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Numerical modelling of static hysteresis phenomena using a vector extension of the Loss Surface model

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Abstract—This paper proposes a vector extension of the Loss Surface model for the numerical modelling of hysteretic phenomena in isotropic ferromagnetic materials. The vectorization strategy is based on Mayergoyz’s approach. The procedure has been applied to the finite element analysis of TEAM problem 32, leading to accurate results and short computation times.

Index Terms—Vector magnetic hysteresis modelling, Loss Surface, Finite Element Method

I. INTRODUCTION

In the analysis of electromagnetic devices, the Finite Element Method (FEM) is generally used. In this context, the nonlinear behaviour of ferromagnetic materials is commonly represented by a scalar, one-to-one magnetization curve in the FEM procedure. The magnetic core losses are computed then in post-processing mode from the determined space and time variations of the flux density with *a posteriori* approaches such as the Bertotti [1] or Loss Surface (LS) [2] models. However, even if the losses estimation may be accurate with these methods, it excludes hysteresis phenomena from the magnetic field computation.

In the past, several authors have addressed the problem of incorporating hysteresis models into FEM formulations. The Jiles-Atherthon [4] and Preisach [5] hysteresis models are the most commonly used. One of the main difficulties lies in the conversion of the standard B(H) models into an inverse H(B) hysteresis operator that is more adapted to formulations stated in terms of the magnetic vector potential. Moreover, a scalar model can only describe the hysteretic behaviour of unidirectional fields. To account for rotating fields, such as the ones occurring in electromechanical devices, an extension of the scalar model to a vector model is needed.

In this paper, a vector extension of the LS model is proposed using the well-known Mayergoyz vectorization method [3]. The LS model is a scalar H(B) hysteresis model developed by the G2Elab over the past twenty years, providing good results for any magnetic flux density waveform B(t) [6]. It presents several advantages, including good accuracy and short-computation times. Consequently, the scalar LS model is a natural candidate for vectorization.

The application of this vector extension of the LS model to the finite element analysis of a 2D transient magnetic hysteresis problem is also discussed in this paper.

II. STATIC LOSS SURFACE SCALAR MODEL

In this work, only the static LS model is considered. In this context, the static magnetic field intensity H_{stat} is expressed as the sum of the reversible and irreversible contributions H_{anhys} and H_{comp} :

$$H_{stat} = H_{anhys} + H_{comp}. \quad (1)$$

H_{anhys} represents the anhysteretic field, which is assumed to be history independent. This component corresponds to the median curve of a hysteresis loop of the saturated material. The history dependency is considered through H_{comp} , which represents the magnetic field intensity component caused by both the bending and displacement of the domain walls.

For any hysteresis loop, H_{comp} is defined as the difference between H_{stat} and H_{anhys} . The main purpose of the model is to estimate the value of H_{comp} in a simple way. To achieve this objective, two quantities H_{env} and ΔH are defined. The first corresponds to the equivalent of H_{comp} for a major hysteresis loop. The second is the difference between the static field of any hysteresis loop and the major envelope. Equation (2) summarizes the relationships between H_{comp} , H_{env} and ΔH , which are further clarified in Fig. 1a.

$$H_{env} = H_{stat}^{major} + H_{anhys} \text{ and } \Delta H = H_{comp} - H_{env} \quad (2)$$

The model evaluates $\Delta H(B)$, which decreases monotonically from ΔH_{rev} to its minimum value ΔH_{revp} when the flux density varies from B_{rev} to B_{revp} for any case (i.e, either a centred hysteresis loop or reversal curves of any order). In [6] H_{anhys} , H_{comp} and H_{env} are analysed and expressed by analytical formulae. The approach will be detailed in the full article. The analytical expressions involve the identification of 22 parameters, which may be obtained through the measurement of few centered hysteresis cycles and through data-fitting. An example of results is presented in Fig. 1b.

III. ISOTROPIC VECTOR MODEL

Scalar hysteresis models are not suitable for describing the behaviour of a material subjected to rotating fields. Consequently, a vector extension of the LS model based on Mayergoyz’s method (i.e., the superposition of scalar models continuously distributed in space) is here proposed. Vector \vec{B} is projected on all directions on which the scalar model is applied separately. Thus, each direction has its own history. \vec{B}

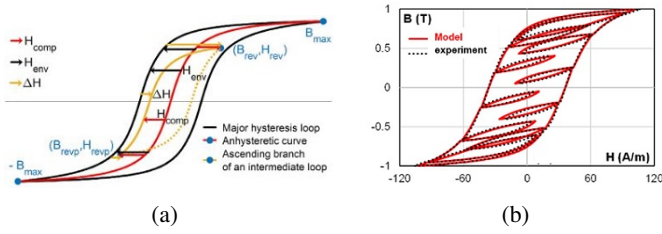


Fig. 1: Key quantities of the static LS model (a) and comparison between measurements and results [6] yielded by it (b).

