Modelling Eddy Current Losses in Anisotropic Electrical Steel under Rotational Magnetic Field

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This paper presents a methodology to model magnetic anisotropy in electrical steel as well as the computation of Eddy current losses under such anisotropy. The parameters of the anisotropic model are estimated from measurements under rotational flux density. The computation of the Eddy current losses is performed with an advanced one-dimensional numerical model, where the skin effect is accurately accounted for. The results show that only few harmonic terms of the magnetic reluctivity are needed to achieve good accuracy. Further, the results from the Eddy current model show that the losses depend strongly on the reluctivity.

***Index Terms*—Eddy current, magnetic anisotropy, magnetic losses, magnetic materials.**

I. Introduction

Electrical steel is used in electromechanical energy conversion devices to shape and amplify the magnetic flux. Anisotropic high-grade grain oriented steel is used in power and distribution transformers since the magnetic flux density in these devices is mostly unidirectional, whereas non-oriented (NO) steel is most commonly used in small transformers and rotating electrical machines. Even NO steel is known to be anisotropic and many machine manufacturers remedy to this anisotropy by transposing the electrical sheet while constructing the stack of their machines. Regardless of the fact that the electrical sheets are transposed or not, a model of the anisotropy in NO steel is needed for the estimation of the operation characteristics of the machine. These characteristics are nowadays exclusively computed with the finite element method either in 2D or 3D approach.

Many models of anisotropy with different complexities have been presented earlier. In [1] several models of anisotropy are compared in view of the computation of the torque and losses in a synchronous machine. In [2] and [3] a vectorization of a Preisach-type hysteresis model accounting for the anisotropy is presented. The vectorization is based on the so-called Mayergoyz model, where the flux density vector is projected on several redundant directions and the magnetic field is computed from the unidirectional model. The level of anisotropy in the above models are however not very strong. This level of anisotropy is known to depend on the quality of the steel and in some cases, the anisotropy is very pronounced even if the material is NO. In these cases it is expected that the Eddy current losses due to the skin effect in the electrical steel will increase for rotational or elliptic variations of the magnetic flux density.

In this paper we aim at accurately modelling this eddy current loss increase. We thus present an anisotropic model of NO electrical steel sheets and use it to compute the eddy current losses in a situation comparable to the one that happens in the rotor teeth of an induction machine, which is characterized by a strong bias low-frequency magnetic flux density around 1.5 T on top of which an elliptic high frequency component of about 0.5 T due to the stator tooth harmonic is present.

II. Methods

A. Anisotropy model

The anisotropy of the electrical steel is modeled with its corresponding reluctivity ν . At first approach, we neglect the phase shift between the magnetic flux density $\boldsymbol{B}$ and the magnetic field strength $\boldsymbol{H}$ vectors caused by the anisotropy and compute the reluctivity as the ratio between the amplitudes of these vectors. This reluctivity, which depends on the angular position θ and the amplitude B of the flux density vector, is written as Fourier series in terms of the angular position as:

$$\nu(B,\theta) = \nu_0(B) + \sum_{\substack{n=2 \\ n,even}}^{N} \nu_n(B)\cos(n\theta - \varphi_n(B)) , \quad (1)$$

where n is the order of the harmonic, N the total number of harmonics accounted for, $\nu_n(B)$, and $\varphi_n(B)$ are the amplitude and the phase of the n^{th} harmonic, which depend on B.

In (1) the amplitude and phase of each harmonic are written as cubic splines of the amplitude of the magnetic flux density. The breaks and coefficients of theses splines have been estimated from measurements as will be shown in Section III.

B. Eddy current model

The Eddy currents in the electrical steel sheet are modelled with an advanced one dimensional numerical method that consists of solving the following diffusion equations in the depth of the material (aligned with the z-axis) [4], [5]

$$\begin{aligned} \frac{\partial}{\partial z}\left(\nu \frac{\partial a_x}{\partial z}\right) + \sigma \frac{\partial a_x}{\partial t} = 0 \\ \frac{\partial}{\partial z}\left(\nu \frac{\partial a_y}{\partial z}\right) + \sigma \frac{\partial a_y}{\partial t} = 0 \end{aligned} \quad (2)$$

where $\boldsymbol{a} = a_x\left(z,t\right)\boldsymbol{e}_x + a_y\left(z,t\right)\boldsymbol{e}_y$ is the magnetic vector potential and σ the conductivity of the material. The needed boundary conditions for the solution of (2) are given by

$$a_x(d,t) = d.B_y(t); \quad a_x(0,t) = 0$$
$$a_y(d,t) = -d.B_x(t); \quad a_y(0,t) = 0 \quad (3)$$

where d is half the thickness of the iron sheet and B_x and B_y are the two components of the average magnetic flux density.

