Magnetic Hysteresis under an Applied Continuous External Magnetic Field

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Abstract: Electromagnetic systems such as AC machines have to support supply voltages containing a DC component which induces both an increase of the total magnetic losses and the premature saturation of the magnetic core. In the present paper, we present an approach for predicting the hysteresis loop of a magnetic material such as non oriented FeSi 3% which is subjected to a DC bias. The measurements are carried out with a bench test built around an Epstein frame. The material is excited with a damped sinusoidal flux density superimposed to a known continuous field. We obtain superimposed asymmetrical hysteresis loops. The cycles are modeled via the Preisach Model (PM) [1], which provides both a mathematical model for the B(H) curve and an analytical approach which identifies and predicts the parameter behavior needed by the PM.

Key words: Hysteresis, Preisach Model, continuous field, magnetic material.

1. Introduction

The magnetic properties of soft material such as Fesi 3% are very sensitive to both applied mechanical and thermal stresses as well as the external electromagnetic field. Magnetic materials such as Fesi 3% are commonly used in the manufacturing of electromagnetic devices which are supplied by a sinusoidal electrical network. The flux density is symmetrical, a very important property for the good functioning of this type of device.

Many devices operating in the low- and medium-frequency range, ranging from rotating machinery (dc machines, permanent magnet motor) to magnetic cores in electronic drives, are employed under special supply conditions, which may include dc bias and generally non-sinusoidal induction with local minima. The pre- diction of the core losses under such conditions, which are far removed from the standard conditions required for conventional magnetic testing of materials [1], may present special difficulties, inherent to the general features of hysteresis (e.g. Non-local memory effects) and their evolution with the magnetizing frequency [2].

This work attempts to investigate the function b(h) take account the continue component of the excitation. The pm model is chosen because, on one hand, it merely accounts for all the parameters involved in process of magnetization of magnetic materials such as saturation, minor cycles, etc, and on the other hand, the simplicity of its implementation.

In order to validate the simulations, we carried out tests on two types of sheets: Fesi 3% with oriented-grains 0.5mm thickness on the Epstein bench.

2. Preisach Model

The classical Preisach model together with quite a few generalizations has been efficiently applied to describe hysteresis phenomena under various conditions [1,2]. It consists in a set of hysteresis operators (ideal switches with rectangular characteristics) and features some very favourable properties: fast and memory sparing numerical implementation based on the everett integrals, well defined and reliable experimental identification procedure based on measurement of first order reversal curves. It can adequately describe the static magnetic behavior of various ferromagnetic materials. Combined with eddy current computation, the dynamic operation of homogeneous materials or thick parts having randomly oriented, tiny domains can be simulated with acceptable accuracy [3]. This method fails however to encompass the effects of domain wall displacement [5], important in the case of electrical steel sheets and it is also costly—in terms of computing time and memory requirement.

Preisach represented the magnetic state of magnetic material, at any time, has two possible states of magnetization (m=1 and m= -1), defined by a rectangular elementary cycle on the input-output diagram. The latter is characterized by the inversion fields of \(\alpha\) and \(\beta\) (with \(\alpha\geq\beta\)) for which...
there is an irreversible transition from the high state (m=1) to the low state m= -1 and vice versa; that is, α and β correspond to up and down switching values of the input, respectively. The calculation of total magnetization requires knowledge of the statistical distribution of the elementary cycles. This function is called Preisach function [1], [2][4]. Assuming the input and output variables as function of time, the Preisach function of magnetization resulting from the application of an h(t) field is given by:

\[ M(t) = \iint \rho(\alpha, \beta) \Phi_{\alpha, \beta}[h(t)] \, d\alpha d\beta \quad (1) \]

With: (the value is (+1) if h=α and (-1) if h=β)
\[ \rho(\alpha, \beta) \]: Density function—also referred as Preisach measure-. It depends on the nature of the material [1].
\[ \Phi_{\alpha, \beta}[h(t)] \]: Operator associated to the magnetic entities referred to as elementary Preisach hysteron operator.

I.1. Geometrical Interpretation of the Model

There is a known one-to-one correspondence between the operator \( \Phi_{\alpha, \beta}[h(t)] \) and the points (\( \alpha, \beta \)) located in the half plane \( \alpha \geq \beta \). Geometrically, S can be subdivided into two parts, which are separated by the border \( l(t) \), which is itself time dependent. The surface \( S(t) \) represents all the entities whose state of magnetization is (+1), while \( S_-(t) \) represents those with state of magnetization (-1). Model (1) can then be written in the following form:

\[ M(t) = \iint_{S_+} \rho(\alpha, \beta) l d\alpha d\beta - \iint_{S_-} \rho(\alpha, \beta) l d\alpha d\beta \quad (2) \]

I.2. The Distribution Function

The complete determination of the Preisach model requires the knowledge of the density function \( \rho(\alpha, \beta) \), which is the basis for the calculation of the total magnetization. For this purpose and at a given time, intuitively two approaches contrast.

