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3-D Simulation of a Rotor Suffering a Bar Breakage

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Abstract—The development of Condition-Based Maintenance and Prognostics and Health Management systems can be fostered by simulations that accurately reproduce the effects and propagation of faults. Conventional methods applied to the analysis and simulation of rotor asymmetries in induction machines are based in the classical 2-D finite element approach, which is unable to reproduce its complex effects, such as interbar currents and their interaction with the stator flux density wave. This work applies a 2D-3D multiphysics finite element procedure to assess the impact of a bar breakage on a rotor cage during stationary operation, with reduced computational cost compared to a full motor 3-D simulation. Initial results show the potential of the approach and confirm previous analytical studies.

Keywords—induction motors, finite element analysis, fault diagnosis, rotors, vibrations, multiphysics.

I. INTRODUCTION

Rotor bar breakages are a relatively uncommon fault, only causing 10% of the motor failures; however, it usually affects large machines which have difficult replacement thus involving long outages and high repair costs [1, 2]. Taking advantage of the slow evolution of the failure process until the motor yields inoperative, the research community has developed a panoply of methods for its detection since the seminal work by Deleroi [3]. Currents measured at the motor mains [4, 5], stray flux and voltages after disconnection [6, 7] and vibrations [8], among others, have been proposed as magnitudes whose study can provide an insight on the symmetry of the rotor cage and thus diagnose the fault.

All these early developments were based on the detection of certain patterns in those magnitudes, patterns predicted theoretically based on Deleroi's analytical approach. Although methods to numerically integrate the field equations in the cross section of the machine had already been introduced (what is commonly known as the 2-D Finite Element approach), these were primarily focused on design purposes where, due to symmetry reasons, just a sector, usually a pole, of the machine was computed [9]. An insight on the behavior of the inherently asymmetric faulty motor using this method, especially concerning time-stepping simulations, had to wait until more computational resources were made widely available and the entire cross section could be processed [10].

A bar breakage is generally reproduced under this approach increasing the resistance of one bar several orders of magnitude above the rest. However, this practice, although correct for predicting the magnetic flux density distortion, in general cannot reflect the complex phenomena that actually surrounds

this kind of fault, such as interbar currents and the forces that arise in their interaction with the stator flux density wave [8].

Moreover, diagnosis techniques are evolving from just a mere tool endowed with the task of establishing the actual state of the equipment in the frame of corrective maintenance, to being able to predict its future state, within a time span long enough to schedule the corresponding repairs or replacement and thus avoiding disruptions in production, under what it is called the Condition-Based Maintenance and Prognostics and Health Management (CBM/PHM) architecture [11]. Within this framework models that depict the failure mechanism can provide a valuable insight into conditions involved in the inception and progression of the defect and the expected variable effects on external, measurable, magnitudes, complementing the information obtained from actual equipment and fatigue tests [12].

Thus, the aim of this work is to study the electromagnetic and mechanical effects of a bar breakage caused by interbar currents during stationary operation of an induction motor. With this aim, 3-D finite element simulations of a full induction's machine rotor (including the shaft and the end rings) are carried out in both healthy and broken bar states. Following the method introduced in [13], to reduce computational costs, some assumptions are made. First of all, the stator is not computed in 3-D, but the magnetic vector potential values obtained in a 2-D finite element simulation for the same machine imposed as a boundary condition on the surface of the rotor iron. Secondly, only a weak coupling between the mechanical and electromagnetic effects is assumed, meaning that the displacements of the rotor have no influence in the electromagnetic computation. Finally, the value of the radial conductivity of the rotor iron is limited to show the same interbar resistance as it was chosen in [14].

For this purpose, the remaining of this paper is structured as follows: Section II introduces in detail the computational method used, Section III explains the conditions under which both simulations were carried out, Section IV presents the results and Section V yields the conclusions reached.

II. APPROACH FOLLOWED

The approaches used for the electromagnetic and the magnetic forces calculations are presented here.

A. Electromagnetic Analysis

Among the several formulations for 3-D Finite Element electromagnetic modelling [15] in this paper, the AV-A is used for the 3-D simulation because its availability in the FEM software ELMER [16]. This formulation organizes the

variables used to solve the Maxwell equations in the three components (A_x , A_y , A_z) of the magnetic vector potential $\mathbf{A}$, whose curl yields the magnetic flux density ($\mathbf{B} = \nabla \times \mathbf{A}$), and an electric scalar potential V :

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V \quad (1)$$

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \nabla V = \mathbf{0} \quad (2)$$

$$\nabla \cdot \left(\sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \nabla V \right) = 0 \quad (3)$$

where (2) is derived from the Ampere's law and Faraday's law (1) and (3) accounts for the divergence free nature of currents. However, when compared to the widespread 2-D approach, the complete 3-D model of a machine can multiply the number of nodes and degrees of freedom by 50 and 200 respectively, thus being computationally very expensive [17].

