COMPARAT IVE ANALYSIS OF DIFFERENT POINTWISE IDENTIFICATION TECHNIQUES, USED IN SCALAR PREISACH MODEL

Veronica MANESCU (PALTANEA)[1], Gheorghe PALTANEA[1], Horia GAVRILA[1], Gelu IONESCU[1]

The Preisach model is widely used for hysteresis modeling in magnetic materials. The main difficulty of the scalar models is the computation of the distribution function (PDF). In this paper are presented two approaches for the calculus of the PDF, by using different sets of experimental data. The two implementations generate equation systems, based on 3N and respectively N points uniform distributed on the magnetic material hysteresis cycle and normal magnetization curve. Using a double discrete integration over the distribution function, the magnetic polarization is determined.

Keywords: scalar Preisach model, pointwise identification techniques, equation systems, double integral solver.

1. Introduction

The modeling and estimation of the ferromagnetic material hysteresis cycle consists of using appropriate input data for the numerical implementation and identification of the hysteresis model. The state of the magnetic materials depends on their magnetization history and special characterization devices are needed. Following the magnetization process, combined with the nonlinearity of the magnetic properties, the hysteresis representation is usually obtained. In the device manufacture these phenomena are approximated by mathematical or physical models.

The physical models derive directly from the hysteresis phenomenon and they are combined with some empirical quantities that describe the magnetic characteristics [1-4]. Unfortunately, this type of models has a limited applicability, because the physical mechanisms of the hysteresis in different ferromagnetic materials are not entirely understood [5]. Today, great efforts are made, in order to identify and explain the model parameters, to accurately simulate the magnetic hysteresis. A major disadvantage of the physical models is that they are linked to a particular material [6].

[1] Dept. of Electrical Engineering, POLITEHNICA University from Bucharest, Romania, e-mail: gheorghe.paltanea@upb.ro.

Another group of models is based on the phenomenological characteristics and it describes in a mathematical manner the noticed phenomenon [7-13]. The Preisach model is one of the most investigated and developed mathematical concept and it has found intense application for modeling the magnetic hysteresis in electrical devices [14-17]. Through keen mathematical implementation, even it is not providing a physical description of the problem, the Preisach model can predict to some extend the behavior of the real physical systems. Thus, it is a mathematical tool for hysteresis identification and compensation [12].

Each material with magnetic hysteresis is associated, in the Preisach model, with a set of non-ideal Preisach elemental operators (hysterons) that has two parameters *a* and *b*, which represent the switching up and down fields, respectively. This set of elemental operators determines the Preisach density function (PDF). Its identification procedure has different approaches. For each magnetic material, an optimal distribution function and parameters are determined, in order to generate the best results in comparison with the experimental data [18].

In this paper two classical scalar Preisach models (CSPM) are implemented to determine the hysteresis behavior of non-oriented electrical steels.

2. Mathematical description of classical scalar Preisach models

The Preisach model was firstly introduced in 1935 by Ferenc (Franz) Preisach in the academic journal *Zeitschrift fuer Physik* [19]. In this paper, he proposed a method for characterizing the hysteresis and the principal element of his model is the “hysteron”. The hysteron is an element, which can take only two numerical values -1 and 1. A transition from upper to lower value takes place when the value *b* is attained and a transition from lower to upper value is possible for the value *a* (Fig. 1).

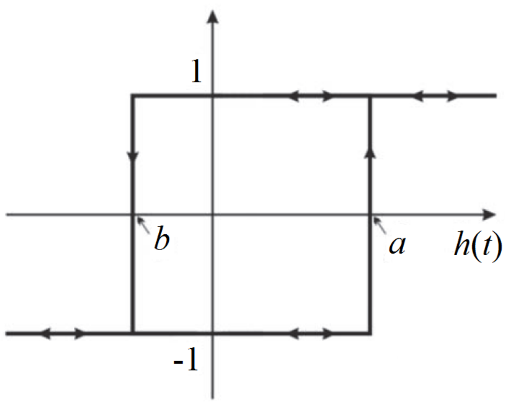

Fig. 1. Representation of a rectangular hysteresis cycle of a hysteron.

