h} - r \cdot \frac{\mathbf{h}-\mathbf{h}_{re0}}{\left|\mathbf{h}-\mathbf{h}_{re0}\right|} & \text{if } \left|\mathbf{h} - \mathbf{h}_{re0}\right| \geq r \end{cases} \tag{2}$$

where r, representing the maximum limit of the irreversible field component $\mathbf{h}_{ir}=\mathbf{h}-\mathbf{h}_{re}$, abbreviated as irreversible limit, is a given parameter, and $\mathbf{h}_{re0}$ is the initial value of $\mathbf{h}_{re}$.

The vector play operator of (2) in a fixed direction, or the scalar play operator, can be illustrated by Fig. 1(a).

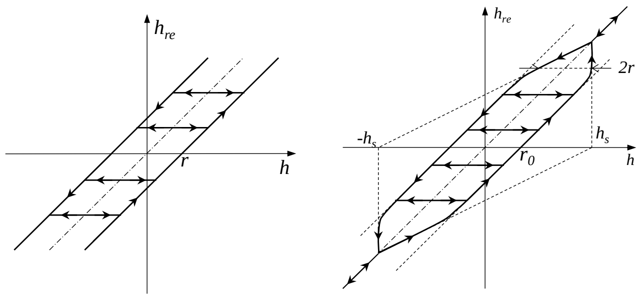
Finally the flux density is computed from

$$\mathbf{b} = \mu_0(\mathbf{m}+\mathbf{h}) = \mathbf{b}_{re} + \mu_0(\mathbf{h}-\mathbf{h}_{re}) \tag{3}$$

where

$$\mathbf{b}_{re} = \mu_0(\mathbf{m}+\mathbf{h}_{re}) \tag{4}$$

which can be understood as an anhysteretic, or reversible, *b-h* curve.



(a) Ordinary play operator

(b) Improved play operator

Fig. 1. Scalar play operators

Equation (3) shows that when |**h** - $\mathbf{h}_{re}$| < r, which means **h** varies within the major hysteresis loop, the point ($\mathbf{h}_{re}$, $\mathbf{b}_{re}$) will be fixed on the reversible *b-h* curve, and **b**(**h**) will trace on a recoil line with constant slop of μ_0.

B. Play Operator with Variable Irreversible Limit

With the ordinary vector play operator, if the applied field rotates, it can be proved that at the steady state, the irreversible component $\mathbf{h}_{ir}$ will be perpendicular to the reversible component $\mathbf{h}_{re}$. The magnitude of $\mathbf{h}_{ir}$, or r, is constant no matter how large the applied field is, which means $\mathbf{m}$, in the same direction of $\mathbf{h}_{re}$, will always lag $\mathbf{h}$ a certain angle. Therefore, the ordinary vector play model does not satisfy the rotational loss property.

To satisfy the rotational loss property beyond saturation, the irreversible limit r has to be zero when field is saturated. Therefore, in play operator (2), the irreversible limit r can be defined as a function of the reversible field h_{re}, and is proposed to be

$$r(h_{re}) = \begin{cases} r_0 \cdot \left(1 - \left|h_{re}/h_s\right|^{h_s/r_0}\right) & \text{if } \left|h_{re}\right| < h_s \\ 0 & \text{if } \left|h_{re}\right| \geq h_s \end{cases} . \tag{5}$$

where r_0 is the irreversible limit at $h_{re} = 0$, which represents the intrinsic covercivity.

The improved play operator with variable limit r is shown in Fig. 1(b), from which one can observe that the ascending and descending operator curves are tangential to the two parallel ordinary operator lines, and are inscribed in the dashed parallelogram.

C. Play Hysteron with Variable Recoil-Line Slope

In the ordinary play model, all recoil lines inside the hysteresis loop have the same slope of μ_0. The ordinary play model with only one play hysteron is able to provide reasonable accuracy for major loop behavior. However, due to the same slope for all recoil lines, the area of a minor hysteresis loop which is bounded within the major loop and two parallel recoil lines is normally much larger than the measured one. In order to more accurately represent minor loop behavior, a variable slope algorithm is introduced so that the area of a derived minor loop can best match the area of the measured minor loop.

The flux density of a play hysteron with variable recoil-line slopes is expressed as

$$\mathbf{b} = \mathbf{b}_{re} + \mu_v(\mathbf{h} - \mathbf{h}_{re}) \tag{6}$$

where

$$\mu_v = k_\mu \mu_0 (\mu_r - 1) + \mu_0 = k_\mu \mu_0 \frac{dm_{an}(h_{re})}{dh_{re}} + \mu_0 \tag{7}$$

with k_μ being a new parameter to be identified.

D. Play Model with Series-Distributed Play Hysterons

The play model with only one play hysteron can simulate the major hysteresis loop very well. However, the minor loop behavior is over simplistic. To better represent realistic minor loop behavior, a play model with series-distributed play hysterons is proposed, as shown in Fig. 3, where field intensity $\mathbf{h}_k$ is expressed as the function of flux density $\mathbf{b}_k$ for the k-th play hysteron. The total field for series-distributed play hysterons is

$$\mathbf{h} = \sum_{k=1}^{n} w_k \mathbf{h}_k(\mathbf{b}) \tag{8}$$

where parameters w_k, to be identified, are the weighting factors for all play hysterons.

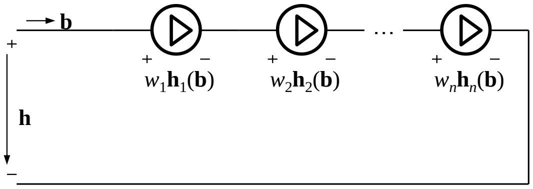


Fig. 2. Play model with series-connected play hysterons

III. APPLICATIONS

The proposed model has been implemented in 2D and 3D transient FEA solvers. One of the test cases is a 4-pole, 24-slots, 550W, 1500rpm hysteresis motor. The motor is operated at locked rotor with balanced three-phase ac voltage supply. The simulated rotor hysteresis loss is compared with the electro-magnetic power in Fig. 3. According to electrical machine principle, the electro-magnetic power should equal to rotor loss at the steady state. One observes from Fig. 3 that when the steady state is reached after time ≥ 20ms, the hysteresis loss balances the electro-magnetic power very well. More results will be provided in the final paper.

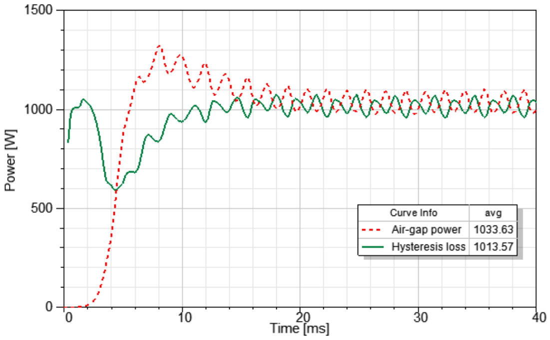


Fig. 3. The hysteresis loss compared with the electro-magnetic power

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