Study of the Start-up of an Induction Machine with Broken Rotor Bars by Means of FEM-Based Simulation

Leonard LIVADARU, Alecsandru SIMION, Adrian MUNTEANU, Sorin MIHAI, Margareta COJAN, Adrian MALANCIUC
"Gheorghe Asachi" Technical University of Iasi
Bd. D. Mangeron, No. 51-53, 700050 Iasi, ROMANIA
livadaru@ee.tuiasi.ro, asimion@ee.tuiasi.ro, amunteanu@ee.tuiasi.ro

Abstract—**The paper presents an investigation concerning the effects produced by broken rotor bars of an induction machine upon start-up characteristics. The study involves a computer-aided FEM-based analysis and suggests a possible experimental method in evaluation of rotor integrity.**

Index Terms—**induction motor, broken rotor bars, start-up FEM simulation**

I. INTRODUCTION

Investigations on the abnormal operation of the rotor of an induction machine represent an oldish issue that focused the attention of engineers or academic staff. They say that around 5% to 10% [1,2,3] of motor failures come from rotor broken bars. The major problem of such a failure consists in the difficulty of detecting it. On one hand, the cage is completely buried in the rotor body and except the end rings which are in full view, the broken bars can not be visually detected. On the other hand, there is no conductive coupling to rotor winding and consequently the common electric tests are useless.

Monitoring and detection of cage failures can be performed only by distortion evaluation of "effect quantities" brought by broken bars such as voltages and currents in stator winding, magnetic fluxes or air-gap electromagnetic torque.

For a better understanding of investigation opportunities, the related to broken bars phenomena have to be clarified. Any healthy induction machine represents a cuasi-symmetrical system. As consequence, both stator and rotor windings create nothing but forward traveling magnetic field waves. The presence of one or more broken rotor bars brakes the symmetry. As a result, a backward traveling wave is acting up. This magnetic field induces in stator winding the well-known sideband current harmonic of frequency

$$(1-2s)f_1 \tag{1}$$

Further, this current component creates a torque component of frequency

$$2sf_1 \tag{2}$$

which determines specific torque ripples and speed ripple consequently. As a result, a second sideband current component of frequency

$$(1+2s)f_1 \tag{3}$$

appears in the stator current spectrum (s-slip, f_1-supply frequency). That is way the most used methods in diagnosing the cage failures are the so-called frequency-domain methods. One of the most popular is Current Signature Analysis (CSA) [4,5,6]. The use of the Fast Fourier Transform (FFT) put in view the presence or absence of the two sideband current components. Moreover, an estimation of the number of broken bars is possible with (4), [5]

$$N \cong \frac{2 \cdot Z_2}{10^{d/20} + p} \tag{4}$$

where: N-number of broken bars, Z_2 –number of rotor slots, d-average decibel difference between f_1 current component and $\pm 2sf_1$ sidebands, p-number of pole pairs. The method, which is a steady-state type one, is however affected by some disadvantages. For example, the diagnosis has to be performed under load since the no-load operation (very small value of the slip, s) pushes the sidebands components very close to fundamental frequency and it is difficult to distinguish them.

A similar method (frequency-domain analysis) but applied on start-up condition is based on Discrete Wavelet Transform (DTW), [7,8]. It has the advantage of load voidness.

A different type of method investigate the cage integrity by analyzing the induced voltage in the stator winding after disconnection from the supply [9,10]. The still existing rotor currents induce stator voltages of particular frequencies. Any broken bar modifies this pattern and allows an evaluation analysis.

Interesting to be mentioned is the so-called Pattern Recognition Technique [11]. The method is based on the existence of a "reference pattern" characterized by voltage and current values of the healthy machine. Then, vectors of characteristic features corresponding to different failures are created and continuously adjusted and compared to reference.

Vienna Monitoring Method (VMM), [12], makes a comparison of the electromagnetic torque created by a healthy machine (reference model) and by the investigated machine where broken bars create torque components of frequency $2sf_1$.

Another very interesting method uses the presence of interbar currents [13]. In every machine with non-insulated rotor bars, there are currents that flow through the magnetic circuit between bars. These currents create shaft axial fluxes with the harmonic components of $\pm ksf_1, k = (1,3,5...)$. The fluxes can be evaluated with search coils placed on the shaft ends. When one or more bars are broken, harmonics with a different frequency are presented in the flux spectrum. The frequency-domain analysis of the induced voltages in the search coils can prove the presence of broken bars.