III. Result and Discussion

A. Measurements of anisotropic characteristics

The measurements of the magnetic characteristics of the electrical steel have been conducted on a PC-controlled Rotational Single Sheet Tester (RSST). The setup consists of a magnetizing double U-shape yoke, a controlled feeding power amplifier, and the cross-shaped sample. The magnetic flux density in the sample is measured by two orthogonal B-coils, and the magnetic field strength on the surface of the sample is measured by a bi-directional magneto-resistive sensor. Measurements with rotational fluxes of varying amplitudes between 0.1 and 1.75 T at 10 Hz frequency have been conducted. The control performs circular shapes of the flux density loci with an accuracy of 0.5%. The effect of losses on the measured field strength has been removed from the measurements by removing the average phase shift between ***B*** and ***H*** over one cycle.

The dependency of the anisotropy level on the amplitude of the magnetic flux density can be very well appreciated from Fig. 1, where the measured field strength loci at two different amplitudes of the magnetic flux density are shown. These results are similar to the ones presented in [6].

The measured and modelled reluctivities of the material at the same amplitudes of the magnetic flux density are shown in Fig. 2. In the model of reluctivity described by (1), besides the dc-component, the five even first components (2, 4, 6, 8 and 10) of the Fourier series have been used.

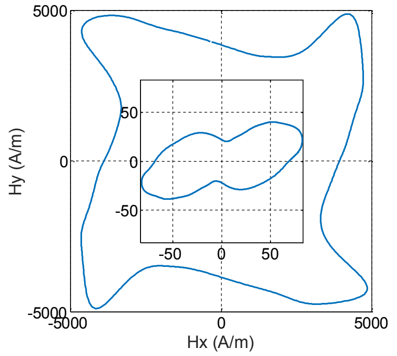

Fig. 1. Measured loci of the magnetic field strength at 10 Hz circular flux density of amplitude 1.75 T (outside) and 0.6 T (inside). Note the difference in the axis scale.

B. Computation of Eddy current losses

The Eddy current losses have been computed using the above mentioned advanced model fed by an average flux density in the lamination. We simulated a situation similar to the one in the teeth of the rotor of an induction machine. Such situation is characterized by a rotational tooth harmonic on the top of a low frequency (slip frequency) component. The slip frequency component was 1 T at 0 Hz in the x-direction and the tooth frequency component was 0.5 T at 1800 Hz.

The computed Eddy current losses as function of time are shown in Fig. 3 and compared with the losses computed with the classical method i.e. proportional to the square of the flux density time-derivative. It is clear from Fig. 1 that the change in the reluctivity of the material results in different behavior of the skin effect and thus affects the losses strongly.

In the full paper, we will investigate the effect of lamination transposition and apply the anisotropic model in the simulation of an induction machine [7].

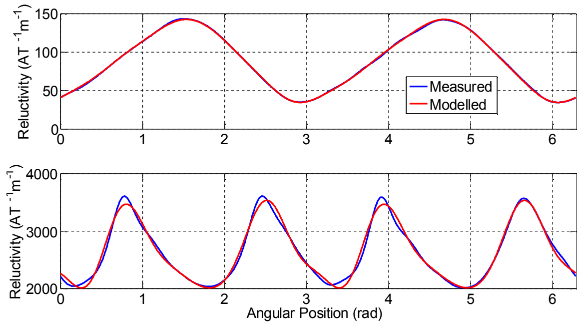

Fig. 2. Measured and modelled (1) reluctivity of the material at 0.6 T (up) and 1.75 T (down). In the model, only the dc-component and the five first even harmonics are used.

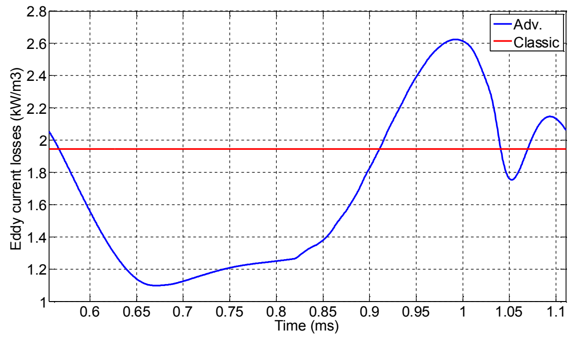

Fig. 3. Time dependence of the Eddy current losses when the flux density is 0.5 T rotating at 1800 Hz on top of a 1 T dc-bias in the x-direction. The difference in the losses is due solely to the change in the reluctivity of the material and the corresponding skin effect.

IV. References

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