

# Efficient Use of Preisach Hysteresis Model in Computer Aided Design

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**Abstract**—The paper presents a practical detailed analysis regarding the use of the classical Preisach hysteresis model, covering all the steps, from measuring the necessary data for the model identification to the implementation in a software code for Computer Aided Design (CAD) in Electrical Engineering. An efficient numerical method is proposed and the hysteresis modeling accuracy is tested on magnetic recording materials. The procedure includes the correction of the experimental data, which are used for the hysteresis model identification, taking into account the demagnetizing effect for the sample that is measured in an open-circuit device (a vibrating sample magnetometer).

**Index Terms**—computational electromagnetics, electro-magnetic modeling, magnetic materials, magnetic hysteresis, numerical analysis.

## I. INTRODUCTION

The magnetic hysteresis complexity [1], [2] generated a large palette of hysteresis models [3]-[6], which can be used for a refined modeling of electromagnetic devices. The Compumag Society focused on this subject by periodical papers [7]-[9] containing the state of the art.

In Electrical Engineering, a hysteresis model must be able to approximate the real magnetic material behavior for different technical problems, with a good balance between the simulation accuracy and the required computing resources. This is the reason for the large spreading of a general hysteresis model like the Preisach one [10] in Computer Aided Design (CAD), despite its known limits.

This work presents a practical detailed analysis regarding the use of the classical Preisach hysteresis model, covering all the steps, from measuring the necessary data for the model identification to the implementation in a software code. An efficient procedure is proposed for the identification and the implementation of Preisach model in Electrical Engineering CAD, outlining the importance of each detail during the data processing for the model efficiency estimation.

Partial studies were previously published by our team, but the entire methodology of the hysteresis treatment in a CAD process is now presented for the first time, allowing a better understanding of the problem complexity and how a researcher could manage it. The proposed method is original by the combining several distinct components: the measured data correction, the use of an efficient storage and precise updating of the state line in the Preisach hysteresis model,

the numerical error reduction by an adequate coupling of the hysteresis model to the electromagnetic field model and the use of the numerical Everett function [11] instead of an analytical Preisach function.

## II. HYSTERESIS MODELING IN CAD

The numerical analysis of electromagnetic devices requires an efficient hysteresis model describing the time-dependent material relationship. There are scalar hysteresis models included in 2D finite element (FEM) analysis [12], [13] and a magnetic reluctivity tensor was used for a 2D material relationship [14]. The numerical results were compared with measurements [15] and neural network hysteresis modeling was included in FEM analysis [16].

The modeling of steel laminations in the FEM analysis of transformers or electrical machines [17] is very useful in CAD. Many works (e.g. [18]-[20]) are dedicated to the numerical methods used for nonlinear problems - the fixed-point method and the Newton-Raphson method; the results are useful to adapt the procedure for problems including materials with hysteresis. Another useful general method in Electromagnetic CAD is based on the surface impedance boundary conditions [21], its application covering both the high frequency and the low frequency technical devices.

The simulation of magnetic recording process was studied including the Preisach model in an integral equation [22], in 2D FEM [23] or considering a vector Preisach model [24]. Implementation in 3D FEM models was reported in [25] and the losses estimation considering a dynamic hysteresis model can be found in [26].

The micro- and nano-magnetic approaches (e.g. [27]) are also present in literature, especially for magnetic hysteretic nondestructive testing, magnetic sensor design, losses estimation or studies about the magnetization processes [28]. However, the phenomenological hysteresis models (Preisach [10], Stoner-Wohlfarth [29] or Jiles-Atherton [30]) are preferred in engineering.

The tendency is to implement more complex hysteresis models, like vector or dynamic models. But the coupling between the hysteretic material model and CAD procedures are still difficult and the existing commercial software (e.g. FLUX, ANSYS, JMAG, MagNet) does not include a real general hysteresis model. Usually, the hysteresis cycle of the soft magnetic materials is approximated by the average nonlinear magnetization curve and the behavior of the hard magnetic materials (e.g. permanent rare-earth magnets) is reduced to the linear segment of the  $B$ - $H$  characteristic in the second quadrant. An alternative could be the use of a very simple but efficient hysteresis model, based on the

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approximation of magnetization curves by lines and arcs [31].

Another difficulty is that many problems are solved using the magnetic vector potential formulation and an inverting of the hysteresis model is required. This inverse model imposes the problem reformulation and an inefficient iterative computation [32], [33]; an improvement could be implemented considering the parallel computing [34].