Therefore, during the last two decades several combined models have been proposed to study certain motor features in detail whilst keeping the relatively simplicity of the 2-D analysis wherever possible, with complexity following the increasing availability of computational resources. In [17] end effects are simulated using linear 3D simulation coupled with 2-D time stepping and input into the 2-D solver as modifying parameters of the voltage equations. The procedure was widened in [18], where the magnetic flux density in the airgap was computed by 2-D time-stepping FE simulation and the main harmonics used to perform a 3-D time harmonic one on the rotor with the aim of studying stray losses. Interbar currents in a healthy state were obtained both for the fundamental and for higher order harmonics in a one bar pitch mesh, with a considerable computational cost decrease as compared to the full 3D solution. The focus on losses is continued in [19] where a similar approach, called in this case a hybrid model, is used in order to calculate rotor eddy current losses in the laminations of an electrical machine. Time stepping is used for both 2-D and 3D simulation in this work, as well as an additional $\mathbf{A}\text{-}\mathbf{T}$ formulation to enforce the non-conductivity of the lamination boundaries, otherwise a natural boundary condition approximately fulfilled. Following that, the present study relies on a similar hybrid model using the original AV-A formulation solved by time stepping and presenting a weak coupling between 2-D and 3-D field simulation i.e. the corresponding 2-D simulation is not affected by the computed 3-D solution [13].

The fundamentals of the coupling between both electromagnetic models is based on the fact that a fully determined field distribution within the rotor can be obtained by setting the normal components of the flux and current densities on its boundaries. By imposing for each time step the value of the tangential component of $\mathbf{A}$ on those same boundaries [19] this normal component of $\mathbf{B}$ can be defined. Thus, the field solution in the 3D mesh is approximated by mapping on the iron's surface as tangential component A_z of $\mathbf{A}$ the values obtained from 2-D magnetic vector potential solution on the rotor. This mapping needs an interpolation procedure, since the number of nodes in the perimeter of the

rotor are different in both meshes, and a rotation is needed to follow the bar skewing. Magnetic and electric insulation is imposed on the external boundaries of air surrounding the end rings' regions. The concepts are illustrated in Fig. 1.

Fig. 1. Boundary conditions in the 3-D rotor case when the source of the field is the 2-D field solution (A_{2-D})

B. Nodal Forces

The magnetic force is calculated, according to the virtual work principle [20], differentiating the magnetic energy with respect to a virtual displacement $\mathbf{f}_s$ that depends on a real parameter s such as:

$$\lim_{s \rightarrow 0} \mathbf{f}_s(\mathbf{x}) \rightarrow \mathbf{x} \quad (4)$$

$$\frac{\partial \mathbf{W}_s}{\partial s} = \int \mathbf{H}(\mathbf{B}) \cdot \frac{\partial}{\partial s} \mathbf{J}_s \cdot \mathbf{B} - \frac{\partial \det \mathbf{J}_s}{\partial s} \left(\mathbf{H}(\mathbf{B}) \cdot \mathbf{B} - \int_0^B \mathbf{H} \cdot d\mathbf{B} \right) dx$$

where a change of variables and the Piola transformation for the magnetic flux density have been applied. $\mathbf{J}_s$ is the Jacobian of $\mathbf{f}_s$. For $\mathbf{f}_s = \mathbf{x} + s\mathbf{u}N(\mathbf{x})$, where $\mathbf{u}$ is the unit vector and $N(\mathbf{x})$ a nodal shape function, (4) yields:

$$\frac{\partial \mathbf{W}_s}{\partial s} = \int \mathbf{H}(\mathbf{B}) \cdot \mathbf{u} \nabla N \cdot \mathbf{B} - \mathbf{u} \nabla N \left(\mathbf{H}(\mathbf{B}) \cdot \mathbf{B} - \int_0^B \mathbf{H} \cdot d\mathbf{B} \right) dx \quad (5)$$

These nodal forces are applied in the linear elastic module as body forces and the dynamical equation for elastic deformation of solids solved. Magnetostriction is not taken into account in this formulation.

As boundary conditions, the displacement at both ends of the rotor are limited by setting spring boundary conditions on the shaft's cross-sections.

III. SIMULATIONS

For comparison purposes two simulations spanning 2.5 electrical cycles in fixed $1e-4$ s time steps have been carried out on a mesh depicting the rotor of a one pole pair 1.5 kW induction motor [13] (Fig. 2 (a)). In its cage, one of the bars (Bar 1) was divided in three bodies, two short ones (spanning 1.5 mm) at the beginning and end of the bar, next to the end

rings (Fig. 2 (b)), and a 97 mm-long central part in-between. Defining as air region any of the bodies at the extremes of the bar, a full bar breakage can be simulated, as well as a complete decoupling of the bar from both end rings. Initially, two simulations have been carried out: healthy, when all three bodies were defined as aluminum, and broken bar in one of its extremes, when the furthestmost ($L_z=100$ mm) was considered air during the simulation. The full mesh comprised 241,580 nodes and the simulations of stationary operation during 50 ms took 25 days in a PC utilizing a single core.

