NONLINEAR MAGNETIC MODELING BY FVM FOR JILES-ATHERTON HYSTERESIS MODEL USING A GENETIC ALGORITHM PARAMETER'S IDENTIFICATION

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Abstract: A modified Jiles–Atherton model presenting the magnetic induction as an independent variable is proposed in order to be directly used in time-stepping finite-volume calculations applied to the magnetic vector potential formulation. This model is implemented in the field calculation procedure by introducing a differential reluctivity. The parameters set of the Jiles–Atherton hysteresis model is identified by using a real coded genetic algorithm. The parameters identification is performed by minimizing the mean squared error between experimental and simulated magnetic field curves. The calculated results are validated by experiences performed in an SST's frame.

Keywords: Magnetic hysteresis, Jiles-Atherton model, genetic algorithm, parameters identification, finite volume method (FVM).

1. Introduction

To design and to study electromagnetic systems, field calculation codes are more and more used. We have at our disposal a virtual prototype in which geometrical dimensions and material characteristics can easily be modified. But, to achieve an efficient design procedure, the used models have to be accurate and fast. Satisfying these two criteria simultaneously is not easy; therefore a compromise has to be made. Lots of electrical devices are made up of ferromagnetic materials. To represent the behaviour of such materials in field computation codes, nonlinear univocal function are generally used. But, in this case, the hysteresis phenomenon is neglected. In that context, the use of a constitutive relationship which takes into account the hysteresis phenomenon would be more useful to improve the accuracy. Different hysteresis models are available for incorporation into the finite volume framework. Although the Preisach model appears to be the hysteresis model of choice, the J–A model is attractive because of its simplicity and ease of implementation. The attributes of the J–A hysteresis model including level of accuracy for several practical materials, ease of implementation into the FVM (Finite Volume Method), and computational efficiencies make it a viable choice for implementation into a 2-D finite volume model [1], [2]. This study will choose the model best suited from the standpoint accuracy, processing speed and ease of implementation. The working hypotheses are restricted to the case of static regime and the equation that we solve axis-symmetric in two dimensions 2-D, is the magnetodynamic non-linear. Thus, the finite element method has proved it self as an effective tool in solving differential equations, it allows another to take into account complex geometries and non- linearity's possible, only its implementation is against a fairly complicated. So we choose in our study for the method of finite volume, which is less difficult to achieve and simple design.

2. Finite Volume Formulations Including Magnetic Hysteresis

2.1 Basic Field Axi-Symmertical Equations

The derivation of the finite volume equations begins with Maxwell's field equations

$$div \vec{B} = 0 \tag{1}$$

$$curl \vec{H} = \vec{J} \tag{2}$$

Where

$\vec{B}$: Magnetic flux density,

$\vec{H}$: Magnetic field intensity,

$\vec{J}$: Total current density.

Where $\vec{J}$ is the total current density which is the sum of the conductive current density $\vec{J}_c$ and the displacement current density $\vec{J}_d$.

The Maxwell field equations are extended to allow treatment of hysteresis by including the constitutive equation for magnetic material. The general equation for a ferromagnetic material can be expressed as

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \tag{3}$$

Where $\vec{M}$ the nonlinear magnetization is function, and μ_0 is the permeability in free space [1]. The flux density $\vec{B}$ can be expressed as the circulation of a potential vector, $\vec{B} = \nabla \times \vec{A}$, where $\vec{A}$ is the magnetic vector potential naturally satisfying Maxwell's equation $\nabla \cdot \vec{B} = 0$ since the divergence of the curl is zero.

The most obvious way is to directly use μ_0 (or $\nu_0 = 1/\mu_0$) and $\vec{M}$ in the field equation by applying the vector form of (3) Ampere's law. The field equation is then given by

$$\nabla \times \left(\nu_0 \nabla \times \vec{A}(t + \Delta t) \right) = \vec{J}(t + \Delta t) + \nabla \times \vec{M}(t + \Delta t) \tag{4}$$

where $\vec{A}(t + \Delta t)$, $\vec{J}(t + \Delta t)$ and $\vec{M}(t + \Delta t)$ are, respectively, the magnetic vector potential, the current density, and the magnetization vectors at time $(t + \Delta t)$, Δt is the time step.