This survey on the hysteresis modeling in CAD shows the large diversity of approaches and the difficulty of building a general method for any application. The complexity of the hysteresis phenomenon imposes a great difference between the nonlinear problems and the electromagnetic field problems involving magnetic materials with hysteresis.

### III. CLASSICAL PREISACH MODEL IN ELECTROMAGNETICS

The classical Preisach model [10] replaces the ferromagnetic material by a collection of dipoles (hystérons) having a magnetic behavior described by a rectangular hysteresis cycle. The hystérons distribution as a function of their up- and down-switching values  $(a, b)$  identifies the modeled material. The model output (the magnetic flux density  $B$ ) is computed as:

$$B(H) = \iint_{S_+(H)} P(a, b) \cdot da \cdot db - \iint_{S_-(H)} P(a, b) \cdot da \cdot db, \quad (1)$$

where  $P(a, b)$  is Preisach distribution function and  $S_+$ ,  $S_-$  are the areas corresponding to the positive and negative saturated hystérons in the Preisach triangle  $(-H_s \leq b \leq a \leq +H_s)$  – see Fig. 1. The magnetic history is recorded by the staircase line between  $S_+$  and  $S_-$ , which depends on all the previous values of the magnetic field  $H$  (model input). The model is static, scalar and it considers the irreversible magnetization only.

The Preisach function identification may be done by analytical or numerical approximation. In the first case, one can determine the Preisach function by double differentiation of experimental Everett functions [3] or by identifying the parameters of particular density functions (e.g. a factored –Lorentzian or a lognormal-Gauss distributions [4]); the first procedure amplifies the inherent measurement noises and the other presents unpredictable modeling errors because there is no real justification for assuming one particular distribution function [35].

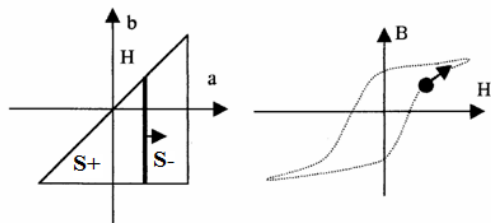


Figure 1. Magnetic state in the Preisach triangle (left) and in the  $H$ - $B$  plan (right).

The model using the analytical Preisach function has a few parameters (scalars), its implementation is simple, but the function type must be correlated to the magnetic material properties and the accuracy depends on the experimental data used for identification.

The numerical approximation involves a step-function defined on the meshed Preisach triangle (see Fig. 2). A numerical Preisach distribution could involve numerical errors, but it can be adapted for any material. The model identification requires complex measured data (e.g. first-order reversal curves – FORCs), but it may use limited experimental data [36].

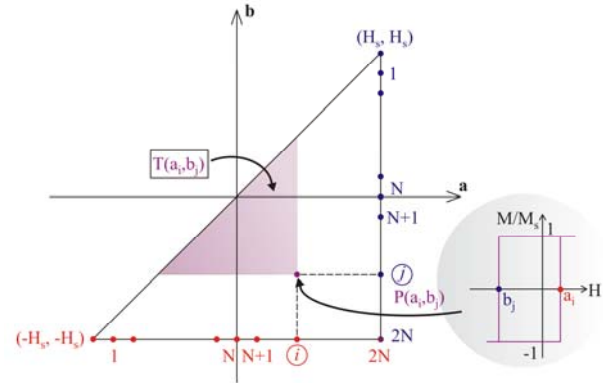


Figure 2. Preisach triangle

In our study, the model numerical parameters are the values of the Preisach integrals over a rectangular triangle having the corner in each node of the Preisach triangle mesh (Everett function), marked by  $T(a_i, b_j)$  in Fig. 2.

### IV. DATA PROCESSING FOR THE MODEL IDENTIFICATION

A numerical analysis of the electromagnetic field uses the **B-H** constitutive relationship for the magnetic material modeling. However, the hysteresis phenomenon is related to the magnetization processes and many experimental data, which are involved in the hysteresis model identification, are obtained by measuring the total magnetic moment  $\mathbf{m}$  of the magnetic material sample. Consequently, the relationship between the magnetic field strength  $\mathbf{H}$  and the magnetization  $\mathbf{M}$  is preferred for the hysteresis model identification; the magnetic flux density  $\mathbf{B}$  can be easily computed with the fundamental relation

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (2)$$

The measurements were made in our Laboratory of Technical Magnetism using a vibrating sample magnetometer VSM-7304 Lake Shore. The model identification requires a set of first order reversal curves (FORCs) [37] related to magnetic recording tapes (isotropic and anisotropic materials), the samples being disks with 4 mm diameter. For example, Fig. 3 presents the measured FORCs for the easy axis of a subway magnetic card.

