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REPRESENTATION OF MAGNETIC HYSTERESIS IN TAPE WOUND CORE USING FEEDBACK PREISACH MODEL

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Abstract: This paper presents a mathematical model for the hysteresis phenomenon in ferromagnetic tape wound core. The feedback scalar Preisach model of hysteresis is used to simulate magnetic behavior of the grain oriented silicon strip of ET114-27 type. Determination of *B-H* hysteretic curve is based on measurement of the initial magnetization curve and the main hysteresis loop. The Preisach distribution function (PDF) of ET114-27 material is approximated by functional series including two-dimensional Gauss expressions. Feedback function is represented by the third order polynomial. For identification of the PDF parameters the Levenberg-Marquardt optimization algorithm was used. The model has been validated by comparing measured and calculated results obtained from tests. Experiments and simulations confirm the accuracy of worked out hysteresis model.

Keywords: magnetic hysteresis, feedback hysteresis model, Preisach distribution function.

1. INTRODUCTION

Several efforts to model magnetic hysteresis have been until now reported. Among many models proposed so far, the hysteresis model based on the Preisach's theory [1] is considered to be a good method for accurate modeling and prediction of the magnetic characteristic. The Preisach model (PM) is classified into so-called macroscopic models of hysteresis [2]. In the PM the double integral of Preisach distribution function $\mu(\alpha,\beta)$ is involved to find usually magnetic flux density *B* as function of the magnetic field intensity *H*. The induction *B* depends not only on the magnetic field but also on the history of magnetization of the material. To describe the magnetization process the concept of Preisach diagrams is used which appeared after 1950 and published among other things in [3,4].

The PM had been initially utilized in the field of magnetism but its mathematical generality suggested implementation of this model in many areas of science. A pure mathematical form of the PM separated from its physical meaning was proposed by Krasnosel'skii [5]. This approach was further developed by Mayergoyz [6-7] for determining the conditions for the representations of the hysteresis nonlinearities and generalization of the PM.

Classical PM has two characteristic properties: the so-called wiping-out property, and the so-called congruency property. The wiping-out property is consistent with the experimental results and means that all the magnetization states of the material connected to its magnetic history can be eliminated by applying a high enough magnetic field. The congruency property means that all minor loops calculated between the same field limits are congruent - minor loops has the same shape and size. Congruent hysteresis minor loops as results of classical Preisach model of tape wound core with ET114-27 type material [8] are shown in Fig.1. This property, however, is not reflected by the experimental hysteresis loops.

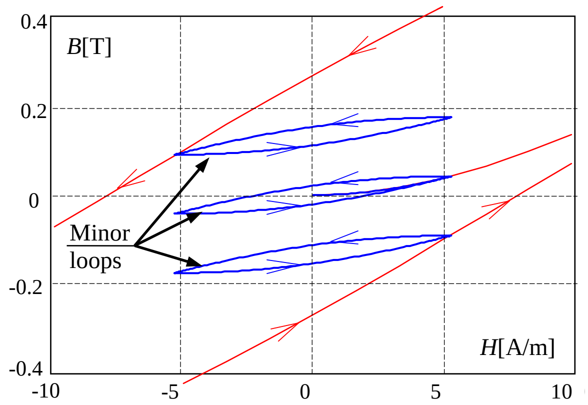

Fig. 1. Congruent hysteresis minor loops – simulation results of classical Preisach model of tape wound core build with silicon steel of ET114-27 type

Nowadays there are several generalizations of the original classical PM in other to improve its ability to represent complex experimental results. One possible solution to relax the congruency property of minor loops and to gain more accuracy for the representation of hysteresis nonlinearity is to use the so-called feedback PM [9,10]. Other modifications of classical PM (generalized PM, moving PM, dynamic PM, vector PM) can be found in [11].

In this paper the scalar feedback Preisach model of hysteresis is shortly presented for representation of magnetic hysteresis in tape wound core. The implementation of this model was previously given in [12]. In this paper more numerical aspects on this model are discussed and original results of simulations are presented. The Preisach distribution function $\mu(\alpha,\beta)$ is proposed as an analytical formula approximated by functional series and feedback function is assumed as the third order polynomial.