With a different strategy works the method based on rotor magnetic field space vector orientation [14]. In fact, by using as input quantities the currents and voltages but also the stator winding parameters (R_s, L_s and M_s), the rotor magnetic field orientation is established (in terms of angular displacement) and compared to the reference healthy motor.

Finally has to be mentioned the FEM-based techniques [15,16,17] capable to put in view particular elements that occur in induction motors with broken rotor bars such as: rotor currents, actual flux lines distribution during start-up or under rated load, flux density values across the magnetic circuit.

II. CHARACTERISTIC FEATURES AND FEM ASSUMPTIONS

This paper represents a sequel of a previous published study upon broken rotor bars influence [18]. For that case a magnetodynamic analysis was performed. The main conclusions pointed out the following facts:

- with the increase of the broken bars number is the torque-slip characteristic more significantly altered. Mainly, there is a decrease of both pull-out and rated torque value;
- current values in adjacent rotor bars become much higher and there is an obvious unequal distribution of the currents in the remained healthy rotor bars (Fig. 1);
- flux lines distribution proves a much higher distortion at start-up in comparison to rated operation.

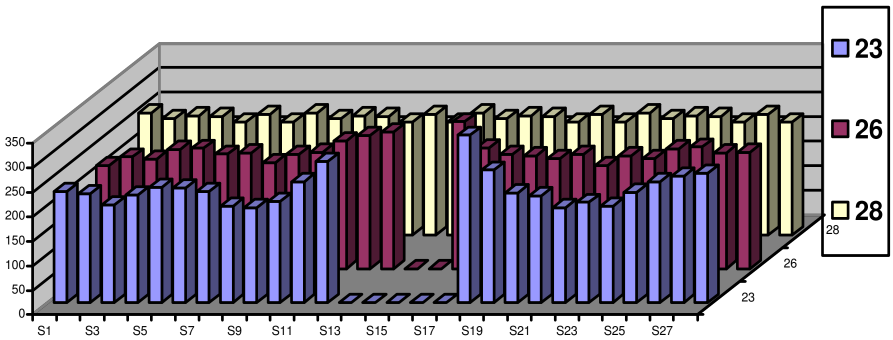


Fig. 1 Rotor bar current distribution for healthy motor (28), two broken bars (26) and five broken bars (23)

The last statement leads to the next research level: transient analysis. It has to be pointed out that both magnetodynamic and transient analyses give trustful results. But, as many authors approved [15,16,17], transient analysis is more proper for detection of broken rotor bars influence in comparison with steady-state (magnetodynamic) analysis.

As a reminder, our simulation study took into discussion a three-phase induction machine with P=3kW, U=380V, f_1=50Hz, n_1=1500rev/min, Z_1=36 and Z_2=28. Five distinct situations were considered: healthy motor and one, two, three and five broken rotor bars, respectively. The simulation of the broken bars consisted in replacing the aluminium with a non-conductive material. From the viewpoint of the electric parameters of the cage, this kind of approach determines nothing but exclusion of the broken rotor bar resistance and lack of any electric current.

During the study, the simulation took into consideration no-load operation and under-load with 12 Nm and 19 Nm load torque values, respectively. Besides, the following required values for a transient analysis came as input quantities: moment of inertia - $0.6{\cdot}10^{-3}$ kg·m^2; coefficient of viscous friction - 0.02 N·m·s; torsion constant of the spring - $0.1{\cdot}10^{-4}$ N·m; simulation time – 0.6 sec. Due to the lack of space, the paper should present the results corresponding to under-load operation with a load torque of 19 Nm.

The simulation used a commercial software package, FLUX 2D, produced by CEDRAT.

III. SIMULATION RESULTS

Pertinent conclusions (in case of a FEM simulation) can be judged from speed and torque evolution, stator currents variation and flux lines distribution.

