Segregation of Iron Losses from Rotational Field Measurements and Application to Electrical Machine

A. Belahcen[1,2], P. Rasilo[1], A. Arkkio[1]
[1]Department Of Electrical engineering, Aalto University
P.O.Box 13000, FI-00076, Aalto, Finland
[2] Department of Electrical Drives and Power Electronics, TUT, Tallinn, Estonia
Anouar.belahcen@aalto.fi

Abstract—**This paper presents a methodology for identifying a novel iron loss model and segregating the different loss components from measurements on a single sheet tester with alternating and rotating fields. The eddy current losses are first extracted with a 1D numerical approach and the hysteresis and excess losses are then estimated with an analytical method that allows the separation of alternating and rotational hysteresis as well as excess losses. The elaborated iron loss model can be applied in case of distorted flux density and on a wide frequency range. The identified model is further applied in the time-stepping computation of an induction machine in view of better estimation and segregation of iron losses.**

Index Terms— **Electric machines, electromagnetic analysis, loss measurement, magnetic materials, magnetic losses.**

I. INTRODUCTION

Owing to the increasing demand on high efficiency electrical motors, the designers of electrical machines need more and more accurate computation methods and estimation methodologies for the losses in these machines. The two-dimensional time-stepping finite-element method with coupled field-circuit equations is nowadays de facto standard in the design process of electrical machines. This procedure allows an accurate computation of the magnetic field in different parts of the machine as well as a rather good estimation of the resistive losses in its windings and other operation characteristics. However, this methodology is applied with a single valued BH-curve to account for the iron nonlinearity, whereas the iron losses are usually computed from different analytical equations as a posteriori quantities.

Several publications presented different methodologies for the inclusion of iron losses in the 2D FE computation of electrical machines [1]-[4]. The effect of the inclusion of iron losses in the FE computation on the operation quantities of these machines has also been investigated in [5], [6]. The main conclusion was that in machines with air gaps, i.e., rotating machines the inclusion of iron losses in the computation has very little effect on both the operation quantities and the computed iron losses provided the loss model is accurate. It is also obvious from the literature that magnetodynamic vector hysteresis models such as the one presented in [1] and [7] can predict iron losses with higher accuracy than the analytical equations and also enables the separation of its different components. However, the identification of hysteresis models and their use in FE computations is very laborious and requires both extensive measurements for different materials before hands and prohibitive computation times during the design process. On the other hand, the analytical equations for the iron loss estimation require only few parameters but they usually do not allow for the segregation between the different loss components and their accuracy is not satisfactory.

In this paper we present a hybrid loss model in which the eddy current part is computed based on the 1D FE approach [8] and the other loss components are based on analytical equations. The identification procedure of the model is described and the predicted losses are compared with measurements on both single sheet tester and an induction machine. The comparison with the results from an advanced hysteresis model will be presented in the extended paper.

A remarkable aspect from the measurements is in the fact that the measured iron losses present a certain amount of anisotropy, which shows in the rotational losses too. Such a phenomenon needs an anisotropic model of losses.

II. THE IRON LOSS MODEL

In our approach the iron power losses in W/kg are segregated into eddy-current, rotational and alternating hysteresis, and excess losses.

A. Eddy current losses

The Eddy current losses are computed from the magnetic flux density based on the 1D eddy current model [8], which ignores the closing path of the currents. Such a model requires only the knowledge of the magnetic flux density waveform, which in both cases of measurements and computations is well defined for both *x*- and *y*-components.

B. Hysteresis losses

The hysteresis losses in our model are separated into two components, the alternating and the rotational hysteresis losses. The alternating hysteresis losses are arising from the time variation of the amplitude of the flux density vector:

$$P_{ha} = \frac{k_{ha}}{\rho T}\int_0^T |\boldsymbol{B}|\left|\frac{\partial|\boldsymbol{B}|}{\partial t}\right| dt \qquad (1)$$

where ρ is the mass density of the material, T the period of one cycle of the flux density $\boldsymbol{B}$ and k_{ha} a model parameter to be estimated among other parameters. The notation $|\;|$ stands for either the absolute value of a scalar or the amplitude of a vector depending on the context.

The rotational hysteresis losses on the other hand arise from the angle between the flux density vector and its time-derivative and are expressed as:

$$P_{hr} = \frac{k_{hr}}{\rho T}\int_0^T \frac{\left(1-\frac{|\boldsymbol{B}|}{Bs}\right)}{1+a\left(1-\frac{|\boldsymbol{B}|}{Bs}\right)^2}\left|\boldsymbol{B}\times\frac{\partial \boldsymbol{B}}{\partial t}\right| dt \qquad (2)$$

where k_{hr}, a and B_s are model parameters.

C. Excess losses

In Bertotti's theory the excess losses are compensating for the skin effect in the lamination and are also used to account for the microscopic eddy currents arising from the domains wall motion. In our model, the skin effect is accurately modeled by the 1D FEM but we still need to have excess losses as to compensate for the domains wall motion and the interdependence between eddy current and hysteresis as explained in [9]. The excess losses are expressed as:

$$P_e = \frac{k_e}{\rho T}\int_0^T \left|\frac{\partial \boldsymbol{B}}{\partial t}\right|^{1.5} dt \qquad (3)$$

Where k_e is a model parameter. It should be noted that (3) accounts for both rotational and alternating excess losses, whereas (1) accounts for alternating losses only and (2) accounts for rotational losses only.

