An Efficient Implementation of the Classical Preisach Model

Sajid Hussain[1], *Member, IEEE,* and David A. Lowther[1], *Fellow, IEEE*

[1]Department of Electrical and Computer Engineering, McGill University, Montreal, QC, H3A 0E9, Canada
david.lowther@mcgill.ca

The incorporation of iron losses in the finite element method is important for the accurate predictions of the performance of low-frequency electromagnetic devices. Hysteresis models such as Jiles-Atherton and Preisach are frequently used for this purpose. The Preisach model is more accurate and can represent a broad range of magnetic materials. However, it is computationally very expensive and therefore hysteresis coupled finite element simulations take too much time to solve. In this work, a computationally efficient method of implementing the Preisach model is presented using the closed form expression for modeling the Everett function which not only reduces the total execution time of the model but also simplifies its implementation. The results computed using the proposed approach are compared against the conventional implementation and a speed up of 2.75 times has been achieved. The proposed approach is also valid for the *H*-based vector Preisach models.

***Index Terms*—Ferromagnetic materials, finite Element Method, hysteresis modeling, iron loss, Preisach Model.**

I. Introduction

With the development of more powerful computers and numerical techniques, the use of hysteresis models, such as the Jiles-Atherton [1] and Preisach [2] models is becoming increasingly popular in finite-element method (FEM) based computer-aided design (CAD) simulations for the calculation of iron losses in electromagnetic devices.

Out of the two hysteresis models, mentioned above, the Preisach model is considered to be more accurate [3]. However, the solution of the classical Preisach model (CPM) is very time-consuming. The problem becomes even more computationally expensive for the vector extensions of the CPM. This is because the vector Preisach model is merely the sum of scalar models needed to solve a number of projections of the input vector magnetic field in the space [2]. Therefore, any improvement in terms of the computational cost of the CPM will have a major impact on the vector Preisach model for speeding up hysteresis coupled FEM simulations.

In this paper, we have proposed a closed form expression to model the Everett function with five unknowns only. The use of a closed-form expression for modeling the Everett function not only reduces the computational time of the Preisach model but also simplifies the algorithm by eliminating the need for search and interpolation schemes. A brief review of the CPM is presented in Section II. The conventional implementation of the CPM using the "raw" Everett function and the proposed modification are presented in Section III. Finally, the results using the proposed modification are presented in Section IV where they are compared against the conventional implementation of the CPM. A speed up of 2.75 times is achieved.

II. The Classical Preisach Model

The CPM [1] is a phenomenological model that presumes a ferromagnetic material to be composed of a large number of rectangular switches similar to magnetic domains [4]. Based on the history of the input magnetic field, the next value of the output is determined.

The mathematical description, identification, and implementation of the Preisach model are described in [5]. The output of the CPM is calculated using the equations given below [2].

for dB/dt > 0

$$B(t) = 2\sum_{k=1}^{n-1}\big(EF(M_k, m_{k-1}) - EF(M_k, m_k)\big) + 2EF(H(t), m_{n-1}) - EF(\alpha_o, \beta_o). \quad (1)$$

for dB/dt < 0

$$B(t) = 2\sum_{k=1}^{n-1}\big(EF(M_k, m_{k-1}) - EF(M_k, m_k)\big) - 2EF(M_k, m_{k-1}) - 2EF\big(M_n, H(t)\big) - EF(\alpha_o, \beta_o). \quad (2)$$

Where, $B(t)$ is the output magnetic flux density, $H(t)$ is the input magnetic field intensity, $EF(M_k,m_k)$ is the Everett function corresponding to the history of input extrema (M_k,m_k), and α_o and β_o are the maximum switching fields which correspond to the positive and negative saturation, respectively.

III. The Everett Function

The Everett function is one of the identification methods [5] of the CPM and can readily be computed using the measured data i.e. concentric *B-H* hysteresis loops. The use of the Everett function eradicates the need for solving the double integration in the original model equation [2].

Conventionally, the Everett function is stored in memory as a two-dimensional upper triangular matrix, and 2D interpolation schemes, such as bilinear or bicubic, are used to obtain data in between the rectangular grid of the matrix $EF(x,y)$ for the given input points. To do this, a search algorithm is implemented and a 3x3 or 4x4 matrix inversion is needed multiple times at each time step (for every function call) to compute the unknown coefficients needed for the bilinear interpolation scheme. This adds to the computational cost of the CPM.

It has been shown in [6] that the higher order derivatives of the Everett Function should be continuous to improve the convergence of the hysteresis coupled FEM simulations. Therefore, the bicubic interpolation scheme is considered to be better from the convergence point of view than the bilinear interpolation [6] but its use increases the complexity of the algorithm.

