Parameters Estimation of Squirrel Cage Induction Motors with Closed Rotor Slots

Victor P. B. Aguiar[1], Ricardo S. T. Pontes[1]andTobias R. Fernandes Neto[1]

[1]Department of Electrical Engineering – Federal University of Ceará – Fortaleza,CE, Brazil
victorpba@dee.ufc.br, ricthe@dee.ufc.br, tobias@dee.ufc.br

***Abstract*—The paper presents a method to estimate the equivalent electric circuit of an induction motor with closed rotor slots. This method uses a two-dimensional finite-element model and a new strategy of "no load" and "locked rotor" analysis. To calculate $L_{l,2D}$ and $R'_{r,2D}$ the magnetizing inductance was obtained by simulating the locked-rotor test, instead of the generally used no-load test. The estimated parameters were validated by testing a small induction motor, utilizing the IEEE Form F2 in the IEEE 112/2004 – Method F1.**

***Index Terms*—Finite Element Analysis, Time-Harmonic, Efficiency, IEEE FormF2-Method F1.**

I. Introduction

After the introduction of the minimum efficiency performance standards (MEPS) to three-phase induction motors (IM) the motors classified as "High Efficiency" are launched in the market whereas standard motors (with low efficiency) are withdrawn from the production [1]. They were carefully designed to be as cost-effective as the standard motor [2]. Among the design modifications, the manufacture of rotors with closed slots was required to reduce the spatial harmonics and the values of stator currents. Furthermore, the electrical vibrations and noise were also reduced [3]. Due to the closed rotor slots, the leakage reactance (stator and rotor) is significantly increased, reducing the NEMA/IEC performance characteristics for the starting and the maximum load.

Finite element (FE) analysis of IM has been often used in combination of analytical method, showing good results [3]. FE model simulations of the locked-rotor and no-load tests present results that can be used to determine the motor performance in the analytical model [4]. The determination of the electrical equivalent circuit (EC) parameters (e.g. 2D rotor resistance) is illustrated in Fig. 1. Figure 1 shows that the 2D rotor resistance ($R'_{r,2D}$) and 2D leakage inductance ($L_{l,2D}$) values are dependent of magnetizing inductance value obtained from of the no-load test simulation (L_{m0}) [4].

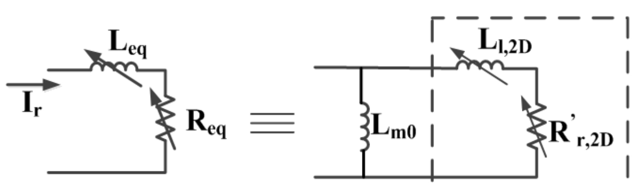

Fig. 1.Classical method for locked rotor test simulations [4].

However, we expect that parameters are dependent of magnetizing inductance value from of the locked rotor test simulation (L_{m-f}) as shown in Fig. 2 (red dotted line).On the other hand, a simple way to model the iron wedge of rotor slot is unclear [4]. Since this wedge (or bridge) easily saturates, it produces visible more slot harmonics and a different behavior for the voltage and current (V-I) curve plot during the locked rotor test [5].

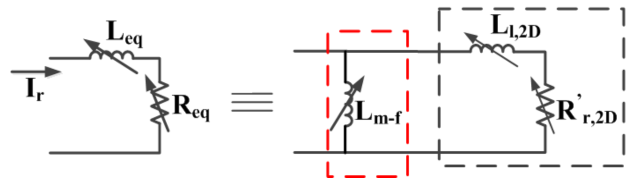

Fig. 2.Proposed method for locked rotor test simulations.

Finally, this paper proposes an approach that combines the finite element analysis and the analytical method to calculate the motor performance NEMA/IEC indicators with more precision, including the efficiency. Moreover, the EC approach depicted in Fig. 3 was obtained by prediction of the rotor parameters by the FE analysis as shown in Fig. 2. The time-harmonic field model was used as well as the magnetostatic field model. Thus, two no-load FE test simulations were performed in both field models with different aims. Likewise, two locked-rotor test simulations were carried out for two frequencies of interest, 60 Hz (starting) and 15 Hz (full-load).

