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Original Article

A Robust Approach for FE-Based Analysis of Electromagnetic Systems with Hysteretic Materials

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Abstract

Magnetic hysteresis affects the performance of electromagnetic devices, e.g., motors, generators, and transformers. However, due to complex, non-linear, and multi-valued nature of this phenomenon, its accurate coupling to Finite Element Analysis (FEA) of these devices has been always a challenging task. A novel approach has been presented in this paper for linking FEA to the Preisach model, which is known as the most accurate hysteresis model. An individual Preisach module has been considered for each field component of each element of the hysteresis material mesh. Hysteresis characteristics between each two successive time steps have been linearly approximated. An iterative algorithm has been proposed for obtaining field distributions along with parameters of these lines, simultaneously. The proposed method has been applied to a general magnetic circuit to predict its behavior over a given time span. Space distributions of flux density at some time steps, time variations of flux density and field intensity for one element, induced voltage, and hysteresis characteristics for some elements have been obtained. In contrast with most previous works, approach of this paper could reflect the details of hysteresis phenomenon, including minor loops, into the FEA. Also, it is applicable to problems with non-uniform and rotating field distributions.

Keywords: Coupling of models, finite element analysis, hysteresis, iterative algorithm, Preisach model, transient modeling.

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1. INTRODUCTION

Hysteresis is an interesting phenomenon which is present in almost all low frequency electromagnetic devices, such as motors, generators, and transformers [1]. In some cases it is impairing, but it is useful in some applications. For example, hysteresis results in energy loss in almost all many electric machines [2], while it is the main source of torque production in hysteresis motors [3].

Hysteresis makes the relation between magnetization and field intensity at any point of a magnetic material to be a complex non-linear and multi-valued characteristic. A sample hysteresis characteristic is shown in Fig. 1. Two arbitrary values of field intensity H_1 and H_2 have been highlighted in this figure. It is observed that there could be five and two values of magnetization for H_1 and H_2, respectively. The magnetization at current time depends on the current value and, also, the previous variations of field intensity, i.e., its history. Fig. 1 clearly shows the strong non-linear and multi-valued nature of hysteresis characteristics. Therefore, accurate consideration of hysteresis during the design and analysis of electromagnetic devices is very difficult. Some approximations, including parallelogram [4] and elliptical [5], have been used in this regard. Unfortunately, they are not the most accurate ones and are limited to specific waveforms of field intensity.

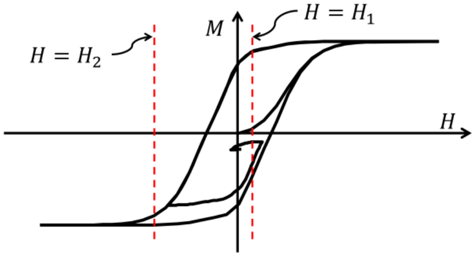

Fig. 1. A sample magnetic hysteresis characteristic, which shows the strong non-linear and multi-valued nature of this phenomenon

Some more actual models have been proposed for hysteresis phenomenon, e.g., Preisach [6], Jiles-Atherton [7], and Hodgdon [8] models. Preisach model, which has several variations, is known as the

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most accurate one [9]. This model receives the current value of field intensity as well as its history, and its output is the current value of magnetization. Also, for an actual electromagnetic device, each point of the hysteresis material experiences its unique field variations, in terms of amplitude and direction. Therefore, hysteresis characteristics differ from point to point within the material. The type of input-output nature of Preisach model and the space variations of hysteresis characteristics makes the coupling of this model to Finite Element Analysis (FEA) of electromagnetic devices to be a challenging task. Many authors have proposed the offline combination of FEA and the Preisach model. This means that they have ignored the effect of hysteresis on the field distribution [10], [11]. This will result into huge errors if the hysteresis property of material is considerable and the magnetic circuit contains air-gaps.

A new approach is introduced in this paper to solve the aforementioned challenges. Instead of using vector Preisach models, which is very time consuming and requires exhaustive physical data of the material [12], a separate classical Preisach module is considered for each field component of each mesh element. Therefore, problems with non-uniform, multi-dimensional, and rotating field distributions could be easily dealt with. These Preisach modules are linked to FEA through a robust iterative algorithm.

The proposed method is described in the next section, where a brief summary of the classical Preisach model is also presented. To show the capabilities of this method, it is employed for transient modeling of a general magnetic circuit in section three. Various results are presented and discussed.

