Y. Soufi
T. Bahi
M.F.Harkat
R.Rouaibia

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Diagnosis and Fault Detection in Induction Motor drive Fed by PWM Voltage Source Inverter

The induction motor is one of the most used electric machines in variable speed system in the different field of industry and takes a particular interest for applications requiring high power and variable speed for its robust and simplicity. The early detection for motor deterioration can increase plant availability and safety in an economical way. Many publications have investigated the detection and diagnosis broken rotor bars in electrical machines supplied directly on line. However, much fewer research results have been published when the induction motor is fed by pulse width modulation (PWM) voltage source inverter which is the most common drive in the industry. This paper presents a technique method based on spectral analysis of stator currents to detect broken rotor bars fault in the rotor when it is fed from PWM-VSI. The obtained results show clearly the possibility of extracting signatures to detect and locate fault.

Keywords: Diagnosis, fault detection, induction motor, voltage source inverter.

1. Nomenclature

q	Number rotor bars.
R_s	Stator phase résistance o-axis stationary frame quantities.
R_e	Ring resistance
R_b	Rotor bar resistance
L_{cb}	Rotor bar inductance
L_{ce}	Rotor ring leakage inductance
P	Number of pole pairs
J	Moment inertia
L_{rii}	Proper inductance of the mesh *i*
L_{rij}	mutual inductance between *i* and *j* rotor mesh
Ω	Rotor angular
T_e	Electromagnetic torque
T_l	Load torque

2. Introduction

The development of interdisciplinary research in the context of surveillance, security and diagnostics of electric drives is growing rapidly in recent years due to the growing interest of industry for the maintenance of electrical drive. The asynchronous motor constitutes the core of these systems because of the simplicity of its implementation, its compactness, its better output and its excellent reliability [1]. In spite of the qualities which this motor presents, it can be the subject of various order defects. The fault diagnosis can not ask problem if we know its characteristics. The most difficult problem is to ignore the existence of the incident until it damages the systems. Therefore, it is beneficial and even required to early detect and diagnose a fault in a cautions manner in order to avoid technical and economical consequences which are invaluable. In the systems for variable speed,

Corresponding author : Y. Soufi
Department of Electrical Engineering, University of Tébessa, Tébessa -Algeria
y_soufi@yahoo.fr,

the induction motor is supplied by an inverter based on IGBT (Insulated Gate Bipolar Transistor) fed by pulse width modulation voltage source inverter (PWM-VSI). The principal function of this inverter is the variation speed. The strong evolution of this function was based, on the one hand, on the development of solid-state components entirely commendable and rapids [2], and on the other hand, on the quasi-generalized use of the techniques of Pulse Width Modulation (PWM) [3] .In these industrial processes, the multiple failures can occur in the induction motor. They can be predictable, unintended, mechanical, electrical, magnetic, or even hybrids. Their causes are diverse. Indeed, the most common drive in the industry is that with a VSI and induction motor .PWM-VSI induction motors are usually more reliable than those supplied directly online [4].

This paper presents a method analysis for broken rotor bars in induction motor fed by a voltage source inverter based on the spectral analysis of a stator phase current (MCSA; Motor Current Signature Analysis). This method showed that the application of this technique offered reliable and satisfactory results has several advantages. Among these advantages two are more interesting: the first is that the implementation of this method has only currents' sensors and a spectrum analyzer, the second is that the detection and the localization can be carried out during the system's operation in real time. A study by simulation was presented. This study showed that the application of this technique offered reliable and satisfactory results for this defect's diagnosis.

3. System and Mathematical Model

The three phase voltage inverter is based on three cells of commutation as shown in Fig. 1. Where V_d is the DC voltage inverter input and presents the logic state corresponding to the conducting. In a three phase's system, the vector components are separate from each other by an angle of 120°. Each commutation cell can be regarded as a phase of the inverter. The considered system is a three-phase inverter controlled by a Pulse Width Modulation (PWM) generator module feeding one induction motor. The command of the complementary switch of the same cell is initially assumed unchanged. Based on this command, a mean variable voltage is applied to the motor at each commutation period. We study the rotor broken bars when the induction motor is fed from PWM voltage source inverter.