Both of these issues have been addressed in this work. First, the raw Everett function is computed from the measured *B-H* loops for a 35WW300 non-oriented electrical at 10 Hz. A modified logistic distribution function (LDF) in 2D (3) is then used to represent the raw data points of the Everett function.

$$EF(H_\alpha, H_\beta) = \boldsymbol{a} + \boldsymbol{b}\left(\tanh\left(\frac{H_\alpha - \boldsymbol{c}}{\boldsymbol{d}}\right) + \tanh\left(\frac{\boldsymbol{c} - H_\beta}{\boldsymbol{d}}\right)\right) + \boldsymbol{e}H_\alpha H_\beta \quad (3)$$

Where a-e are the unknown parameters and their values are given in Table 1. The last term $eH_\alpha H_\beta$ in (3) has been added to the LDF to slightly increase the slope of the flat top area of the surface in Fig. 1 which improves the quality of the fit.

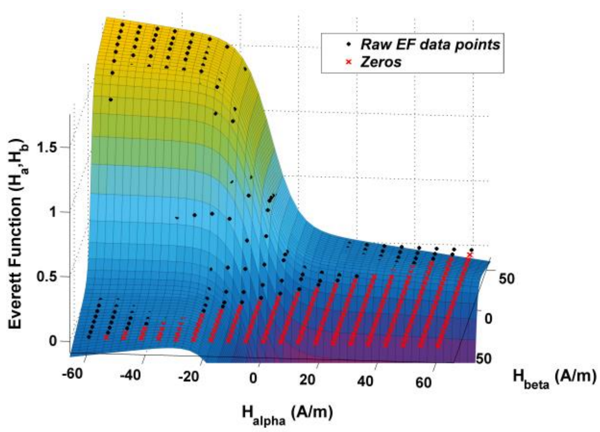

Fig. 1. Surface fitting of the Everett function using the modified 2D logistic distribution function (2). The black dots represent the data obtained from the concentric hysteresis loops and the red dots represent zeros. $R^2_{Adj} = 0.946$

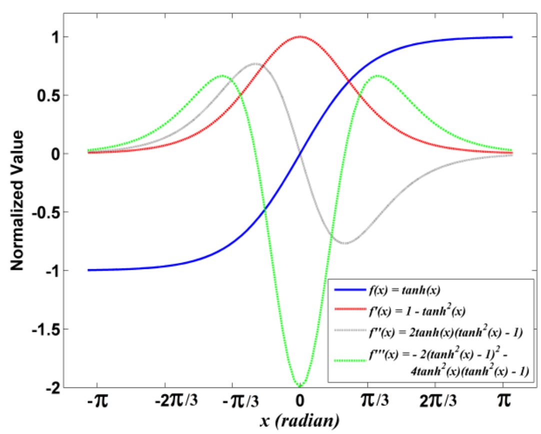

Fig. 2. Plots of the tanh(x) function and its derivatives for $-\pi < x < \pi$.

TABLE I
PARAMETERS IDENTIFIED USING SURFACE FITTING OF (3) TO THE RAW EVERETT FUNCTION

Parameters	Value
a	0.07313
b	-0.7111
c	9.498
d	9.115
e	-4.478×10^{-6}

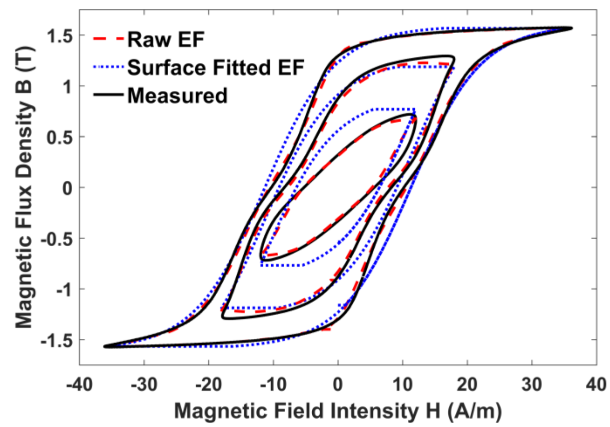

Fig. 3. Comparison between the *B-H* loops computed using raw and surface fitted Everett functions.

It can be seen in Fig. 1 that the Everett function is symmetric around $H_\alpha = -H_\beta$ line in the H_α-H_β plane which in turn reduces the number of unknown parameters in (3) to five only. There is no need to store the raw data points of the Everett function. Also, the higher order continuity of (3) for improved convergence has been demonstrated by plotting the tangent hyperbolic function and its higher order derivatives in Fig. 2.

IV. Results and Discussion

After the unknown parameters for (3) are identified using nonlinear least squares method in Matlab curve fitting toolbox, the output magnetic flux density *B* is computed using (1) and (2) for a given input *H* field intensity. The resulting *B-H* loops are compared against the conventional implementation of the CPM using the raw Everett function with the bilinear interpolation scheme in Fig. 3. It can be seen that the *B-H* loops computed using the two implementations are slightly different especially at the lower induction levels. This is because of the fact that the output of the CPM is very sensitive to the quality of the surface fit. On the other hand, the implementation of the scalar Preisach model is 2.75 times faster than the conventional implementation which is very useful in terms of implementing the vector Preisach model in hysteresis coupled FEM simulations. It is also important to note that (3) is only valid for the direct (*H*-based) CPM because the shape of the Everett function is different for the inverse (*B*-Based) CPM.

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