Abstract—This paper presents a method to study the vector magnetic properties of magnetic materials under alternating and rotational magnetic field using 2-D vector hybrid hysteresis model. Combining Preisach model and Stoner-Wohlfarth (S-W) model, the vector hybrid hysteresis model is established for magnetic materials. The alternating and rotational hysteresis properties are calculated under different excitation frequency, respectively. And the computed results are compared with the experimental measurement ones. It is shown that the vector model can simulate the alternating and rotational magnetic properties effectively under low magnetization fields and low excitation frequency.

Index Terms—Hybrid hysteresis model, magnetic materials, vector magnetic properties.

I. INTRODUCTION

Magnetic materials are widely used in electronic devices, accelerators and medical systems. The precise simulation of the vector magnetic properties of magnetic materials, especially those that are magnetized under alternating and rotational excitation magnetic field, directly affects the operation efficiency of electrical equipment [1]. Since the scalar Preisach model had been presented by Preisach in 1935, there are several classical hysteresis models have been presented to accurately simulate the magnetic properties of magnetic materials [2]-[12].

The vector hysteresis model has been investigated from different approaches [3]-[5]. The Mayergoyz model has correct vector properties but it can’t be used under rotational applied field [4]. The Della Torre, Pinzaglia and Careddelli (DPC) model [6]-[8] and Preisach-Stoner-Wohlfarth (PSW) model [9]-[11] are two vector hybrid hysteresis model, which are established based upon the merging of the Preisach model and the S-W model theory at last decade. In the PSW model, the angle of the magnetization is defined by net field, while in the DPC model, the direction of magnetization is determined by the S-W model, and its magnitude can be calculated by the Preisach model. These models combine the advantages of classical models and can simulate the vector magnetic characteristics of magnetic materials more precision in theory.

In previous papers we have presented a new definition method of hysteresis operator and studied the complex rotational magnetic properties of the soft magnetic composite (SMC) materials [12, 13]. In this paper, a two-dimensional vector hysteresis model is established in order to analyze the complex magnetic properties of magnetic material. The hysteresis properties are calculated under different magnetic field frequency and different magnetization fields, respectively. The numerical results are compared with the experiment ones which are obtained by the measurement experiment using three-dimensional magnetic properties tester. Results shows that the simulate method is valid under the low field strength and low excitation frequency.

II. THE DEFINITION OF HYSTERON

The core of the hybrid vector hysteresis model is the definition of hysteron. In this section, we take one isotropic particle as an example to introduce the equipotential curves of the magnetic materials. The isotropic particle is saturated in a magnetization axis, so that we can describe its state by giving the orientation of its magnetization vector \( \mathbf{M} \), or, equivalently, of the unit vector \( \mathbf{m} = \mathbf{M}/M_s \), where \( M_s \) is the Saturation magnetization of the magnetic materials. When an external field \( \mathbf{H}_e \) is applied, \( \mathbf{M} \) will rotate toward to the applied field.

The behavior of the particle is governed by the energy of interaction with the applied field. Combined the modeling principle of S-W model, the parametric representation of the equipotential curves can be obtained by deriving from energy equation. Taking the effect of interaction field \( H_i \) between magnetic particles into account, the parametric representation of the equipotential curves can be described as Eq. (1).
\[
\begin{align*}
    h_y &= H_y - e \sin \theta \\
    h_x &= H_x - e \cos \theta
\end{align*}
\]  
(1)

where \(H_x\) and \(H_y\) are two components of interaction field \(H_i\) along the coordinate axis, the parameter \(e\) represents the constant value of energy along the curve.

The hysteron is defined by the parametric representation equation of equipotential line in stable state. Each hysteron is defined as a closed area bounded by the equipotential curves of the magnetic particles in the applied field space with unit vector magnetization intensity. The direction of magnetization direction is determined according to the astroid properties of S-W model.

A hysteron without interaction field and the magnetization directions under alternating applied field are shown in Fig. 1. The applied field is gradually increased from A to B.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{A hysteron with interaction field and the magnetization directions under the alternating applied field A-B.}
\end{figure}

For the applied field outside the critical surface, magnetization is directed along the radial line from the center of the hysteron to the considered point. For fields inside the critical surface, the magnetization is frozen to the direction that it had just before it entered the critical surface, and it remains constant until it exits the critical surface. There have a barkhausen jump when the applied field crosses the critical surface from inside to outside.