2. MODELING METHOD

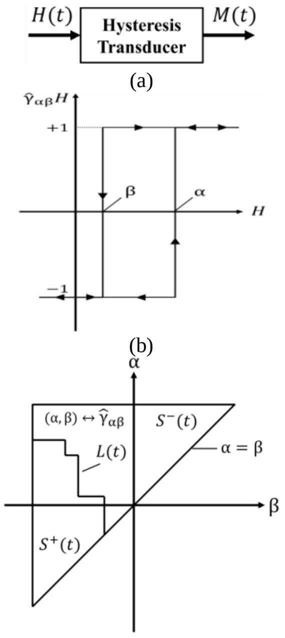
2.1. Preisach model of the hysteresis phenomenon

This section briefly introduces the classical Preisach model. Reference [13] has studied it in depth. Hereafter, this model is simply referred to as Preisach model. A hysteresis transducer is considered as shown in Fig. 2(a). It represents an infinitesimal volume of a magnetic material with hysteresis property. Preisach model could be described by introducing a set of elementary hysteresis operators $\hat{\gamma}_{\alpha\beta}$ and a weight function φ(α,β). This weight function could be determined by standard tests of material. Each operator is represented by a rectangular loop, as shown in Fig. 2(b). Magnetic field intensity at current time, $H(t)$, is the input of these operators. Parameters α and β are the upper and lower switching values of input. The output of these operators, $\hat{\gamma}_{\alpha\beta}H(t)$, could only takes two values ±1. The main relation of the Preisach model gives the current magnetization $M(t)$ as

$$M(t) = \iint_{\alpha\geq\beta} \Phi(\alpha,\beta)\hat{\gamma}_{\alpha\beta}H(t)\,d\alpha\,d\beta \tag{1}$$

Figure 2(c) provides a geometrical interpretation of the Preisach model. In the half-plane α≥β a triangle is considered, which is called the limiting triangle. At any instant t, this triangle is divided into two set of points indicated by $S^{+}(t)$ and $S^{-}(t)$. Each couple (α,β) in $S^{+}(t)$ represents an operator for which $\hat{\gamma}_{\alpha\beta}H(t) = +1$, while each (α,β) point in $S^{-}(t)$ corresponds to an operator with $\hat{\gamma}_{\alpha\beta}H(t) = -1$. In other words, (1) could be rewritten as:

$$M(t) = \iint_{S^{+}(t)} \Phi(\alpha,\beta)\,d\alpha\,d\beta - \iint_{S^{-}(t)} \Phi(\alpha,\beta)\,d\alpha\,d\beta \tag{2}$$



(a)

(b)

(c)

Fig. 2. Description of the Preisach model: (a) A hysteresis transducer; (b) an elementary hysteresis operator; (c) Geometrical interpretation of the Preisach model

The interface between $S^{+}(t)$ and $S^{-}(t)$ is called $L(t)$, which has a stairway shape. Vertexes of $L(t)$ correspond to previous maximum and minimum values of H. In other words, the history of H leaves its effect on the current value of M by the shape of interface $L(t)$. This is the essence of memory mechanism and one the most important aspects of Preisach model.

2.2. The proposed approach

Ignoring the eddy current effects, the governing equation of any electromagnetic system at low frequencies is [14]:

$$\nabla\times\nabla\times\mathbf{A}=\mu_0(\mathbf{J}+\nabla\times\mathbf{M}) \tag{3}$$

where, **A**, **J**, **M**, are the vectors of magnetic potential, current density, and magnetization. Permeability of free space is denoted by μ_0. Equation (3) should be satisfied at any point inside the solution domain and at any instant of time.

For non-magnetic materials, e.g., air, we have $\mathbf{M}=\mathbf{0}$. For magnetic materials with negligible hysteresis property it is possible to express:

$$\mathbf{M}=\chi_m(|\mathbf{H}|)\mathbf{H} \tag{4}$$

where, **H** and χ_m are the vector of magnetic field intensity and magnetic susceptibility, respectively.

For a hysteresis material, the current value of magnetization not only depends on the current value of field intensity, but also on its previous variations, i.e., the history of field intensity. Therefore, in general, it is almost impossible to consider a closed relation between **M** and **H** for a hysteresis material. This makes the FEA of electromagnetic devises with hysteresis materials to be a challenging task.