In the case of soft magnetic materials, whose magnetization processes under external excitation field are described through the magnetic domain theory, each hysteron can be associated with a magnetic domain (Weiss type magnetic domain) that is characterized by two magnetic field values on which the magnetization vector in the magnetic domain switches completely with 180° its direction. In a real material, between the switching fields is the following relationship $a \geq b$, so in a representation in the ab plane the valid hysterons are placed in the triangular half of the graphical representation. When the external field strength H increases from the negative saturation point the magnetic moment of hysteron is equal to -1. If the value of the applied magnetic field exceeds b, the magnetic moment is switched to the positive value + 1. The hysteron state remains + 1, until the direction of the external field is changed. At one point if the external field start to decrease monotonically and the value of the field is lower than a then the magnetic moment switched to negative value and the hysteron state to − 1.

The total magnetic moment is the mathematical integral over all the hysterons.

It is well known that on the secondary diagonal that is defined by $a = -b$ equation no hysteresis appears. This line is usually used for the modeling of the nonlinearity. Unfortunately, the ferromagnetic hysteresis is much more complicated and two-dimensional structures are needed, while one-dimensional structure is enough for the analysis of the nonlinearity. Another important feature is the main diagonal of the Preisach plane $a = b$. The elementary hysteresis cycles are symmetrical on that diagonal.

The model does not accumulate all past extremum values of the input quantity, because some of them are wiped out by subsequent input variations [13]. The wiping out property also occurs for a monotonically decreasing input. Another important property of the Preisach model is congruency that means that all minor hysteresis cycles corresponding to back and forth variations of inputs, between the same consecutive extremum values, are congruent. The Preisach model is also rate-independent, which is equivalent to the affirmation that the output only depends on the levels of the input and not on the speed of the input variations.

In order to simulate the ferromagnetic alloy hysteresis, by using CSPM, the PDF or the Everett function must be determined. For the computation of the PDF, it was used the classical Biorci-Pescetti procedure [20, 21] and a similar method that determines the PDF pointwise, by solving a bilinear system and using as identification data the ascendant loop of the major hysteresis cycle [22-25].

The hysterons are characterized by the following hysteresis operator [24]:

$$m = \gamma\left(a, b, H\left(t_k\right)\right) = \begin{cases} -1 & \text{if } H\left(t_k\right) \le b, \\ +1 & \text{if } H\left(t_k\right) \ge a, \\ \gamma\left(a, b, H\left(t_{k-1}\right)\right) & \text{if } b \le H\left(t_k\right) \le a, \end{cases} \quad (1)$$

where $a \ge b$, $b \ge -H_s$ and $a \le H_s$ (H_s is the saturation magnetic field strength). The hysteron matrix that is defined on an *ab* plane is linked to the ferromagnetic material through the Preisach triangle of the vertices $(-H_s, -H_s)$, $(H_s, -H_s)$, (H_s, H_s). The magnetic polarization J computed through Preisach model can be determined as:

$$J\left(t\right) = \iint_S \mu\left(a, b\right) \gamma\left(a, b, H\left(t\right)\right) db da, \quad (2)$$

where $H(t)$ is the magnetic field strength, used as input function, $\gamma(a, b, H(t))$ are the elementary operators, which describe the hysteresis phenomenon with local memories and $\mu(a, b)$ is the Preisach distribution function that is a weight for the operators and can be considered as a material constant [24, 25, 26]. S represents the surface of the Preisach triangle. In this triangle, based on the state of the operators, there can be determined two zones, one in which all the operators are switched down (zone S_-) and respectively a zone, where all the operators are switched up (zone S_+). The separation line between the two zones is usually called the memory line.