Fig. 2. Rotor mesh (not showing the air regions around the end rings) and partial view of the mesh around the body defined at the end of one bar in its connection to the end ring. The rotor iron has been removed.

The characteristics of the materials (aluminum, silicon steel) utilized in the computations are summarized in Table I, where σ stands for electrical conductivity, E for the young modulus, ν for Poisson ratio, Al for the aluminum cage and Fe for all the steel bodies in the rotor, either iron or shaft.

For time constrain reasons, in this study both solvers were weakly coupled; therefore there is no influence of the elastic field on the magnetic field.

Fig. 3 depicts the values at the surface of the rotor iron of the magnetic vector potential in the z direction computed by the 2D FE simulation of the healthy machine. A slip of just 3.5% causes a limited translation of the wave during the period simulated.

TABLE I. MATERIAL PROPERTIES

σ_{Al}	$22 \cdot 10^8$ S
E_{Al}	$70 \cdot 10^9$ Pa
ν_{Al}	0.35
$\sigma_{iron,x}$	$4 \cdot 10^6$ S
$\sigma_{iron,y}$	$4 \cdot 10^6$ S
$\sigma_{iron,z}$	0
σ_{shaft}	$4 \cdot 10^6$ S
E_{Fe}	$193.1 \cdot 10^9$ Pa
ν_{Fe}	0.29

Fig. 3. Magnetic Vector Potential values around the surface of the rotor for different time steps.

IV. RESULTS

This section presents some of the results obtained from the two simulations: healthy and broken bar (one end).

A. Currents in bars

Fig. 4 shows the current density distribution in the rotor cage at 45 ms. Differences of up to four orders of magnitude can be appreciated in the bars, whereas the disturbance caused by the non-conductive region is also portrayed: higher current density values appear deeper in the bar around the breakage and in the end ring.

Fig. 5 shows the current density difference between the faulty and the healthy state for the bar facing the breakage (Bar 1) along its top (Fig. 5 (a)) and its bottom (Fig. 5 (b)). A steady increase of up to half order or magnitude takes place in the first case, caused by the lack of contact to the end ring at the end of the bar. The bottom of the bar behaves differently, keeping similar values of current density for both states along its length and only suffering a sharp increase –of more than one order of magnitude for some time steps– in the final 15 mm, as the current crosses into the iron. This result is more pronounced than the one obtained by analytical studies for non-skewed bars [21]. The neighboring healthy Bar 2 shows a similar distribution for its bottom part.

Fig. 4. Current density in the rotor cage at 45 ms. The disturbance caused by the defect is appreciated.

B. Interbar currents

According to the simulation results, these currents flowing into the iron distribute evenly, causing a small increase of the current density in that end of the rotor (Fig. 6).

The left-hand-side cross-section in this figure corresponds to the end ring, whose shadow can be appreciated in the current density pattern. No clear variation of the current density in the iron around the faulty bar can be detected in the mid-section either (Fig. 6, center), just a small rise of half to one order of magnitude can be seen in the slice corresponding to the area immediately (0.5 mm) before the breakage (Fig. 6, right).

C. Displacements

Despite the low slip conditions under which the simulations were carried out that cause a small variation of the currents in the rotor bars during the short period studied, the mechanical effects of the breakage are detectable at both ends of the rotor.

Fig. 7 presents the axial displacements at one of the rotor ends. After the sharp initial transient lasting around 4 ms, both waveforms coincide up to 30 ms. From that point on, differences in amplitude and even phase begin to appear, with higher values in the broken bar case, as it corresponds to an increase of interbar currents [8]. Their spectrum is similar, featuring two main components at around 1200 Hz and 1400 Hz. This result couldn't be obtained in [19], where the case of a hot spot during a transient was examined.

V. CONCLUSIONS

The 2D-3D multiphysics simulation approach followed in this work is able to reproduce 3D effects caused by a bar breakage in an induction motor's rotor, such as interbar currents and the consequence of their interaction with the stator flux density wave: axial forces. However, the computational needs are still too high to yield results that can be compared to experimental measurements, such as axial vibrations. Simulations 10-15 times longer would be required to compute a full cycle of the rotor currents and an accurate displacement spectrum. The ability of the software Elmer to carry out

parallel computations could be employed advantageously in future studies.

(a)

(b)

Fig. 5. Difference of current density in Bar 1 between the broken bar case and the healthy one along its length during the simulation. Top of the bar (a) and bottom of the bar (b).

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Fig. 6. Current density in the rotor iron for the faulty rotor showing cross-sections at 0.002 m (bar connected to the end ring, left), 0.05 m (middle of the rotor, center) and 0.098 m (bar separated from the end ring, right). The asterisk indicates the faulty bar.

Fig. 7. Axial displacement at the shafts' end during the simulation

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