This paper presents a new technique which solves this problem, effectively. The essence of this technique is that between each two successive time steps, the hysteresis characteristics are approximated by lines (equation (5) and (6)). Each line expresses the flux density at a point in terms of the field intensity at that point. This provides the ability of defining arbitrary BH relationships in the finite element model. The error of this approximation is negligible, when the number of time steps per cycle is relatively high. Furthermore, to take the multi-dimensional and rotational cases into account, for each component of magnetic field at each point of the material, a separate hysteresis characteristic, and hence, a separate Preisach module is considered. Although, this approach is applicable to 3D models, we consider here the two-dimensional (2D) case for simplicity.

In the time range of t and $t+\Delta t$, and assuming that Δt is relatively small, we introduce the following relations for point (x,y) of the hysteresis material

$$B_x(x,y)=\mu_0\mu_{r,x}(x,y)H_x(x,y)+B_{r,x}(x,y) \tag{5}$$

$$B_y(x,y)=\mu_0\,\mu_{r,y}(x,y)H_y(x,y)+B_{r,y}(x,y) \tag{6}$$

In these equations, B_x and B_y are the x and y components of magnetic flux density, H_x and H_y are the x and y components of magnetic field intensity, $\mu_{r,x}$ and $\mu_{r,y}$ are the relative permeabilities for x and y components, and $B_{r,x}$ and $B_{r,y}$ are the remanent flux densities for x and y components. According to nature of hysteresis characteristics, $\mu_{r,x}$ and $\mu_{r,y}$ are always positive values. However, $B_{r,x}$ and $B_{r,y}$ could take both the positive and negative values, or even they could be equal to zero.

Now, the electromagnetic problem could be solved by FEA. It should be noted that $\mu_{r,x}$, $\mu_{r,y}$, $B_{r,x}$, and $B_{r,y}$ depend on space coordinates and time. In other words, they are not predefined, as the case of permanent magnets, for example. Therefore, a novel FE-based iterative algorithm has been devolved which finds these parameters and field distributions, simultaneously. This is done by successive runs of FE model of the electromagnetic problem and Preisach model of hysteresis phenomenon. It is possible by linking a programing environment to a FE package. The iterations continue until for each space component of each element, the estimated flux densities of both Priesach and FE models converge together. It should be mentioned here that assuming linear relationships between filed intensities and flux densities result in robust convergence of the method. The detailed flowchart of the developed iterative modeling algorithm is shown in Fig. 3. It is emphasized here that although this algorithm has been presented for the 2D case, but it is easily applicable to 3D case.

3. RESULTS AND DISCUSSION

An electromagnetic system is simulated to show the ability of proposed method. Fig. 4 shows the 3D presentation of the selected system, i.e., the case study. It is a general electromagnetic system, which contains air-gap, soft magnetic material and winding, in addition to a hysteresis material. This material is placed at the corner to show that the method could deal with non-uniform, multi-dimensional, and rotating fields. Some of the major loops of hysteresis material, which is from the Steel 4340 family with specific heat treatment (quench-temper), are shown in Fig. 5.

Hysteresis modeling techniques are very time consuming. Therefore, to avoid extensive simulation times, the study has been carried out for the 2D model of the selected system. Fig. 6(a) shows the 2D finite element model of case study and its meshing. The hysteresis material has been meshed by quadratic elements for simplicity. The zoomed view of this mesh is shown in Fig. 6(b), where numbers are assigned to some of the elements for future references.

