Magneto-Dynamic Field Computation Using A Rate-Dependent Preisach Model

Dirk A. Philips, Luc R. Dupré and Jan A.A. Melkebeek

Laboratory for Electrical Machines and Power Electronics, Department of Electrical Power Engineering
University of Gent, B-9000 Gent, Belgium

Abstract — In this paper the use of the Preisach model in magnetodynamic field computations is discussed. The discussion is restricted to soft magnetic laminations of silicon iron. For some materials the hysteresis effects vary considerably with the frequency. Therefore, a generalised, rate-dependent Preisach model is adopted. A method is presented that allows the computation of the magnetodynamic fields inside the laminations in presence of this model. The results of these computations show a remarkable agreement with the measurements.

I. INTRODUCTION

In this paper the use of the classical Preisach model [1] and the generalised, rate dependent Preisach model [2] in magnetodynamics is discussed. The discussion is restricted to soft magnetic laminations of non-oriented silicon iron. The magnetic behaviour of such laminations can be described in terms of the macroscopic magnetodynamic fields. This approach is especially useful in case the magnetic fields are not uniform throughout the thickness of the lamination. With the higher frequencies and distorted waveforms in modern electromagnetic converters and machines this situation becomes increasingly important nowadays.

It is well known in the literature [3] that the Classical Preisach Model (further referred to as CPM) implies some hysteresis properties, such as the congruence property, which are not necessarily met by all materials. It will be shown in section II however that, at least for silicon iron, an acceptable agreement between the CPM and the measurements can be achieved under static conditions.

A further improvement can be obtained if more sophisticated models such as the product model [4] and the moving model [5] are used. However, it is the authors opinion that, as far as the modelling of silicon iron is concerned, the limitations of the CPM under static conditions are not the most important. As will be shown in this paper the frequency dependence of the hysteresis effects can have a much greater impact on the magnetic behaviour of silicon iron.

Therefore in section III a Generalised Preisach Model (further referred to as GPM), introduced by Bertotti [2] is discussed which takes into account such a frequency dependence. A numerical method is presented that allows the computation of the magnetodynamic fields inside the laminations, in presence of this model.

In this paper two different types of non-oriented silicon iron, are discussed, namely V-600-50-A and V-450-50-E (normalised classification described in [6]). Both materials are further referred to as material 1, respectively material 2. Sheets of both materials have been punched in the form of rings, with a diameter ratio of approximately 1.1. These laminations are assembled to form a stacked ring core, on which a (inner) measurement winding and an (outer) excitation winding are wound. For both materials the Preisach distribution function has been identified by measurement of the Everett integrals [7]. These Preisach functions are used in the field computations presented in this paper.

II. MAGNETO-DYNAMIC FIELDS WITH THE CLASSICAL PREISACH MODEL

A. Classical Preisach model

According to the Classical Preisach Model (CPM) [1] a ferromagnetic material is composed of elementary dipoles. Every dipole is characterised by the values of the elementary switching fields, $\alpha$ and $\beta$. The relative density of these dipoles is represented by the Preisach distribution function $P(\alpha, \beta)$ that characterises a specific material. The magnetic induction in the material is determined by the magnetic state of all elementary dipoles which, in turn, depends on the magnetic history of the material.

![Fig. 1a: Non-congruency](image1a)

![Fig. 1b: Accommodation](image1b)

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Dirk A. Philips,
e-mail: philips@edkape.rug.ac.be

fax 32/9/2642421.

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The CPM implies the congruency of secondary loops with identical field limits [8]. As is shown in fig. 1a, material 1 does not completely conform to this requirement. Non-congruency can cause problems when identifying the Preisach function through second order derivatives of the Everett-function [7]. However, these problems can be overcome by measuring the Everett function for several secondary loops with identical field limits and using the average value in later computations. As fig.1a shows, an acceptable agreement between the measured and computed excursions is achieved in this way.

Another deficiency of the CPM is that it cannot represent accommodation [9], i.e. the property of secondary loops to reach the stable position only after several cycles. As fig.1b shows, material 1 suffers from accommodation to some extent. Nevertheless, an acceptable agreement is obtained between the "average" measured loop and the loop computed with the CPM.

**B Magnetodynamics**

The magnetic behaviour of ferromagnetic laminations can be described in terms of the macroscopic fields, taking into account the interacting hysteresis and eddy current phenomena. Making a few justifiable assumptions [10], one obtains the well known diffusion equation:

\[
\frac{\partial^2 H}{\partial x^2} = \frac{\sigma}{\partial t} \frac{\partial B}{\partial t}
\]  

Herein H and B are the magnetic field and the induction respectively; \(\sigma\) is the conductivity of the material. The solution of equation (1) in presence of a CPM is well described in the literature [11]. Using the techniques outlined in [12], the magnetic fields have been computed for both materials, under H-field excitation.

