Improvements in a Jiles-Atherton Vector Hysteresis Model

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Electromagnetic devices can experiment alternating and/or rotational magnetic fluxes. Alternating and rotating losses are associated to these fluxes, wherein the rotating components are generally larger than the alternating ones and concentrated in particular areas of rotating electrical machines and transformers. Under rotational flux conditions a vector relationship between field and induction must be considered. The phenomenon of magnetic hysteresis under rotating flux is only conveniently modeled with vector hysteresis models as the Jiles-Atherton vector version employed in this work, in which some modifications are performed in order to improve its behavior.

***Index Terms*— Magnetic hysteresis, magnetic materials, magnetic anisotropy.**

I. Introduction

Magnetic hysteresis modeling remains a challenge, especially if it is associated to rotating fields. The rotational losses are generally larger than the alternating ones and are concentrated in particular areas as the yoke tooth in electrical machines and in the T-joints of three phase electric transformers. Rotational losses have influence on the efficiency of electromagnetic devices and this research topic is still current and open to further investigations [1], [2]. Under rotating fluxes, magnetic hysteresis exhibits a complex behavior that cannot be accurately modeled with scalar approaches, requiring vector hysteresis models for a suitable representation of the phenomenon.

Starting from the Jiles-Atherton scalar hysteresis model ([3][4]), Bergqvist ([5]), proposed a first vector generalization of it where the variations of the magnetic induction vector **B** could be obtained from the variations of magnetic field vector **H**. Based on the Bergqvist work, an inverse vector generalization of the Jiles-Atherton model was developed and presented in [6]. In this version, the magnetic vector field **H** is obtained from a magnetic vector induction **B**. This approach is better suited in field calculations by numerical methods with a magnetic vector potential formulation because in such cases the induction is known a priori.

In the model proposed in [6], some simplifications were assumed and implemented. In this work the inverse model equations are reviewed looking for a more accurate modeling of the magnetic materials hysteretic behavior. More specifically, the main contribution of this work is to perform a modification on the anhysteretic calculation, in order to improve the model representation of anisotropic and isotropic materials, as well to analyze the impacts of this modification on the convergence of field calculations.

II. The Inverse Jiles-Atherton Hysteresis Model

The model proposed in [6] is based on the following equations. Firstly, a vector variable is introduced

$$\vec{\chi}_f = \vec{k}^{-1}(\mathbf{M}_{an} - \mathbf{M}) \qquad (1)$$

where $\mathbf{M}_{an}$, $\mathbf{M}$ and $\vec{k}$ are, respectively, the anhysteretic magnetization, the total magnetization and a second rank tensor whose terms are obtained experimentally [5]. The effective field vector variation $d\mathbf{H}_e$ is given by

$$d\mathbf{H}_e = d\mathbf{H} + \vec{\alpha}\, d\mathbf{M} \qquad (2)$$

where $d\mathbf{H}$ is the magnetic field variation and $\vec{\alpha}$ is a tensor also obtained from experimental data.

The evolution of the magnetization vector is evaluated accordingly to the sign of the scalar product between $\vec{\chi}_f$ and $d\mathbf{H}_e$ as [6]:

1. If $(\vec{\chi}_f d\mathbf{H}_e) > 0$ then

$$d\mathbf{M} = \frac{1}{\mu_0}\Big[\mathbf{1} + \vec{\chi}_f \left|\vec{\chi}_f\right|^{-1} \vec{\chi}_f(\mathbf{1}-\vec{\alpha}) + \vec{c}\vec{\xi}(\mathbf{1}-\vec{\alpha})\Big]^{-1} \cdot \Big[\vec{\chi}_f \left|\vec{\chi}_f\right|^{-1} \vec{\chi}_f + \vec{c}\vec{\xi}\Big] d\mathbf{B} \qquad (3)$$

2. If $(\vec{\chi}_f d\mathbf{H}_e) \le 0$ then

$$d\mathbf{M} = \frac{1}{\mu_0}\Big[\mathbf{1} + \vec{c}\vec{\xi}(\mathbf{1}-\vec{\alpha})\Big]^{-1}\Big[\vec{c}\vec{\xi}\Big] d\mathbf{B} \qquad (4)$$

Equation (4) is a restriction used in order to avoid non-physical behavior of the total magnetization. A similar approach is also used in the scalar Jiles-Atherton model.

In (3) and (4) μ_0 is the magnetic permeability of the vacuum, $\mathbf{1}$ is the diagonal unity matrix, $\vec{c}$ also is a tensor obtained from experimental data and $\vec{\xi}$ is a matrix of the anhysteretic functions derivatives with respect to the effective field components [4].

