Calculation of Iron loss in Solid Rotor Induction Machine using FEM

M. Fratila[1], A. Benabou[1], A. Tounzi[1], M. Dessoude[2]
[1]L2EP-Lamel, Université Lille1, Bâtiment P2, Cité Scientifique - 59655 Villeneuve d'Ascq, France
[2]EDF R&D, 1 Av. Général de Gaulle Clamart 92141 Cedex, France
E-mail : Mircea.Fratila@univ-lille1.fr

***Abstract* – This paper presents a study on iron loss estimation for a solid rotor induction motor fed by Pulse Width Modulated (PWM) supply. The iron losses are often determined using an *a posteriori* method that can lead to more or less important deviations, compared with measurements, depending on the used models and implementation techniques. The methodology proposed here consists in computing the iron loss with an analytical method implemented in a post-processing of a 2D finite-element analysis. Different implementation techniques are used in order to investigate the impact of the model on the total iron loss.**

***Index Terms* – finite element, magnetic losses, induction motor**

I. INTRODUCTION

Electrical machines are more and more supplied through static converters for variable speed applications. Thus, the use of this type of power supplies has a negative impact on the magnetic losses because of their high harmonic content. Classically, the modeling of these iron losses is based on the loss decomposition proposed by Bertotti [1]. This approach can be either implemented in the post-processing step or in the non-linear resolution of the time step finite element method (F.E.M.). The 3D F.E.M., including a method that takes into account the hysteresis effects and the PWM minor loops is, intrinsically, the most accurate in determining such losses [2]. However, this approach requires high computational time with regard to the improvement that is expected. An alternative is to compute the magnetic losses in a post-processing step of the F.E.M. by using an analytical approach [3], [4], [5].

In this approach the hysteresis loss, for the stator part of the motor, can be computed according to the first harmonic supply frequency. On the other hand, for the rotor part many authors propose to use the first slotting harmonic frequency [3], [5] that can lead to an over-estimation of iron losses whereas others suggest to use the sum of each harmonic of the magnetic field [4] which is questionable because the hysteresis losses depend only on the extrema values of the magnetic field.

In this communication, we propose to use a different implementation procedure. Hence, the rotor iron loss will be computed according to the fundamental frequency of the magnetic field associated to each element mesh. The impacts of the three approaches will be investigated in the case of a solid rotor induction motor.

II. METHODOLOGY

A. Iron Loss Model

As classically admitted, the calculation of iron losses can be achieved by using the decomposition of the total iron losses in three contributions [1]:

$$P_{tot} = P_h + P_{cl.} + P_{exc} \qquad (1)$$

where P_h, P_{cl} and P_{exc} are, respectively, the quasi-static hysteresis, classic eddy currents and excess losses. For a non-sinusoidal excitation, the three contributions can be estimated with these expressions,

$$P_h = k_h f B_m^{\alpha} \qquad (2)$$

$$P_{cl.} = \frac{\sigma d^2}{12}\frac{1}{T}\int_0^T \left(\frac{dB(t)}{dt}\right)^2 dt \qquad (3)$$

$$P_{exc.} = \sqrt{\sigma G V_0 S}\,\frac{1}{T}\int_0^T \left|\frac{dB(t)}{dt}\right|^{1.5} dt \qquad (4)$$

where k_h and α are parameters obtained from measurements, σ the material conductivity, d the lamination thickness, T the period of the excitation waveform, dB/dt the time derivative of the magnetic flux density, G is a dimensionless coefficient, S the lamination cross surface and V_0 a constant determined from measurements.

In this work, the total iron losses, both in the stator and the rotor of the motor, are obtained by summing the iron loss components (2), (3), (4). For the stator, the hysteresis term is obtained using the supply frequency and in the case of the rotor, as mentioned above, we use three different implementation techniques:

1. The first technique (named Ap.1) computes the hysteresis losses term based on the first stator slotting harmonic frequency [3], [5];
2. The second technique (named Ap.2) uses a Fourier transform and the hysteresis loss are obtained from summing the contribution of each harmonic of the magnetic field [4];
3. A third approach (named Ap.3), that we suggest here, consists in computing the hysteresis losses by using the fundamental frequency of the magnetic field associated with each element of the finite element mesh.

Besides, for the reason that (3) and (4) are only valid for laminated materials, the classical eddy currents of the solid rotor are computed by the finite element code and the excess losses are neglected.

The iron losses are computed for both spatial components of the magnetic field locus and we supposed the rotational iron losses to be the sum of iron losses associated to each spatial direction.

B. Studied System

The impacts of the three aforesaid approaches are investigated for a three-phase, 4 poles, 30kW and 400Hz solid rotor induction machine prototype. The stator is made of laminated steel grade M1000-65 with 48 slots and the solid rotor is built with a magnetic core made of a solid single piece of ferromagnetic material (AISI 4130).

Considering the symmetry of the system, only 1/4 of the machine is modelled using one layer of 27400 prismatic elements.

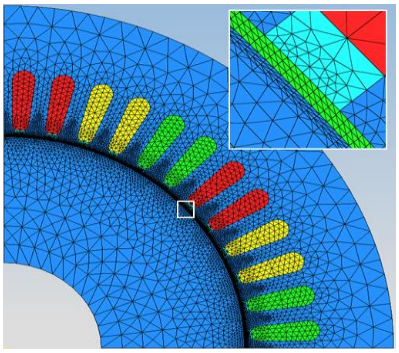

Fig. 1. Induction machine mesh

In order to take into account the eddy currents in the induction machine rotor, we use the electric formulation **A**-φ formulation whose expression is given below, where **A** is the magnetic vector potential, such as **B**=**curl(A)**, and φ the electric scalar potential.

$$\mathbf{curl}\left(\frac{1}{\mu}\mathbf{curl}\mathbf{A}\right)+\sigma\left(\frac{\partial\mathbf{A}}{\partial t}+\mathbf{grad}\,\varphi\right)=\mathbf{0} \qquad (5)$$

III. RESULTS AND DISCUTIONS

The iron losses are measured by feeding the electrical machine from a PWM inverter for two switching frequencies (1 kHz and 2 kHz) and several supply frequencies (150 Hz, 200 Hz et 250 Hz). The FE calculation is realized by imposing the experimental voltage waveform that was previously filtered to remove measurements noise. In Figure 2 the calculated current is compared, at steady state, with the measured one for an electrical phase.