After model description the parameter identification procedure is presented which requires only the initial

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magnetization curve and limiting ascending or descending *B-H* curve. The results predicted by the model have been successfully verified by experiments.

2. THE FEEDBACK PREISACH MODEL

In the classical Preisach model a ferromagnetic material is made up of infinite set of magnetic dipoles (hysteresis operator), each having magnetic characteristics with two separate, randomly distributed properties α, β as shown in Fig.2.

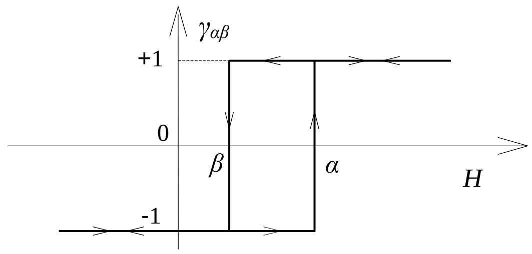

Fig. 2. Rectangular loop of elementary hysteresis operator

Each operator has rectangular hysteresis loop and is defined as mathematical operator $\gamma_{\alpha\beta}(H)$ that can assume only two values, +1 (positively switched) and -1 (negatively switched). The relationship between magnetic field intensity H and flux density B in the classical Preisach model is expressed in the integral form as [6]

$$B = \iint_{\alpha \ge \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}(H)\,d\alpha\, d\beta \qquad (1)$$

where $\mu(\alpha,\beta)$ is a finite weight function having nonzero values within the limits of major hysteresis loop. The term $\mu(\alpha,\beta)$ is also called the Preisach distribution function and can be regarded as a material constant. The weight function $\mu(\alpha,\beta)$ represents a probability density function where $\mu(\alpha,\beta)d\alpha d\beta$ equals the probability that a randomly selected operator has a rectangular loop (α, β).

In the feedback Preisach model (FPM) the positive switching field α is replaced by $\alpha + H_f(B)$ and the negative switching field β is replaced by $\beta + H_f(B)$ in (1). It can be illustrated in the block diagram shown in Fig.3.

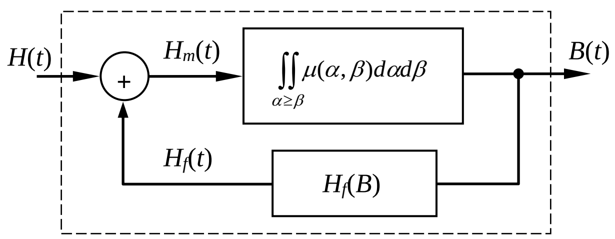

Fig. 3. Block diagram of the feedback Preisach model [12]

In this model, the upper rectangle represents the classical Preisach transducer. The lower rectangle in feedback loop represents the contribution term $H_f(B)$ to the effective magnetic field $H_m(t) = H(t) + H_f(B)$ acting on elementary operators. The scalar feedback Preisach model can be formulated by following integral [14]

$$\begin{aligned} B(t) &= \iint_{\alpha \ge \beta} \mu\left[\alpha + H_f(B), \beta + H_f(B)\right]\gamma_{\alpha,\beta}\left[H_m(t)\right]d\alpha d\beta, \\ H_m(t) &= H(t) + H_f(B(t)), \end{aligned} \qquad (2)$$

where the $\mu(\alpha,\beta,H_f(B))$ also depends on the induction B by a feedback function $H_f(B)$. The function $B(H)$ yields hysteresis loops without the congruency property.

The identification of the feedback Preisach model requires determination of functions $\mu(\alpha,\beta,H_f(B))$ and $H_f(B)$. An analytical approach for determination of feedback field contribution $H_f(B)$ is proposed in [13]. However this approach is applicable only for relatively small feedback factors. A complete parameter identification procedure of FPM is proposed in [14]. In this procedure however a linear feedback function is assumed and it may be applicable to some materials only. In [15] an nonlinear feedback function $H_f(B)$ is taken into account and the factorisation property of the function $\mu(\alpha,\beta)$ is assumed. However this is simplifying assumption and can be usable for a given class of magnetic materials.