III. Results

A. Measurements and model prediction

The measurements were carried out on a double-core single sheet tester that allows for alternating and rotating fields [10]. The field-metric methodology was used to compute the iron losses from the measurements. Fig. 1 shows the measured and segregated losses, and the measured flux density loci at two frequencies. A total of 250 measurements at 10 different frequencies have been carried out. The measured losses have been used to identify the iron loss model. In a first step the measured magnetic flux densities are fed to the 1D eddy current model, which computes the eddy current losses at each measurement point. The difference between the measured and computed eddy current losses is then used to identify the parameters of the model. The parameters of (2) and (3) are first identified at low frequency and rotating flux densities. The rest of the measured losses are then used to estimate the other parameters.

B. Application to an electrical machine

The identified loss model has been used in the computation of iron losses in 37 kW induction machine. Second order FEs and the time-stepping scheme have been applied in conjunction with the coupled field-circuit methodology. The segregation of rotational and alternating hysteresis losses is shown in Fig. 2. The location of segregated losses corresponds to previously presented results computed with advanced hysteresis models. Comparisons between the losses separation with the presented model and advanced hysteresis ones will be presented in the full paper too.

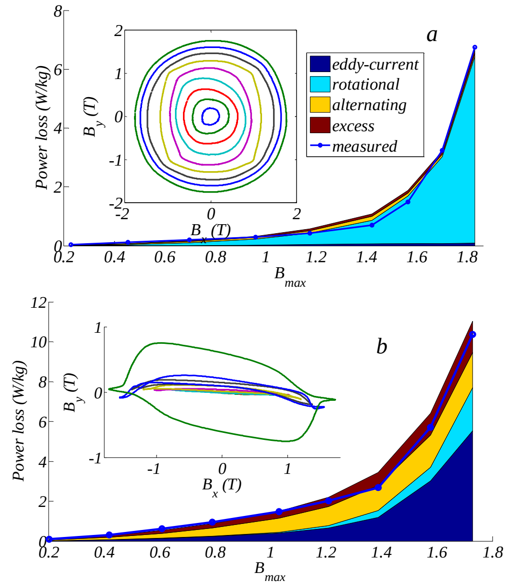

Fig. 1. Measured flux densities and comparison of computed and measured iron losses at 10 Hz circular/square (a) and 50 Hz alternating/elliptic (b).

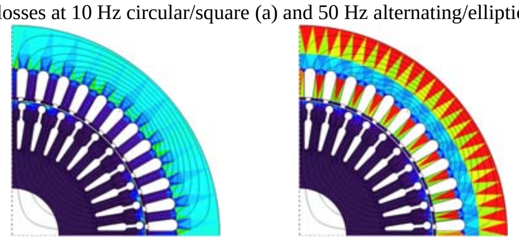

Fig. 2. Fig. 2. Computed rotational (left) and alternating (right) hysteresis losses in a 37 kW machine. The losses are computed over each element, which explains the discontinuities in the plot (denser mesh will be used in the full paper for more accuracy and better visualization).

References

[1] E. Dlala, "Efficient algorithms for the inclusion of the Preisach hysteresis model in nonlinear finite-element methods," *IEEE Trans. on Magn.*, vol.47, no.2, pp. 395-408, 2011.

[2] J. Pippuri, A. Belahcen, E. Dlala, A. Arkkio, "Inclusion of eddy currents in laminations in two-dimensional finite element analysis," *IEEE Trans. on Magn.*, vol.46, no.8, pp. 2915-2918, 2010.

[3] K. Yamazaki, N. Fukushima, "Iron loss model for rotating machines using direct eddy current analysis in electrical steel sheets," *IEEE Trans. on Energ. Conv.*, vol.25, no.3, pp. 633-641, 2010.

[4] N. Kunihiro, T. Todaka, M. Enokizono, "Loss evaluation of an induction motor model core by vector magnetic characteristic analysis," *IEEE Trans. on Magn.*, vol.47, no.5, pp. 1098-1101, 2011

[5] K. Yamazaki, N Fukushima, "Torque and loss calculation of rotating machines considering laminated cores using post 1-D analysis," *IEEE Trans. on Magn.*, vol.47, no.5, pp. 994-997, 2011

[6] P. Rasilo, A. Belahcen, A. Arkkio, "Importance of iron-loss modeling in simulation of wound-field synchronous machines," *IEEE Trans. on Magn.*, vol.48, no.9, pp. 2495-2504, 2012.

[7] E. Dlala, A. Belahcen, K.A. Fonteyn, M. Belkasim, "Improving loss properties of the Mayergoyz vector hysteresis model," *IEEE Trans. on Magn.*, vol.46, no.3, pp. 918-924, 2010.

[8] O. Bottauscio, M. Chiampi, D. Chiarabaglio, "Advanced model of laminated magnetic cores for two-dimensional field analysis," *IEEE Trans. on Magn.*, vol.36, no.3, pp. 561-573, 2000.

[9] E. Dlala, A. Belahcen, J. Pippuri, A. Arkkio, "Interdependence of hysteresis and eddy-current losses in laminated magnetic cores of electrical machines," *IEEE Trans. on Magn.*, vol.46, no.2, pp. 306-309, 2010.

[10] M. Belkasim, "Identification of loss models from measurements of the magnetic properties of electrical steel sheets" M.Sc. thesis, TKK, Finland, 2008. [Online]: http://lib.tkk.fi/Dipl/2008/urn012787.pdf