Two Methods of Scalar Preisach Function Identification for Grain Oriented Steel

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***Abstract* – This paper presents the implementation of the Preisach hysteresis model of a soft magnetic material. The model application is especially useful in the study of transition effects in power transformers like an inrush current or a ferroresonance. The main problem in the use of the Preisach model is to find a suitable weighting function. We considered two basic methods: estimation and systematic derivation. Application of both the methods revealed that the systematic method leads to a better agreement with the experiment. However both results are applicable for investigation of annealed grain oriented steel in transformer core.**

Keywords-Hysteresis, Preisach model; soft magnetic materials; current excitation; grain oriented steel

I. INTRODUCTION

At present time the design of a new electrical system is followed by the immediate simulation of the circuit at each step. This approach allows us to judge if the circuit output parameters are near to the expected ones and to find optimal solution. The simulation packages use limited number of non-linear elements given by an analytical formula or a graph. However the non-linearity connected with hysteresis cannot be described by a standard analytical formula.

Since circuit elements using the ferromagnetic material are often used (as transformers first of all), a lot of work was devoted to make reliable models of these devices. The most universal model is the Preisach one [1, 2]. The key part of the model is the weighting function that characterizes magnetic properties of the material. It can be derived from the measurements on the material. The basic procedure is presented [1]. Due to experimental errors, some modifications of the theoretical procedure are necessary. Different attempts are presented in the literature [3–5]. Another possible approach is to estimate the weighting function [6, 7].

In the paper, we describe the Preisach model, present the experiment, mention data processing and compare both approaches to obtain the weighting function.

II. THEORY

Since the Preisach model is not familiar to many readers, we'll describe it briefly. Its basic part is an ideal elementary hysteresis dipole, characterized by magnetic momentum $+m_o$, low and high

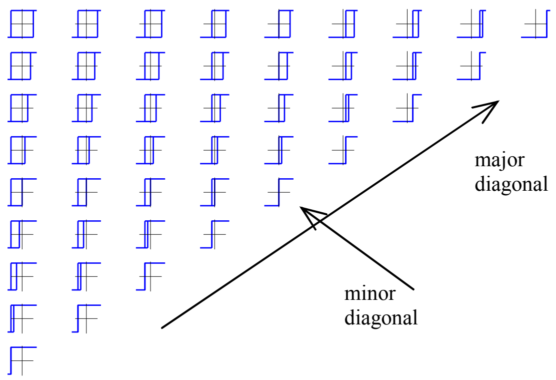

Figure 1. Elementary dipoles

transition field strengths H_d and H_u, respectively. If the external field H is higher than H_u, $H > H_u$, the dipole has momentum of m_o. If the field H is lower than H_d, $H < H_d$, the dipole momentum is $-m_o$. In the case of external field between transitions limits, $H_d < H < H_u$, the momentum depends on the previous history. If the field decreases under H_u, the momentum does not change and remains m_o. Analogically, if the field increases over H_d, the momentum does not change and remains, in this case, equal to $-m_o$. The condition of $H < H_d$ and simultaneously $H > H_u$ is not physically possible.

We can suppose that $H_d \le H_u$ and each of them can be positive or negative. Several hysteresis loops for systematic values of H_d and H_u are given in Fig. 1. Because of condition $H_d \le H_u$, they form a triangle, not a square.

Several specific elementary hysteresis loops can be found in Fig. 1. No hysteresis is on the major diagonal. The symmetric loops are in the minor diagonal. Therefore we can expect the maximum of the weighting function on that minor diagonal. On the left hand vertical side the value H_d is fixed. On the contrary, on the upper horizontal side the upper field H_u is fixed.

Mathematically, the Preisach model for the computation of the material magnetic momentum M at time t is given by the (1)

$$M(t) = \iint_{H_u \ge H_d} w(H_u, H_d)\hat{m}(H_u, H_d)H(t)dH_u dH_t \quad (1)$$

The hysteresis operator $\hat{m}$ (H_u, H_d) makes the elementary magnetic momentum for the given field strength $H(t)$ according to the explanation in the

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beginning part of this chapter. Therefore, $\hat{m}$ (H_u, H_d).$H(t)$ means either $+m_o$ or $-m_o$. The weighting function $w(H_u, H_d)$ is determined by the material and it should be found.

The work of the Preisach model can be explained simply by geometrical means. The elementary dipoles in the net like that in Fig. 1 are oriented up (represented by plus sign) or down (circles) depending on previous history. Suppose that the sample was polarized down and external field strength H increases from its minimum value. For the selected time instant its position on the waveform and its level on the Preisach diagram are shown in the left and right hand part of Fig. 2, respectively. The horizontal field level moves in the up direction. All elementary dipoles with $H_u < H$ are polarized positively.