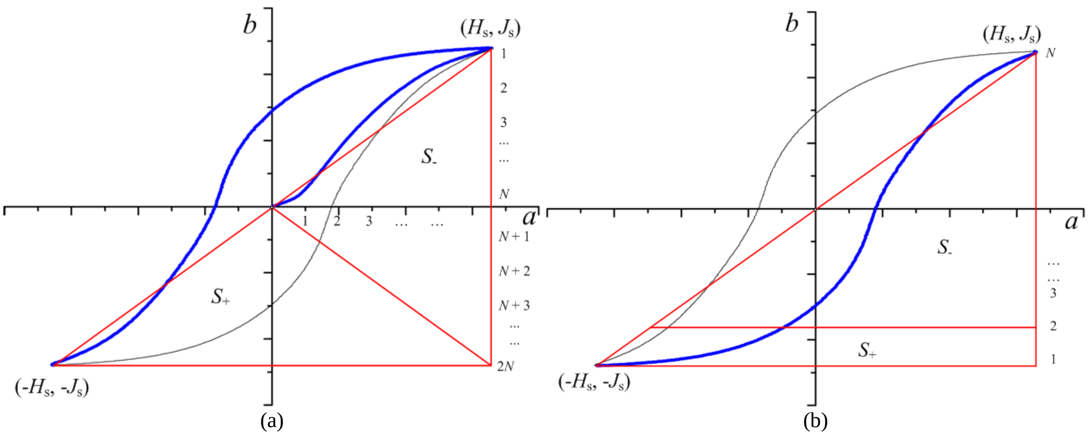

Fig. 2. Association between the experimental data and corresponding values in the Preisach plane for: (a) the $\mu_1(a)$ and $\mu_2(b)$ functions – method I; (b) φ function – method II (J_s is the saturation magnetic polarization) [24, 27].

The first approach, used to compute the PDF, is the Biorci-Pescetti method, in which the distribution function can be written as $\mu(a, b) = \mu_1(a)\ \mu_2(b)$ [27, 28]. The experimental data involved in the PDF identification, are the normal magnetization curve and the saturation hysteresis loop. The normal magnetization curve must have N points equally spaced and the major hysteresis must contain an equally spaced distribution of N points from positive saturation H_s to zero value and another N points uniform distributed from zero to negative saturation value $-H_s$.

Due to the symmetry of the Preisach distribution, the function μ_1 is defined by N values and μ_2 is characterized by $2N$ values (Fig. 2a) [27, 28]. Using these hypothesis, the aforementioned system of equations becomes:

$$\begin{cases} J_{k+1}-J_k=\dfrac{H_s^2}{N^2}\mu_1\left(a_{k+1}\right)\displaystyle\sum_{i=0}^{k}\left[\mu_2\left(b_{N-i}\right)+\mu_2\left(b_{N+i+1}\right)\right]; \\ J_{N+k}-J_{N+k+1}=\dfrac{H_s^2}{N^2}\mu_2\left(b_{k+1}\right)\displaystyle\sum_{i=0}^{k}\mu_1\left(a_{N-i}\right); \\ J_{2N+k}-J_{2N+k+1}=\dfrac{H_s^2}{N^2}\mu_1\left(a_{k+1}\right)\left[\begin{array}{l}\displaystyle\sum_{i=0}^{k}\left[\mu_2\left(b_{N-i}\right)+\mu_2\left(b_{N+i+1}\right)\right]+ \\ +\dfrac{H_s^2}{N^2}\mu_2\left(b_{N+k+1}\right)\displaystyle\sum_{i=k+1;i\le N}^{N}\mu_1\left(a_i\right)\end{array}\right]. \end{cases} \tag{3}$$

It must be imposed that $\mu_1(a_N) = 1$, in order to solve the above described system of equations. The magnetic polarization can be determined as it follows [28]:

$$J=J_s\left[\iint_{S_+}\mu\left(a,b\right)dadb-\iint_{S_-}\mu\left(a,b\right)dadb\right]. \tag{4}$$

