Bar Faults Diagnosis of An Indirect Vector Control Squirrel Cage Induction Motor

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Abstract—In this paper, the performance study of the vector control method applied to a three phase squirrel cage induction motor with rotor broken bars faults as well as with both faults simultaneously is being presented. The fault diagnosis technique used in this work is based on the spectral analysis of electrical and mechanical quantities such as currents (id, iq), speed error (ew), direct current error (eId), quadratic current error (eIq) and voltage. Simulation as well as experimental results are being carried and presented to illustrate the influence of vector control on a faulty squirrel cage induction motor.

Keywords— induction motor, squirrel cage, vector control, rotor faults, spectral analysis, speed error, direct current error, quadratic current error

Notation

- \( f \) Rating frequency 50Hz
- \( s \) Slip
- \( nb \) Squirrel cage rotor bars number 28
- \( R_b \) Resistance of a rotor bar 61 \( \mu \Omega \)
- \( R_s \) Resistance of a stator phase 9.8 \( \Omega \)
- \( R_e \) Resistance of a short circuited ring segment 0.56 \( \mu \Omega \)
- \( N_s \) Stator phase winding turns number 464
- \( r \) Average radius of the machine 45 mm
- \( l \) Effective length of the machine 54 mm
- \( g \) Thickness of air gap 0.58 mm
- \( P \) The number of pole pairs 2
- \( L_{sb} \) Stator phase leakage inductance 0.02H
- \( L_{rb} \) Rotor bar leakage inductance 0.8\( \mu \)H
- \( L_{ls} \) A short-circuited ring segment leakage inductance 1.7 nH
- \( J \) Moment of inertia of the machine 0.0125Kg.m²
- \( K_f \) Coefficient of friction 0.00119 Nm / rad
- \( e_{id} \) Direct current error
- \( e_{Iq} \) Quadratic current error
- \( e_w \) Speed error

I. INTRODUCTION

The objective of this work lies at the level of the synergy between control and diagnosis, in order to provide reliable and efficient solutions. One should therefore consider these two functions together so they work effectively; a relevant control can help the diagnosis by injection of sensitizing signals, and reciprocally each diagnosis may contribute to the dynamic reconfiguration of the control. In addition, diagnosis and control can share strategic information. [1][2][3]

The diagnosis is divided into two functions: detection and localization functions. In most of the research work so far being carried, the developed methods for detecting and locating faults of induction machines are based on an open loop system representation. However, in most industrial applications, the system is inserted in a control or command loop, driven by a controller in order to increase its performance and maintain it in spite of unknown inputs that may affect it.

So the goal of our work is to study the influence of vector control on the response of the induction machine which has faulty rotor. The development of methods of diagnosis is increasing due to progress in microelectronics (microprocessor) and signal processing [3][4][7]. The technique used in this study to detect and locate online faults in cage induction machine is based on detecting frequency components generated throughout the spectrum of electrical and mechanical quantities. \[8][9\]

In this paper, at first, we have presented a model for the induction machine adapted to the simulation with the rotor bar breaks modeled by multi-winding model. Using this model, we were able to highlight the phenomena related to the rupture of the rotor bars. Calculated the spectral content of the electrical and mechanical variables was also the goal of our work.

II. MODELING OF THE MACHINE

A three-phase cage motor is considered. Its rotor is made of \( nb \) isolated bars uniformly distributed over the surface of the rotor and short-circuited by two rings. To study the performance, we used a model where the cage is considered as a mesh circuit (Fig.1).

Figure 1. Squirrel cage rotor mesh circuit

The number of differential equations obtained is equal to the number of bars plus one (to take into account one of the U.S. Government work not protected by U.S. copyright
two rings). [3][4][9][10][11]

Under conventional assumptions, the mathematical model of the machine is given by the equations of voltages [11]:

\[
[V] = [R + \frac{dL}{dt}] [I] + [L] \frac{d[I]}{dt}
\]

(1)

Hence

\[
\frac{d[I]}{dt} = -[L]^{-1} [R + \frac{dL}{dt}][I] + \frac{d[L]}{dt}[V]
\]

(2)

With

\[
[V] = \begin{bmatrix} V_s \\ \vdots \end{bmatrix}, \quad [I] = \begin{bmatrix} I_s \\ \vdots \end{bmatrix}
\]