When the external field in Fig. 2 reaches its maximum, the sample is perfectly polarized in the up direction. Then the external field H decreases. The situation in this time instant is given in Fig. 3. Now the external field level is vertical and moves from right to left. All the dipoles with condition $H_d > H$ are polarized negatively.

This procedure ensures the application of the Preisach operator $\hat{m}$ in (1). Now these results should be multiplied by the weighting function and summed in digital representation in order to get the total magnetic momentum, or magnetization.

Since the weighting function reflects the material properties, it should be determined by experiment. In order to ensure simple and stable initial conditions, the external magnetic field should increase from its negative saturation to a local maximum (which is less than absolute maximum)

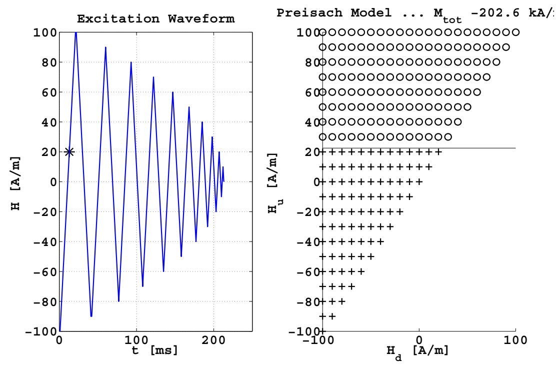

Figure 2. Preisach model for increasing the external field

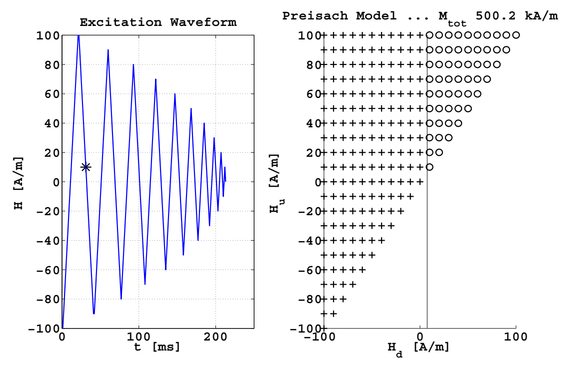

Figure 3. Preisach model when the external field decreases

and then decreases again to negative saturation. The procedure repeats several times for increasing of local maximums up to positive saturation. The curve from local maximum, $H_u^{(1)}$, to negative saturation is termed the first order transition curve. Some of these transition curves for the investigated material are shown in Fig. 4. The branch corresponding to field increase should be the same for all the transition curves bellow the maximum $H_u^{(1)}$ and these curves should lie above it.

Let $[H_u^{(1)}, H_d^{(1)}]$ is a point on the transition curve with magnetic momentum $M(H_u^{(1)}, H_d^{(1)})$. It follows from the geometrical interpretation of the Preisach model [1] that the momentum is determined by the weighting function according to formula

$$M\left(H_u^{(1)},H_d^{(1)}\right)-M\left(H_u^{(1)}\right)=-2\int_{H_d^{(1)}}^{H_u^{(1)}}\int_{H_d}^{H_u^{(1)}} w(H_u,H_d)\,\mathrm{d}H_u\,\mathrm{d}H_d\,, \qquad (2)$$

where $M(H_u^{(1)})$ is material momentum at the point when the transition curve starts. According to (2) we can simply get the relation between the experimental magnetic momentum and the weighting function

$$w\left(H_u^{(1)},H_d^{(1)}\right)=\frac{1}{2}\frac{\partial^2 M\left(H_u^{(1)},H_d^{(1)}\right)}{\partial H_u^{(1)}\partial H_d^{(1)}}\,. \qquad (3)$$

Two partial derivatives are necessary. In [1], the modified magnetic momentum is defined as a function $m(H_u^{(1)},H_d^{(1)}) = ½\,(M(H_u^{(1)}) - M(H_u^{(1)},H_d^{(1)}))$ for completeness. Then the formula (3) has not coefficient ½ and opposite sign.

III. EXPERIMENT

The task of experiment is to get the first order transition curves like those in Fig. 4. We have used a standard full automated experimental apparatus with one exception. The source of harmonic current is suitable for reliable measurements. It can be realized from a voltage source by simple way using series resistor or by applying the current control of a voltage source. Since we have the universal voltage source Kikusui PCR 2000LA, both ways were possible. We preferred the simple one. However, in each case the source cannot operate at power net frequency of 50 Hz, since the coil impedance is high and a voltage source of thousands volts is not available for required currents. Therefore we decreased the frequency to 1 Hz, which caused other problems.