A. Flux lines distribution and air-gap flux density wave

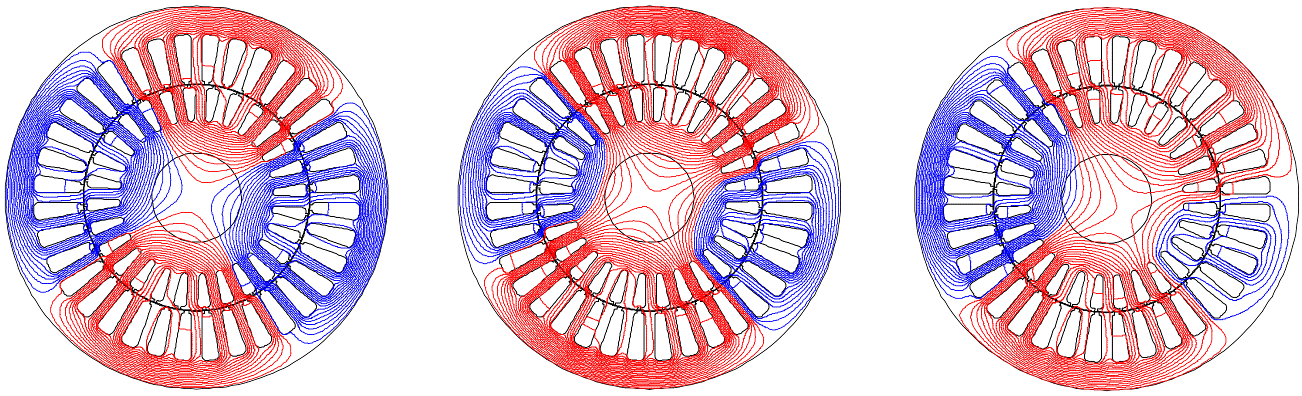
Fig. 2 presents the situation of flux lines corresponding to the moment *t=0.4* sec. (stabilized operation of the motor) for healthy motor (28 rotor bars), two broken bars (26 rotor bars) and five broken bars (23 rotor bars).

The healthy motor proves a harshly symmetrical distribution of the four poles. The higher the number of broken rotor bars, the more unsymmetrical the body of the poles. This fact comes from the alteration of rotor currents distribution. In fact, the lack of rotor currents of the broken bars determines cancellation of their individual fluxes. Consequently, the stator flux lines get free access in the fault area. The flux lines distribution is distorted and the magnetic poles occupy unequal areas. This anomaly is present in air-gap flux density wave as well (Fig. 3).

B. Torque and speed variation

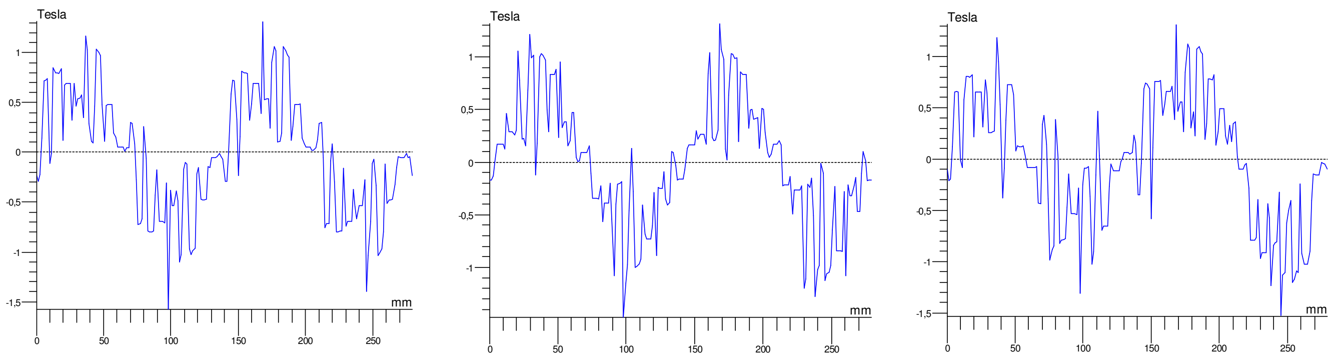
Fig. 4 shows the start-up electromagnetic torque variation. Two major phenomena have to be pointed out: stabilization time increases with the number of broken bars; permanent oscillations act significantly with three or more broken bars.

Obviously, the oscillations are present in speed variation as well (Fig. 5).



