Torque-Slip Characteristic of Squirrel Cage Induction Motor by New FEA Technique

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***Abstract*—The present paper deals with a new technique of finite elements analysis (FEA) of the rotor cage induction motor which enables its application to the study of other electrical devices. This technique has the great advantage of enabling the determination of the torque-slip characteristic, of the currents and of other parameters, given that the motor is supplied by a nominal voltage, without requiring however a numerical analysis with motion (of the rotor). There are only harmonic analyses in the frequencies domain that are performed, that are determined by the corresponding slips and therefore the necessary time and hardware/software resources are much more reduced. The results obtained by this method are compared to those given by measurements and thus the accuracy of the method can be confirmed.**

Index Terms—finite, elements, frequency, domain, analysis, induction, motor, torque, characteristic.

I. Introduction

The finite elements method (FEM) has been applied in engineering for over four decades [1] and it is the most used and developed of all numerical methods. In case of A.C. rotating electrical machines without permanent magnets, the mathematical model, solved by FEM, derives from well-known Maxwell's equations, specific to quasi-stationary electromagnetic field by magnetic type. The general equation which must be solved is

$$\nabla\times\left(\frac{1}{\mu(B)}(\nabla\times\overline{A})\right)=-\sigma\nabla V-\sigma\frac{\partial\overline{A}}{\partial t}+\sigma(\overline{v}\times(\nabla\times\overline{A}))\,. \quad (1)$$

In (1) we have noted: B, magnetic flux density [T], A, magnetic vector potential [Wb/m], μ, magnetic permeability [H/m], V, electric scalar potential [V], σ electric conductivity [S/m] and v, speed of moving conductors [m/s].

The solutions of (1) are those values that minimize the associated energy functional

$$\begin{aligned}F(\overline{A})&=\iiint_V\frac{1}{2\mu}(\nabla\times\overline{A})(\nabla\times\overline{A})dV-\\&-\iiint_V\left(\int_0^A\left(-\sigma\nabla V-\sigma\frac{\partial\overline{A}}{\partial t}+\sigma(\overline{v}\times(\nabla\times\overline{A}))\right)d\overline{A}\right)dV\end{aligned}\,. \quad (2)$$

The way in which the equation system derives from the minimizing condition of the energetic functional is thoroughly described in the specialized literature and will not be approached in the present study.

II. The Finite Elements Analysis of Induction Motor

A. *The parameters of induction motor*

In accordance with the equivalent circuit of three-phase induction motor (fig.1), the phase parameters of the machine are: magnetizing reactance, $X_m=\omega L_m$, resistance corresponding

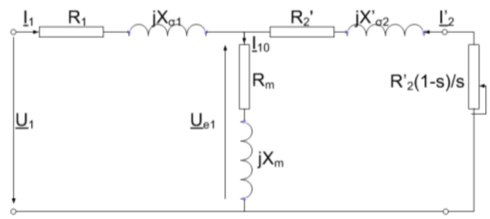

Fig. 1. Equivalent circuit of induction motors

to iron core loss, R_m, leakage reactance and resistance of the stator winding, $X_{\sigma 1}=\omega L_{\sigma 1}$ and R_1 respectively, rotor leakage reactance referred to the stator, $X'_{\sigma 2}=\omega L'_{\sigma 2}$ and rotor resistance referred to the stator, R'_2, where s is the rotor slip, ω is the angular frequency and L is the corresponding inductance.

The values of the current and of the torque during the starting process are imposed by the parameters of the equivalent sketch. In FEA the parameters of the two windings are often divided into two parts. One part is to be found in the 2D numerical model and the other part corresponds to the 3D model without being present in the 2D model. In order to study the transient regimes or to determine the mechanical characteristic or the current variation during starting process the 2D analysis is usually performed. The parameters corresponding to 3D model are inserted in the winding circuits of the motor. This approach is preferred due to the higher accuracy of the results and to the reduced amount of time that is required, as compared to the 3D analyses.

New analytical [2] or experimental [3], methods keep coming, that enable to determine quite precisely these parameters, but the finite elements analysis is the most accurate in the case of a machine in design stage.

References [4], [5], [6] and [7] describe different FEA techniques or circuit-field coupling methods and, respectively, ways of determining the parameters based on the values of the numerically computed electromagnetic field.

In the following, there will be described a new technique of determining the torque-slip characteristic and, also, the current-slip curve, when the stator winding of the rotor cage induction motor is supplied at nominal voltage.

B. *The proposed FEA technique*

It is known that the determination of the torque-slip characteristic at constant current can be performed by means of harmonic numerical analyses. The stator winding is supplied from current sources and the frequencies are imposed by the rotor slip, according to the relation $f=sf_n$.

In order to determine the torque-slip curve at nominal voltage, the stator winding must be supplied by voltage sources. The rotor speed is either set or is derived from the field values. In conclusion, a harmonic analysis with motion is necessary, but it requires important resources and much time.

A new technique of analysis in the frequency domain which enables the determination of the torque-slip and current-slip curves will be proposed. The stator winding is supplied by a three-phase voltage source at different frequencies, according to the rotor slip. As the voltage frequency in the stator winding is, actually, constant and equal to the nominal frequency, some changes in the numerical model need to be done, so that the stator winding current should not be affected by the frequency value. These changes result from the voltage equation of stator winding

$$\underline{U}_1 = R_1 \underline{I}_1 + j\omega_n L_{\sigma 1} \underline{I}_1 + (R_m + j\omega_n L_m)\underline{I}_{10} . \qquad (3)$$

The stator current will be

$$\underline{I}_1 = \frac{\dfrac{\underline{U}_1}{\omega_n} - \left(\dfrac{R_m}{\omega_n} + jL_m\right)\underline{I}_{10}}{\left(\dfrac{R_1}{\omega_n} + jL_{\sigma 1}\right)} = \frac{\dfrac{\underline{U}_1}{2\pi f_n} - \left(\dfrac{R_m}{2\pi f_n} + jL_m\right)\underline{I}_{10}}{\left(\dfrac{R_1}{2\pi f_n} + jL_{\sigma 1}\right)} . \qquad (4)$$

Some remarks are necessary. In case of high power motors and/or at rated load motors, the I_{10} current is much lower than the I_1 current. The magnetizing reactance is also much higher than the resistance corresponding to the magnetic-core losses. All these remarks taken into account, the losses in the stator core hardly influence the stator winding current. They can be even neglected in the case of large motors. In this paper they have been considered, however, but in a simplified way.