Where

\[
[V_s] = [V_{s1} V_{s2} V_{s3} ]^T, \quad [I_s] = [0 0 \ldots 1]_{1 \times n+1}
\]

The mechanical equation is written in the following way:

\[
J \frac{d\omega}{dt} + T_e = T_s
\]

(3)

\[
\omega = \frac{\theta}{d t}
\]

Where \( \omega \) is the rotor speed and \( T_e \) the electromagnetic torque:

\[
T_e = \frac{1}{2} [I] \frac{d[L]}{dt}[I]
\]

(4)

After the transformation of park, one has leads to a small-scale model:

\[
\begin{bmatrix}
L_m & 0 & -\frac{n_2}{2} M & 0 & 0 & I_p \\
0 & L_m & 0 & -\frac{n_2}{2} M & 0 & I_p \\
-\frac{3}{2} M & 0 & L_m & 0 & 0 & I_p \\
0 & 0 & 0 & L_m & 0 & I_p \\
R_s & -a_d & 0 & -\frac{n_2}{2} M & 0 & 0 & I_p \\
-a_d & R_s & -\frac{n_2}{2} M & 0 & 0 & 0 & I_p \\
0 & 0 & S_{i1} & S_{i2} & S_{i3} & 0 & I_p \\
0 & 0 & S_{i4} & S_{i5} & S_{i6} & 0 & R_I \\
0 & 0 & 0 & 0 & R_I & 0 & I_p \\
\end{bmatrix}
\]

(5)

Where:

\[
S_i = \frac{2}{n_2} \begin{bmatrix}
R_{s2} + R_{s3} + R_{s(n-2)} \cos 0\alpha & + \left( \frac{R_{s2} + R_{s3} + R_{s(n-2)}}{n_2} \right) \cos^2 0\alpha \\
+ & + \left( \frac{R_{s2} + R_{s3} + R_{s(n-2)}}{n_2} \right) \cos(0\alpha - 1) \alpha \\
+ & + \left( \frac{R_{s2} + R_{s3} + R_{s(n-2)}}{n_2} \right) \cos(0\alpha - 2) \alpha \\
& \cdots \\
& \cdots \\
& \cdots \\
& \cdots \\
& \cdots \\
\end{bmatrix}
\]

A. Modeling of the Broken Rotor Bars:

The Model shown previously, and rewritten below, makes it possible to simulate the broken rotor bars.

If one wants to simulate the rupture of a bar or two bars the only values which will change are those of: \( S_1, S_2, S_3 \) and \( S_4 \).

The broken rotor bars is one of the most frequent faults in the rotor. Our simulations will enable us to identify the signatures of this defect and to consider the deteriorations generated in the motor. [1][2]

III. STYLING VECTOR CONTROL OF INDUCTION MACHINES

The principle of vector control is to represent the behavior of the induction machine similar to that of the separately excited dc machine where there is a total decoupling between the quantity controlling the flux (the excitation current), and the one related to the torque (the armature current). This decoupling enables a very fast response of the torque. In our work, we use the indirect vector control method. This choice is appropriate because in this case the flux is not measured or reconstructed but is set in an open loop.[1][2][12][13][14]

A. Control structure using rotor flux orientation

The machine equations in a rotating field referential frame and after Laplace transformer application are expressed as follows [1][2]:

\[
V_{d} = (R_s + p a_d) I_{d} + p \frac{M}{L_s} \varphi_x - \omega \frac{d}{dt} I_{q} + p \frac{M}{L_s} \varphi_x
\]

(5)

\[
V_{q} = (R_s + p a_d) I_{q} + p \frac{M}{L_s} \varphi_x + \omega \frac{d}{dt} I_{d} + p \frac{M}{L_s} \varphi_x
\]

(6)

\[
\varphi_x = \frac{M}{1 + p \tau_s} I_{d} \quad \text{Hence } \varphi_x = M I_{d} \text{ in steady state mode,}
\]

\[
\omega = \frac{M}{\tau_s \varphi_x} I_{q}
\]

The figure 2 shows a vector control diagram based on rotor flux orientation of a voltage inverter fed three phase induction machine. The speed setting is carried by a classical PI controller.
IV. SPECTRAL CONTENT OF CURRENT, VOLTAGE, $E_{eq}$, $E_{ew}$ AND $E_{eq}$ WITH AND WITHOUT FAULT

The principle of the technique presented in this work is based on the exploitation of spectral content of electrical and mechanic quantities.[14][15][16][17]

A. Without fault

In the spectra of the voltage and current, for a healthy squirrel cage induction motor appears the fundamental harmonic frequency of 50Hz supply.