The second approach calculates the PDF pointwise from the ascendant branch of the major hysteresis cycle, divided into N equal subintervals (Fig. 2b). This method is a very advantageous one, because it needs only a small amount of data, by comparing it with the Everett function method, whose identification procedure uses first order reversal curves (FORC) or concentric minor hysteresis loops [24, 25]. Based on the symmetry of the concentric hysteresis loops the PDF can be written as:

$$\mu(a,b) = \varphi(-b)\varphi(a), \tag{5}$$

where φ is a one-dimensional function, which can be computed pointwise. The magnetic permeability, determined on the increasing branch of the major hysteresis cycle could be calculated through (6) [24- 26]:

$$\frac{\mathrm{d}J}{\mathrm{d}H} = 2\varphi(H) \int_{-H_s}^{H} \varphi(-b)\,\mathrm{d}b, \tag{6}$$

Supposing that dJ/dH and the function φ have constant values in each subinterval and considering that φ(–b) = φ(a) the magnetic permeability is [22-26]:

$$\left.\frac{\mathrm{d}J}{\mathrm{d}H}\right|_i = \frac{J^{i+1} - J^i}{H^{i+1} - H^i} = 2\varphi(H_i) \sum_{j=1}^{i} \varphi(H_i)\Delta h, \tag{7}$$

where $\Delta h = 2H_S/N$.

Using the following notations $F_i = \frac{1}{2\Delta h}\frac{J^{i+1} - J^i}{H^{i+1} - H^i}$ and $\varphi(H_i) = \varphi_i$ for the evaluation of (7) in each subinterval it results a bilinear equation system for $1 \leq k \leq N$ [24]:

$$(k):\ \varphi_k \left(\sum_{i=1}^{k} \varphi_{N-i+1} \right) = F_k, \tag{8}$$

The two identification procedures of the PDF were applied, to estimate the hysteresis cycle of non-oriented silicon iron strips M400-65A industrial grade.

3. Results and Discussions

Characterization of the material was made by means of a laboratory single strip tester with digital control of the sinusoidal magnetic flux waveform according to the measuring standard IEC 60404-3 [34]. The form factor of the secondary voltage was kept at all frequencies within the interval 1.1102 ± 0.4%. The primary winding (173 turns) was supplied by a NF HSA4101 power amplifier, driven by an Agilent 33210A arbitrary function generator. The secondary winding (101 turns) was made directly around the surface of the samples.

This device can perform accurate measurements, offer an AC frequency characterization and provide the hysteresis cycle, the relative magnetic permeability and the total power loss data.

The M400-65A non-oriented electrical steel has the following physical properties: average mass m = 42 g, mass density τ = 7.65 g/cm^3, thickness = 0.65 mm and electrical resistivity $\rho = 44\times10^{-8}$ Ωm.

The experimental data, used in the identification procedures of the Preisach density values are the normal magnetization curve and the major hysteresis cycle, measured at frequency f = 10 Hz and peak magnetic polarization J_P = 1500 mT. The normal magnetization curve is defined as the geometrical place of the (H, J) maximum point values, extracted from the symmetric hysteresis loops, extending from the demagnetized state to saturation. The input data for the computation of the PDFs were extracted from the experimental data through a linear interpolation in N = 100 points.

After solving in Matlab environment the equation systems, described in eq. (3) and eq. (8), the Preisach density matrices are presented in Fig. 3 and Fig. 4. The Preisach density can be considered as a distribution of hysteresis coercivity, as each hysteron could be associated as a component of the main hysteresis cycle with different coercivity fields [35].