![Image](image-url)

Fig. 2a: \(H(t)\), \(B(t)\) at 150 Hz  
Fig. 2b: BH-loops at 10 Hz and 150 Hz

The results for material 1 are depicted in fig. 2. Fig. 2a shows the magnetic field H and the magnetic induction B at the surface and in the middle of the lamination. The corresponding B-H excursions are depicted in fig. 2b. The satisfactory agreement between the simulation (full line) and the measurements (dotted line) indicate that the CPM describes the hysteresis effects in material 1 quite well up to fairly high frequencies.

Apparenters, this is not the case for material 2. As fig. 3 shows, the CPM describes the magnetic behaviour of the material 2 very well under static conditions. However, it can be observed from figs. 4a and 5a that a systematic discrepancy occurs between the measured and the calculated B-H loops at higher frequencies. As will be shown further, this discrepancy can be attributed to a frequency dependence of the hysteresis properties for the material 2.

![Image](image-url)

Fig. 3: Static BH-loops

The CPM is not capable of modelling such a frequency dependence, since it is essentially a static model in which the magnetisation is independent of the rate of excitation.

**III. MAGNETO-DYNAMIC FIELDS WITH THE GENERALISED PREISACH MODEL**

**A. Generalised Preisach model**

The frequency-independence of the CPM originates from the assumption that the elementary dipoles switch instantaneously. In the Generalised Preisach Model (further referred to as GPM) described in [2], this property is relaxed. In the GPM, the dipoles are assumed to switch instantaneously, but the time rate of switching being proportional to the difference between the local magnetic field H and the elementary loop switching fields, \(\alpha\) and \(\beta\). According to the model the time derivative of the magnetic induction satisfies:

\[
\frac{\partial B}{\partial t} = \int_{D_1} k_{(H-\alpha)} P(\alpha, \beta) \, \mathrm{d}A + \int_{D_2} k_{(H-\beta)} P(\alpha, \beta) \, \mathrm{d}A
\]

Herein k is a material constant which can be given a physical interpretation [13]. \(D_1\) and \(D_2\) are the domains in the Preisach plane representing dipoles in an intermediate state, switching to positive and negative saturation respectively. In the limit of infinite k the domains \(D_1\) and \(D_2\) shrink to line segments, and the GPM reduces to the CPM.

**B. Magnetodynamics**

The diffusion equation (1) is valid irrespective of the type of hysteresis model used. Only the interpretation of the right-hand side changes from model to model.
In case the GPM is used, the right-hand side can be split into two terms \( \frac{\partial B}{\partial t} = \frac{\partial B_1}{\partial t} + \frac{\partial B_2}{\partial t} \) which satisfy:

\[
\begin{align*}
\frac{\partial B_1}{\partial t} &= k_{12} \int_{D_1} P(a, \beta) \, da \, db \\
\frac{\partial B_2}{\partial t} &= -k_{21} \int_{D_1} a, P(a, \beta) \, da \, db 
\end{align*}
\tag{3a}
\]

The first term (3a) is composed of the classical Everett-integrals. The second term (3b) can be computed in an identical manner, the only difference being the weighing variables \( a \) and \( \beta \) in the integrand. Both terms (3a) and (3b) can be computed for a discrete set of domains \( D_1 \) and \( D_2 \) before the solution of equation (1) is actually carried out. During the field computation then a mere interpolation is required, which can shorten the computation time considerably.

The numerical solution of equation (1) requires a discretisation in space and time [14]. A finite element formulation based on quadratic interpolation functions results in a system of the following type:

\[
[M] \frac{d}{dt} [H] + [K] [H] = [F]
\tag{4}
\]

For the integration in time a Crank-Nicholson time stepping scheme has been applied.

IV. RESULTS

Using the method described in the foregoing section, the macroscopic fields have been computed again using the GPM. In fig.4b the resulting BH-loops for material 2 at 50 Hz are depicted. Comparison of fig.4a and fig.4b shows a remarkable improvement of the correspondence between the measured and the computed BH-loops.

In fig.5 the BH-loops for material 2 at 150 Hz are shown. Apparently, the GPM is capable of describing the hysteresis effects in material 2 up to fairly high frequencies.

In future work the presented study will be extended to B-type excitation. Methods will be investigated to determine the material constant \( k \) experimentally.

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REFERENCES