The novelty of our method is the identification of the values for the Preisach integrals over a rectangular triangle having the corner in each node of the Preisach triangle mesh (Everett function), directly from the measured FORCs, eliminating the measuring and processing errors [38]. This procedure is stable and allows a fast numerical computing during the CAD process. For example, the obtained Everett function for a recording tape is very smooth (Fig. 4.a) comparing to the corresponding numerical Preisach function (Fig. 4.b).

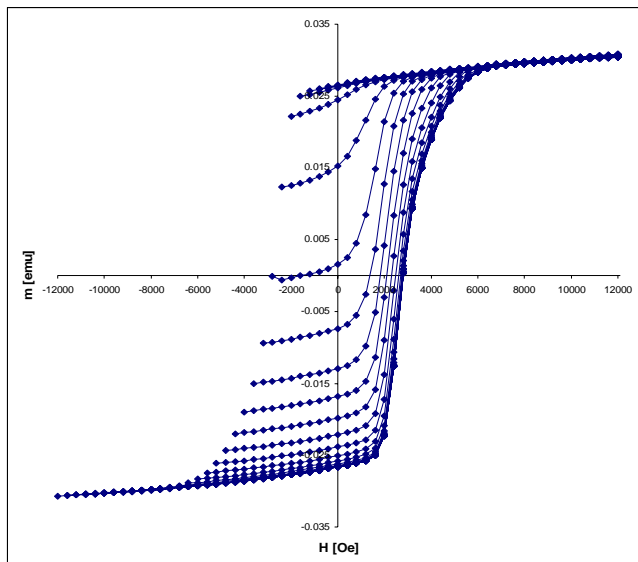
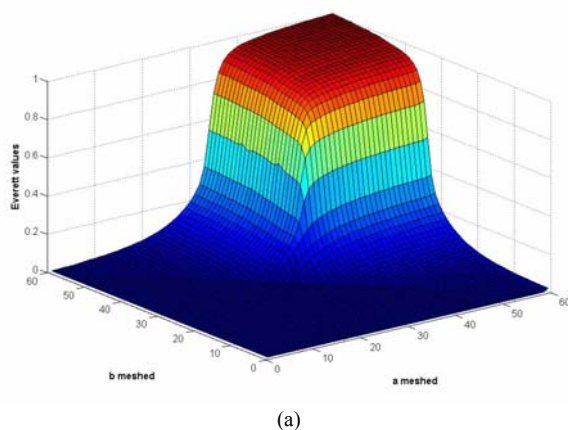
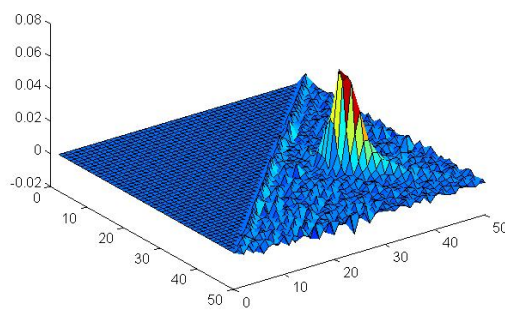


Figure 3. Experimental FORCs for the easy axis of the subway card.



(a)



(b)

Figure 4. Identified Preisach model for a magnetic tape: a) Everett function; b) Preisach function.

A serious judgment about the hysteresis model accuracy must consider the error sources and how these errors could be reduced by a proper acquisition and processing of experimental data. One must take into account:

- the correlation between the FORCs number, the saturation magnetic field  $H_s$  and the curve slope;
- the presence of the reptation phenomenon and the saturation of the VSM yoke (producing the “image effect”);
- the equipment noise that could affect the experimental

data accuracy, especially for small samples with weak magnetic moment; the FORCs smoothing can improve the numerical identification, but it changes the real numerical hysteresis curves;

- the demagnetizing field (depending on the sample shape and magnetic susceptibility) and the position of the magnetic field sensor inside the VSM air gap.