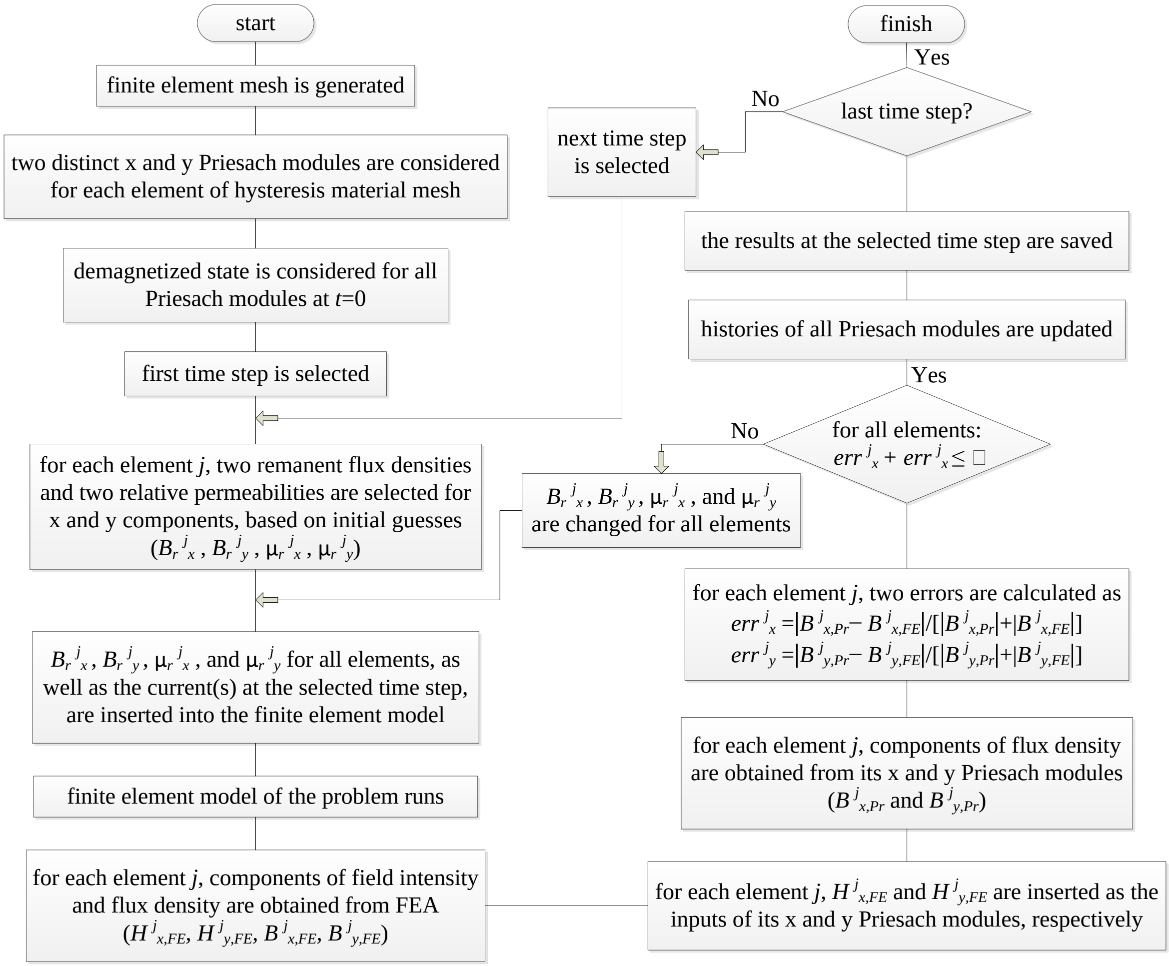


Fig. 3. The proposed algorithm for FE analysis of problems with hysteresis material

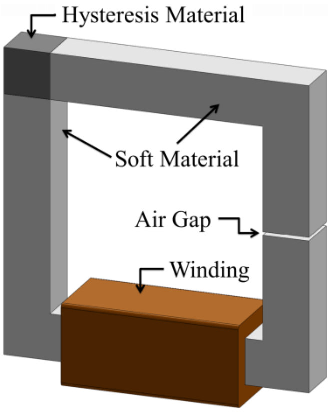


Fig. 4. 3D view of the case study

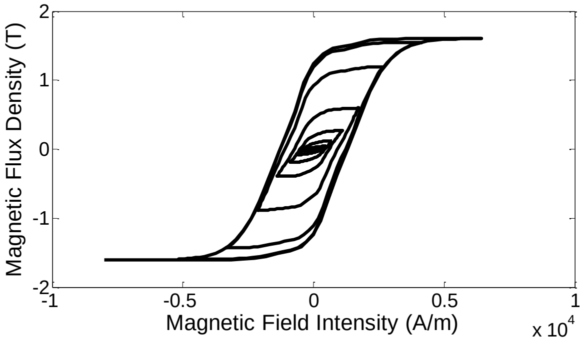
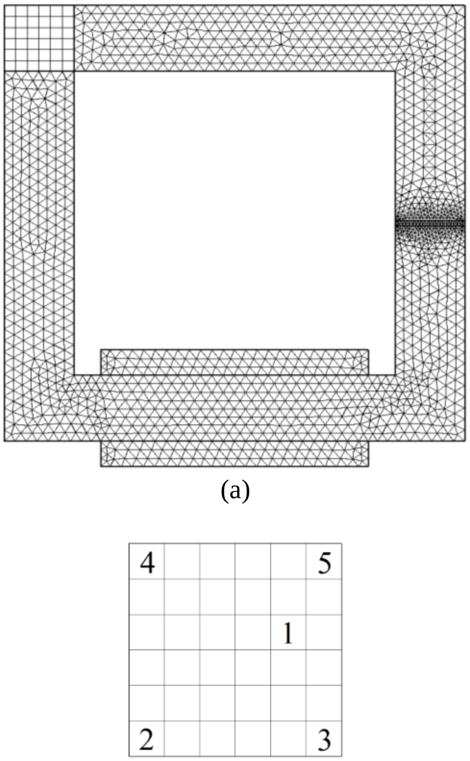


