Modelling Dynamic Losses Under Rotational Magnetic Flux

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Abstract — The rotational magnetic flux can be observed in some parts of three-phase transformers and rotational electric machines. The iron core under rotational flux presents magnetic losses, usually, greater than alternating ones, for the same flux magnitude. The rotational losses also increase with the increase of excitation frequencies. In this work the iron losses behavior is investigated under rotational flux by combining vector hysteresis, eddy current and excess losses models. Experimental curves are obtained from a rotational single sheet tester and the losses components are analyzed.

I. INTRODUCTION

Despite the efforts of electrical steels manufacturers, the iron core losses of transformers and electrical machines remain consuming a significant part of all electrically generated energy. Trying to reduce these losses new materials have been developed or employed more efficiently. In parallel, accurate material models are needed in order to design and analyze electromagnetic devices.

Traditionally, the core losses are given by the sum of hysteresis and eddy current losses. Recently an excess loss or anomalous loss component has been considered as well.

Moreover, electromagnetic devices combine hysteresis and magnetodynamic effects as eddy current and excess losses in the cases of alternating as well as rotational fields.

Rotational iron losses occur when the magnetic flux vector rotates in the iron lamination plane, for instance, in the T-joints of three-phase transformers as well as in some parts of the stator of rotational electric machines. It has been reported that the rotational losses are larger than the iron losses caused only by alternating flux, with the same magnitude and frequency [1]. The magnetization under rotational flux is different of the magnetization under alternating flux, requiring a vector model to represent its behavior. It is observed that the losses increase with the increase of excitation frequency, evidently by the increase of eddy currents and anomalous losses. As vector hysteresis modeling has started only recently, little has been done with respect to the modeling of the magnetodynamic effects under rotational excitation.

The main contribution of this work is to propose a frequency dependent vector model in order to represent the magnetic losses under rotational flux. The rotational losses will be represented by a model which combines a vector hysteresis, eddy current and anomalous losses. The accuracy of the model will be analyzed by comparing calculated and measured data.

II. MAGNETIC HYSTERESIS LOSSES UNDER ROTATIONAL MAGNETIC FLUX

If a magnetic induction vector **B** rotates in the lamination plane of an iron electrical sheet, it produces a magnetic field vector **H** rotating in a similar way but shifted in space. This rotational flux behavior can be very complex depending on the characteristics of the material. Figure 1 shows a rotational induction vector locus turning with an angular velocity ω. It is convenient to write the rotational induction in terms of its orthogonal components B_x, and B_y. A vector hysteresis model must be able to calculate the magnetic field orthogonal components H_x and H_y .

The Jiles-Atherton (JA) vector hysteresis model has proven to be well adapted to the representation of hysteresis under rotational flux [3].

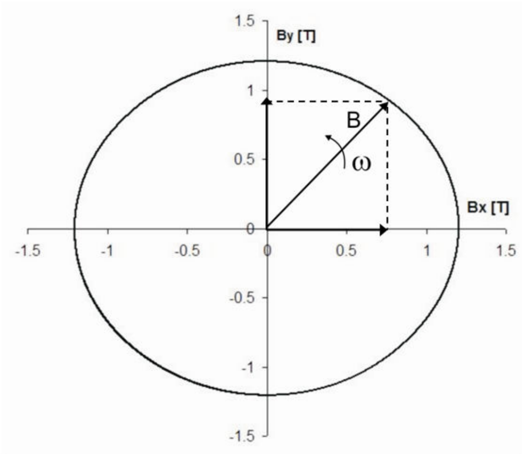

Fig. 1. Rotational magnetic induction vector turning at angular velocity ω.

In the JA vector model, one can calculate the variations of the total magnetization **M** with respect to an imposed induction vector **B**. The main equation of the JA vector hysteresis model is

$$d\mathbf{M} = \frac{1}{\mu_0}\left[\mathbf{1}+\mathbf{F}(1-\vec{\alpha})+\vec{c}\vec{\xi}(\mathbf{1}-\vec{\alpha})\right]^{-1}.\left[\mathbf{F}+\vec{c}\vec{\xi}\right]d\mathbf{B} \qquad (1)$$

where μ_0 is magnetic permeability of vacuum, **1** is the identity matrix, $\vec{\alpha}$ and $\vec{c}$ are diagonal tensors including some of the model parameters, $\vec{\xi}$ is a diagonal matrix with the derivatives of the anhysteretic function. **F** is a vector function related to the hysteresis losses into the material [3].

Figure 2 shows some measured and calculated BH curves in a square iron sample under an imposed rotational magnetic induction locus with amplitude of 1.0 T at excitation frequency of 5 Hz. The BH loops were obtained with a Rotational Single Sheet Tester (RSST) [2]. The field and induction components were measured for the rolling and transverse directions. At 5Hz the magnetic losses are predominantly due to the hysteresis component.