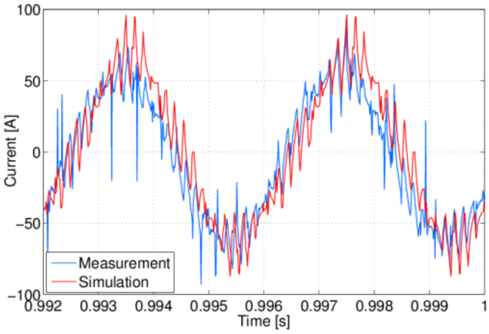

Fig. 2. Comparison of measured and simulated current

The computed losses obtained from the approach Ap.1, shown in Table I, are compared with the measured losses.

TABLE I
IRON LOSS COMPARISON WITH APPROACH AP.1

Switching frequency		*1 kHz*			*2 kHz*
Supply frequency [Hz]		**150**	**200**	**250**	**250**
Iron Loss [W]	**Stator**	1072	1520	1837	1846
	Rotor	926	1267	1409	1336
Rotor Joule Loss [W]		2428	3548	3628	3620
Total losses [W]		4426	6335	6874	6802
Measured total losses [W]		**3945**	**5529**	**6444**	**6444**

We can notice that the total iron losses are over-estimated by the first approach (Ap.1) with a maximum relative error of 15% for the 200Hz case. In fact, the rotor being made of solid steel, the skin effect acts like a low pass filter causing a filtering of the high frequency magnetic field progressively with its penetration. Thus, the magnetic field frequency is higher at the surface than inside the rotor. Therefore, the assumption of calculating the quasi-static losses from the first stator slotting harmonic frequency will introduce an overestimation on the computed rotor iron loss.

Another technique that can account also for the losses introduced by the minor loops is to determine the static losses from a harmonic decomposition of the magnetic field, using the Ap.2 approach (Table II). One can note that the stator losses remain unchanged, only the rotor losses are shown. This approach remains questionable given the fact that, in the absence of minor loops, it can lead to an overestimation of quasi static hysteresis losses. In fact, the hysteresis losses typically depend on the edge values of the induction.

Therefore, this type of model should be used with caution, depending on the application. In this case the maximum relative error is of 7.7 %.

TABLE II
IRON LOSS COMPARISON WITH APPROACH AP.2

Switching frequency	*1 kHz*			*2 kHz*
Supply frequency [Hz]	**150**	**200**	**250**	**250**
Rotor Iron Loss [W]	270	383	483	491
Computed total losses [W]	3770	5451	5948	5957
Measured total losses [W]	**3945**	**5529**	**6444**	**6444**

To avoid the use of a technique that can lead to an overestimation of the iron loss, it is possible to use the approach consisting in detecting the fundamental frequency associated to each element of the rotor. The Table III presents the results obtained from this new approach (Ap.3).

TABLE III
IRON LOSS COMPARISON WITH APPROACH AP.2

Switching frequency	*1 kHz*			*2 kHz*
Supply frequency [Hz]	**150**	**200**	**250**	**250**
Rotor Iron Loss [W]	162	245	377	389
Computed total losses [W]	3662	5313	5842	5856
Measured total losses [W]	**3945**	**5529**	**6444**	**6444**

In the Ap.3 approach, we observe a significant reduction of the iron losses in the rotor. The maximum relative error observed between the measurement and the calculation drops from 15% to 9% when using Ap.3 instead of Ap.1.

These three approaches show that the model described by the equations (2), (3) and (4) should be used with caution in determining the correct frequency, for every element of the rotor, in order to be used with the iron loss model.

The next step will be to model the asynchronous motor using a 3D F.E.M. in order to take into account more accurately the eddy currents in the solid rotor.

REFERENCES

[1] G. Bertotti, “General properties of power losses in soft ferromagnetic materials,” *IEEE Transactions on Magnetics*, vol. 24, no. 1, pp. 621–630, Jan. 1988.

[2] E. Dlala, “Efficient Algorithms for the Inclusion of the Preisach Hysteresis Model in Nonlinear Finite-Element Methods,” *Magnetics, IEEE Transactions on*, vol. 47, no. 2, pp. 395 –408, Feb. 2011.

[3] M. A. Mueller, S. Williamson, T. J. Flack, K. Atallah, B. Baholo, D. Howe, and P. H. Mellor, “Calculation of iron losses from time stepped finite element models of cage induction machine,” in *Electrical Machines and Drives, 1995. Seventh International Conference on (Conf. Publ. No. 412)*, 1995, p. 88.

[4] P. A. Hargreaves, B. C. Mecrow, and R. Hall, “Calculation of iron loss in electrical generators using finite element analysis,” in *Electric Machines Drives Conference (IEMDC), 2011 IEEE International*, 2011, pp. 1368 –1373.

[5] K. Yamazaki, “Harmonic copper and iron losses calculation of induction motor using nonlinear time-stepping finite element method,” in *Electric Machines and Drives Conference, 2001. IEMDC 2001. IEEE International*, 2001, pp. 551 –553.