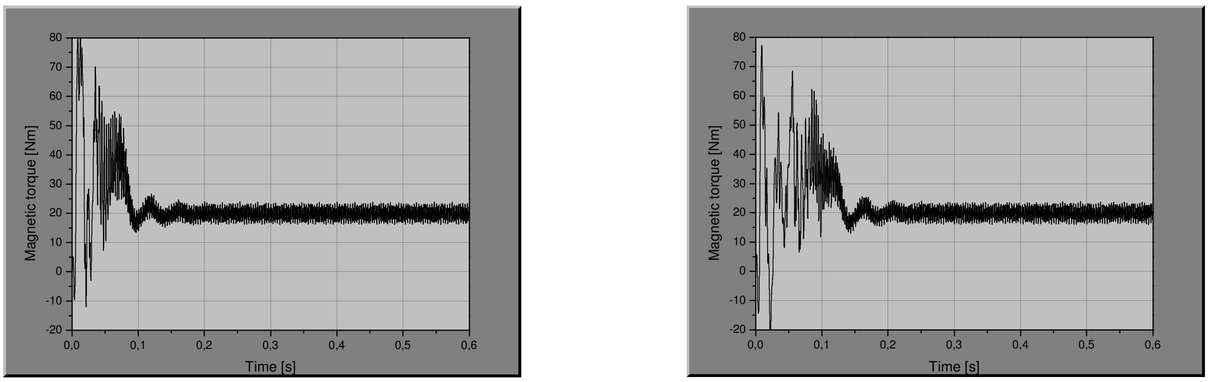
a) Healthy motor b) 2 broken bars c) 5 broken bars

Fig. 2 Flux lines distribution

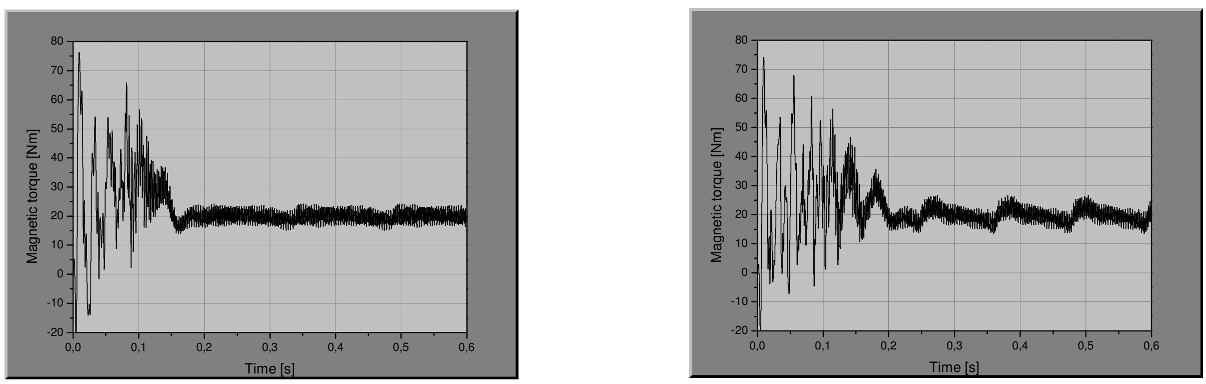


a) Healthy motor b) 2 broken bars c) 5 broken bars

Fig. 3 Air-gap flux density



a) Healthy motor b) 2 broken bars



c) 3 broken bars d) 5 broken bars

Fig. 4 Torque variation during start-up

C. Current - time variation

Fig. 6 and Fig. 7 show the variation of the three stator currents corresponding to the extreme studied situations: healthy motor and five broken bars, respectively. Again, stabilization time increases for the faulty cage and there is an important current modulation. As a matter of fact, both torque and currents are affected by the sideband current harmonics at frequencies $(1 \pm 2s)f_1$, which act as a consequence of rotor asymmetry created by broken bars.