Supplementary, it is very difficult to maintain a constant setup of the equipment and constant environmental conditions for a long time measurement. The high slope of the material characteristic around the coercive field imposes a great number ( $N$ ) of FORCs for identification; the total number of measurement points will be  $N(N+1)$ . For example, if only (100x100) cells are used for Preisach plane meshing and the average time for each measurement point is 10 sec., the total measurement time will be around 28 hours. The temperature and the saturation of the VSM yoke can determine a drift of the saturation point for different FORCs. A solution could be to normalize each FORC to its maximum value.

Our algorithm for experimental data processing includes a numerical correction of the magnetic field  $H$  inside the sample, taking into account the magnetometric demagnetizing factor  $N_m$  and the field correction factor  $N_H$ :

$$H = N_H \cdot H_a - N_m \cdot M, \quad (3)$$

where  $H_a$  is the applied magnetic field component along the magnetization axis in the field probe zone. The field correction factor  $N_H$  is very useful in the open-circuit magnetic measurements, allowing the use of the correct value of the magnetic field on the sample surface, instead of the value measured by the Hall sensor. These values can be different if the sensor is not situated close to the material surface and the field lines are concentrated through the sample having high magnetic permeability.

The demagnetizing factor  $N_m$  depends on the sample shape and on the susceptibility value, so the correction must be made for each measurement point. Our approach (detailed in [38]) considers an accurate 3D magnetostatic model, which is analyzed for any sample shape with the FLUX (Cedrat®) software package, based on the finite element method (FEM). This procedure allows computing both the demagnetizing factor  $N_m$  (Fig. 5) and the field correction factor  $N_H$  (Fig. 6), which depends on the position of the magnetic field probe (fixed), the material susceptibility and the VSM modeling (considering the air gap only, the electromagnet poles or the entire magnetic circuit).

The material magnetic history is recorded only using the corners coordinates of the state staircase line in the Preisach triangle. Consequently, the model output is computed very fast, starting only from the associated values of the Everett function for the state line corners. The accuracy is maximized using the real state line corners, not the mesh nodes, the values of the Everett function being computed by linear Lagrange interpolation for each rectangular mesh element – see Fig. 7. The new point of the state staircase line is determined depending on the magnetic field evolution (increasing or decreasing) and the mesh element (cell) where the interpolation will be performed is identified.

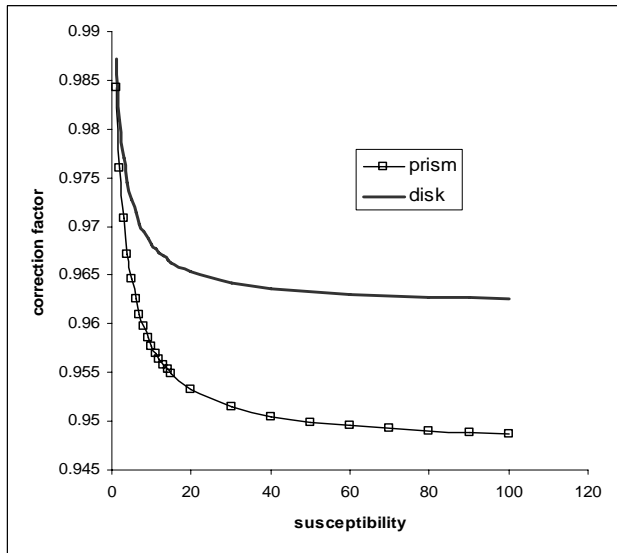
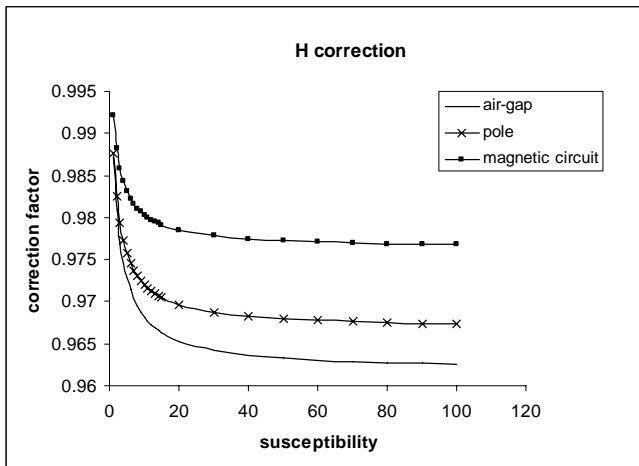
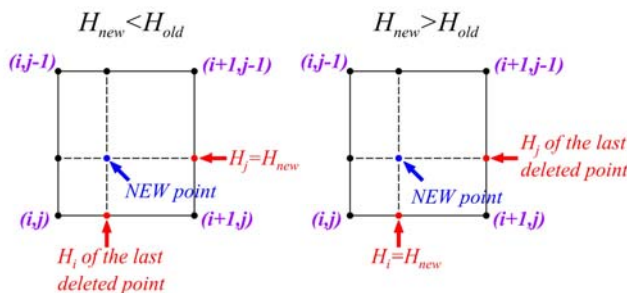
Figure 5. Values of the demagnetizing factor  $N_m$ .Figure 6. Values of the field correction factor  $N_H$ .

