Vector hysteresis models in comparison to the anhysteretic magnetization model

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***Abstract*—The design and calculation of electrical machines and magnetic actuators requires accurate models to represent hysteresis effects in ferromagnetic materials. The magnetic nonlinearity of the iron core is usually considered by an anhysteretic magnetization curve. With this assumption, hysteresis' effects in the field computation are completely neglected. This paper presents a comparative study of different hysteresis models, particularly vector stop model and Pragmatic Algebraic Model (PAM), with regard to the anhysteretic vector magnetization model. The analysis shows the resulting accuracy of different material models under alternating and rotating magnetizations. By integrating material models into the in-house finite element (FE) tool, named iMOOSE, the distribution of magnetic flux density in an electrical machine, a power transformer are depicted.**

***Index Terms*—soft magnetic materials, nonlinear magnetics, vector hysteresis modeling, parameter identification, finite element simulation.**

I. Introduction

Even though the development of quasi-static hysteresis models has been studied intensively, the parameter determination of measured data, numerical efficiency and stability of FE calculation remain a challenge. The main aim of this paper is to present a comparison study of vector stop model and the proposed Pragmatic Algebraic Model (PAM) as shown in [1], focusing on accuracy and numerical efficiency. By integrating these hysteresis models in the FE tool the flux density distribution can be evaluated on electrical machines, which is contrasted with the outcome by means of the anhysteretic magnetization model.

II. Vector Hysteresis Models

In the following, both vector hysteresis models are implemented and validated with measured data. The selected material is the non-oriented electrical steel sheet M400-50A. The measurements are performed on a rotational single sheet tester (RSST).

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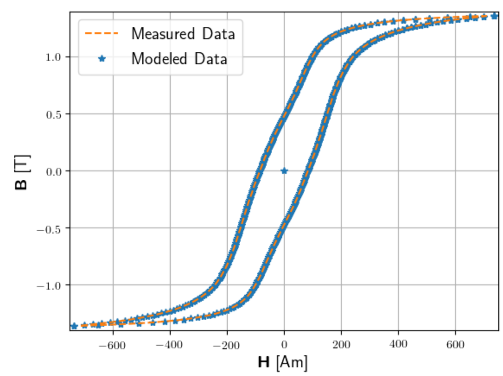

Fig. 1. Comparison of measured data (dashed) and theoretical predictions with vector stop model (star).

With the laws of thermodynamic consistency, the description of vector hysteresis model is decoupled into reversible and irreversible components [2]. The implemented vector stop model has the flux density as an input variable and as the output. It is an inverse model of vector play type according to the approach described in [3]. The parameters of the implemented vector stop model are solely based on the quasi-static major loop of the measured data. Fig. 1 depicts the comparison of measured material characteristics and responses of the stop model.

As an alternative to vector stop model, PAM was proposed in [4]. This model is based on an algebraic representation (1), which considers magnetic hysteresis and eddy current effects. The parameters $p_0 - p_2$ characterize the anhysteresis magnetization curve, while p_3 describes eddy currents effects and $p_4 - p_5$ the hysteresis effect. Table I summarizes p_k parameters as being identified with the same measured data for the stop model.

$$\begin{aligned}\vec{H}(\vec{B},\dot{\vec{B}},p) = (p_0 + (p_1 \mid \vec{B} \mid^{2p_2}))\vec{B} + \\ (p_3 + \frac{p_4}{\sqrt{p_5^2 + \mid \dot{\vec{B}} \mid^2}})\dot{\vec{B}}\end{aligned} \quad (1)$$

TABLE I
IDENTIFIED PARAMETERS FOR PAM

p_0	p_1	p_2	p_3	p_4	p_5
155.9	1.5	9.0	1.279	110	0.15

The output of PAM from (1) is compared to the measurement shown in (Fig. 2).

The hysteresis models described above are in good agreement with the measured shape of the hysteresis loop for M400-50A measured under an amplitude of 1.6 T and a frequency of 50 Hz. In particular, the stop model depicts the major loop better than PAM. Therefore, both models will be implemented into the FE tool. The anhysteretic characteristic in the form of $\nu(B^2)$ is obtained from the same measured main loop and extrapolated to 1.9 T with the Fröhlich-Kennelly formulation.

III. FEM Approach

In order to evaluate the electromagnetic fields, the previously presented hysteresis models will be integrated in FE tool. The formulations of electromagnetic problem can be solved with in-house FE tool iMOOSE, which is based on magnetic vector potential formulation.

$$\vec{\nabla} \times (\nu \vec{\nabla} \times \vec{A}(x,t)) = \vec{J}(x,t) \tag{2}$$

where $\vec{A}$ is the magnetic vector potential, ν reluctivity of the material and $\vec{J}$ the current density.

This approach results in the necessity that the hysteresis model is formulated as a function of $\vec{B}$, as an input and $\vec{H}$, as an output, which is represented in differential reluctivity ν_d, in a weak formulation of (2). In combination with a time-step iteration and a differential Newton iteration in each time-step, as presented in [1] [5], the hysteretic field problem is solved.

IV. Application

In the following, the presented hysteresis models are evaluated in the context of a three-phase transformer in terms of accuracy, computational effort and convergence. The transformer consists of a ferromagnetic core with a three-limbs.

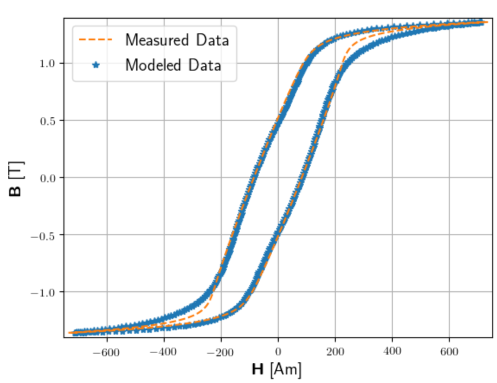

Fig. 2. Comparison of measured data (dashed) and theoretical predictions with PAM (star).

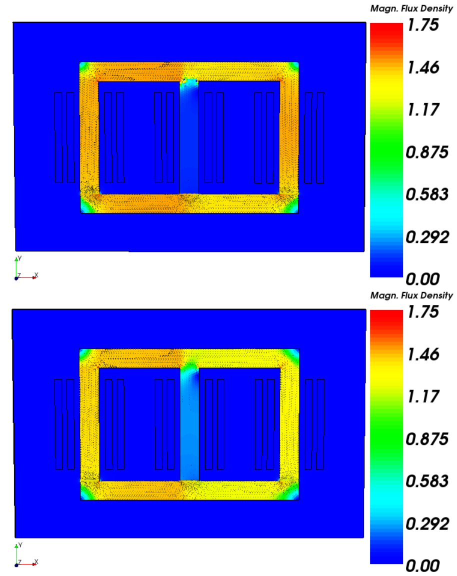

Fig. 3. Comparision of the distribution of magnetic flux density in 3-phase transformer between (a) anhysteretic magnetization model and (b) PAM.

The windings are excited with three sinusoidal currents, which with phase shift of 120° electrical degrees. The model is simulated in a time step of 1 ms. Fig. 3 depicts the distribution of magnetic flux density in the three-phase transformer with anhysteretic material model and PAM.

V. Conclusions

This paper discusses different hysteresis models and were validated by comparing calculated and measured data from a M400-50A steel sheet. The simulation with and without a hysteresis model shows a difference in the distribution of the magnetic flux density in a 3-phasse transformer. More details of comparison of hysteresis models under alternating and rotating excitations and their numerical calculations will be presented in the full paper.

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