Numerical Calculation of Iron Losses in Electrical Machines with a Modified Post-Processing Formula

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***Abstract*— In this paper, the numerical simulation of iron losses in electrical machines is conducted with Bertotti‘s post-processing formula. The parametrisation of the formula is not done with measurements in the machine but systematically with manufacturer data. The validity range of the formula is enlarged through the analytical consideration of the skin effect of the eddy currents in the steel sheet. Calculated and measured data are compared for an asynchronous machine at various load states and for a permanent-magnet synchronous generator at no-load.**

I. INTRODUCTION

The numerical calculation of iron losses has nowadays a capital importance for the design of high efficiency drives. Two different approaches are possible:

- the phenomenological description of the iron losses mechanisms (eddy current and hysteresis) in the numerical solver [1] or,
- the utilization of a post-processing formula [2]-[5].

The first approach can be very accurate with the right model and parametrisation. It is specially suited for the study of iron losses in electromagnetical devices, where one of the loss mechanisms is negligible in comparision with the other one, but it presents huge disadvantages for the general study of losses in electrical machines. The hysteresis losses are in this case about 60 % of the total losses, so that both mechanisms must be implemented in the solver. This fact increases the computational effort hugely. Moreover, the physical description of the hysteresis and eddy current mechanisms in steel sheets requires a high number of parameters, which are not supplied by the manufacturer. That means that the designers should conduct new experiments for each new material to be used.

On the other hand, the ”post-processing” approach is easy to implement and does not increase the computational effort. But it is not as accurate as the previous approach, because the influence of hysteresis and eddy current in the field solution is neglected. Moreover, the parametrisation of the formula is usually done directly with loss measurements in the machine [3], where the losses are to be calculated. This procedure allows to achieve a high agreement ”a posteriori” between measurements and computations through adjustments of the parameters but it can hardly be used to predict the iron losses ”a priori” or to accurately study the influence of the geometry or the material in the efficiency of the machine. In this paper, the parametrisation of the formula is only done with data provided by the manufacturer [2],[4]. The parameters for the iron losses calculation are not corrected with measurements in the machine. These measurements are only used to study the validity of the approach. The study is conducted in an asynchronous machine at various load states and in a permanent-magnet synchronous generator at no-load.

All the ”post-processing” formulas have a reduced validity range. This paper reduces the computational error at high frequencies through the consideration of the skin effect of the eddy currents.

II. POST-PROCESSING FORMULA

The implemented formula is based on the loss separation principle [2]. The iron losses (p_{Fe}) are separated in hysteresis losses (p_h), classical eddy current losses (p_{ec}) and excess losses (p_{ex}).

The classical eddy current are calculated from the contributions of each harmonic as follows:

$$p_{ec} = k_{ec} \sum_{n=1}^{\infty} B_n^2 \cdot (n \cdot f)^2, \tag{1}$$

where B_n is the peak value of the magnetic flux density for the harmonic order n and f the fundamental frequency. If the skin effect of the eddy current is neglected, k_{ec} can be written as:

$$k_{ec,classic} = \frac{\pi^2 \cdot d^2}{6\rho \cdot \rho_e}, \tag{2}$$

where d is the sheet thickness, ρ the sheet density and ρ_e the specific electrical resistance of the steel.

The excess losses are calculated in an analogous way from the flux density of the different harmonics as

$$p_{ex} = k_{ex} \sum_{n=1}^{\infty} B_n^{1.5} \cdot (n \cdot f)^{1.5}. \tag{3}$$

The hysteresis losses, under the assumption that there are no minor loops, depend only on the frequency and the peak value of the magnetic flux density B [2]. On the other hand, hysteresis losses are known to be strong influenced by the flux distortion. The distortion is quantified in each point of the model through the ratio $c = \frac{B_{min}}{B_{max}}$. Figure 1 shows the loci of the magnetic flux density for different point of a PMSM. It can be observed that in the middle of the tooth and in the yoke the flux density is almost alternating ($c \rightarrow 0$), whereas in the root and in the back of the tooth is almost circular ($c \rightarrow 1$). The increase of the hysteresis losses due to the flux distortion is considered through an empirical factor r,

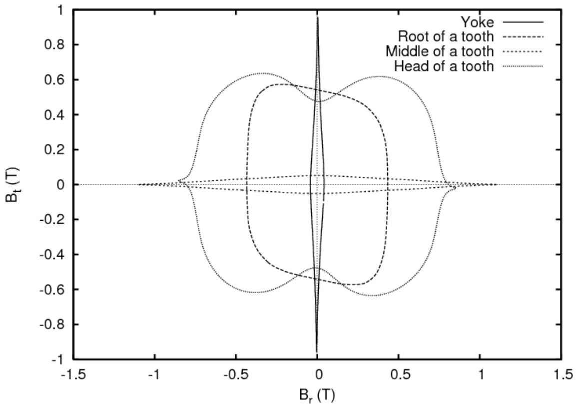

Fig. 1. Flux distortion in different points of a PMSM.

which depends on the value of the flux density but it can be considered independent of the steel type [2],[5]. Hysteresis losses can then be calculated as follows:

$$p_h = k_h[1 + c(r - 1)]B^2 \cdot f. \tag{4}$$

k_h and k_{ex} are material constants, which can be determined from the value of the specific losses of the electrical steel for 1.5 T and 50 Hz ($p_{1.5\mathrm{T},50\mathrm{Hz}}$) and for 1.0 T and 50 Hz ($p_{1.0\mathrm{T},50\mathrm{Hz}}$).