When considering $\vec{J}_d$ as negligible in the azimuth direction (axis-symmetrical Formulation), (4) is written using the tow-dimensional (2-D) magnetic vector potential $\vec{A}$ as unknown in cylindrical coordinates as

$$\begin{cases} \dfrac{\partial}{\partial z}\left(\dfrac{\nu_0}{r}\dfrac{\partial A}{\partial z}\right) + \dfrac{\partial}{\partial r}\left(\dfrac{\nu_0}{r}\dfrac{\partial A}{\partial r}\right) - \dfrac{\sigma}{r}\dfrac{\partial A}{\partial t} = -J_{ex} + \left(\dfrac{\partial M_r}{\partial z} - \dfrac{\partial M_z}{\partial r}\right) \\ A = rA_\phi \end{cases}$$

2.2 Jiles-Atherton Model of Hysteresis

The original J–A model presented in [3] gives the magnetization *M* versus the external magnetic field *H*. This model is based on the magnetic material response without hysteresis losses. This is the anhysteretic behavior which M_{an} *(H)* curve can be described with a modified Langevin equation

$$M_{an}(H) = M_s \left[\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right) \right] \tag{6}$$

Where $H_e = H + \alpha M$ is the effective field experienced by the domains: *H* is the external applied field and *α* the mean field parameter representing inter-domain coupling. The constant *a* is an increasing function of the temperature. The magnetization *M* is decomposed into its reversible component M_{rev} and its irreversible component M_{irr}.

$$M = M_{irr} + M_{rev} \tag{7}$$

The relationship between these two components and the anhysteretic magnetization M_{an} is obtained from physical considerations of the magnetization process and is given by

$$M_{rev} = c(M_{an} - M_{irr}) \tag{8}$$

With

$$\frac{dM_{irr}}{dH_e} = \frac{M_{an} - M_{irr}}{k\delta} \tag{9}$$

Where *a*, *α*, *c*, *k* and the saturation magnetization M_s are parameters which are determined from measured hysteresis characteristics [4], *δ* is a directional parameter and takes the value +1 for $dH/dt > 0$ and -1 for $dH/dt < 0$. Using this method, the magnetization *M* is commonly obtained from the magnetic field *H*.

With the proposed inverse Jiles–Atherton model, *M* will be calculated from the magnetic induction *B*, integrating a differential equation in terms of *dM/dB*. To obtain such a relationship, we will start substituting (8) in (7) and differentiating the resulting term with respect to the effective flux density $B_e = \mu_0 H_e$.

$$M = M_{irr} + c(M_{an} - M_{irr}) = (1 - c)M_{irr} + cM_{an} \tag{10}$$

$$\frac{dM}{dB_e} = (1 - c)\frac{dM_{irr}}{dB_e} + c\frac{dM_{an}}{dB_e} \tag{11}$$

One can write this term as

$$\frac{dM}{dB_e} = \frac{dM/dB}{1 - \mu_0(1 - \alpha)\,dM/dB} \tag{12}$$

Deriving (6) with respect to H_e

$$\frac{dM_{an}}{dB_e} = \frac{M_s}{a\mu_0}\left[1 - \coth^2\frac{H_e}{a} + \left(\frac{a}{H_e}\right)^2 \right] \tag{13}$$

And, with deriving (9) results in

$$\frac{dM_{irr}}{dB_e} = \frac{M_{an} - M_{irr}}{\mu_0 k\delta} \tag{14}$$

In which δ=+1 for $dB/dt > 0$ and δ=-1 for $dB/dt < 0$. The term M_{irr} in (14) is obtained applying (8) in (7)

$$M_{irr} = \frac{M - cM_{an}}{1-c} \tag{15}$$

Finally, written (11) using (12) and (13), and isolating dM/dB gives the main equation of the proposed inverse Jiles-Atherton model

$$\frac{dM}{dB} = \frac{(1-c)\frac{dM_{irr}}{dB_e} + c\frac{dM_{an}}{dB_e}}{1+\mu_0(1-c)(1-\alpha)\frac{dM_{irr}}{dB_e} + \mu_0 c(1-\alpha)\frac{dM_{an}}{dB_e}} \tag{16}$$