Author of this paper proposed a functional series of two-dimensional Gauss expressions to approximate the Preisach distribution function [12]

$$\mu(\alpha,\beta) = \\ = \frac{1}{2\pi}\sum_{n=1}^{N}\frac{A_n}{S_{x,n}S_{y,n}}\exp\left(\frac{-(\alpha+\beta)^2}{2S_{x,n}^2}\right)\exp\left(\frac{-(\alpha-\beta)^2}{2S_{y,n}^2}\right), \qquad (3)$$

where A_n, $S_{x,n}$, and $S_{y,n}$ are material-dependent constant parameters. A feedback function is proposed to be the third order polynomial

$$H_f(B) = K_1 B + K_3 B^3, \qquad (4)$$

where K_1, K_2 are material-dependent constant parameters.

3. PARAMETER IDENTIFICATION OF THE FPM

The identification of the FPM requires the determination of A_n, $S_{x,n}$, $S_{y,n}$, K_1, and K_2 parameters by means of a convenient set of measured data. Measurements were carried out on grain oriented silicon steel strip of ET114-27 type. An iron core was prepared as tape wound torus. Its internal diameter is 506 mm and the cross section dimensions are 35 x 100 mm. The experimental setup is illustrated in Fig.4.

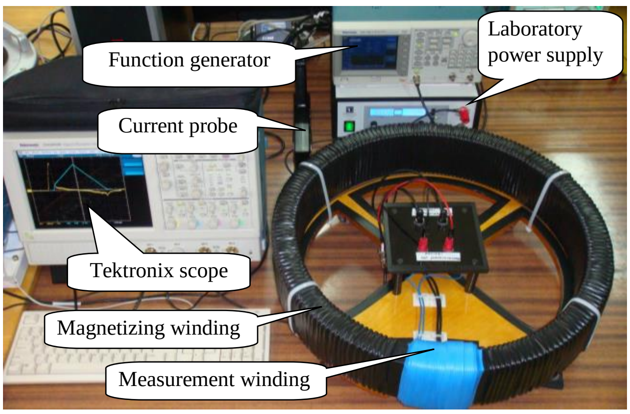

Fig. 4. Experimental setup for measurements of hysteresis loops and hysteresis model parameters[12]

The magnetizing winding is uniformly distributed on most of the core (93%) whereas the measurement winding is lumped on a small part (5%) of the torus. The magnetizing winding is energized by laboratory power supply PS 8000 DT type (*Elektro-Automatik GmbH*) controlled by function generator AFG3011 type (*Tektronix, Inc.*). The magnetic field intensity is calculated from the current in the magnetizing coil, which is measured by means of TCP312 type current probe connected to a Tektronix scope. The flux density is obtained by numerical integration of the voltage induced in the measurement coil. The core was demagnetized before measurements. Measurements have been done under slow time varying excitation current. The frequency equal to 0,020 Hz for the major loop was applied in other to reduce the dynamic effects in magnetic material.

A method for determination of A_n, $S_{x,n}$, $S_{y,n}$, K_1, and K_2 parameters is presented in detail in [12]. This method uses the Levenberg-Marquardt optimization algorithm [16]. Initial magnetization curve and limiting ascending or descending *B-H* curve is utilized for calculation of these parameters. Parameter values of the FPM obtained from identification procedure are shown in Tab.1 and Tab.2. For approximation of the Preisach distribution function only three terms n = 1,2,3 of the functional series have been used.