The first method relies on extensive experimental hysteretic loops while the second method consists of approximating real loops by means of some analytical function. In our study, we consider the second approach.

1.3. Analytical Approach

Several analytical expressions can be used. One of these approximations is the Lorentz function given by [1], [2]:

\[ \rho(\alpha, \beta) = \frac{K}{1 + \left( \frac{\alpha}{H_c} - 0.5 \right)^2} \left( 1 + \left( \frac{\beta}{H_c} + 0.5 \right)^2 \right) \quad (3) \]

With
\[ K \]: constant of standardization adjusted to have \( M(Hs(t))=Ms \),
\( H_c \): the coercitive field.
For a better approximation of the experimental loop, the Lorentzian function is modified by adding parameters and takes the form:

\[ \rho(\alpha, \beta) = \frac{Ka}{\alpha + (\alpha - b)^2} \left( 1 + \left( \frac{\alpha}{H_c} - 0.5 \right)^2 \right) \quad (4) \]

Experimental measurements show that the two parameters \( a \) and \( b \) depend on the the nature of the material, i.e. remanent induction, coercitive field and permeability of the material. On the other hand, the area of \( B(H) \) increases with the frequency [3]. An adjustment of the parameters \( a \) and \( b \) is necessary to have a correct modelling of the \( B(H) \) behaviour. The parameters \( a \) and \( b \) are defined as follow: \( a \in \mathbb{R}^+_\ast \) and \( b \in \left[ 1, \frac{H_s}{H_c} \right] \).

1.4. Mathematical Modified Formulation

With the PM model and the modified Lorentz function, we obtain the following expression.

\[ M(t) = M_{t-1}(t) \pm 2 \iint_D \rho(\alpha, \beta) d\alpha d\beta \quad (5) \]

\( M_{t-1} \) stands for the previous magnetization moment. This formulation makes the calculation easier. Figure 1 shows the influence of the continuous component of the magnetic field on the hysteresis loop of the ferromagnetic material.
This figure shows that the hysteresis loop is asymmetrical. Hence, the magnetic properties of the material are modified under the solicitation field with constant component.

2. Simulation of the Hysteresis Loops under Solicitation with Constant Component

The solicitation considered is a combination of dc bias and ac magnetization with linearly diminishing amplitude. In order to modelize the hysteresis, we subdivide the considered signal into other periodical signal, and we use the Preisach Model for the simulation.

The combined signal from dc bias and ac magnetization as well as the linearly diminishing amplitude and the hysteresis loops obtained using PM are shown in Fig.2 and Fig.3 respectively.

The figure 4 shows the anysteretic curve obtained by varying the amplitude of the dc bias magnetization.

3. Experimental Bench

The Figure 5 illustrates the experimental measurement setup composed from:

- An Epstein frame standardized
- A power amplifier KEPCO
- A numerical generator programmable WAVETEK 39.
- A digital scope (MXOX2000) for the visualisation and for data acquisition.
- A PC for data acquisition and processing.
- A current sensor.
4. Experimental validation

The Epstein test method is used to perform measurements for an FeSi 3% sheet. The primary winding is supplied with a sinusoidal voltage superimposed to a known DC voltage component. The amplitude of the maximum alternating voltage is decreasing linearly (Figure 4). We keep constant the parameter b in the Lorentz distribution function while the parameter a is adjusted to draw hysteresis loops as is described in Fig. 6. We obtain a linear evolution for the parameter a as a function of the magnetisation and the loops are converging to the magnetic state determined by the dc field, as shown in Figure 7.

The same process is reproduced by considering an exponential decrease of the maximum amplitude of the alternating voltage. Figures 8 and 9 show the comparison between predicted and experimental hysteresis loops and the dependence of parameter a with maximal induction Bmax.
Conclusion

Measurements have been carried out in 0.5mm thick non-oriented FeSi 3% laminations. The material is excited with a deadened sinusoidal field superimposed on a continuous component. The obtained asymmetric loops are modeled through the proposed approach based on the Preisach Model (PM) combined with a mathematical model which predicts the parameters that the PM needs. The experiment validation results are in agreement with several experiments. As a perspective for this work, the study of the modeling of the B(H) curve through the new approach could be extended to predict magnetic losses.

References


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Table 1: Comparison between DC magnetization values (experimental and predicted)