With such of operation, the spectra of the speed error, direct current error and quadratic current error does not contain any harmonics specific

B. broken bar fault

In the spectra of the voltage and current, the generated frequencies around the fundamental frequency of the supply due to a faulty bar or ring portion are given by [3]:

$$f_s = (1 \pm 2ks)f$$

So, in the spectra of the speed error, direct current error and quadratic current error, there appear frequencies given by the following expression:

$$f_s = 2kf$$

with $k = 1, 2, 3, \ldots \in \mathbb{N}$, $s$ the slip

V. SIMULATION RESULTS AND INTERPRETATION

Once the global model of the squirrel cage induction machine is being developed, the simulation is then carried out. A program written in Matlab, allows us to highlight the behavior of an induction motor in both healthy and faulty cases.

The following set of figures present the performance behavior of a 1.1kW, 2 pole, 50Hz, 400/230V induction motor, with 28 bars in the rotor.

Simulation and experimental work are carried out for a healthy and then a faulty motor. Good agreement between simulation and experimental results can be observed.

A. In healthy motor

Spectral analyzes of the various electrical and mechanical quantities are illustrated in Figures 3 and 4. It is to be noticed at this stage that the motor used in the test rig for experimental work has an eccentric rotor. This will justify additional eccentric fault characteristic harmonics (around 25 Hz and 75 Hz) in all experimental results presented in this paper.
The stator current and voltage spectral analyses for a healthy motor are illustrated in Fig.3-a and 3-b respectively for simulation results and in Fig.4-a and 4-b respectively for experimental results. Spectral analysis of \( e_w \), \( e_d \) and \( e_q \) for a healthy motor are illustrated in Fig.5-a, 5-b and 5-c respectively for simulation results and in Fig.6-a, 6-b and 6-c respectively for experimental results.

The stator current and voltage spectral analyses show a harmonic supply frequency of 50Hz. Spectral analysis of \( e_w \), \( e_d \) and \( e_q \) have no important lines. The additional harmonics in the spectra are due to the PWM frequency of the voltage inverter.

B. With broken bar fault

In this case, we note from Fig.7-a, 7-b, Fig.8-a and 8-b that we can identify the harmonics which are due to faulty bars, which appear on both sides of the fundamental at frequencies \( f_{b1,2} = (1 \pm 2s)f \).

From Spectra of \( e_w \), \( e_d \) and \( e_q \) (Fig.9, Fig.10-a and 10-b for simulation and Fig.11-a, 11-b and 11-c for experimentation), we can identify the harmonics which are due to faulty bars at frequencies \( f_{b} = 2sf \). This shows that these signals are responsive to presence of a defect rotor.
The interest of the FFT analysis of the electrical and mechanical quantities for the diagnosis of fault lies in the simplicity of the sensor used. Indeed, the measure of the stator current and its treatment is easier and less expensive than a speed, a vibration or an axial flux analysis [1] [2].

Simulation and experimental results are obtained from the healthy machine operation and are used as a reference for the motor operation study under fault conditions. The experimental work allowed us to validate the performance behavior predicted by the theory (the presence of characteristic harmonics for each type of fault in the signal spectrum obtained).

VI. CONCLUSION

The machine model developed allows us to study the dynamic behavior of a faulty machine under indirect vector control. Simulation results are obtained and experimental work is being carried out to validate and illustrate the merit of this work.

The second merit of this work is to show that in the indirect vector control in closed loop for the dq currents and the speed, the errors of the PI controller have the information of the rotor faults. The spectra of this errors show the presence of characteristic line at 2sf (for broken bars). In practice, for the three cases, this characteristic line is 10db above of the other lines.

VII. THE MOTOR TEST RIG

The bench test consists of a machine LS 90 induction squirrel cage Leroy Somer of 1.1 kW with two pairs of poles, coupled to a DC motor operating as a generator to serve as a load (Fig.12). This machine has been specially designed to simulate faults of short-circuit type, reduction of turns on one or more phases and rotor broken bars.

The modules for electrical signals (line voltages and currents) measurement include anti-aliasing analog filters with cutoff frequency of 500Hz, as well as a data acquisition system (FAST lab card). The speed measurement is performed using an incremental encoder 1024 points.

REFERENCES