Table 1. Parameter values of $S_{x,n}$, $S_{y,n}$ given in A/m

$S_{x,1}$	$S_{x,2}$	$S_{x,3}$	$S_{y,1}$	$S_{y,2}$	$S_{y,3}$
35,17	107,4	1232	17,65	41,67	91,77

Table 2. Parameter values of K_1, K_2, and A_n

A_1	A_2	A_3	K_1	K_3
2,92	0,895	3,43	19,07	–14,86

4. EXPERIMENTAL AND SIMULATION RESULTS

As an example, the FPM has been applied for representation of some symmetrical hysteresis loops at different magnetic field intensity *H*. Figure 5 shows simulated symmetrical major loop compared with the experimental one. In Fig.6 simulated symmetrical minor loop and the experimental one are shown. Differences between measured and simulated hysteresis loops are relatively small.

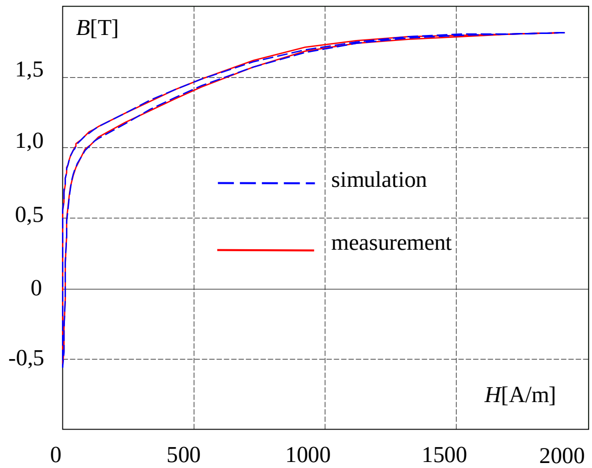

Fig. 5. Simulated and measured parts of symmetrical major hysteresis loops – verification of applied model

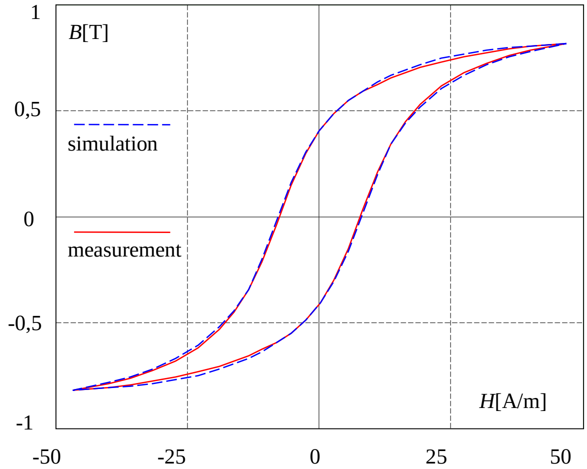

Fig. 6. Simulated and measured symmetrical minor hysteresis loops – verification of applied model

The surface 3D plot of the Preisach distribution function defined by (3) at parameter values given in Tab. 1 and Tab. 2 is shown in Fig.7.

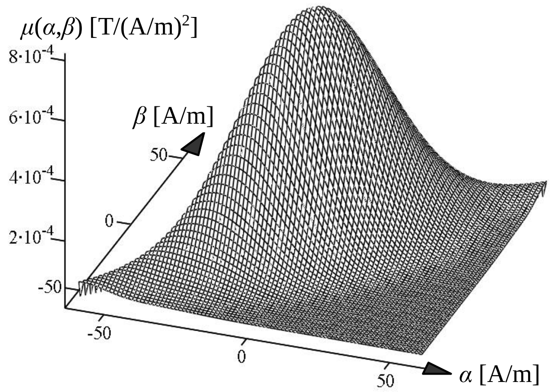

Fig. 7. Preisach distribution function of grain oriented silicon steel of ET114-27 type

The Preisach distribution function has global maximum at $\alpha = \beta = 0$ and is symmetrical with respect to the $\alpha = -\beta$ line. For $|\alpha|>40$ A/m or $|\beta|>40$ A/m it returns relatively small values.

The discussed FPM can be implemented for circuit simulation when magnetic field intensity is assumed time-dependent function. An example of sinusoidal and exponentially decreasing magnetic field $H(t)$ applied to the discussed FPM is shown in Fig.8.