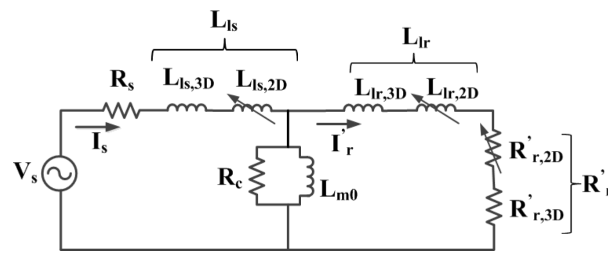

Fig. 3.Electrical EC for Induction Motor.

II. Improved Method to Calculate EC Parameters of an Induction Motor with Closed Slots

The calculated parameters obtained from the proposed method will be compared with parameters, which were determined by utilizing the calculations of form-F2 in IEEE 112/2004 - F1 [6]. Furthermore, we would like to clarify the difference of the improved method in relation to the classical method [4]:

1) All FE simulations include the stator circuit composed by voltage source, per-phase stator resistance (R_s), per phase stator leakage inductance 3D ($L_{ls,3D}$).

2) The no-load analysis needs one extra simulation using the time-harmonic model in order to calculate the stator leakage inductance 2D ($L_{ls,2D}$) [7].
3) Iron losses are calculated separately.
4) Some EC parameters determination is done as shown in Fig. 2, being required the magnetizing inductance from the locked rotor test simulations
5) Regarding the locked rotor test simulations two frequency values were used as previously mentioned. These frequency values are a recommendation of the Std. IEEE 112\2004 - F1 (the impedance test 1) [6]. Fig. 4 illustrates the proposed method.

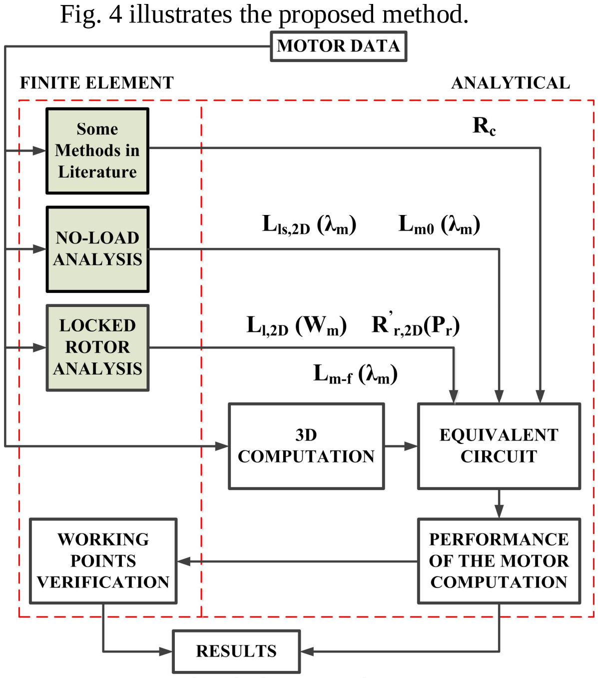

Fig. 4.Improved method to extract the IM parameters.

III. Results, Discussion and Final Remarks

First it was carried out the no-load test and the impedance test (including the locked-rotor test with 60 Hz) of a 1.5 HP, 2-pole, 380 V, squirrel cage induction motor. It is connected in star being classified as "High Efficiency" or "IE2" and it has the closed rotor slots. After the test, the measured values are: efficiency (η), 82.8%, and breakdown torque (T_{BK}), 8.9 N.m. The efficiency and the breakdown torque errors are 0.2% and 4.3% compared with the nameplate values (η=83%, T_{BK}=9.3N.m). Then, it was measured the starting current value (I_{LR}=17.7 A). It has an error of 1.7% compared with the nameplate value (17.4 A). The locked-rotor torque (T_{LR}) could not be measured by the F1 method, thus, we used the nameplate value (9.6 N.m) as the benchmark. All measured performance characteristics are the benchmarks in this work, except locked-rotor torque.