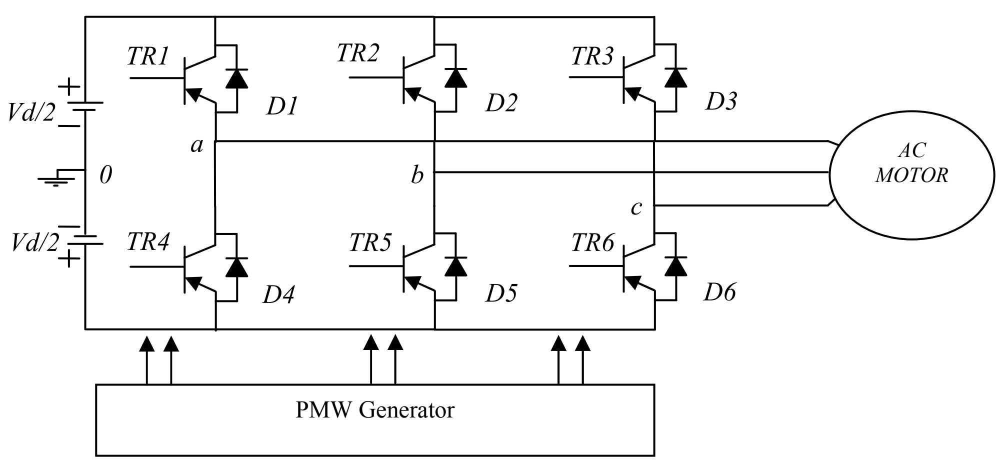

Fig. 1: Voltage fed PWM inverter system

We consider that the machine consists of a stator winding back and a rotor squirrel cage. The proposed model is based on an approximation of magnetically coupled circuits where the current in each mesh in the rotor cage is an independent variable [5, 6]. This approach offers a compromise in terms of model accuracy and computational time. In addition, this type of model can take into account a number of electromagnetic faults such as broken bars and eccentricity faults. Each bar of the rotor cage is modeled by a resistance R_b [7, 8, 9] in series with a leakage inductance L_b and each portion of the ring of short circuit with a resistance R_e in series with a leakage inductance Le, as shown in Fig. 2.

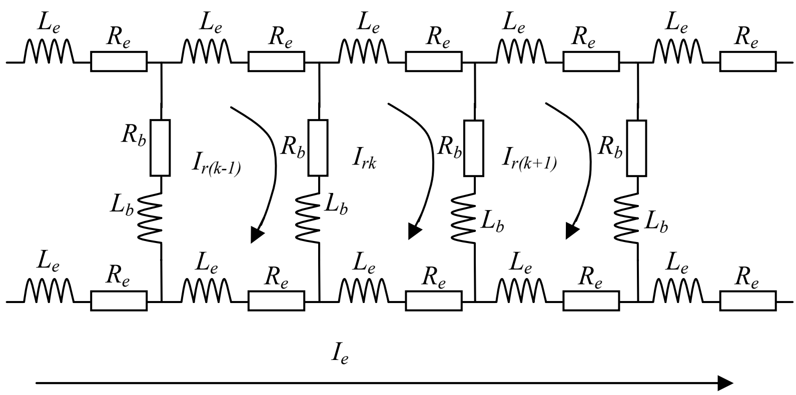

Fig. 2: Rotor mesh circuit

The application of Kirchoff's law on a grid gives us:

$$2.(R_b + R_e).i_k - R_b.i_{k+1} - R_b.i_{k-1} - R_e.i_e = 0 \tag{1}$$

$$\frac{d}{dt}[(L_{rkrk}) + 2(L_b + L_e).i_k + (L_{rkrk+1} - l_b).i_{k+1} + (L_{rkrk-1} - l_b).i_{k-1} + \ldots - L_e.i_e + L_{rks1}.i_{s1} + \Lambda + L_{rksm}] = 0 \tag{2}$$

For the stator, it is assumed that it is composed of three phases each consisting of coils placed in series, regularly distributed in slots on all of its bore. We'll develop an analytical model of induction machine from the general equations we calculate different inductance of the machine. For this purpose, it suffices to consider the mechanical angle (Θ_{sisj}) in the calculation of flux. This angle represents the angular difference between the phase *i* and phase *j* stator.