The numerical solution of (5) including hysteresis cannot be done with the same method as the one used with univocal functions (Newton–Raphson scheme for example). We have chosen the fixed-point method already presented in [1]. The hysteretic constitutive relationship is then rewritten under the form

$$H = f(B) = \nu_{FP} + M_{FP}(B) \tag{17}$$

The reluctivity ν_{FP} is a constant and must respect some conditions to achieve convergence [2]. The studied hysteretic models assume B and H collinear; consequently the magnetization MFP has the same direction as ν_{FP} B. Its magnitude is obtained by calculating $MPF = f(B) - \nu_{FP} B$. Finally, the partial differential equation (5) becomes

$$curl\,\nu_{FP}\ curl\,A = J - curl\,M_{FP} \tag{18}$$

The discretization with nodal shape functions for the potential vector of (18) using the finite volume method leads to the matrix system

$$[S_{FP}][A] = [J] - [M_{FP}], \tag{19}$$

Where the vector [A] represents the nodal values of vector potential. [SFP] a square matrix called stiffness matrix, [MFP] and [J] the vectors which take into account the magnetization MFP and the current density J. One can note that the matrix [SFP] is constant because the permeability ν_{FP} is constant as well. The non-linearity's introduced by ferromagnetic materials are reported in the source term [MFP] which depends on B (i.e. A). To take into account the coupling with the external circuit of a coil made up of stranded conductors flowed by a current i, a vector [D] is introduced such that [J] = [D] i. Then, we obtain the system

$$\begin{bmatrix} S_{FP} & -D \\ 0 & R \end{bmatrix}\begin{bmatrix} A \\ i \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ D^t & 0 \end{bmatrix}\frac{d}{dt}\begin{bmatrix} A \\ i \end{bmatrix} = \begin{bmatrix} 0 \\ u \end{bmatrix} + \begin{bmatrix} M_{PF} \\ 0 \end{bmatrix}. \tag{20}$$

3. Genetic Algorithms

3.1 Introduction

Genetic algorithms are developed for the purpose of optimization. They allow the search for a global extremis. These algorithms are based on natural selection mechanisms (Darwin) and the genetic evolution. A genetic algorithm is changing a population of genes using these mechanisms. It uses a cost function based on a performance criterion to calculate a (fitness). Those most "strong" will be able to reproduce and have more offspring than others.

Originally, the coding of individuals was in transcribing binary parameters to optimize to form a gene. These genes are then put together to form the chromosome. There is, however, an approach called real coding, where the functions of change and passing are rewritten to apply directly to the vector of parameters without going through the binary. We have identified a coding real, more flexible and precise. This avoids some problems due to binary encoding. The actual coding also provides a direct view of settings throughout the evolution of the population. These modified genetic operators are used in this paper as well as the improvement tools presented in [7].

3.2 Parameters Identification Procedure

The schematic representation of the parameters identification procedure is shown in [8], [9], the first step is the characterization of the individuals that will form the population. The individuals θ are composed by the five parameters of the JA model (in real coding, it is not necessary to code the variables in binary representation) [6], [10]. We consider the case where the population is given by

$$pop^n = \begin{bmatrix} M_s^{n,1} & k^{n,1} & c^{n,1} & a^{n,1} & \alpha^{n,1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ M_s^{n,np} & k^{n,np} & c^{n,np} & a^{n,np} & \alpha^{n,np} \end{bmatrix} \tag{21}$$

Where each line represents an individual (a point in the optimization space), n is the generation, and np is the population size.

The initial values assigned to the population are random values in the allowable range, as shown in Tables I.

Each individual of the population is evaluated using the fitness between calculated and experimental results.