The stator core losses are mainly represented by the hysteresis losses as the eddy currents are limited because of the small thickness of the stator laminations. These losses are approximately proportional to the frequency, which means that the resistance R_m can be written $R_m = f_n(R_m/f_n) = f_n r_m$, where r_m stands for the resistance R_m referred to the nominal frequency.

Consequently, the stator winding current can be written as follows

$$\underline{I}_1 = \frac{\dfrac{\underline{U}_1}{2\pi f_n} - \left(\dfrac{r_m}{2\pi} + jL_m\right)\underline{I}_{10}}{\left(\dfrac{R_1}{2\pi f_n} + jL_{\sigma 1}\right)} . \qquad (5)$$

When an analysis is performed at a frequency $f = sf_n$, which is the rotor currents frequency, the stator current will be

$$\underline{I}_1(s) = \frac{\dfrac{\underline{U}_1(s)}{2\pi f} - \left(\dfrac{r_m}{2\pi} + jL_m\right)\underline{I}_{10}}{\left(\dfrac{R_1(s)}{2\pi f} + jL_{\sigma 1}\right)} . \qquad (6)$$

In order that the current in (5) be the same as in (6), the following terms must be equal

$$\frac{\underline{U}_1}{2\pi f_n} = \frac{\underline{U}_1(s)}{2\pi f} , \quad \frac{R_1}{2\pi f_n} = \frac{R_1(s)}{2\pi f} . \qquad (7)$$

Resulting

$$U_1(s) = sU_1 , \; R_1(s) = sR_1 . \qquad (8)$$

In conclusion, the stator winding current is not dependent of the voltage frequency if the voltage value and the stator winding resistance are multiplied by the slip s. The stator winding current is only imposed by the rotor bars currents.

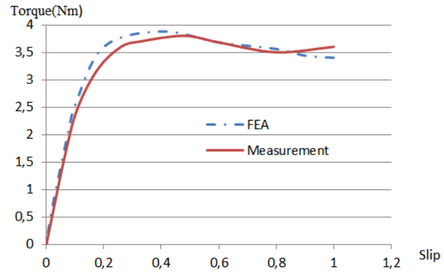

Fig. 2. Torque-slip characteristic at nominal voltage

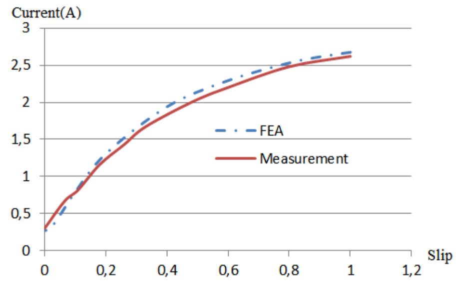

Fig. 3 Current-slip cuve at nominal voltage

For confirmation purposes, the numerical model of the stator has been carried out, with air in the rotor space. Having performed numerical analyses at three different frequencies, the same stator winding currents have been obtained.

The curves: torque-slip (fig. 2) and current-slip (fig. 3) have been determined by the FEA and by measurements for a three-phase induction motor with the following main data: rated power 0.37kW, nominal phase voltage 230V, stator core length 75mm, inner and outer diameter of the stator 70 mm and 106.5 mm respectively, two pole-pairs, stator slots number 36 and number of turns in a coil 133.

III. Conclusions

The described technique enables the analysis in the frequency domain at constant voltage. For induction motors, it avoids the analysis with motion which requires important amounts of time.

References

[1] Zienkievics O. C., Cheung Y. K., *The finite element method in Continuum and Structural Mechanics*, McGraw Hill, London 1967.

[2] T. Lubin, S. Mezani, and A. Rezzoug, “Analytic Calculation of Eddy Currents in the Slots of Electrical Machines: Application to Cage Rotor Induction Motors,” *IEEE Trans. Magn.*, vol. 47, no. 11, pp. 4650-4659, Nov. 2011.

[3] T. Marčič, G. Štumberger and B. Štumberger, “Analyzing the magnetic flux linkage characteristics of alternating current rotating machines by experimental method”, *IEEE Trans. Magn.*, vol. 47, no. 9, pp. 2283-2291, Nov. 2011.

[4] O. A. Mohammed and S. Ganu, “FE-circuit coupled model of electric machines for simulation and evaluation of EMI issues in motor drives,” *IEEE Trans. Magn.*, vol. 46, no. 8, pp. 3389–3392, Aug. 2010.

[5] R. Lin, A. Haavisto and A. Arkkio, “Validation of a time-harmonic numerical model for solving magnetic field in end region of a radial-flux machine,” *IEEE Trans. Magn.*, vol. 45, no. 12, pp. 5360-5367, Dec. 2009.

[6] R. Lin, A. Arkkio, „Calculation and analysis of stator end-winding leakage inductance of an induction machine,” *IEEE Trans. Magn.*, vol. 45, no. 4, pp. 2009-2014, April 2009.

[7] Bianchi N., *Electrical machine analysis using finite elements*, CRC Press, Taylor & Francis Group, 2005.