Figure 7. Finding a new history reversal point in a Preisach cell.

The magnetic history management for each finite element considers the adequate replacement of the deleted reversal points of the staircase state line, according to Fig. 8.

The accurate model identification by a careful data management has good results in the numerical implementation of the hysteresis model. An example of numerical test involves second order reversal curves and minor hysteresis loops, the results showing a good accuracy for magnetic recording materials (Fig. 9). The presented example shows the importance of the maximum magnetic field  $H_{max}$ , which is used for the model identification - in the FORCs measurement and, consequently, for the Preisach triangle boundaries. If  $H_{max}$  is higher, close to the saturation value, the evolution on FORCs is accurately

simulated, but the error increases for the higher order reversal curves, due to the larger step meshing (the number of the mesh cells in the Preisach triangle is the same for 6 kOe and 12 kOe). A better solution could be obtained if the mesh step was variable, but the computing complexity would dramatically increase.

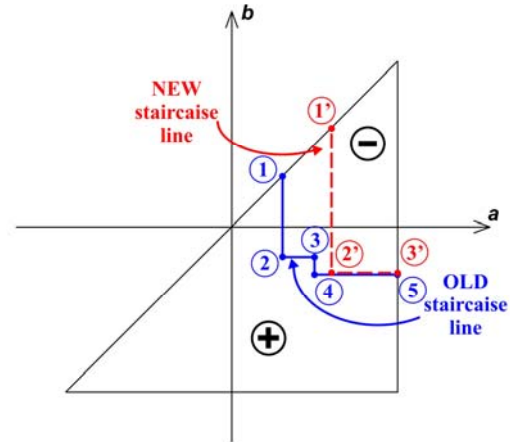


Figure 8. History line updating.

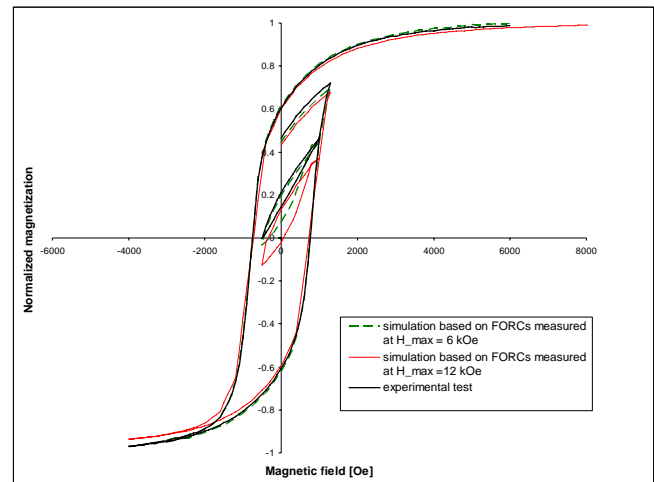


Figure 9. Testing the hysteresis model accuracy.

## V. REQUIREMENTS REGARDING THE IMPLEMENTATION OF THE PREISACH HYSTERESIS MODEL IN CAD CODE

The implementation of a hysteresis model to describe the magnetic material relationship in an electromagnetic field problem is very complex, even for a scalar model like the classical Preisach one. Indeed, the computed solution accuracy depends on the experimental data, which must be precisely measured and corrected in order to represent the magnetic material relationship and not a sample-dependent characterization.

The correct experimental data guarantee the results of the hysteresis model identification for the given material. Our proposed method for processing the experimental data measured with VSM assures the correct identification of the numerical Everett function for the Preisach model that will be incorporated in CAD software.

Another requirement for using hysteresis models in electromagnetic field problems is the compact storage of the model parameters and of the magnetic history for each element of the problem domain (e.g. finite elements). For



the Preisach model, the use of Everett integrals is recommended for a compact storage and a robust computation.

