Finite Element Diagnosis of Squirrel Cage Induction Motors with Rotor Bar Faults

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Abstract — This paper deals with the finite element analysis of a specific fault of the squirrel cage induction motors consisting in rotor bars breaking. Several variants of rotor bar faults are studied, using both quasi-static and transient magnetic field analyses. The numerical results in the reference case of healthy motor are experimentally validated by laboratory measurements.

I. INTRODUCTION

The three-phase squirrel cage induction motor is one of the most reliable, efficient and cost saving electrical machines, representing today a major electric energy consumer in industry. The potential faults that may affect the good operation of the machine are therefore crucial for the production safety and that is why a special attention is paid to such investigations in many research papers in the last decade [1-6].

Among the widespread failures of the induction machine we can mention broken rotor bars and end ring connectors, eccentricities etc. This paper will focus on the study and diagnosis of the completely and partially broken rotor bars type failure of the induction motors. These flaws may occur due to the small cracks appeared at the welding points or during the pressure die-casting process of the squirrel cage that gradually aggravate by the thermal stress and mechanical vibrations specific to the machine operation.

In order to elaborate an accurate diagnosis methodology, a preliminary step supposes a deep analysis of the consequences of the broken rotor bars on the machine parameters and operation. In this context a lot of interesting and helpful information can be obtained by using modern numerical investigation tools based on finite element method in order to comparatively analyze the healthy and damaged motors. Such deep investigations that could not be done in the past due to the significant limitations of the computers performances in terms of memory size and CPU speed are now available and could provide useful information in this area.

II. FINITE ELEMENT MODEL

The finite element field-circuit model of the machine takes into account the non-linearity of the magnetic materials and is suitable for a deep study of squirrel cage induction machine behavior with rotor faults.

A complete finite element analysis of induction motor considers the coupling between the field model, Fig. 1 and the associated electrical circuit model, Fig. 2. This coupling is justified by the following reasons:

- in most cases, the currents through the rotor and stator slots, that represent the source of the electromagnetic field, are not apriori known, but they can be indirectly computed by using the field-circuit coupling where the generally known motor rated voltage is imposed;
- the squirrel cage of the induction motor is a particular circuit that supposes a strict dependence between the currents through adjacent rotor slots, easily taken into account through additional circuit equations coupled to the field model;
- the taking into account in pure 2D field models of the frontal sections of the stator and rotor circuits is not apriori possible, this requiring additional circuit equations connected to the field model equations.

The 2D electromagnetic field computation domain represented by a cross section through the induction motor and the corresponding finite element mesh that includes around 14600 nodes are presented in Fig. 1. In order to analyze both the healthy and the damaged motor, the 2D electromagnetic field computation domain could not be reduced by exploiting the geometrical or physical symmetries.

The stator and rotor magnetic cores made of laminations are nonlinear with a saturation flux density of \( B_s = 2.1 \) T and initial relative magnetic permeability \( \mu_r = 1000 \). The stator armature contains 24 slots and the rotor armature 20 slots. Boundary conditions consist of zero magnetic flux conditions on the two circles delimiting the computation domain, i.e. outer surface of the stator magnetic core and inner surface of the rotor magnetic core in contact with the motor shaft.

Figure 1. Geometry and mesh of the computation domain
The stator winding with $w_1 = 208$ turns per phase, is of two layer type with shortened step 8/12 (expressed in slots). The rotor winding, aluminium casted, is of double squirrel cage type.

The numerical simulations in this paper use the following features of FLUX2D software package: quasi-static and transient magnetic modules, field-circuit coupling, rotating air-gap (field-circuit-mechanical coupling).

The resistivity values associated to the rotor and stator electrical circuits correspond to the aluminium and copper respectively, at the standard temperature of 155°C, i.e. $\rho_{\text{Al}_{155}} = 4.8 \times 10^{-8} \Omega \text{m}$ and $\rho_{\text{Cu}_{155}} = 2.77 \times 10^{-8} \Omega \text{m}$.

The 2D electromagnetic field computation model in $(x, y)$ cartesian coordinates is based on the magnetic vector potential formulation characterized by the partial differential equation:

$$\text{curl} \left( \frac{1}{\mu} \text{curl} A \right) = J_s - \sigma \frac{\partial A}{\partial t}$$

where $A[0, 0, A(x, y, \theta)]$ is the magnetic vector potential, $J_s[0, 0, J_s(x, y, \theta)]$ is the current density in the stator slots (apriori unknown), $\mu$ is the magnetic permeability and $\sigma$ the electric conductivity. Since the studied induction motor is voltage supplied, Fig. 2, the two unknowns quantities $A$ and $J_s$ in (1) are determined by a field-circuit coupling model of the machine. Once the magnetic vector potential chart is determined, all the derived quantities associated to the electromagnetic field, such as magnetic flux density, current density etc. are easily computed.

### III. EXPERIMENTAL VALIDATION OF 2D MODEL

In order to validate the 2D numerical model we studied numerically and experimentally, the dynamic behavior of the motor during the no-load start-up for rated supply voltage. The numerical results related to the stator currents on phase W, obtained using the FLUX2D model, Fig. 3a), are compared with experimental results in Fig. 3b). By the analysis of the results in Fig. 3 we can state that the measured results are in good agreement with the corresponding FLUX2D numerical results, proving the utility of the 2D numerical model in the finite element diagnosis of the induction machine.

The simulator of the induction motor operation with broken bars was based on the 2D finite element numerical model of the machine presented in the previous section of the paper, the single modification being the resistivity of the broken bars that was considered $10^3$ times higher than the resistivity of the healthy bars.