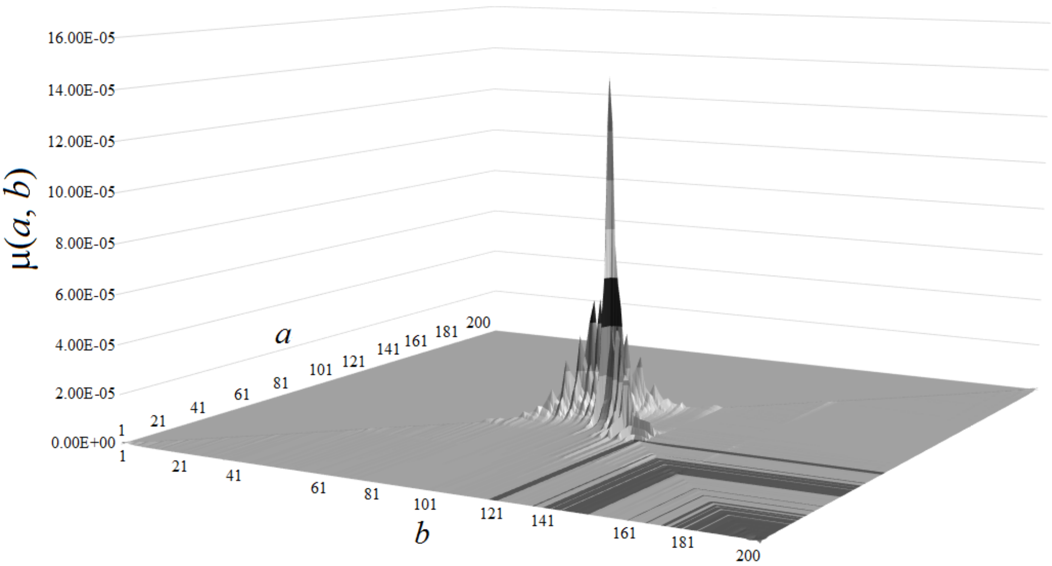

Fig. 3. Preisach density calculated pointwise through $\mu_1(a)$ and $\mu_2(b)$ functions method.

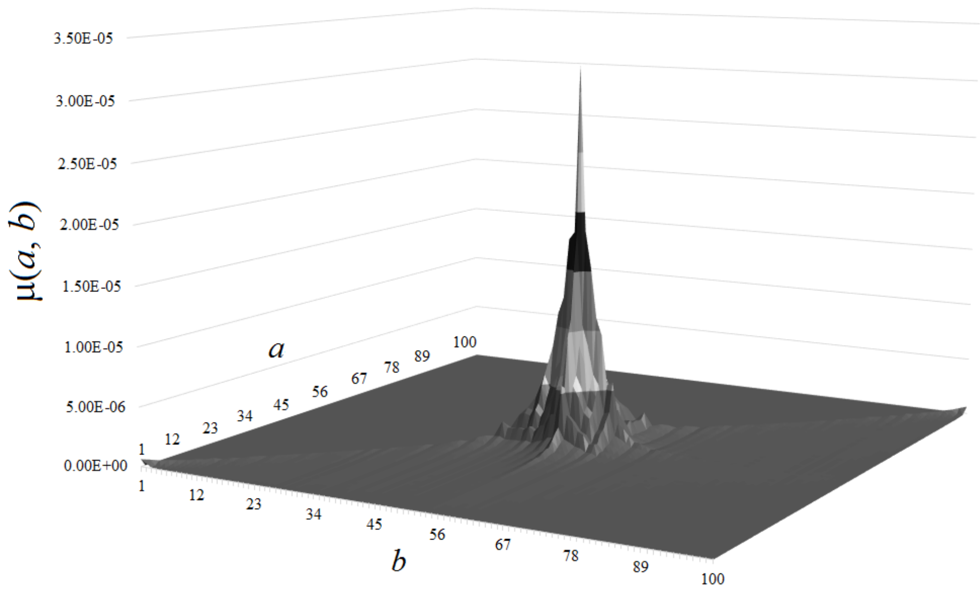

Fig. 4. Preisach density calculated pointwise through φ function method.

It can be noticed that the Preisach density, computed through Biorci-Pescetti method leads to higher values of the function μ(*a*, *b*) (Fig. 3), in comparison with the unidimensional approach (Fig. 4). The variation of the Preisach density has almost the same shape in the two cases and it has positive values, which are usually linked to the counter-clockwise hysteresis phenomenon [27]. The highest peak, observed in both cases, could be associated with the existence of a particular field strength (the coercive field), where hysteresis switching response is very strong, thus the material becomes more homogenous and the magnetic domains response to the switching field in the same time [35-38].