That minimizes the fitness function given by [11]

$$ff(\theta) = \sum_{i=1}^{n}\left(M_s(t_i) - \hat{M}_s(t_i,\theta)\right)^2, \tag{22}$$

Where $M_s(t_i)$ and $\hat{M}_s(t_i,\theta)$ represent the measured and estimated magnetization, respectively. The optimal parameter vector is obtained solving $\hat{\theta}_{GA}^{n} = \min(ff(\theta))$ and also on a maximum allowed number of generations.

Figure 1 shows the variation of the function of adaptation (fitness) according to the number generations, and table I give the final results of the genetic algorithm.

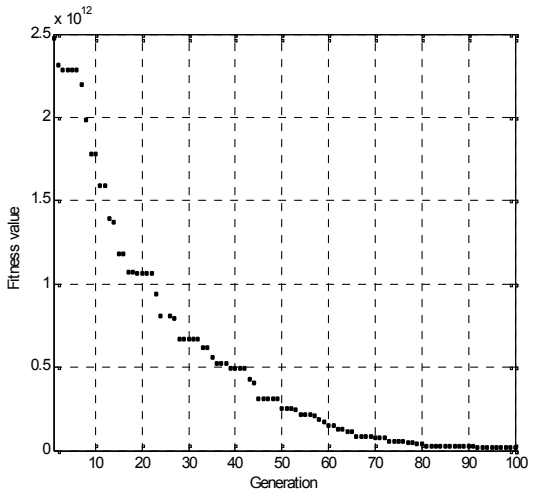

Fig. 1. Evolution of the total error.

TABLE 1: Material Parameters

Parameter	Design Variable Range	Optimized Values
Ms	$0.5\times10^{6} - 2.5\times10^{6}$	1.2865×10^{6}
k	75 - 450	195.68
c	0.15 – 0.65	495×10^{-3}
a	170 - 750	195.2
α	$1\times10^{-4} - 3\times10^{-4}$	1.75×10^{-4}

3.3 The Solution Procedure

The finite volume method is a discretization method which is well suited for the numerical simulation of various types (elliptic, parabolic or hyperbolic, for instance) of conservation laws, it has been extensively used in several engineering fields, such as fluid mechanics, heat and mass transfer or petroleum engineering [12].

Some of the important features of the finite volume method are similar to those of the finite element method, it may be used on arbitrary geometries, using structured or unstructured meshes, and it leads to robust schemes. An additional feature is the local conservatively of the numerical fluxes, which is the numerical flux, is conserved from one discretization cell to its neighbor.

This last feature makes the finite volume method quite attractive when modeling problems for which the flux is of importance, such as in fluid mechanics, semi-conductor device simulation, heat and mass transfer…

The finite volume method is locally conservative because it is based on a "balance" approach: a local balance is written on each discretization cell which is often called "control volume", by the divergence formula, an integral formulation of the fluxes over the boundary of the control volume is then obtained. The fluxes on the boundary are discretized with respect to the discrete unknowns.

The solution of the posed problem is constructed using finite volume method. With this purpose let us multiply magnetodynamic equation (5) by function of projection β_i and integrate obtained equation over domain Ω, we get

$$\int_t^{t+\Delta t}\int_r\int_z \beta_i\left[\frac{\partial}{\partial z}\left(\frac{1}{r\mu_0}\frac{\partial A}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{r\mu_0}\frac{\partial A}{\partial r}\right)\right] rdrdzdt$$
$$= \int_t^{t+\Delta t}\int_r\int_z \beta_i\left[\frac{\sigma}{r}\frac{\partial A}{\partial t} - J_{ex}\right] rdrdzdt +$$
$$\int_t^{t+\Delta t}\int_r\int_z \beta_i\left(\frac{\partial M_r}{\partial z} - \frac{\partial M_z}{\partial r}\right) rdrdz\,dt \qquad (23)$$

With B_i is function of selected projection 1/r.