is expressed in two dimensions as in (3), where e_ϕ is a unit vector along the direction defined by angle ϕ :

$$\vec{B} = \frac{1}{\pi} \int_0^\pi \vec{B} \cdot \vec{e}_\phi d\phi \approx \frac{2}{\pi} \sum_{i=1}^N \omega_i \vec{B} \cdot \vec{e}_{\phi,i}. \quad (3)$$

Unlike the classical Mayergoyz approach, only the irreversible part H_{comp} is projected, while H_{anhys} , the reversible part remains co-linear to \vec{B} . This is physically consistent and ensures that static rotational losses tend to zero at saturation, as observed experimentally [7]. Indeed H_{comp} is zero close to saturation, making \vec{H}_{stat} and \vec{B} parallel in this case. Equation (3) also highlights that a Gauss-Legendre quadrature procedure is adopted to evaluate the integral and ω_i is the quadrature weight assigned to direction i . The 2D, isotropic, vector LS model may then be stated as follows:

$$\vec{H}_{stat} = H_{anhys}(\|\vec{B}\|) \frac{\vec{B}}{\|\vec{B}\|} + \frac{2}{\pi} \sum_{i=1}^N \omega_i \vec{e}_{\phi,i} \vec{H}_{comp}(\vec{B} \cdot \vec{e}_{\phi,i}) \quad (4)$$

IV. FEM IMPLEMENTATION

The developed model has been used for solving magnetic transient nonlinear problems. This section outlines the FEM implementation procedure, in which the Newton-Raphson method is used to solve the non-linear system of equations at each time step.

To ensure good convergence, an accurate approximation of the differential permeability tensor below is required:

$$\left[\frac{\partial H}{\partial B^t} \right] = \frac{dH_{anhys}(\vec{B})}{d\vec{B}^t} + \frac{dH_{comp}(\vec{B})}{d\vec{B}^t} \quad (5)$$

Due to the intrinsic characteristics of the LS model (i.e., the analytical description of quantities mentioned in section II), an accurate computation of the incremental permeability tensor is possible. The detailed calculation of (5) will be presented in the extended paper. The transient problem is solved using a backward Euler scheme.

V. VALIDATION AND RESULTS

To validate the vector extension of the LS model and its implementation in a FEM code, the numerical procedure was applied to the TEAM problem 32 shown in Fig 2 which is a test case dedicated to vector hysteresis problem [8]. The three-limbed transformer with a ferromagnetic core is made from a stack of five 0.48 mm thick non-grain oriented steel

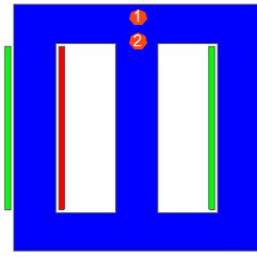


Fig. 2: Geometry of the TEAM problem 32 and position of sensor 1 and 2

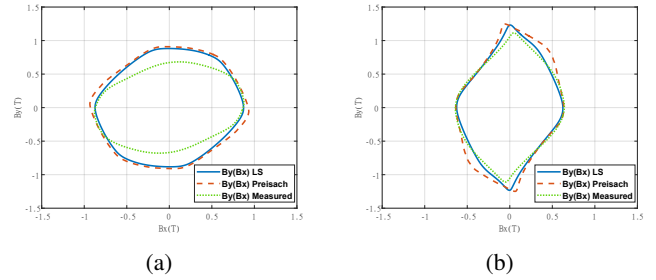


Fig. 3: Computed and measured B-loci at (a) sensor 1 and (b) sensor 2

laminations. In test case no.3, the left and right windings of 90 turns are fed by two sinusoidal currents at 10 Hz, out of phase by 90° producing rotating field at the T-joint of the transformer. For comparison, the same device was modeled in Altair FluxTM with its transient magnetic FEM application. In FluxTM, the same mesh was employed and the hysteretic behaviour of the core was described by its built-in vector Preisach model [5]. The results for sensors at the T-joint are compared with the experimental data provided by Bottauscio [8] in Fig. 3a and 3b. A good agreement between the proposed vector extension of the LS model and the Preisach model may be verified at both positions. It must also be mentioned that both models was identified using measurements in the rolling direction, which could explain the discrepancy between simulations and the experiment.

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