In M400-65A steel the magnetization processes are mostly irreversible and they are due to the magnetic domain wall motion. Reversible processes, made by spin magnetic moment rotations, are noticed only in the saturation zone. The magnetization mechanism that can be modeled through classical Preisach formalism could be associated only with irreversible processes, because of the relationship between the hysteron switches and the Barkhausen jumps of the moving domain wall [27, 28, 39, 40, 41].

In Fig. 5 the measured and computed symmetric hysteresis loops for the analyzed sample are presented. It can be observed that major differences appear only in the positive and negative saturation regions, between the measured and computed loops, which are expected due to the limitations of the classical Preisach model. This approach could be useful in the case of determination of the hysteresis energy component of the total energy losses [28].

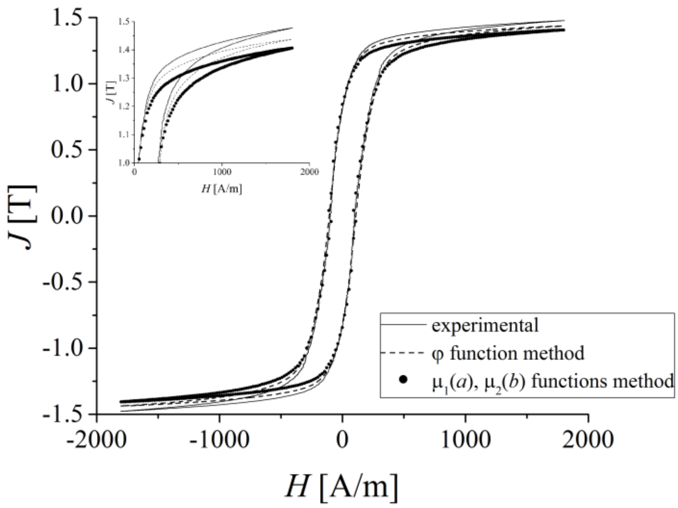

Fig. 5. Measured and computed symmetric hysteresis loops for M400-65A electrical steel at peak polarization J_P = 1500 mT and frequency f = 10 Hz; inset representation - the positive saturation region.

In table 1 are presented some comparisons between the values of saturation (J_s), remanence (J_r) and coercivity (H_c) points that are obtain from experimental and modeled analysis.

Table 1

Comparison between the values of different points from the hysteresis cycle (saturation, remanence and coercivity)

	J_s [T]	J_r [T]	H_c [A/m]
experimental	1.4776	0.81378	98.82023
φ method (I)	1.43643	0.82787	108.35449
error_I [%]*	2.786275041	-1.731426184	-9.648085215
$\mu_1(a)$ $\mu_2(b)$ method (II)	1.40615	0.8438	100.135304
error_II [%]*	4.835544126	-3.688957704	-1.330774073

$$*\text{error} = \frac{\text{experimental - modeled}}{\text{experimental}} \times 100.$$

In the case of saturation polarization, the computed values are lower that the experimental ones, because of the limitation of Preisach model in computation of the spin magnetic moment rotation processes. For remanence polarization and coercivity field the modeled values are higher than the experimental ones. The φ method approximates better the remanence point and the $\mu_1(a)$ $\mu_2(b)$ method leads to a low error in the coercivity point.

4. Conclusions

Two methods of PDF computation, by using the classical Preisach model of hysteresis has been analyzed and compared. Different identification procedures of the classical Preisach model can be chosen based on the particular application and the available measuring laboratory system. Preisach modeling could be considered as a powerful tool for the study of soft magnetic materials. The Preisach distribution describes the up and down magnetization reversals and controls all the hysteresis properties of a given system. The φ function method is a factorization of the PDF that is expected for systems, where domain wall motion is the dominant magnetization mechanism.

It is well known, that every magnetic material has a more accurate model and it can be concluded that the φ method approach leads to results comparable with the experimental ones. The observed results are linked to the fact that Preisach-relays-based models are mathematical tool for the modeling of hysteresis rather than phenomenological or physical ones.

The practical importance of our study resides in the electro-energetical implications in what concern the energy losses in various equipment, having ferromagnetic cores, and thus finally to the grid efficiency [41-43].

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