With $d\mathbf{M}$, the vector magnetic field is evaluated in both, isotropic and anisotropic materials from a known induction vector **B**.

In the model, the anhysteretic part ($\mathbf{M}_{an}$) of the total magnetization ($\mathbf{M}$) is represented by $\vec{\xi}$ and is modeled with vector Langevin functions, playing an important role in the total magnetization [6]. Here we propose some improvements in $\vec{\xi}$ with respect to the original proposition given in [6], as follows.

III. Anhysteretic Magnetization Modeling

In [6], $\vec{\xi}$ was assumed as a diagonal matrix containing the derivatives of the anhysteretic functions with respect to the effective field as given, for the two dimensional case, in (5):

$$\vec{\xi} = \begin{bmatrix} \frac{dM_{anx}}{dH_{ex}} & 0 \\ 0 & \frac{dM_{any}}{dH_{ey}} \end{bmatrix} \qquad (5)$$

In equation above indexes *x* and *y* are related to the two main spatial directions in the Cartesian plane (*x,y*).

The assumption above allowed a good model numerical performance as well to represent anisotropic and isotropic materials with enough accuracy for a large set of magnetic materials.

However, for some magnetic materials, (5) does not represent appropriately the magnetic material behavior [7]. In order to overcome this drawback and after some physical considerations (5) can be rewritten as

$$\vec{\xi} = \begin{bmatrix} \frac{dM_{anx}}{dH_{ex}} & \frac{dM_{anx}}{dH_{ey}} \\ \frac{dM_{any}}{dH_{ex}} & \frac{dM_{any}}{dH_{ey}} \end{bmatrix} \qquad (6)$$

where all the partial derivatives are now taken into account. In the full paper (6) will be showed in details as well its identification method.

IV. Results

A simple two dimensional case was chosen, supposing that the magnetic flux alternates at 0° and 45° with respect to the *x* direction on an isotropic material. Figure 1 shows the BH loops obtained with the model using (5) to model matrix $\vec{\xi}$.

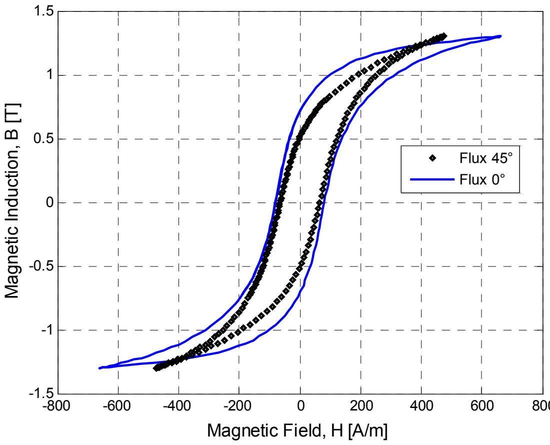

Fig. 1. BH loops for alternating fluxes at 0° and 45°. Loops obtained with (5).

As the material is isotropic, any pulsating flux should originate identical loops, independently of the spatial direction of the flux. These results show that, for this material, the isotropic characteristic is not well represented and a significant difference between the losses obtained for both directions is expected, highlighting the model deficiency.

Figure 2 shows the results obtained replacing (5) by (6) in the model equations. Now the loops are superposed giving rise to the same hysteresis losses.

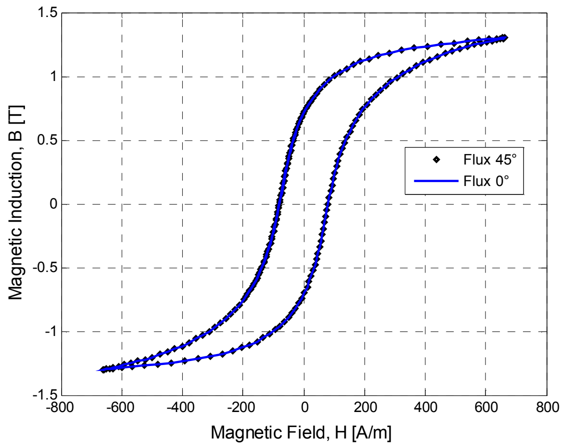

Fig. 2. BH loops for alternating fluxes at 0° and 45° . Loops obtained with (6).

V. Conclusions

The modifications performed on the equations leads a more physical behavior of the model. Preliminary results have shown additionally that this new approach can improve the convergence of field calculations by numerical procedures taking the inverse model in its formulation. With the new approach calculation time with a finite element program was reduced in about 45%. This topic will be explored in the full version of the paper as well calculated results will be compared with experimental ones to show the modeling effectiveness.

VI. References

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