Dynamic Preisach Modelling of Ferromagnetic Laminations Under Distorted Flux Excitations

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Abstract—In this paper, the computation of the macroscopic fields inside ferromagnetic laminations is discussed. The magnetodynamic model of non oriented steel laminations is coupled with a dynamic Preisach model. The main goal is the comparison of two previous developed numerical procedures for the electromagnetic field analysis by considering alternating flux excitations containing higher order harmonics. It is shown that a very good agreement is obtained between the measured and computed material response with both techniques. In the comparison, no remarkable drawback was observed for one of the methods.

Index terms—dynamic Preisach model, energy losses, distorted flux patterns

I. INTRODUCTION

A considerable amount of research has been carried out in recent years to gain a deeper insight in the magnetic behaviour of electrical steel under a distorted flux waveform, see e.g.[1]. Indeed, standard characterisation techniques are performed under a sinusoidal waveform of magnetic induction. However, the actual magnetic induction waveform, for example in the stator teeth of an asynchronous machine, is not sinusoidal and often includes higher order harmonics, e.g. due to rotor slots. A way to study the phenomena inside the ferromagnetic laminations of a machine core is to describe the hysteresis and eddy current effects in terms of the macroscopic fields [2]. The authors developed two different numerical techniques to evaluate the material behaviour under arbitrary alternating excitation conditions, using the Preisach theory [3]. These two techniques have been extensively evaluated in [4] under standard sinusoidal flux excitation. In this paper, the authors compare the two different numerical procedures for the magnetic field analysis of ferromagnetic sheets, subjected to a time-periodic excitation with imposed flux containing higher order harmonics. The two procedures have been applied to the solution of the same problems and they have been compared on the basis of dynamic hysteresis cycles, overall losses and the variation of the local magnetic quantities throughout the lamination thickness. Finally, the numerical results have been compared with measurements under distorted flux waveforms. A good correspondence between the measurements and the numerical results from the two models is obtained.

II. THEORETICAL MODELS

In [5], [6] a magnetodynamic model of one lamination has been studied in detail. Throughout the lamination, the time periodic flux \( \phi \) flows in the \( z \)-direction and the magnetic field \( H \) as well as the magnetic induction \( B \) have only one component, viz. \( H = H(x,t) \cdot \hat{e}_z \) and \( B = B(x,t) \cdot \hat{e}_z \) respectively. The macroscopic electromagnetic fields are described by the well known diffusion equation, see [7],

\[
\frac{1}{\sigma} \frac{\partial^2 H}{\partial x^2} = \frac{\partial B}{\partial t} \tag{1}
\]

The relation between the local \( B(x,t) \) and \( H(x,t) \) is modelled by the dynamic Preisach model (DPM) proposed by Bertotti [8], to take into account the magnetisation process inside the material. Both procedures employ a finite element method for the spatial discretisation in the direction orthogonal to the lamination plane. In the first procedure, starting from Maxwell equations formulated in terms of a magnetic vector potential \( A \), the computational scheme is obtained by applying the Fixed Point (FP) technique in the \( H \)-version [9] to linearize the problem. The linearized field problem is then treated in the frequency domain:

\[
\nu_{FP} \nabla \times \nabla \times \bar{A}_i^{(m)} = -jmw\sigma \bar{F}_i^{(m)} + jm w \int \bar{A}_i^{(m)} d\Omega - \nabla \times \bar{R}^{(m)}, \quad \forall m = 1, ..., M \tag{2}
\]

where \( i \) is the iteration index, \( m \) is the harmonic index, \( R \) is the FP residual, \( \nu_{FP} \) is the FP coefficient and \( \omega \) is the fundamental angular frequency. The DPM is implemented in the time domain introducing the concept of macro-operators detailed in [10]. In the second procedure, the Maxwell equations are rewritten as a partial differential equation (PDE) for the magnetic field strength \( H \):

\[
\frac{1}{\sigma} \frac{\partial^2 H}{\partial x^2} = \frac{\partial B}{\partial t} = \mu_{re} H + \mu_{k1}(x,t) \cdot H - k_2(x,t) \tag{3}
\]
where $\mu_{rd}$ is the reversible differential permeability. The DPM is properly taken into account by using well defined material coefficients $k_1$ and $k_2$ in the PDE. The numerical methods rests upon a modified finite element discretisation in the space variable, using quadratic interpolation functions and a suitable $\theta$-family of finite difference approximations with respect to the time variable. Finally, to evaluate the material coefficients in the computational scheme, the Preisach plane is discretised by means of an adaptive mixed triangular-rectangular grid [5].