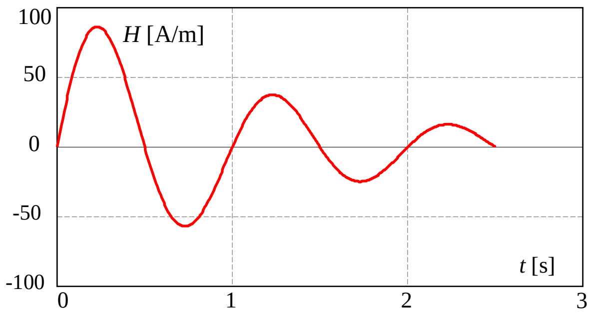

Fig. 8. Application of a assumed H(t) function for circuit simulation of $B(H)$ hysteresis trajectories

A simulation results of $B(H)$ trajectories corresponding to the assumed $H(t)$ function is shown in Fig.9.

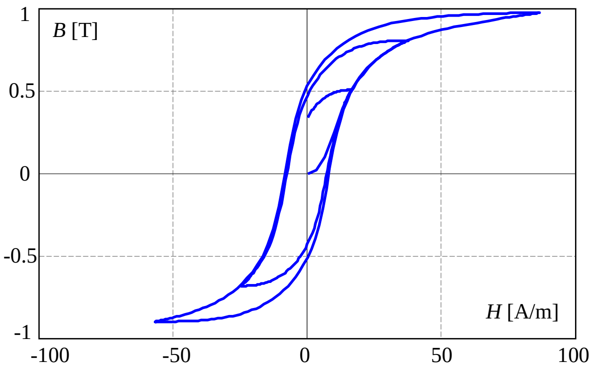

Fig. 9. $B(H)$ hysteresis trajectories solution for assumed $H(t)$ waveform shown in Fig.8

5. CONCLUSIONS

In this paper the ability of the scalar feedback Preisach model to predict magnetic behavior of the grain oriented silicon steel ET114-27 type was examined. The numerical implementation of the applied model is based on the analytical formula of the distribution function as functional series of two-dimensional Gauss expressions. The first three terms of functional series have been used to approximate the distribution function. The feedback function is represented by the third order polynomial. For parameters identification procedure the Levenberg-Marquardt algorithm have been used. This algorithm yields the numerical solution of the nonlinear least squares problem of finding minimum between measured and simulated hysteresis curves.

The measured characteristic parameters of the major loop are: the saturation induction B_s=1.815 T, the saturation field H_s=2100 A/m, the remanence induction B_r=0.55 T, and the coercive field H_c=9 A/m. A good agreement is observed between the measured and simulated hysteresis loops.

The developed hysteresis model can be applied for circuit simulations when time-dependent function of magnetic field $H(t)$ is assumed.

5. REFERENCES

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MODELOWANIE HISTEREZY MAGNETYCZNEJ PRZY ZASTOSOWANIU MODELU PREISACHA ZE SPRZĘŻENIEM ZWROTNYM W RDZENIU ZWIJANYM Z BLACHY

Key-words: histereza magnetyczna, model histerezy ze sprzężeniem zwrotnym, funkcja dystrybucji Preisacha

Skalarny model histerezy Preisacha (MHP) z nieliniowym sprzężeniem zwrotnym został w tej pracy przedstawiony oraz wybrane wyniki symulacji wykonano w celu jego weryfikacji na podstawie eksperymentów. Funkcję dystrybucji Preisacha (FDP) aproksymowano za pomocą skończonego szeregu funkcyjnego zawierającego funkcje Gaussa z dwiema zmiennymi. Współczynniki FDP wyznaczono na podstawie procedury optymalizacyjnej Levenberga-Marquardta przy wykorzystaniu jedynie pierwotnej krzywej magnesowania oraz głównej pętli histerezy. Weryfikacja modelu histerezy dla materiału ET114 wykazała bardzo dobrą zgodność wyników symulacji z wynikami pomiarów w zakresie głównej, jak też małych pętli histerezy.