One can write (23) as

$$\int_t^{t+\Delta t}\iint_{r\,z}\left[\frac{\sigma}{r}\frac{\partial A}{\partial t} - \frac{\partial}{\partial z}\left(\frac{1}{r\mu_0}\frac{\partial A}{\partial z}\right) - \frac{\partial}{\partial r}\left(\frac{1}{r\mu_0}\frac{\partial A}{\partial r}\right)\right] drdzdt$$
$$= \int_t^{t+\Delta t}\iint_{r\,z}\left[J_{ex} + \frac{\partial M_z}{\partial r} - \frac{\partial M_r}{\partial z}\right] drdzdt \qquad (24)$$

The equation (24) discretized once is written as follows

$$a_P A_P = a_E A_E + a_W A_W + a_N A_N + a_S A_S + d_0 + \frac{\sigma_p \Delta r \Delta z}{r_p \Delta t} A_p^0 + \left[(M_z)_e - (M_z)_w \right] \Delta z - \left[(M_r)_n - (M_r)_s \right] \Delta r \quad (25)$$

The indices P, W, N, E and S refer to the values of the nodes and indices p, w, n, e and s refer to the values of the faces of volumes of control (look Figure (2)).

The coefficients a_W, a_N, a_E, a_S and d_0 is given by

$$a_E = \frac{\Delta z}{\mu_0 r_e (\delta r)_e},$$
$$a_W = \frac{\Delta z}{\mu_0 r_w (\delta r)_w},$$
$$a_N = \frac{\Delta r}{\mu_0 r_n (\delta z)_n}, \quad (26)$$
$$a_S = \frac{\Delta r}{\mu_0 r_s (\delta z)_s},$$
$$a_P = a_E + a_W + a_N + a_S + \frac{\sigma_P}{r_P} \frac{\Delta r \Delta z}{\Delta t},$$
$$d_0 = J_{ex}(t) \Delta r \Delta z .$$

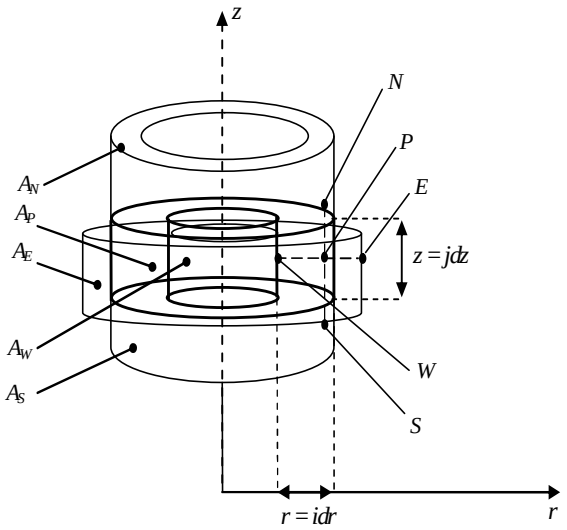

Fig. 2. Control volume in Axi-Symmertical cylindrical coordinates.

Once that the various formulations in finite volumes integrating the model of hysteresis are established, a method of resolution of the nonlinear problem must be selected.

4. RESULTS

4.1 Measured Curves

The determination of the magnetic quality of materials rests primarily on the nature of the systems of measurement used. The evolution of the standard in the field of the characterization of material is a significant factor for the taking into account of the physical nature of magnetic materials and the conditions of their uses. The reproducibility of measurement and the facility of handling are also factors which make it possible to choose the type of magnetic circuit to implement. Accordingly our choice is related to the realization of framework SST (Single Sheet Tester) 500*500 mm^2. The device planned for characterization of sheets with not oriented grains must make it possible to take measurements by a simple introduction of the sample, iron silicon 3% not oriented inside a sleeve, with a perfect positioning and without deterioration of the polar faces of the magnetic circuit of closing of flux. The characterization of materials studied done by determining the following quantities expressed in terms of characterization of the frame and measuring output voltages measured by an oscilloscope: V_2, V_{H1}, and V_{H2} (look figure. 3).