As it is known, the Newton-Raphson procedure could be non convergent for material characteristics with inflexion points, like the hysteresis branches. The polarization method (fixed-point type) is preferred, but a reasonable computing time in CAD imposes a fast computation of the model output value during the iterative process. The use of the Preisach classical model, identified by Everett integrals, and the compact storage of magnetic history by the extreme values allows a fast computation in CAD.

The numerical solving of an electromagnetic problem takes into account the regime type (static, quasi static or time-dependent) and the materials that compose the analyzed electromagnetic device. An enhanced problem formulation could involve the magnetic vector potential and the hysteresis model must have  $\mathbf{B}$  as input, so one must have the possibility to use an inverse hysteresis model.

The implementation of a hysteresis model (e.g. Preisach) in CAD software is possible if the solver code is accessible or if new functions related to the materials modeling could be added. The existing commercial software for CAD does not allow this user control and it is recommended to build a dedicated solver, which could use existent professional pre- and post-processors.

Our method starts from the partial differential equations describing the electromagnetic field problem. Their solving use a classical numerical method, like finite differences, finite elements etc. A linear model is used for the magnetic material relationship:

$$B = \mu H + I, \quad (4)$$

where the optimal value of the magnetic permeability  $\mu$  for the virtual linear material is chosen according [39] and the polarization  $I$  is iteratively corrected. Indeed, the computed  $H$  is the input of the Preisach hysteresis model, which was identified for the materials involved in the electromagnetic problem; the output  $B$  allows to correct the polarization  $I$  and the new linear relationship (3) is used for the next iteration – re-computation of the solution for the linear electromagnetic problem. The proposed algorithm is presented in Fig. 10.

The algorithm can be improved by: the adaptive change of the permeability value as a function of the current hysteresis curve slope, the computation parallelization (e.g. applying the hysteresis model for different finite elements), and the use of artificial intelligence techniques for preserving the same possible evolution path for neighbor finite elements.

## VI. CONCLUSION

The paper shows that the accuracy of a numerical model, involving the use of the classical Preisach hysteresis model, depends on all the steps, from measuring the necessary data for the model identification to the implementation in a software code for CAD in electrical engineering.

The proposed methodology starts from a Preisach hysteresis model identification, which requires a set of first order reversal curves (FORCs). These experimental data are corrected taking into account the sample demagnetization

and the position of the field sensor. Data processing continues with the identification of the values for the Everett function directly from FORCs, minimizing the measuring and processing errors. The procedure is stable and allows a fast numerical computing during the CAD process.

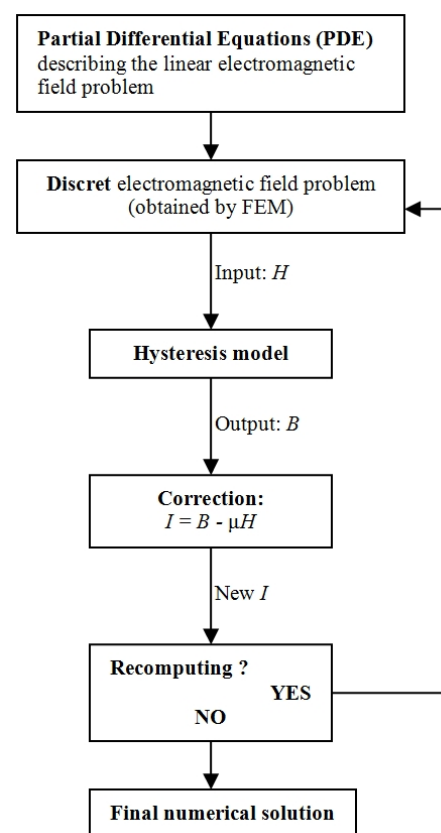


Figure 10. Iterative method for solving electromagnetic problems involving hysteretic magnetic materials.

The computation is enhanced by considering the material magnetic history that is recorded using the corners coordinates of the state staircase line in the Preisach triangle. The global accuracy is maximized using the real state line corners, not the mesh nodes of the Preisach triangle. The method efficiency was proven for magnetic recording media and the algorithm is able to be implemented in a finite element software code used in Electrical Engineering CAD.

The main requirements imposed on the hysteresis model implementation in CAD and the associated procedure can be used for a future development of an efficient software code, able to compute the electromagnetic field in devices involving magnetic materials with hysteresis. The development of a general numerical procedure for solving 2D or 3D electromagnetic problems, including a complex constitutive relationship that describes vector and/or dynamic hysteresis properties, is a top challenge for the scientific community in the next years.

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