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Physica B 372 (2006) 260–264

PHYSICA B

www.elsevier.com/locate/physb

Dynamic hysteresis modelling for toroidal cores

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Abstract

The dynamic hysteresis loops of a range of strip wound cores have been obtained over a wide frequency range (50–1000 Hz). A dynamic hysteresis model from measurements using an artificial neural network has been developed. Input parameters include the geometrical dimensions of wound cores, peak magnetic induction and magnetizing frequency. The neural network dynamic hysteresis model has also been compared with the dynamic Preisach, energetic and viscous-type dynamic hysteresis models after they have been applied to toroidal wound cores. The results show the neural network model has an acceptable estimation capability for dynamic hysteresis loops of toroidal cores.

PACS: 75.50.−y; 75.60.−d; 85.70.−w; 76.60.Es; 84.35.+i

Keywords: Dynamic hysteresis model; Toroidal wound core; Neural network

1. Introduction

Rapid and accurate prediction of iron loss in electromagnetic devices is becoming more important in their design and specifications for many reasons such as economy, competition, time, etc. Theoretical approaches are still not accurate for hysteresis loops and its corresponding power losses the dynamic Preisach model (DPM) is often used [1] however a discrepancy with experiment is observed at low induction because the domain wall motion mechanism and anisotropy of the material is not precisely described. The energetic model (EM) has been applied for different magnetic materials. The aim of the EM is the interpretation of magnetization process as based on Newton's probability formula [2]. The distinctive features of the viscous-type dynamic hysteresis model (DHM) are its arbitrary frequency dependence and the ability to control the shape of the dynamic hysteresis loop [3]. The toroidal core, although simple in geometry, is subjected to different factors which have an influence on its magnetic properties [4]. It is a closed magnetic circuit; this avoids problems due to the demagnetizing field. It has the disadvantage that internal stresses due to bending can influence the shape of the hysteresis loop [5]. Therefore the hysteresis loop measured in a toroidal geometry is different as compared to a single sheet. An artificial neural network (ANN) has recently been used as an alternative mathematical model for the magnetic hysteresis loops in magnetic materials. The ANN model can provide a computational model that has a cost in terms of the time comparable to that of more conventional polynomial based systems [6]. The ANN is also increasingly becoming a useful tool to predict magnetic performance of transformer cores [7]. Recently the power loss and permeability has been predicted using the geometrical dimensions and material properties of wound cores and the neural network trained experimental data [8]. An ANN model was also formed to predict the hysteresis loops with the training data calculated by the Preisach theory [9].

The parameters of DPM, EM and DHM have been determined by fitting them to the measured hysteresis loops of 0.27 mm thick grain oriented 3% SiFe toroidal wound cores. In this investigation, an ANN model is formed to predict the hysteresis loops with the geometrical dimensions of toroidal cores using the trained experimental data.

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doi:10.1016/j.physb.2005.10.062

2. Dynamic Preisach model

According to Preisach theory, the magnetisation can be calculated by [10]

$$M = M_{\mathrm{s}} \int_{h_{\mathrm{c}}} \mathrm{d}h_{\mathrm{c}} \int_{h_i} \mathrm{d}h_i p(h_{\mathrm{c}}, h_{\mathrm{i}}) Q(h_{\mathrm{c}}, h_{\mathrm{i}}), \tag{1}$$

where $Q(h_{\mathrm{c}}, h_{\mathrm{i}})$ is the current state of the Preisach hysterons (Fig. 1.) defined by a critical field $h_{\mathrm{c}} = (u-v)/2$ and interaction field $h_{\mathrm{i}} = (u+v)/2$. $p(h_{\mathrm{c}}, h_{\mathrm{i}})$ is the Preisach distribution function (PDF). The PDF has a Lorentzian form [11]

$$p(u, v) = \frac{K}{[1+(u-1/2)^2][1+(v+1/2)^2]}, \tag{2}$$

where K is a normalizing constant.

DPM parameters are determined by fitting Eqs. (1) and (2) using Matlab$^{\mathrm{TM}}$ to the measured hysteresis loop for the toroidal core. The value $K = 0.15$ has been obtained from a core with 80 mm outer diameter, 50 mm inner diameter and 25 mm strip width.

