Vector extension of the Loss Surface model for modelling static and dynamic hysteresis

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This paper proposes a vector extension of the Loss Surface model used for modelling static and dynamic hysteresis phenomena that appear in electromagnetic devices containing soft ferromagnetic materials. The aim being to include the behavior of the material during a solving process based on the finite element method (FEM). The vectorization strategy is based on the Mayergoyz approach. The developed model has been implemented in the 2D FEM formulation. The nonlinear problem is solved using the Newton-Raphson algorithm with an exact approximation of the magnetic reluctivity tensor. Several test cases of the TEAM 32 problem have been studied for validation purposes. The results are in agreement with the measurements combining good accuracy and saving of computation time.

Index Terms— **Ferromagnetic materials, Magnetic hysteresis, Electromagnetic modeling, Finite element analysis**

I. Introduction

IN ORDER to improve the energy efficiency of electromagnetic devices, it is essential to have an accurate estimation of losses. For example, with the widespread use of electric motors in transportation applications, iron losses in the magnetic circuit of these devices have become a significant part of the losses and their reduction, even marginal, can lead to significant overall savings.

These losses are generally computed by an analysis of these devices by the finite element method (FEM). In this context, the nonlinear behavior of ferromagnetic materials is generally represented by a scalar and univocal magnetization curve. The losses in these materials are then calculated in post-processing from the spatial and the time variations of the magnetic flux density computed with a posteriori approaches such as the Bertotti model [1].

These scalar models can only describe the hysteretic behavior of unidirectional magnetic fields. To take into account the rotational magnetic fields, such as those occurring in electromechanical devices, an extension of the scalar model to a vector version is necessary.

On the other hand, a hysteresis model called Loss Surface (LS) has been developed at G2Elab over the last twenty years and has proven itself in predicting losses in electrical machines [3]. Like Bertotti's, this model is used a posteriori in FEM simulations. Recently, its accuracy has been greatly improved and extended to saturation and high frequencies [4], thus increasing its robustness.

Furthermore, this scalar model is by definition a $H(B)$ model and is therefore a good candidate for vectorization and implementation in a 2D FEM formulation.

In this paper, we present a vector extension of the LS model using the vectorization method based on the Mayergoyz approach [5]. This model is then incorporated into a 2D FEM formulation in order to include the material behavior during the solving process. This approach is validated by comparison with measurement results.

II. Scalar Loss Surface Model (LS)

The LS model used in this work is a scalar static and dynamic hysteresis model that reproduces the magnetic behavior of a material as a function of waveform and excitation frequency. It is a $H(B)$ model based on the knowledge of the magnetic induction $B(t)$ and its time variation dB/dt . It is a superposition of the two parts static one H_{stat} and dynamic one H_{dyn} :

$$H\left(B,\frac{dB}{dt}\right) = H_{stat}(B) + H_{dyn}\left(B,\frac{dB}{dt}\right) \quad (1)$$

The static magnetic field H_{stat} is expressed as the sum of two contributions reversible and irreversible:

$$H_{stat}(B) = H_{anhy} + H_{comp} \quad (2)$$

where H_{anhy} represents the anhysteretic magnetic field, which is assumed to be independent of the history of the material. This component corresponds to the median curve of a quasi-static hysteresis loop of the saturated material. The history dependence is taken into account through H_{comp} , which describes the proportion of the field related to the irreversible deformation mechanisms and domain walls displacement.

The dynamic part of this model H_{dyn} is built from a series of measurements that take into account macroscopic induced currents as well as excess losses. More details on the analytical expressions of each quantity of the scalar model presented above are given in [4].

III. Vectorial Loss Surface Model (LS)

In this section, we will present the developed approach of the vector extension of the LS model. It is based on the Mayergoyz method. The main idea of this method is to combine the contribution of scalar models continuously distributed in the space. The magnetic flux density $\mathbf{B}$ is projected in all directions and can be expressed in 2D as in equation (3), where $\mathbf{e_\phi}$ is a unit vector along the direction defined by an angle ϕ.

$$\mathbf{B} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \mathbf{B}\cdot \boldsymbol{e_\phi}\, \mathrm{d}\phi \ \text{ with } \ \boldsymbol{e_\phi} = [cos(\phi), \sin(\phi)] \quad (3)$$

Then, each projected value of $\mathbf{B}$ on a direction ϕ is considered as an input of the scalar model. So, each direction has its own history. Finally, $\mathbf{H}$ is obtained by the vector sum of each output of the scalar models.

$$\mathbf{H}\left(\mathbf{B},\frac{\mathbf{dB}}{\mathbf{dt}}\right) = \frac{1}{\pi}\int_0^{\pi} \mathbf{e}_{\boldsymbol{\varphi}} \cdot \left(H_{Stat}(\boldsymbol{B}\cdot\mathbf{e}_{\boldsymbol{\varphi}}) + H_{Dyn}\left(\boldsymbol{B}\cdot\mathbf{e}_{\boldsymbol{\varphi}}, \frac{\mathbf{dB}}{\mathbf{dt}}\cdot\mathbf{e}_{\boldsymbol{\varphi}}\right)\right) d\mathbf{e}_{\boldsymbol{\varphi}} \quad (4)$$

For the static part, we choose to project only the irreversible part $\mathbf{H_{comp}}$, while the reversible part $\mathbf{H_{anhy}}$, remains collinear to $\mathbf{B}$ as indicated in (5):

$$\mathbf{H}_{\boldsymbol{Stat}}(\mathbf{B}) = H_{anhys}(\|\mathbf{B}\|)\frac{\mathbf{B}}{\|\mathbf{B}\|} + \frac{1}{\pi}\int_0^{\pi} \mathbf{e}_{\boldsymbol{\varphi}} \cdot \left(H_{Comp}(\boldsymbol{B}\cdot\mathbf{e}_{\boldsymbol{\varphi}})\right) d\mathbf{e}_{\boldsymbol{\varphi}} \quad (5)$$