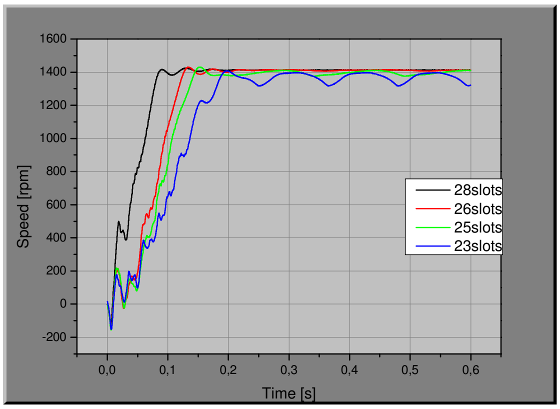


Fig. 5 Speed variation during start-up

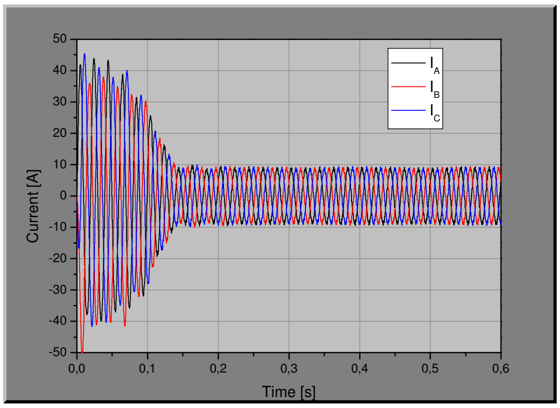


Fig. 6 Current-time variation, healthy motor

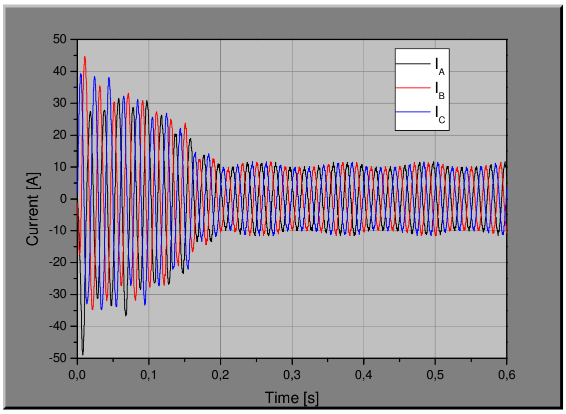


Fig. 7 Current-time variation, 5 broken bars

IV. CONCLUSION

The results obtained through FEM analysis consist with the phenomena described by scientific literature. Definitely, the transient simulation gives more accurate and reliable results then the magnetodynamic study. None the less that the results prove the presence of a rotor asymmetry (which often is determined by cage failure), but a quantitative evaluation (number of broken rotor bars) is more complex. Something similar to a pattern recognition strategy would be probably useful. However, a question stands over. How can be detected the cage failures with minimum in-house facilities. This is a general situation of the small service centers, which do not have systems of high quality capable to run FFT analyses or other modern techniques. Moreover, it must be accepted that one or two broken bars have a small influence upon the apparent operation of the machine. Additional noise or vibrations, easily to neglect, may be exhibited. A possible solution with minimum capital costs require the monitoring of the rotor speed during no-load start-up. A speed sensor and a simple data acquisition system could offer useful pieces of information regarding a possible existence of cage failures.

REFERENCES

[1] C. Yung and A. Bonnett, “Repair or Replace – A decisional model for industrial electric motors”, IEEE Ind. Appl. Magazine, vol. 10, Iss. 5, pp. 48-58, Sept./Oct. 2004.

[2] D. Durocher and G. Feldmeier, “Predictive Versus Preventive Maintenance”, IEEE Ind. Appl. Magazine, vol. 10, Iss. 5, pp. 12-21, Sept./Oct. 2004.

[3] J. Robinson, C. Whelan and N. Kent Hagerty, “Trends in Advanced Motor Protection and Monitoring”, IEEE Trans. Ind. Appl., vol. 40, No. 3, pp. 853-860, May/June 2004.

[4] A. Bellini, F. Filippetti, G. Franceschini, C. Tassoni and G. Kliman, “Quantitative Evaluation of Induction Motor Broken Bars by Means of Electrical Signature Analysis”, IEEE Trans. Ind. Appl., Vol. 37, No.5, pp. 1248-1255, Sept./Oct. 2001.

[5] I. Culbert and W. Rhodes, “Using Current Signature Analysis Technology to Reliably Detect Cage Windings Defects in Squirrel-Cage Induction Motors”, IEEE Trans. Ind. Appl., Vol. 43, No.2, pp. 422-428, March/April 2007.