3. Energetic model

In this model, magnetic field is calculated by [2]

$$H = H_{\mathrm{d}} + \mathrm{sgn}(m) H_{\mathrm{R}} + \mathrm{sgn}(m - m_0) H_{\mathrm{I}}, \tag{3}$$

where H_{d} is the demagnetizing field:

$$H_{\mathrm{d}} = -N_{\mathrm{d}} M_{\mathrm{s}} m. \tag{4}$$

H_{R} is the reversible field:

$$H_{\mathrm{R}} = h[((1+m)^{1+m}(1-m)^{1-m})^{g/2} - 1). \tag{5}$$

H_{I} is the irreversible field:

$$H_{\mathrm{I}} = \left(\frac{k}{\mu_0 M_{\mathrm{s}}} + c_{\mathrm{r}} H_{\mathrm{R}}\right) + \left[1 - \kappa \exp\left(-\frac{q}{\kappa}|m - m_0|\right)\right]. \tag{6}$$

$\mathrm{sgn}(x)$ function provides four quadrant calculation, m is the rate of magnetization (M) to saturation magnetization (M_{s}). All of the quantities in Eqs. (4)–(6) have been elaborately described in [2] and [5].

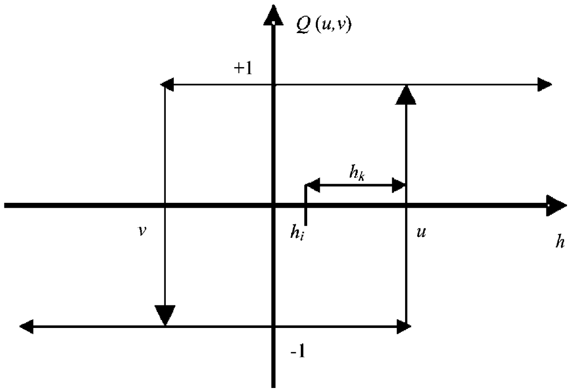

Fig. 1. Characteristic parameters of a single Preisach hysteron.

The EM correlation parameters g, k, h and q have been found to be 10.2, 18.5, 0.82 and 19.5 for toroidal wound cores made from 0.27 mm thick grain oriented 3% SiFe with 80 mm outer diameter, 50 mm inner diameter and 25 mm strip width, respectively.

4. Viscous-type model

The viscous-type dynamic effects observed in the magnetic materials are described by the expression [3]

$$\frac{\mathrm{d}B}{\mathrm{d}t} = r(B)(H - H_0), \tag{7}$$

where $r(B)$ is dynamic magnetic resistivity and H_0 is a threshold field.

The DHM hysteresis loops for toroidal cores have been obtained by experimental data fitting and by using a history dependent model [3,12].

5. Neural network model

A neural network is an interconnected assembly of simple processing elements, units or nodes, whose functionality is loosely based on the human neuron. The processing ability of the network is stored in the inter-unit connection strengths or weights, obtained by a process of adaptation to, or learning from, a set of training patterns. Implicit knowledge is built into a neural network by training it. Some neural networks can be trained by being presented with typical input patterns and the corresponding expected output patterns. The error between the actual and expected outputs is used to modify the strengths, or weights, of the connections between the neurons. The back-propagation algorithm in Eq. (8) [8] is used in this study.

$$\delta_{\mathrm{k}} = \sigma a_{\mathrm{k}} (t_{\mathrm{k}}^{\mathrm{p}} - y_{\mathrm{k}}^{\mathrm{p}}), \tag{8}$$

where a_{k}, $t_{\mathrm{k}}^{\mathrm{p}}$, $y_{\mathrm{k}}^{\mathrm{p}}$, δ_{k} and σ are neuron k activation, neuron k target pattern, neuron k output pattern, hidden layer neuron k error and output transfer function respectively.

The main problem with an ANN model has been to establish representative training data, particularly when a large number of variables are considered as is in this research. It was necessary to develop a rapid magnetic measurement system to achieve a large database. The developed measuring system is integrated with high-speed data capture and analysis software developed in LabVIEW$^{\mathrm{TM}}$ [13]. The experimental data was obtained for dimensions ranging from 35 to 160 mm outer diameter, 25–100 mm inner diameter and 10–70 mm strip width, a magnetic flux density range of 0.2–1.7 T at frequencies 50, 100, 200, 400 and 1000 Hz. The data was captured in the form of 1000 data points for one period of the distorted and undistorted waveform of magnetic field strength (H) and magnetic flux density (B). Fig. 2 shows a developed neural network model. In this network the input parameters for a wound core built from M4 material consisted of the geometrical dimensions ($d_1 =$ outer diameter,