The excitation peak field, which is submitted the sample is obtained by interpolation from tensions measured at the terminals of two coils tangential H_1 and H_2 located at distances different from the sample

$$\frac{dH(t)}{dt} = \frac{d_2}{d_2 - d_1} \frac{dH_1(t)}{dt} - \frac{d_1}{d_1 - d_2} \frac{dH_2(t)}{dt} \quad (27)$$

Where

$$\frac{dH_1(t)}{dt} = \frac{V_{H1}(t)}{\mu_0 n_1 S_1} \quad (28)$$

And

$$\frac{dH_2(t)}{dt} = \frac{V_{H2}(t)}{\mu_0 n_2 S_2} \quad (29)$$

The magnetic induction is obtained by time integration of the V_2 (t) voltage in secondary coil measuring B by

$$B_{\exp}(t) = \frac{\overline{V_2}}{4 N_2 S f} \quad (30)$$

And

$$\overline{V_2} = \frac{1}{T} \int_0^T V_2(t)\, dt \quad (31)$$

Where

d_1, d_2: Distance to sample the coil Field 1, 2 (m).

N_2: Number of turns of the coil measuring B.

n_1, n_2: Number of turns of the coil Field N^o *1*, N^o *2*.
S: Section of the sample (m^2).
S_1, S_2: Surface of the coil H_1, H_2 (m^2).
V_{H1}, V_{H2}: power output of the coil H_1, H_2 (V).

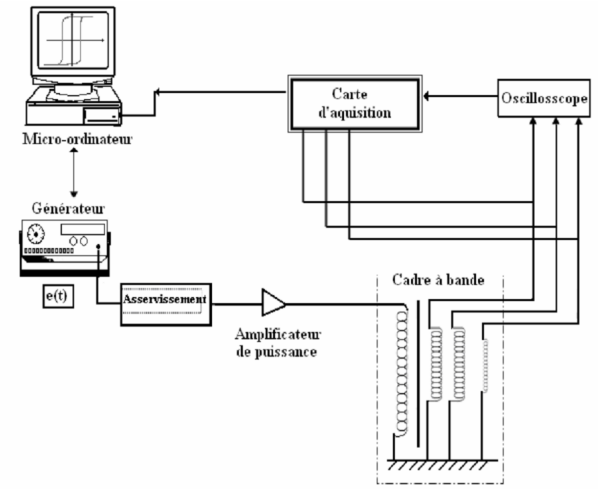

Fig. 3. Single Sheet Tester (SST) 500*500 mm^2.

It is important to remark that the use of the inverse JA model for the parameters identification has an additional advantage compared with the original model: the input of the inverse model is the magnetic induction waveform. Since the magnetic induction is obtained from integration, it is naturally filtered, with fewer oscillations than those of the magnetic field waveform. The noise present in the field waveform brings additional difficulties to the parameters identification procedure.
The obtained set of parameters is valid for models, original and inverse, allowing good agreement between measured and calculated data [6].

4.2 Comparison with Simulation

The test consists of a cylinder ferromagnetic with a length of *40 cm* and *10 cm* diameter characterized by a cycle of hysteresis *(Ms*=1.2865×10^6, *k*=195.68, *c*=495×10^{-3}, *a*=95.2, *α*=1.75×10^{-4}*)*, the cylinder is surrounded by a coil of the same length traversed by a stream of density $J = 10^5\ A/m^2$. The drivers which constitute the inductor have a diameter $D = 1\ cm$ and *50 cm* length. The gap is $E = 2\ cm$. The geometry of the system studied, it presents two symmetries, the first axially (*oz*) and the second according to the plan (*or*). We can then consider magnetic problem in a cylindrical coordinate system, a quarter of domain.
For a numerical modeling the theoretical limits (with infinite, $A = 0$) are brought back to a finite distance which can vary according to the desired precision. In this study, these limits were fixed at a distance $L = 50\ cm$ of the studied device.
The boundary conditions associated with the magnetic equation are the conditions of Neumann $\partial A/\partial n = 0$ and the conditions of the Dirichlet $A=0$.
For the validation of the parameters obtained, one superimposed on the figure 4, the cycle experimental and the cycle of simulation obtained starting from the identified parameters. This superposition shows the degree of accuracy of the cycle identified by genetic algorithm.