The equation expresses the electrical functioning of the cage induction machine is:

$$\begin{bmatrix} [V_s] \\ [V_r] \end{bmatrix} = [R] \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} + \frac{d[\phi]}{dt} \tag{3}$$

With voltage and current stator are:

$$[V_s] = [V_{sa} \quad V_{sb} \quad V_{sc}]^T \tag{4}$$

$$[I_s] = [I_{sa} \quad I_{sb} \quad I_{sc}]^T \tag{5}$$

$$[V_r] = [0 \quad 0 \quad 0 \quad \mathrm{K} \quad 0]^T{}_{1\times q+1} \tag{6}$$

$$[I_r] = [I_{r1} \quad I_{r2} \quad I_{r3} \quad \mathrm{K} \quad I_{rq} \quad I_e]^T \tag{7}$$

The resistance and inductance matrices are respectively represented by the following general form (8):

$$[F] = \begin{bmatrix} [F_s] & [F_{sr}] & [0] \\ [F_{sr}] & [F_r] & [-F_e] \\ [0] & [-F_e] & [q.F_e] \end{bmatrix} \tag{8}$$

With:

$F \equiv R$, resistance matrix

$F \equiv L$, inductance matrix

$Frs \equiv Fsr = 0$, for considered resistance matrix

The matrix of inductances of stator phases expressed by the relationship (9) is of the order *(m, m)*, with $m=3$:

$$[L_s]_{3\times 3} = \begin{bmatrix} L_{saa} & L_{sab} & L_{sac} \\ L_{sba} & L_{sbb} & L_{sbc} \\ L_{sca} & L_{cb} & L_{scc} \end{bmatrix} \tag{9}$$

With:

L_{sii} if ($i=j$): The proper inductance of the phase *i;*

L_{sij} if ($i \neq j$) : Mutual inductance between i and j stators phases.

The order matrix of rotor inductance is ($q+1$, $q+1$).

$$[L_r]=\begin{bmatrix} L_{r11} & L_{r12} & K & K & L_{r1q} & L_e \\ L_{r21} & L_{r2p} & \Lambda & \Lambda & L_{r2q} & L_e \\ M & M & M & M & M & M \\ M & M & M & M & M & M \\ L_{rq1} & L_{rq2} & \Lambda & \Lambda & L_{rqq} & L_e \\ L_e & L_e & \Lambda & \Lambda & L_e & qL_e \end{bmatrix} \tag{10}$$

The mutual inductance matrix between stator phases and rotor mesh is of the order *(m, Nb):*

$$[L_{sr}]=\begin{bmatrix} L_{s1r1} & L_{s1r2} & \Lambda & \Lambda & L_{s1r_q} \\ L_{s2r1} & L_{s2r2} & \Lambda & \Lambda & L_{s2r_q} \\ L_{s3r1} & L_{s3r2} & \Lambda & \Lambda & L_{s3r_q} \end{bmatrix} \tag{11}$$

The rotor resistance matrix is:

$$[R_r]=\begin{bmatrix} R & -R_b & 0 & \Lambda & 0 & -R_b & R_e \\ -R_b & R & -R_b & 0 & \Lambda & 0 & R_e \\ O & O & O & O & O & O & M \\ O & O & O & O & O & O & M \\ O & O & O & O & O & O & M \\ -R_b & 0 & \Lambda & 0 & -R_b & R & R_e \\ R_e & R_e & \Lambda & \Lambda & \Lambda & R_e & qR_e \end{bmatrix} \tag{12}$$