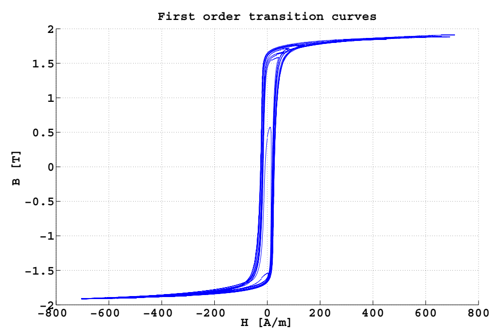

Figure 4. Experimental transition curves of the first order

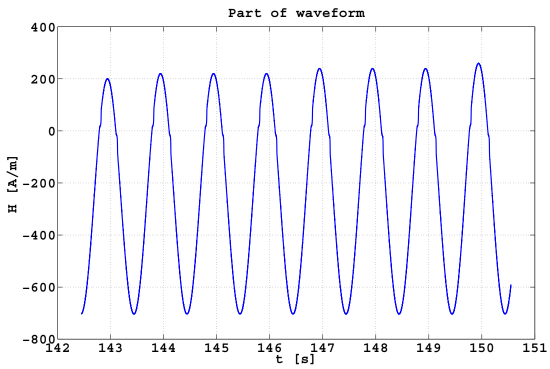

Figure 5. Experimental magnetic field strength waveform

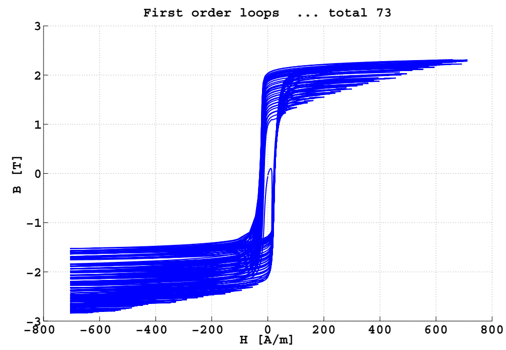

Figure 6. Measured transition curves of the first order.

The measured specimen is the toroidal transformer made from a standard grain oriented M130 laminated steel of 0.3 mm thickness. The core diameters are D = 220 mm and d = 160 mm with depth = 30 mm. The primary winding has n_p = 100 turns and secondary n_s = 300.

The current should start at a negative value and gradually increase. This method is known as the first order reversal curves FORC [3]. In order to get good results, the transition curves should be as close as possible; therefore the current steps should be low. The part of the applied magnetic strength waveform is shown in Fig. 5. After every 3 periods the field strength was increased by a step of about 20 A/m. This approach makes it possible to store all the data in one file. Otherwise many files are necessary.

The low frequncy and long time measuring sequence, of about 4 minutes, cause some problems. The induced secondary voltage is low and noisy, especially at 50 Hz, and it distorts the output waveform. However the integration of the secondary voltage reduces the effect.

The most important second order effect was the zero drift of the secondary voltage due to the measuring chain offset. Although it was almost eliminated at the start of measurement, due to the long-time measurement it led to the vertical shift of the transition curves. Typical results from this expriment after integration are in Fig. 6. The spread is very high, therefore data processing is necesssary.

On the other hand, the low frequency reduces eddy currents. Therefore the loops may be closer to the ideal ones.

IV. DATA PROCESSSING AND CALCULATIONS

The experimental data processing was necessary in order to reduce the effect of drift. The simple method used peak values of the flux density to determine and compensate drift as in [8]. The effect of this simple data processing can be judged by comparing original results in Fig. 6 with results from processing in Fig. 4. In Fig. 4 there are only the important curves, but the effect is almost the same for all the curves.

Application of the Preisach operator in (1) is relatively simple, as it is presented in Fig. 2 and 3. But the determination of the weighting function is very complicated. Because of the high noise level, the numeric derivation is impossible. Really, a lot of local maximums were found in the area of the passage through zero, where the magnetic momentum changes most rapidly.

If we do not consider interpolation, proposed in [1], there are two basic ways for the weighting function determination

1. Estimation of the weighting function [5, 8, 9].
2. Follow the systematic procedure on experimental data suggested in [1].

Both approaches are used in the literature and we have tried both of them.

In the first simpler approach, we have used the weighting function in the form of probability density of Gauss-Gauss distribution

$$w(H_d, H_u) = C\left(b + e^{\frac{(H_u - H_u^{(1)})^2 + (H_d - H_d^{(1)})^2}{2\sigma^2}}\right), \quad (4)$$

where σ is the standard deviation. In general, a small constant b is added. The coefficient C follows from the condition that the sum of all field values of the weighting function gives the value of saturated polarization.