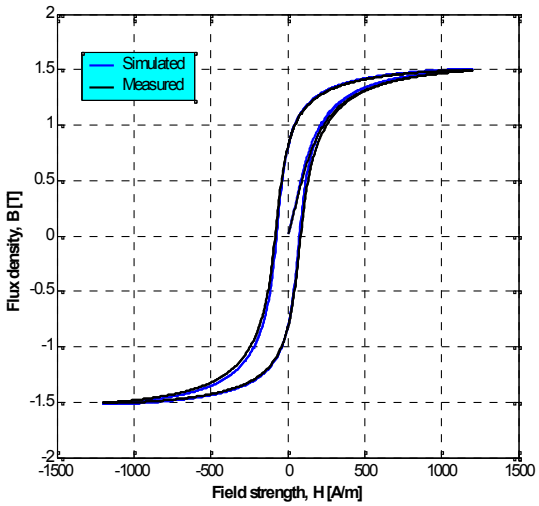

Fig. 4. Measured and calculated *B (H)* loops at 50 Hz.

Figure 5 shows, for an operation frequency of 50 Hz, the experimental and simulated field curves of this material when submitted to a 1.52 T peak value sinusoidal induction.

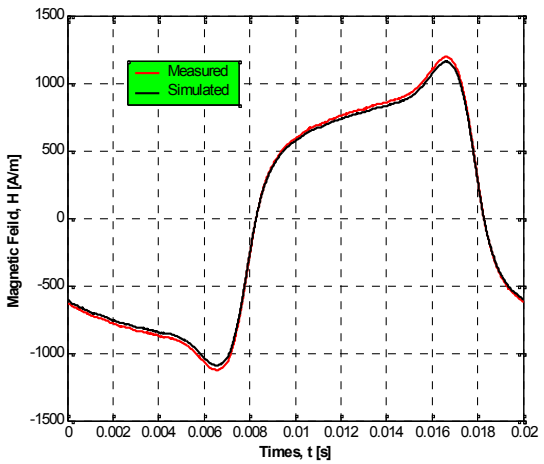

Fig. 5. Field measured and modeled at 50 Hz.

Additional resultants are given in figure 6, where the axial variations of potential vector magnetic *A.* One notices well that the value of A is maximal on the level of the center of the inductor (z=10cm) then decreases gradually until being cancelled in extreme cases of the field of study.

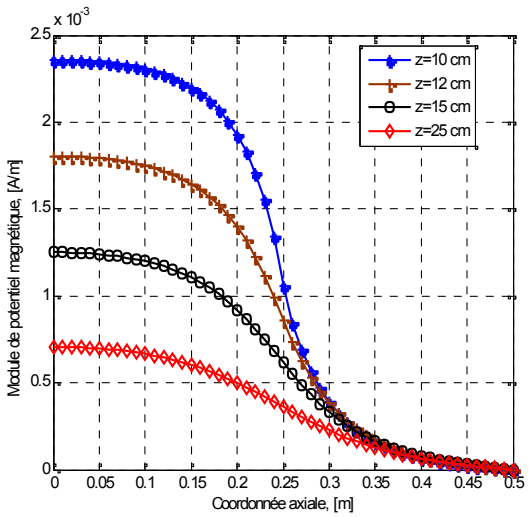

Fig. 6. Axial variation of the magnetic potential vector A.

5. CONCLUSION

In this work, a finite volume-based transient simulation method for investigating hysteresis effects using the J–A scalar hysteresis model has been extended to 2-D problems. The identification of the parameters Jiles-Atherton model is a difficult process with to realize, but the use of the techniques of optimization by genetic algorithm makes it possible to free this difficulty. Results obtained by applying our model to the axisymmetrical magnetodynamic device based on an inverse Jiles–Atherton model and a differential reluctivity has good performances with regard to numerical convergence and gives very satisfactory results on an SST's frame. In the near future, the use of a dynamic model of magnetic hysteresis to study the behavior of material in the systems at high frequencies and the application to other devices will be undertaken.

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