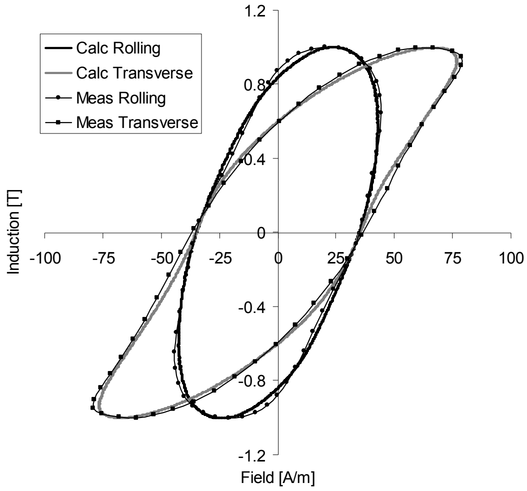

Fig. 2. Measured and calculated BH loops for the rolling and transverse direction at 5 Hz – hysteresis losses are predominant.

In Fig. 2 the error between measured and calculated losses are close to 3%. The model accuracy can be observed by comparing coercivity, field tips, and remanence.

III. MODELING EDDY CURRENTS AND EXCESS LOSSES UNDER ROTATIONAL FLUX

The hysteresis is a quasi-static phenomenon being independent of excitation frequencies. In [4], Jiles proposed a dynamical extension for the JA scalar hysteresis model modifying its equations to include eddy current and excess losses obtaining a frequency dependent model. For an electrical sheet under unidirectional alternating flux the eddy current losses are given by:

$$\frac{dW_{ec}}{dt} = \frac{d^2}{2\rho\beta}\left(\frac{dB}{dt}\right)^2 \tag{2}$$

where d is sheet thickness, ρ is the electrical resistivity and β is a geometrical parameter equal to 6 for laminated sheets [4].

In the same work, the excess losses for alternating flux variations are calculated by:

$$\frac{dW_{ex}}{dt} = \left(\frac{GdwH_0}{\rho}\right)^{\frac{1}{2}}\left(\frac{dB}{dt}\right)^{\frac{3}{2}} \tag{3}$$

where G is a constant equal to 0.1356, w is the sheet width and H_0 is a material parameter related to the domain walls [4].

One approach to include the eddy currents under rotational flux is to decompose the rotational locus into two alternating components shifted 90° in its rolling and transverse directions. The eddy currents can be calculated for these two independent directions. In a vector way (2) can be rewrite as:

$$\frac{dW_{ec}}{dt} = \frac{d^2}{2\beta}\vec{\rho}^{\,-1}\left(\frac{d\mathbf{B}}{dt}\right)^2 \tag{4}$$

where $\vec{\rho}$ is a second order tensor related to the sheet resistivity at rolling and transverse directions.

The same approach can be applied to the excess losses.

$$\frac{dW_{ex}}{dt} = \vec{g}\,\vec{\rho}^{\,-\frac{1}{2}}\left(\frac{d\mathbf{B}}{dt}\right)^{\frac{3}{2}} \tag{5}$$

where $\vec{g}$ is a second order tensor representing parameters $GdwH_0$ for the two principal directions.

With (4) and (5) eddy current and excess losses, under rotational flux, can be added to the hysteresis losses calculated by (1).

Fig. 3 shows measured and calculated BH loops for the sample under rotational induction locus of 1.0 T and excitation frequency of 60 Hz.

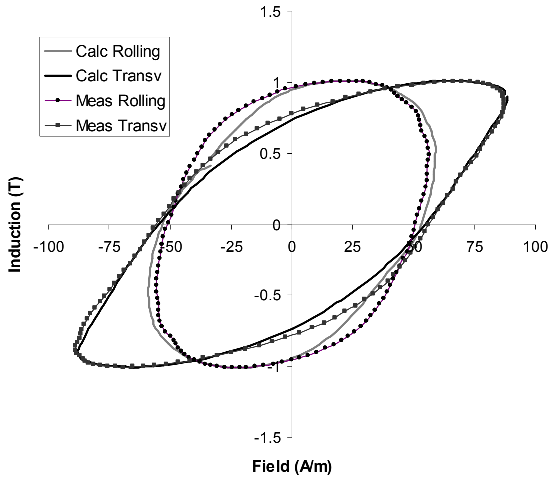

Fig. 3. Measured and calculated BH loops for the rolling and transverse direction at 60 Hz – eddy currents and excess losses increase the magnetic losses.

The increase of losses due the dynamical effects is now considered. The error between calculated and measured total losses is close to 5% showing the effectiveness of the modeling.

IV. REFERENCES

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