Fig. 5. Some major hysteresis loops of the material used in the construction of case study (Steel 4340 with specific heat treatment)



(a)

(b)

Fig. 6. 2D FE mesh: (a) Whole solution domain; (b) Hysteresis material

One of the main advantages of proposed method is that there is no necessity for limiting the input current to a pure sinusoidal waveform. Therefore, to illustrate this capability, a current waveform with considerable harmonic content has been selected, as shown in Fig. 7. The fundamental frequency of this current is 50 Hz. The FE model was linked to Priesach modules by coupling Matlab programing environment to COMSOL Multi-physics FE package. The simulation was carried out for 1.5 cycles and each cycle was divided into 100 time steps. The average number of iterations for each time step was about 20. This means that the FE model was run for about 3000 times. Total elapsed time was 26339 seconds on a PC with Intel® Core™ i5-2430M CPU and 4 GBs of RAM. Flux density distributions at three different time steps are depicted in Fig. 8, along with some flux lines and their directions.

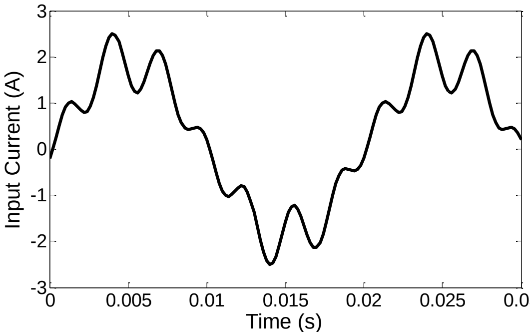
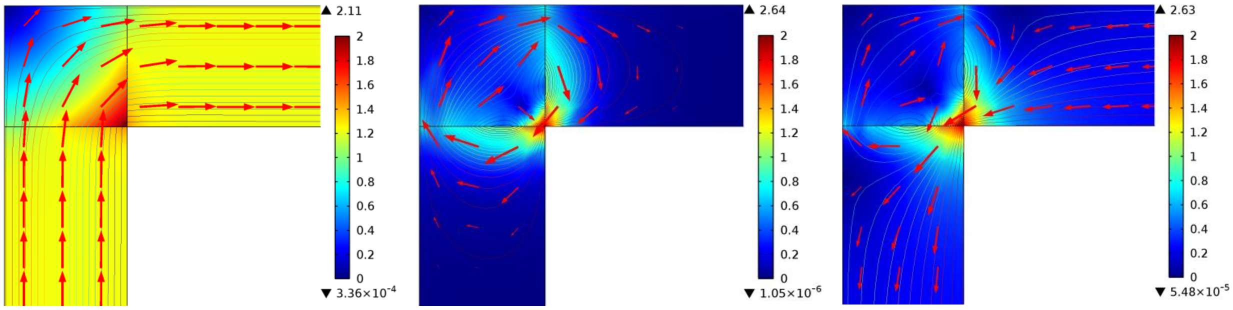


Fig. 7. Time variations of the input current

Fig. 8(a), which is related to t=0.0078 s, clearly shows that the flux density distribution in the hysteresis material is non-uniform and two-dimensional (2D). However, it does not provide an explicit sign of hysteresis property. This property is evident in two other time steps. Input current is approximately equal to zero at t=0.0102 s. Flux distribution at this instant is shown in Fig. 8(b). Since the winding current is zero here, it does not produce any flux lines. However, due to remanent flux densities of hysteresis material, it acts like a source and produce some flux lines in neighboring areas. At the next time step, i.e., t=0.0104 s, the direction of flux lines in the soft magnetic core is reversed (Fig. 8(c)), because the sign of winding current is negative now. Interestingly, the flux lines in hysteresis material preserve their direction. Delay between flux densities and field intensities of the hysteresis material is the reason is this phenomenon.