III. MODIFIED POST-PROCESSING FORMULA

The formula presented in the previous chapter is valid for flux densities until 1.5 T [2] and for frequencies, in which the skin effect in the steel sheet can be neglected. These both limits are problematic for the use of the formula in electrical machines due to two reasons:

- most machines are at least in tooth highly saturated (> 1.5 T) and
- converter-driven machines present high frequency harmonics, which have a big influence in the losses. At these high frequencies, the neglection of the skin effect will conduct to an overestimation of the eddy current losses.

In this paper, the eddy currents in a steel sheet are studied analytically, in order to determined a new expression for the eddy current losses coefficient k_{ec} to replace (2) and which takes into consideration the skin effect.

Figure 2 shows the considered model and the eddy current density distribution. It can be expressed as:

$$J(x) = J\left(\frac{d}{2}\right)\frac{\cosh(\underline{k}x)}{\cosh(\underline{k}\frac{d}{2})},\ \underline{k} = \sqrt{\frac{j\omega\mu}{\rho}} \tag{5}$$

Using this result, the eddy current losses can be calculated as in (1) with the new constant:

$$k_{ec} = k_{ec,classic}\left(\frac{\frac{1}{m}\sinh(md) + \frac{2}{m}\sin(md)}{\frac{1}{m}\cosh(md) + \frac{2}{m}\cos(md)}\right), \tag{6}$$

where

$$m = \sqrt{\frac{\omega\mu}{2\rho}}. \tag{7}$$

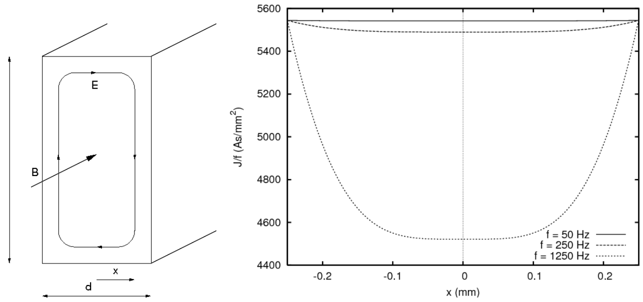

Fig. 2. Analytical model and correspondent distribution of the eddy currents.

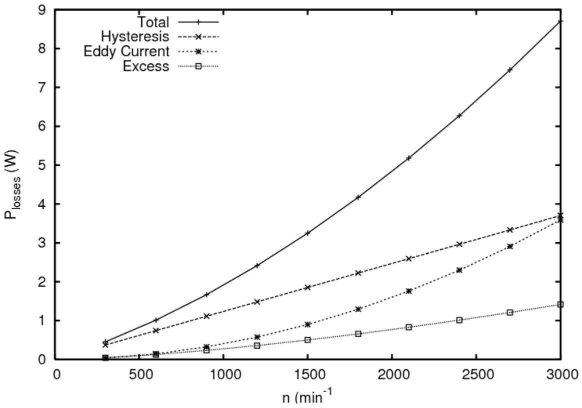

Fig. 3. Iron losses in a PMSM as generator at no load.

IV. RESULTS

The modified formula is applied to the calculation of iron losses in an PMSM as generator at no-load. Figure 3 shows the hysteresis, eddy current and excess losses for this case.

V. CONCLUSIONS

This paper presents the implementation of a modified Bertotti‘s formula for the calculation of iron losses in electrical machines. The influence of the skin effect in the eddy current losses is implemented to achieve better results in the calculation of inverter-driven machines. Comparison of the calculations with measurements and further results for an asynchronous machine will be presented in the full paper.

REFERENCES

[1] J.J.C. Gyselinck, L. R. L. Dupré, L. Vandevelde and J. A. A. Melkebeek, “Calculation of no-load induction motor core losses using the rate-dependent Preisach model”, IEEE Transaction on Magnetics, 34(6):3876-3881, November 1998.

[2] G. Bertotti, A. Boglietti, M. Chiampi, D. Chiarabaglio, F. Fiorillo and M. Lazzari, “An improved estimation of iron losses in rotating electrical machines”, IEEE Transaction on Magnetics, 27(6):5007-5009, November 1991.

[3] N. Sadowski, M. Lajoie-Mazenc, J.P.A. Bastos, M.V. Ferreira da Luz and P. Kuo-Peng, “Evaluation and analysis of iron losses in electrical machines using the rain-flow method”, IEEE Transaction on Magnetics, 36(4):1923-1926, July 2000.

[4] Lei Ma, Masayuki Sanada, Shigeo Morimoto and Yoji Takeda, “Prediction of iron losses in rotating machines with rotational losses included”, IEEE Transaction on Magnetics, 39(4):2036-2041, July 2003.

[5] O. Bottauscio, A. Canova, M. Chiampi, M. Repetto, “Iron losses in electrical machines: influence of different material models”, IEEE Transaction on Magnetics, 38(2):805-808, March 2002.