The hysteron satisfies the second principle of thermodynamic and the Mandelung rule describing the magnetic hysteresis. It has the vector congruency property and vector deletion property, can simulate vector hysteresis effectively.

III. VECTOR MAGNETIC PROPERTIES MODEL

In this paper, the hysteron is defined by the equipotential curve in the magnetic field \(H\). Each hysteron is a calculating unit, referred to as hysteresis operator. The vector magnetic properties model is established based on the definition of hysteron. The magnetization contributions of each hysteron is calculated by Eq.(2).

\[
M_j = P_j m_j \cdot M_s
\]  
(2)

where \(M_j\) is the magnetization contribution generated by the \(j\)th hysteron, which has unit magnitude, \(P_j\) is the distribution function of the \(j\)th hysteron, which indicates the existence probability of the \(j\)th hysteron with parameters \(H_{ixj}\), \(H_{iyj}\) and \(e_j\).

In this paper, the distribution functions of hysteron use the hysteron's probability distribution in total, calculated by the formula: \(P_j = n / N_{sum}\). And \(m_j\) is the magnetization vector of the \(j\)th hysteron.

The total magnetization is computed as the vector sum of magnetization contributions generated by every hysteron. The equation can be described by Eq.(3).

\[
M_{sum} = \sum_{j=1}^{N_{sum}} M_j = \sum_{j=1}^{N_{sum}} P_j m_j \cdot M_s
\]  
(3)

where \(N_{sum}\) is the total number of the hysteron considered in the calculation.

Take the alternating magnetization of three hysteron with different interaction field as an example to introduce the implementation of the vector hysteresis model, as shown in Fig. 2(a). The total magnetization is computed as the vector sum of magnetization contributions generated by three hysteron. The equation can be described by Eq.(4).

\[
M = \frac{1}{3} (m_1 + m_2 + m_3) \cdot M_s
\]  
(4)

where the distribution functions \(P_j\) of each hysteron is 1/3. And \(m_1\), \(m_2\) and \(m_3\) are magnetization vector of each hysteron. The magnetization (hysteresis) loops correspond to path \(l_1\): \(A_1-B_1-A_1\) are shown in Fig. 2(b). In this case the absolute value of the magnetization at saturation state in a.u. is 3. There have three barkhausen jumps when the applied field crosses the critical surface of each hysteron from inside to outside.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{(a) Three hysteron and the alternating magnetization path (b) Magnetic loops correspond to path \(l_1\): \(A_1-B_1-A_1\).}
\end{figure}

When a number of hysteresis operators are considered, the
calculated hysteresis loop becomes very smooth. Fig. 3 shows the magnetization (hysteresis) loops of magnetic materials with saturation magnetization intensity $M_s=1.7T$ under alternating magnetic field, which are calculated by the vector Magnetic properties model.

Fig. 3. The magnetization loops of magnetic materials under alternating magnetization field

IV. SIMULATION OF VECTOR MAGNETIC PROPERTIES FOR SMC MATERIALS

In order to verify the practicability and validity of the model, the magnetic properties of SMC material were calculated under the alternating excitation field by using the vector hysteresis model. The calculated results were compared with the measured results which were tested by the improved 3-D tester with flexible excitation coils and novel sensing coils [14]-[20]. The test sampled is a cubic SMC sample (22 mm$^3$) named SMC-SOMALOY™ 500. In order to compare the experimental data and the calculated ones, the magnetic flux density $B$ is converted to magnetization $M$ by using Eq.(5).

$$B = \mu_0 (H + M)$$  \hspace{1cm} (5)

The magnetic properties of SMC-SOMALOY™ 500 were measured under the given alternating experimental condition. And the alternating magnetic properties of the SMC material are calculated by using the vector hysteresis model under the density of alternated applied field is about 0.5T-1.3T when the frequency is 5Hz, 0.5T, 1.5T when the frequency is 20Hz, and 0.5T, 1.6T when the frequency is 50Hz, respectively.