(a) (b) (c)

Fig. 8. Flux density distribution and flux lines at some time steps: (a) t=0.0078 s; (b) t=0.0102 s; (c) t=0.0104 s. The effect of hysteresis phenomenon on the flux lines is observed clearly

The induced voltage has been obtained by integrating the *z* component of vector magnetic potential on the winding area, and is plotted in Fig. 9. As expected, it is highly polluted by harmonics.

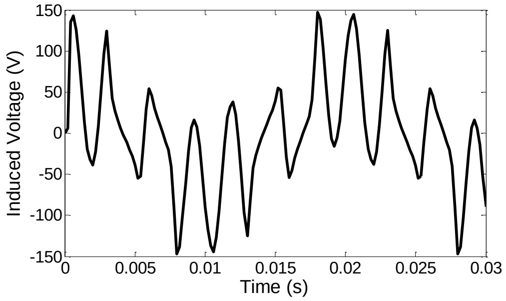


Fig. 9. Time variations of the winding induced voltage

Each element of hysteresis material experiences different field variations. Therefore, as explained before, two distinct *x* and *y* Preisach modules have been considered for each element (total number of 36×2=72 Preisach modules). Consequently, each component of each element has its own unique hysteresis characteristic. For example, Fig. 10(a) presents the variations of *x* and *y* components of field intensity at element No. 1 (refer to Fig. 6(b)). Flux densities variations for this element are shown in Fig. 10(b). These figures clearly show the difference between *x* and *y* field variations inside an element. Also, the nonlinear relations of flux densities and field intensities could be understood.

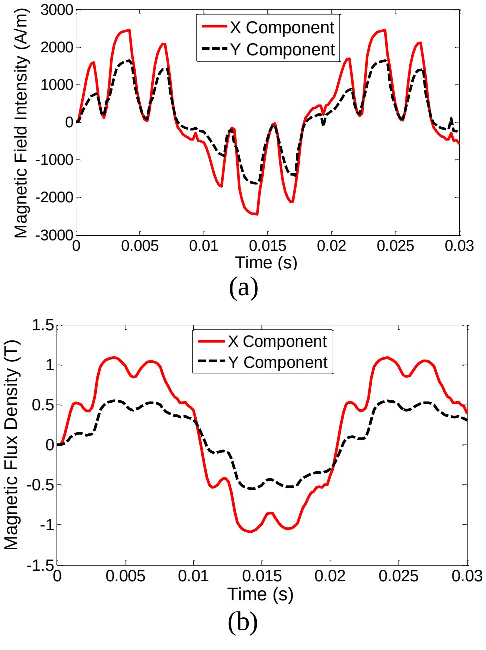


Fig. 10. Time variations of *x* and *y* field components for element No. 1 of hysteresis material mesh: (a) Magnetic field intensity; (b) Magnetic flux density