This is physically consistent because the phase shift between $\mathbf{H}$ and $\mathbf{B}$, in the case of a rotating field, is due to the irreversibility of the magnetization process which is estimated by $\mathbf{H_{comp}}$ in the model. To ensure equivalence between the scalar and vector models, some quantities of $\mathbf{H_{comp}}$ must be expressed by considering $\|\mathbf{B}\|$:

$$\mathbf{H}_{Comp}(\mathbf{B}) = \frac{1}{\pi}\int_0^{\pi} \mathbf{e}_{\boldsymbol{\varphi}} \cdot sign\left(\Delta(\mathbf{B}\cdot\mathbf{e}_{\varphi_i})\right)\left(H_{Comp}^{env}(\|\mathbf{B}\|) - \Delta H(\|\mathbf{B}\|, \mathbf{B}\cdot\mathbf{e}_{\boldsymbol{\varphi}})\right) d\mathbf{e}_{\boldsymbol{\varphi}} \quad (6)$$

Finally, the integral in (4) is carried out numerically using Gauss-Legendre quadrature.

IV. Implementation Of The LS Model In FEM2D Code

This section describes the procedure for implementing the model in a finite element code based on a 2D nonlinear transient electromagnetic formulation. It is a magnetic vector potential $\mathbf{A}$ formulation.

The transient problem is solved using a conventional implicit Euler scheme. At each time step, the nonlinear problem is solved using the Newton-Raphson (NR) algorithm. To ensure good convergence, a precise approximation of the incremental reluctance tensor presented below (7) is necessary:

$$\left[\frac{d\mathbf{H}_{LS}(\mathbf{B},{}^{d\mathbf{B}}/_{dt})}{d\mathbf{B}^t}\right] = \left[\frac{d\mathbf{H}_{\boldsymbol{Anhys}}}{d\mathbf{B}^t}\right] + \left[\frac{d\mathbf{H_{comp}}}{d\mathbf{B}^t}\right] + \left[\frac{d\mathbf{H_{dyn}}}{d\mathbf{B}^t}\right] \quad (7)$$

As described in Section II, all component quantities of the Loss Surface model are expressed by analytical functions. Thus, an exact computation of the tensor is possible. This improves the convergence of the nonlinear problem and a saving of computation time. The detailed computation of (7) will be presented in the extended paper.

V. Validation And Results

To validate the model, we compared the results of the LS model with those obtained from measurements made on the Epstein frame and those obtained with the Preisach model. In this last case, the model is completed by solving the diffusion equation in the depth of the sheet. The results are presented in Fig. 1 and highlight a very good agreement with the measurements for the proposed approach at 400 Hz.

The model is then used to study the TEAM32 problem which is an international workshop dedicated to the modelling of vector hysteresis [6]. It is a three-column transformer with two windings placed on the external columns that can be connected together or fed by two independent voltage sources. The geometry of the studied problem is described in detail in [6]. Several test cases have been experimented. We choose to present here the test case n° 2 with windings connected in series and therefore powered by the same sinusoidal current at 10 Hz. The signal is distorted with harmonic n°5 in phase with the fundamental.

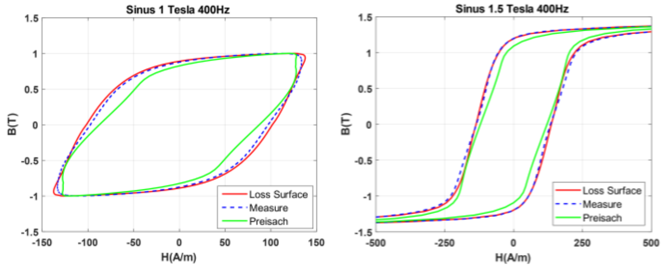

Fig. 1 Hysteresis cycle at 400Hz with excitation source: (a) 1T, (b) 1.5T

For comparison, the same device was modelled with Altair-Flux™ software [7]. In the software, the same mesh was used and the hysteretic behavior of the magnetic circuit was described by the Preisach vector model [2]. For the FEM problem, the geometry is meshed with 3000 first-order triangular elements. Two periods with 200 time steps per period were simulated.

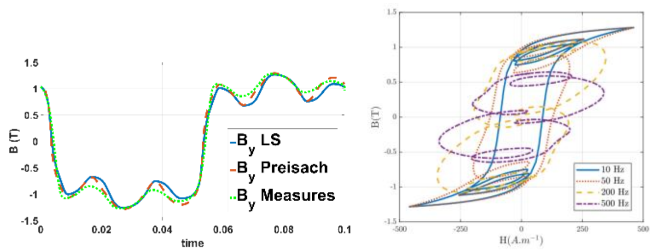

Fig. 2 : (a) Computed and measured magnetic flux density at the sensor C4 at 10Hz, (b) Simulated cycles at C4 for different excitation frequencies.

Fig. 2(a) shows the magnetic flux density at the sensor C4 at 10Hz, there is a good agreement between the measurement results, the proposed model and the Preisach model. Fig 2(b) presents Hysteresis cycles for different excitation frequencies. At 50 Hz, the cycles widen but maintain the same maximum induction. From 200 Hz, this widening is accompanied by a reduction in maximum induction as the frequency increases.

The results show the ability of the model to predict hysteresis losses accurately with very good numerical performances (at most, about 10 NR iterations are required for each time step).

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