The comparison between the calculated magnetization loci and measured ones are shown in Fig. 4 (a), (b), Fig. 5 (a), (b) and Fig. 6 (a), (b), respectively.
From the comparison loci shown in Fig. 4 (a), Fig. 5 (a) and Fig. 6 (a), it can be concluded that the hysteresis loops are matched well with the measured loops when the density of measurement error have small flaws in calculation curve due to the presence of measurement error.

The conclusion can be obtained from Fig. 4, 5, 6 and 7. The alternated magnetic loops are matched with the measured loops better than the rotational ones. The frequencies of applied field have influence to the simulation result, especially for rotating magnetic field. It can be described as that the vector model can simulate the alternated and rotational magnetic properties under the low strength and low frequency applied field.

V. CONCLUSIONS

A simulation method of the vector magnetic properties of magnetic materials is presented based on 2-D hybrid hysteresis model. The alternated and rotational magnetic properties were studied under different excitation conditions, respectively. The comparison shows that results under low excitation frequency had better agreement with measured ones than high excitation frequency, and the simulation of alternated properties is better than rotational ones. It is indicated that the simulation method can simulate well the alternated magnetic properties with low applied magnetization fields and low excitation frequency.

REFERENCES

[1] Q. X. Yang, Y. J. Li, “Characteristics and Developments of Advanced Magnetic Materials in Electrical Engineering: A Review,” Transactions of China Electrootechnical Society, vol. 31, no. 20, pp. 1-12, 2016.
[2] F. Preisach, “Uberdie magnetische Nachwirkung,” Z. Phys., vol. 94, no. 3, pp. 277-302, 1935.
[3] E. C. Stoner, E. P. Wolhfarth, “A mechanism of magnetic hysteresis in heterogeneous alloys,” Phil. Trans. Roy. Soc., vol. 240A, pp. 599-642, 1935.1948.
[4] M. Kuczmann, “Vector Preisach hysteresis modeling: Measurement, identification and application,” Phys. B Condensed Matter, vol. 406, no. 8, pp. 1403-1409, Jan. 2011.
[5] I. D. Mayergoyz, A. Adly and G. Frienman, “New Preisach-type models of hysteresis and their experimental testing,” J. Appl. Phys., vol. 67, no. 9, pp. 5373-5375, Jun. 1990.
[6] E. D. Torre, E. Pinzaglia and E. Cardelli, “Vector Modeling-Part I: Generalized hysteresis model,” Phys. B: Condensed Matt., vol. 372, no. 1, pp. 111-114, Feb. 2006.
[7] E. D. Torre, E. Pinzaglia and E. Cardelli, “Vector Modeling-Part II: Ellipsoidal vector hysteresis model. Numerical application to a 2D case,” Phys. B: Condensed Matt., vol. 372, no. 1-2, pp. 115-119, Feb. 2006.
[8] E. Cardelli, E. D. Torre, A. Faba, “Numerical implementation of the DPC model,” IEEE Trans. Magn., vol. 45, no. 3, pp. 1186-1189, Apr. 2009.
[9] E. D. Torre, E. Cardelli, “A Preisach-Stoner-Wohlfarth Vector Model,”
IEEE Trans. Magn., vol. 46, no. 1, pp. 3520-3523, Nov. 2011.

17. Y. J. Li, J. G. Zhu and Q. X. Yang, “Magnetic Measurement of Soft Magnetic Composite Material by an Improved 3D Tester with Flexible Excitation Coils and Novel Sensing Coils,” IEEE Trans. Magn., vol. 46, no. 6, pp. 1971-1974, Jul. 2010.

18. Y. J. Li, Q. X. Yang and J. G. Zhu, “Magnetic properties measurement of soft magnetic composite materials over wide range of excitation frequency,” IEEE Trans. Ind. Appl., vol. 48, no. 1, pp. 88-97, Oct. 2012.

19. Y. J. Li, Y. F. Liu and F. G. Liu, “Magnetic Anisotropic Properties Measurement and Analysis of the Soft Magnetic Composite Materials,” IEEE Trans. Appl. Super., vol. 24, no. 5, pp. 1-4, Oct. 2014.

20. C. G. Zhang, Y. J. Li, J. S. Li, Q. X. Yang and J. G. Zhu, “Measurement of Three Dimensional Magnetic Properties with Feedback Control and Harmonic Compensation,” IEEE Trans. Ind. Electron., vol. 64, no. 3, pp. 2476-2485, Jan. 2017.

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