III. MEASUREMENT SET UP

Non-oriented 2.4 wt% Fe-Si laminations, 0.501 mm thick, were cut as 305 mm x 30 mm strips by means of spark erosion. Cutting was made along different directions and the strips (12 in all) were inserted in a standard Epstein frame. The strip insertion sequence followed the order $0^\circ$, $30^\circ$, $90^\circ$, $60^\circ$ for the angle of cutting to the Rolling Direction (RD). A set of measurements was then performed. First, a complete quasi-static characterization ($f = 0.1$ Hz) was carried out, in order to reconstruct the Preisach Distribution Function. Second, 50 Hz hysteresis loops and losses were determined under varying degrees of distortion of the induction waveform. In a first run, the waveform was composed of a fundamental $B_1$ plus a third harmonic $B_3$, with values of the ratio $B_3/B_1$ and the phase $\varphi_3$ kept within the minor loop limits. In this case, a straightforward prediction of the energy loss dependence on distortion can be made using the formulation given in [11]. The minor loop limit was then overcome, both by increasing the ratio $B_3/B_1$ and introducing a fifth harmonic component ($B_5$, $\varphi_5$). In this case, however, the direct control on the induction waveform could be accomplished only partially and the exact harmonic composition was determined a posteriori by Fourier analysis. The same was done in a further series of measurements, where, in order to emulate the real magnetization wave shape encountered in the stator teeth of asynchronous motors, the 16th, 17th, 31st and 33rd components were introduced.

IV. EXPERIMENTAL AND NUMERICAL RESULTS

The two calculation procedures have been applied to the solution of the same problem. Here, two types of excitation conditions are considered.

A. Flux patterns with 3rd and 5th harmonic

The average magnetic induction waveform, enforced through the lamination, contain a 3rd and 5th harmonic and is given in Fig.1. Fig.2 reveals the very good correspondence between the numerical results obtained by both numerical procedures and the measured dynamic hysteresis cycle. Also a good correspondence between the two models is obtained for the local magnetic induction $B(t)$ and magnetic field strength $H(t)$. In Fig.3 and 4 the local $B$ and $H$ respectively are given at the outer boundary.

and in the middle of the lamination. Finally, the two models give rise to a good prediction of the total iron losses, see table I. Moreover, the classical losses obtained by the spatial variation of the magnetic field strength along the x-axis of the lamination are almost identical for both models. Similar results are obtained for the hysteresis and excess losses described by the DPM.

B. Flux pattern in stator tooth of asynchronous machine

We consider a three phase 3kW 4-pole asynchronous machine. The stator has a single layer winding with three slots per pole and per phase. The flux pattern in the mid-tooth of one phase zone has been measured using a search coil. As it is a difficult task to control the complex flux pattern in the Epstein frame, we performed the calculations using a pattern in the Epstein frame which is similar but not identical to the one in the machine. Fig.1


TABLE I

Comparison of the losses (mJ/kg): A: measured total losses, B: total losses model 1, C: total losses model 2, D: classical losses model 1, E: classical losses model 2, F: hysteresis and excess losses model 1, G: hysteresis and excess losses model 2

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Table depicts the used flux pattern. Fig.5 shows the complex dynamic hysteresis cycles obtained from the two models and the corresponding measurements. The agreement is satisfactory. Some discrepancies are found in the minor order loops at higher induction values.

V. CONCLUSIONS

We have dealt with two different approximation procedures for the evaluation of the total iron losses in non-oriented steel laminations for arbitrary flux excitations. The two models allow us to evaluate local electromagnetic quantities in the steel lamination. The experimental verification revealed that the DPM combined with the lamination model is accurate for describing the behaviour of the material under complex alternating excitations, in particular flux patterns appearing in rotating electrical machines. Once the two procedures have been validated by experiments, they can be efficiently used to analyse the physics of the phenomena and to understand the effects of the supply conditions on the material behaviour.

REFERENCES