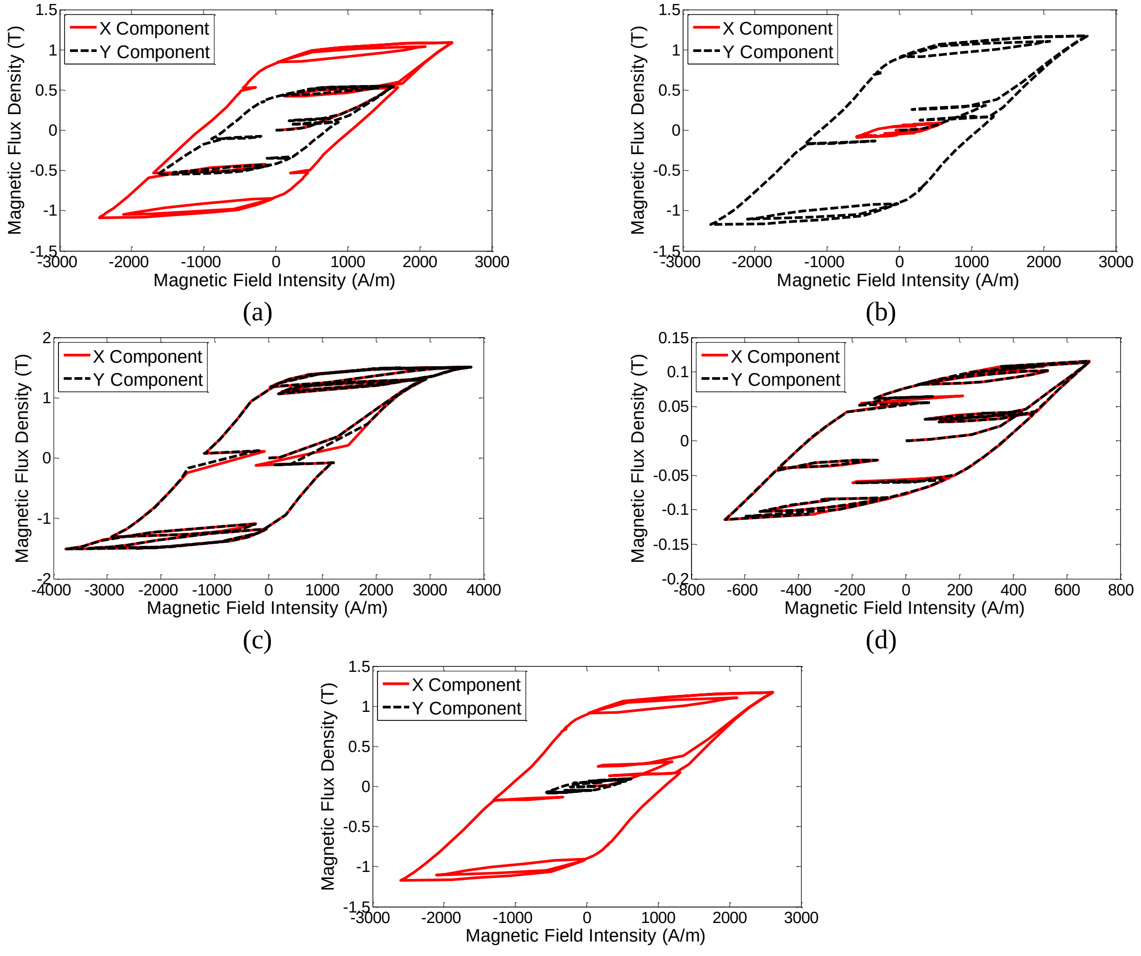
By eliminating the time variable between Fig. 10(a) and Fig. 10(b), *x* and *y* hysteresis characteristics are obtained for element No. 1, as shown in Fig. 11(a). For this element, *x* hysteresis characteristic is larger than *y* characteristic. Also, it should be noted that minor hysteresis loops have been appeared on these characteristics, which are the consequences of time harmonics of fields. Hysteresis characteristics for elements 2, 3, 4, and 5 are also depicted in Fig.s 11(b)-11(e), respectively. These figures clearly show that the space variations of hysteresis characteristics have been taken into account by the proposed method.

4. CONCLUSIONS

Finite element modeling of electromagnetic devices which contain materials with hysteresis property is challenging. A novel iterative approach was introduced in this paper for linking the Preisach model of hysteresis to FEA. This method is based on the linear approximation of the BH characteristics for each element of mesh, between two successive time steps. A general magnetic circuit was selected as the case study. The proposed approach was implemented by linking the programming environment of Matlab to the FE package COMSOL Multi-physics. Various results were obtained from the transient modeling of the case study. By investigating these results, the following conclusions could be enumerated:

- Modeling with the proposed method does not require any change in the FE formulations and its relevant codes,
- The proposed method could be employed for study of any low frequency electromagnetic device with any type of hysteresis characteristics,
- The proposed method is not limited to pure sinusoidal sources, but arbitrary input waveforms are allowed,
- The proposed method satisfactorily deals with non-uniform, multi-dimensional, and rotating field distributions,
- Details of hysteresis characteristics, such as minor loops, are discernible in the results.

It should be noted that other models of hysteresis phenomenon, such as Jiles-Atherton and Hodgdon, could also be employed in the proposed method. Also, it was assumed that the effects of eddy currents could be ignored. By some modifications, it is possible to extend the proposed method to eddy current problems. This will be presented in future works.



(a) (b) (c) (d) (e)

Fig. 11. Hysteresis characteristics for some elements of the hysteresis material mesh: (a) element No. 1; (b) element No. 2; (c) element No. 3; (d) element No. 4; (e) element No. 5

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