[6] W. Thomson and M. Fenger, "Current Signature Analysis to Detect Induction Motor Faults", IEEE Ind. Appl. Magazine, vol. 7, No. 4, pp. 26-34, July/Aug. 2001.

[7] S. H. Kia, H. Henao and G.-A. Capolino, “Diagnosis of Broken Bar Fault in Induction Machines Using Discrete Wavelet Transform Without Slip Estimation”, IEEE Trans. Ind. Appl., Vol. 45, No.4, pp. 1395-1404, July/Aug. 2009.

[8] J. Antonino-Daviu, M. Riera-Guasp, J. Folch and M. Palomares, "Validation of a New Method for the Diagnosis of Rotor Bar Failures via Wavelet Transform in Industrial Induction Machines", IEEE Trans. Ind. Appl., vol. 42, No. 4, pp. 990-996, July/Aug. 2006.

[9] J. Milimonfared, H. Kelk, S. Nandi, A. Der Minassians and H. Toliyat, “A Novel Approach for Broken-Rotor-Bar Detection in Cage Induction Motors”, IEEE Trans. Ind. Appl., vol. 35, No. 5, pp. 1000-1006, Sept./Oct. 1999.

[10] F. Cupertino, E. de Vanna, L. Salvatore and S. Stasi, “Analysis Techniques for Detection of IM Broken Rotor Bars After Supply Disconnection”, IEEE Trans. Ind. Appl., vol. 40, No. 2, pp. 526-533, March/April 2004.

[11] O. Ondel, E. Boutleux and G. Clerc, "A Method to Detect Broken Bars in Induction Machines Using Pattern Recognition Techniques", IEEE Trans. Ind. Appl., vol. 42, No. 4, pp. 916-923, July/Aug. 2006.

[12] C. Kral and A. Haumer, “Simulation of Electrical Rotor Asymmetries in Squirrel Cage Induction Machines with the Extended Machines Library”, Conf. Modelica 2008, Vienna, pp. 351-359, March 2008.

[13] H. Meshgin-Kelk, J. Milimonfared and H. Toliyat, “Interbar Currents and Axial Fluxes in Healthy and Faulty Induction Motors”, IEEE Trans. Ind. Appl., vol. 40, No. 1, pp. 128-134, Jan./Feb. 2004.

[14] B. Mirafzal and N. Demerdash, "Induction Machine Broken-Bar Fault Diagnosis Using the Rotor Magnetic Field Space-Vector Orientation", IEEE Trans. Ind. Appl., vol. 40, No. 2, pp. 534-542, March/April 2004.

[15] C. Cunha, R. Lyra and B. Filho, "Simulation and Analysis of Induction Machines with Rotor Asymmetries", IEEE Trans. Ind. Appl., vol. 41, No. 1, pp. 18-24, Jan./Feb. 2005.

[16] T. Tudorache, P. Taras and V. Fireteanu, "Finite Element Diagnosis of Squirrel Cage Induction Motors with Rotor Bar Faults", Proc. of the 10th IEEE International Conference on Optimization of Electrical and Electronic Equipments, Braşov, pp. 87-92, 2006.

[17] N. Elkasagby, A. Eastham and G. Dawson, "Detection of Broken Bars in the Cage Rotor on an Induction Machine", IEEE Trans. Ind. Appl., vol. 28, No. 1, pp. 165-171, Jan/Febr. 1992.

[18] L. Livadaru, Al. Simion and S. Mihai, "FEM Analysis upon the Influence of Rotor Bar Faults on the Induction Machine Characteristics", Bul. Inst. Pol. Iasi, Tom LIV (LVIII), Fasc. 5, pp. 933-938, 2008.

[19] Z. Cai, A. Gao and J. Jiang, "Modeling for Interior Faults of Induction Motors and Its Simulation EMTDC", Int. Conf. on Power Systems Transients, New Orleans, CD-Proceedings, 2003.

[20] M. Blodt, M. Chabert, J. Regnier and J. Faucher, "Mechanical Load Fault Detection in Induction Motors by Stator Current Time-Frequency Analysis", IEEE Trans. Ind. Appl., vol. 42, No. 6, pp. 1454-1463, Nov./Dec. 2006.