The results, on the parameter estimation using the improved method to extract the EC parameters, show a good fitting between the experimental data (benchmark) and the estimated values, as shown in Table I. The absolute error of the rotor resistance (R'_r) is very high, however, as it can be observed the new method overestimates the calculated resistance value and it approximates the rotor losses (P_r) value to the benchmark.

TABLE I
Measured (Benchmark) and Estimated EC Parameters

	Benchmark by IEEE 112/2004 F1 Method	Improved Method (Fig. 4)		Classical Method [3]	
		Value	Error (%)	Value	Error (%)
L_{ls} (mH)	17.5	15.8	10.0 %	13.9	-20.6 %
R'_r (Ω)	4.3	5.3	23.3 %	3.5	-18.6 %
L_{lr} (mH)	21.1	25.6	21.3 %	11.1	-47.4 %
P_r (W)	68	71	4.4 %	50	-26.5 %

Table II presents the error rates of the NEMA/IEC performance indicators between the classical [4] and the improved methods. As it can be seen, the improved method has shown a better estimation of the NEMA/IEC performance characteristics in comparison with the classical method [4] for an IM with closed rotor slots.

TABLE II
Comparisons of NEMA/IEC Performance Indicators

	Improved Method (Fig. 4)		Classical Method[4]	
	Value	Error (%)	Value	Error (%)
η (%)	82.7	0.1 %	84.0	1.2 %
T_{BK}(N.m)	8.8	-1.1 %	12.3	39.6 %
I_{LR} (A)	16.2	-9.0 %	20.5	15.2 %
T_{LR} (N.m)	9.6	~ 0 %	11.6	20.8 %

In summary, the use of the locked-rotor magnetizing inductance (L_{m-f}) to estimate EC parameters lead us to higher R'_r and L_{lr} values, since the rotor losses (P_r) is predicted with more precision than the classical method. Even in the motor starting, the error values of R'_r and L_{lr} (improved method) were lower than the classical method.

IV. Acknowledgement

We thank DCAT/UFERSA and CENAPAD/UFC. This project is financially supported by the CNPq (process: 459091/2014-0)

References

[1] E. B. Agamloh, C. T. C. Andrade, I. Husain, "Assesment of Prospects of Prescribing Super-Premium Efficiency Levels with Induction Motor Technology", in Proc. of the 8th International Conference EEMODS'13 vol. 01, pp. 62-77, 2014.
[2] A. Boglietti, A. Cavagnino, L. Ferraris, M. Lazzari, G. Luparia, "No Tooling Cost Process for Induction Motor Energy Efficiency Improvements", IEEE Transactions on Industry Applications, vol. 41, nº 3, pp. 808-816, May/Jun.2005.
[3] K. Delaere, R. Belmans and K. Hameyer, "Influence of Rotor Slot Wedges on Stator Currents and Stator Vibration Spectrum of Induction Machines: A Transient Finite-Element Analysis", IEEE Transactions on Magnetics, vol. 39, nº 3, pp. 1492-1494, May 2003.
[4] L. Albertini, N. Bianchi, S. Bolognani, "A Very Rapid Prediction of IM Performance Combining Analytical and Finite-Element Analysis", IEEE Transactions on Industry Applications, vol. 44, nº 5, pp. 1505-1512, Sep./Oct. 2008.
[5] A. Boglietti, A. Cavagnino, M. Lazzari, "Modelling of the Closed Rotor Slot Effects in the Induction Motor Equivalent Circuit", in Proc. of the 8th International Conference on Electrical Machines vol. 01, pp. 1-4, 2008.
[6] IEEE Test Procedure for Polyphase Induction Motors and Generators, IEEE Std. 112-1996, 2004.
[7] Z. Ling, L. Zhou, S. Guo, Y. Zhang, "Equivalent Circuit Parameters Calculation of Induction Motor by Finite Element Analysis", IEEE Transactions on Magnetics, vol. 50, nº 2, #7020604, Feb.2014.