Other distribution functions can be also used [6]. The centre of the distribution function should by on the minor diagonal of the Preisach diagram in Fig. 2, since the elementary hysteresis loops are symmetrical. The minor diagonal limits the mean value of distribution. The second variable is a standard deviation. Using the method of numerical optimization the best possible agreement can be reached.

The systematic procedure proposed in [1], needs above all to fill the grid by experimental magnetic momentum M. Using the strength waveform from Fig. 5, we have a lot of data for rows, but only several data for columns. The grid constant should be equal to change ΔH. Then the values on rows can be found.

The use of derivation from (3) needs to approximate the data surface $m(H_u, H_d)$. We used the simplest function $\arctan(k(H - H_o))$ that matches data well, if the range of the independent variable is high. It uses two selectable parameters – coefficient k and shift H_0. The approximation is applied in both directions, horizontal with variable H_d and vertical with variable H_u. The surface $m(H_u, H_d)$ of the modified magnetic momentum was approximated by a product of the arctan function with different parameters, see Fig. 7.

The derivation (3) of the approximated momentum is the product of two functions that do not differ substantially from the normal probability density.

V. RESULTS

Theoretical and experimental hysteresis loops are compared for the estimation method in Fig. 8. The agreement is acceptable with an exception of the loop knee.

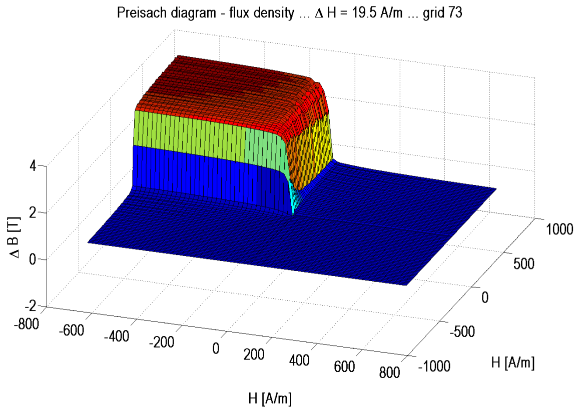

Figure 7. Approximated surface of modified magnetic momentum.

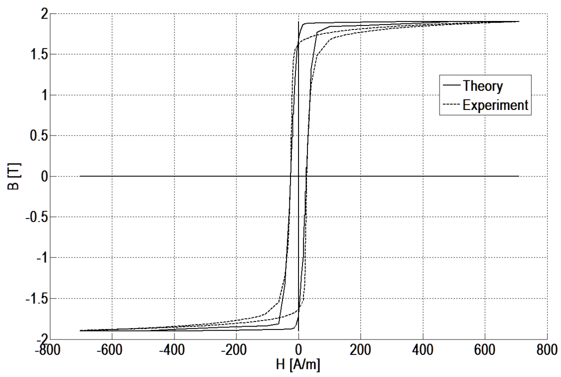

Figure 8. Approximated loop by the estimation method.

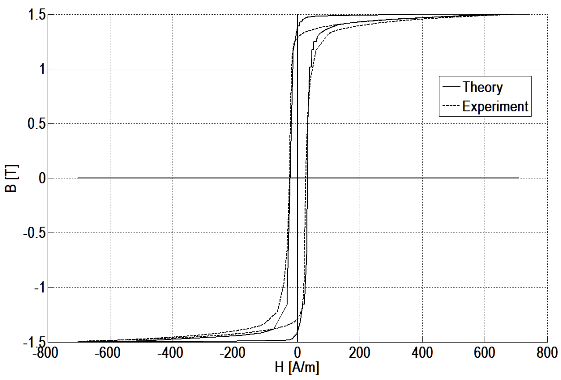

Figure 9. Approximated loop by the systematic method.

The use of the systematic approach leads to results in Fig. 9. The agreement is better, but the shift of the theoretical curve was necessary.

VI. DISCUSSION AND CONCLUSIONS

Both methods for obtaining the theoretical loop using the Preisach model lead to similar results. In general, the estimation method needs only one experimental loop [8], therefore it is faster. Unfortunately, we could not find how the individual variable parameters influence the results. Therefore it is difficult to formulate rules for a fast and effective approximation.

The success of the systematic method [1] depends on the quality of approximation of the magnetic momentum surface, like that in Fig. 7. The present use of the product of two functions, each of one variable, is not the best solution. Nevertheless the agreement is acceptable.

Future work should focus on improvements both in the experimental and computation area. In the experiment, the higher frequency should be used, say 3 or 10 Hz. Sensitivity will increase and noise will be reduced. In the computational area the more general approximation using the function of two variables should be made. The MATLAB function *fminsearch* makes it possible to find its parameters effectively.

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