With:

$$[L_{rs}]=[L_{sr}]^T \qquad \text{and} \qquad R=2(R_b+R_e) \tag{13}$$

These electrical equations must be added to the following mechanical equation:

$$J\frac{d\Omega}{dt}=T_e-T_l+f_v.\Omega \tag{14}$$

The electromagnetic torque is calculated by using the basic principle of energy conversion. The torque developed by the machine Te can be obtained by considering the change in co-energy *(W_{co})* of the system produced by a small change in rotor position when the currents are held constantly [10] deriving the latter expression with respect to the position taken by the rotor towards the stator.
The expression of electromagnetic torque is ultimately determined by the relationship below [11]:

$$T_e=\left[\frac{\partial W_{co}}{\partial \theta_r}\right] \tag{15}$$

It follows that the electromagnetic torque can be expressed as:

$$T_e = [i_s]^T \frac{\partial [L_{sr}]}{\partial \theta_r} [i_r] \tag{16}$$

$$T_e = \frac{1}{2} \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix}^T \frac{d}{d\theta} \begin{bmatrix} [L_s] & [L_{sr}] \\ [L_{rs}] & [L_r] \end{bmatrix} \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} \tag{17}$$

Where, $[L_s]$, $[L_r]$ et $[L_{sr}]$, $[L_{rs}]$ are respectively the matrix of proper and mutual inductances of stator and rotor windings.

A. Multi meshes model rotor broken bars

The modeling of a broken bar or a ring segment of a short circuit occurs (see Fig. 3.) by increasing the value of its resistance so that the current crossing is the most close as possible to zero in steady state.

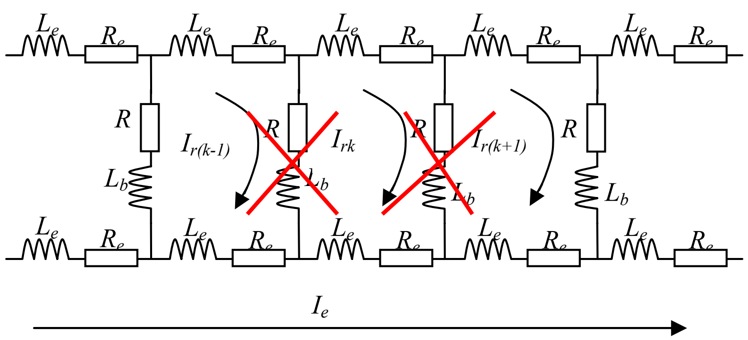

Fig. 3: Broken Rotor bar in rotor mesh circuit

This is introduced in the matrix of resistances by the addition of the matrix of the rotor resistance $[R_r]$ with the default matrix $[R_d]$. In our study, the method of modelling by increasing the resistance of the broken bar, the value of this resistance is multiplied by a factor of $M = 10^3$.

$$[R_d] = \begin{bmatrix} 0 & 0 & 0 & \Lambda & 0 \\ M & 0 & \Lambda & \Lambda & 0 \\ M & R_{k,k} & R_{k,k+1} & 0 & M \\ 0 & R_{k+1,k} & R_{k+1,k+1} & M & M \\ 0 & \Lambda & \Lambda & 0 & 0 \end{bmatrix} \tag{18}$$

With

$R_{k,k} = R_{k+1,k+1} = (M+1)*R_b+2*R_e$;

$R_{k+1,k} = R_{k,k+1} = (-M) *R_b$;