The numerical results at rated load of the healthy and damaged machine, Figs. 4-6, correspond to a quasi-static analysis and reflect the effect of broken bars on the stator and rotor bar current values and on magnetic field lines spectrum.
The analysis of the numerical results in Figs. 5-6 shows that the currents in the rotor bars adjacent to the broken ones increase dramatically with the number of damaged bars. For example, the current on rotor bar No. 8 increases from 388.39 A in case of a healthy machine up to 501.43 A in case of 3 broken bars, i.e. an increase of current with 29.1\% and of Joule losses with 66.41\%. This kind of damage determines a local overheating of rotor bar No. 8 and a supplementary thermal stress that can provoke an avalanche type injury of the rotor cage.

The results in Table I show that both the stator currents and the electromagnetic torque values decrease with the number of broken bars.

The results in Fig. 6 show that an effect of the existence of damaged rotor bars consists in the modifications of the magnetic field lines and magnetic axis of the machine with repercussions on the electromagnetic torque ripples.

A transient magnetic analysis of the motor at rated load, with a time step of $5 \times 10^{-5}$ sec, small enough to take into account the stator and rotor teeth harmonics permitted to compute the time variation of the stator phase currents and electromagnetic torque of the healthy and damaged machine, Figs. 7-9.

<table>
<thead>
<tr>
<th>No. broken bars</th>
<th>$I_x$ [A]</th>
<th>$I_y$ [A]</th>
<th>$I_z$ [A]</th>
<th>$M$ [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.92</td>
<td>8.92</td>
<td>8.92</td>
<td>25.50</td>
</tr>
<tr>
<td>1</td>
<td>8.66</td>
<td>8.79</td>
<td>8.81</td>
<td>24.38</td>
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<tr>
<td>2</td>
<td>7.92</td>
<td>8.78</td>
<td>8.58</td>
<td>23.10</td>
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<tr>
<td>3</td>
<td>7.50</td>
<td>8.79</td>
<td>8.28</td>
<td>21.49</td>
</tr>
</tbody>
</table>

The relative increase of rotor bar currents in case of damaged motor with respect to the healthy machine is shown in Fig. 5.
By studying the transient magnetic analysis results, Figs. 7-9, we can notice that the differences between the results corresponding to the healthy and damaged machine increase with the number of broken bars.

The results in Fig. 9 prove that the instantaneous and the average values of electromagnetic torque diminish with the increase of the number of damaged bars.

V. **TORQUE-SLIP CHARACTERISTIC OF INDUCTION MOTOR**

By simulating the motor operation at various slip values we determined the torque-slip characteristic of healthy and damaged induction machine, Fig. 10.

The numerical modeling results, Fig. 10 are of quasi-static type and show that the machine parameters at rated load worsen with the increase of broken bars number.

VI. **SIMULATION OF INDUCTION MOTOR START-UP WITH COMPLETELY OR PARTIALLY BROKEN BARS**

In order to simulate the motor start-up with partially fissured bars we divided each rotor bar in two portions, an upper one, situated toward the air-gap and a lower one, located toward the rotor shaft.
The numerical results corresponding to a quasi-static analysis of the 2D electromagnetic field-circuit problem associated to the induction motor, Table II, point out that the rotor cage fault determines a decrease of the average value of stator currents and of electromagnetic torque, the decrease deepening with the number of partially or completely broken bars. Another effect of this type of fault, Table III, consists in an important increase with the number of broken bars, of the ratio between the inverse and direct component of stator current (up to 11.64%).

By studying the results in Fig. 12 we notice that the presence of partially or completely broken rotor bars affect strongly the magnetic field lines spectrum at motor start-up.

### Table II.
**Numerical Results at Motor Start-up**

<table>
<thead>
<tr>
<th>No. broken bars</th>
<th>Broken bar portion</th>
<th>(I_u) [A]</th>
<th>(I_v) [A]</th>
<th>(I_w) [A]</th>
<th>(M) [Nm]</th>
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<tr>
<td>0</td>
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<td>49.81</td>
<td>49.81</td>
<td>53.39</td>
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<td>50.27</td>
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<tr>
<td></td>
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<td>49.51</td>
<td>50.29</td>
<td>49.79</td>
<td>52.13</td>
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<td></td>
<td>both</td>
<td>47.28</td>
<td>49.71</td>
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<td>47.37</td>
<td>49.44</td>
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<td>48.81</td>
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<td>49.95</td>
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<td>40.39</td>
<td>49.41</td>
<td>44.62</td>
<td>46.03</td>
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### Table III.
**Direct and Inverse Components of Current at Motor Start-up**

<table>
<thead>
<tr>
<th>No. broken bars</th>
<th>Direct component (I_d) [A]</th>
<th>Inverse component (I_i) [A]</th>
<th>(I_i/I_d) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.64</td>
<td>1.51</td>
<td>2.92</td>
</tr>
<tr>
<td>2</td>
<td>49.94</td>
<td>3.12</td>
<td>6.25</td>
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<tr>
<td>3</td>
<td>47.44</td>
<td>3.52</td>
<td>11.64</td>
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</table>

Figure 11. Field lines in case of healthy and worst damaged induction motor at start-up.
VII. CONCLUSIONS

This paper proves the utility of numerical models in the study and diagnosis of squirrel cage induction motors with fully or partially broken rotor bars.

The presence of one or several broken rotor bars determines an important increase of the current on the rotor bars adjacent to the broken ones and a supplementary thermal stress that can provoke an avalanche type damage of the rotor cage.

Another effect of this type of rotor fault consists in the decrease of the electromagnetic torque and of the stator phase currents, finally determining poor operation parameters of the machine.

The numerical results prove that the inverse component of the stator phase current significantly increase with the number of broken bars, this quantity being representative for the diagnosis of this type of motor damage.

If the induction machine presents the symptoms mentioned in this study the rotor assembly should be meticulously analyzed to detect the possible broken bars.

REFERENCES