4. Simulations and interpretation

The realized simulations with the model proposed are designed in order to analyze the behaviour of induction motor with rotor fault when the motor is fed by a voltage inverter controlled by pulse width modulation. The obtained simulation results are illustrated in Fig. 4 and 5. Remember that, according to the work [12] this type of fault is characterized by appearance of frequency lines according to the following: $f_{1,2} = (1 \pm 2sk) f_s$. In case, where the machine is powered by a purely sinusoidal voltage. However, we know that using a pulse width modulation voltage source inverter, shows the natural frequencies identified in [13]. The first family is centred on the frequency mfs and includes the term of rank m, the pair harmonics of rank *m -2* and *m +2*, *m-4* and, *m+4*. The second family is centred on the frequency $2mf_s$ and includes a pair of harmonics of rank *2m-1* and *2m +1*, *2m-3* and *2m +3* ... The third family is focused on $3mf_s$ and includes the harmonic rank *3m*, and includes *3m-2* and *3m +2*, *3m-4* and *3m+4* ... .However, the interest of our tests and thus this work is to decide if this relationship is still valid. Fig. 4a, b, c and d, respectively represent speed, stator currents, torque and the first four rotor meshes These are calculated when you start the machine powered by a voltage inverter without load and apply torque load of 3 *(N.m)* at time 0.5 seconds. At time 1.5 seconds simulates the breaking of the first bar we do follow the second to 2.5 seconds. In Fig. 4d, we show moments of the two zoom breaking bars. We note at these moments currents of the bar considered void. When applying the failure, envelopes appear on the ends of the current. Fig. 5a, b, c and d, illustrate the result of frequency analysis of current phases (Fig. 4b) before breaking bars (healthy machine) when the motor has a single broken bar and two broken bars (Fig. 5c). At the end, Fig. 5d shows the superposition spectra of the three cases studied. Thus, we note that for the healthy machine that is fed by a voltage inverter with modulation index *(m = 9)*, the appearance of the frequencies of 50,150, 250 and 350 *(Hz)* as shown in the first row of table 1. The frequency analysis is the case of one broken bar (Fig. 5b) shows that for each previous detected frequency there are two other ones that appear on both sides. Or that the spectrum for the case of two breaks of bars (Fig. 5c) there are four pics, two correspond to the first broken bar and two others at the second (see zoom in Figure 5c). So, the frequency analysis shows that corrections must be reported as a result of $f_{1,2} = (1 \pm 2sk) f_s + 2 (k-1) f_s$, where k has the order of the families of harmonics created by the inverter voltage. This correction must be made in order to assess the failure of the break of the bar. Finally, the analysis frequencies of healthy motor and broken bars motor are superposed (see Fig. 5 d).

Table1. Broken bars frequencies

	Healthy	One broken bar		Two broken bars	
	F= m .f	f_1	f_2	f_1	f_2
m-8	50	44.5	55.5	46,66	53,32
m-6	150	144.5	155.5	146,66	153,32
m-4	250	244.5	255.5	245.55	254.44
m-2	350	344.5	355.5	345.55	354.44

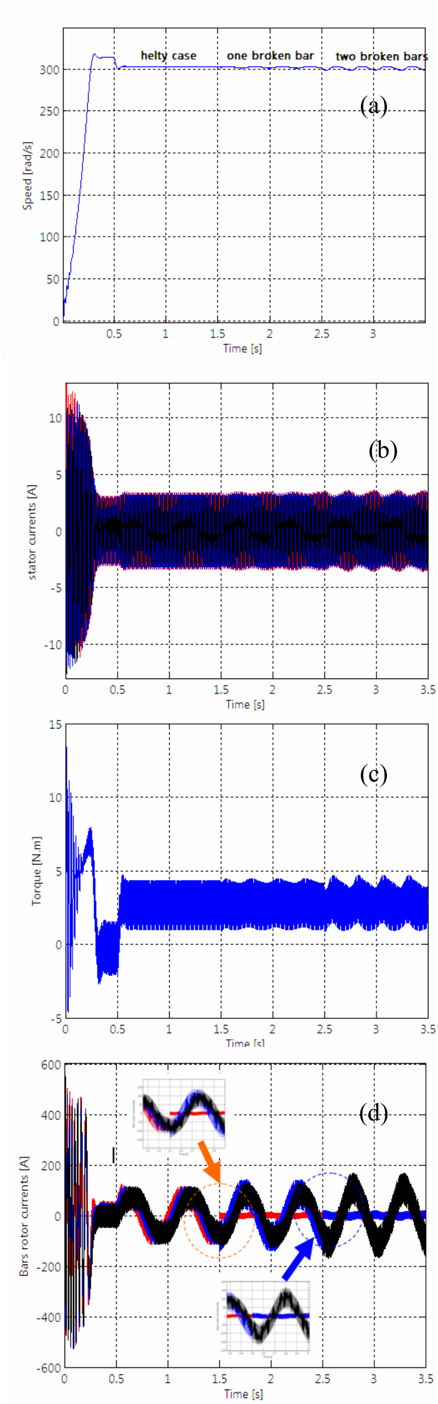

Fig. 4: Waveforms of the drive

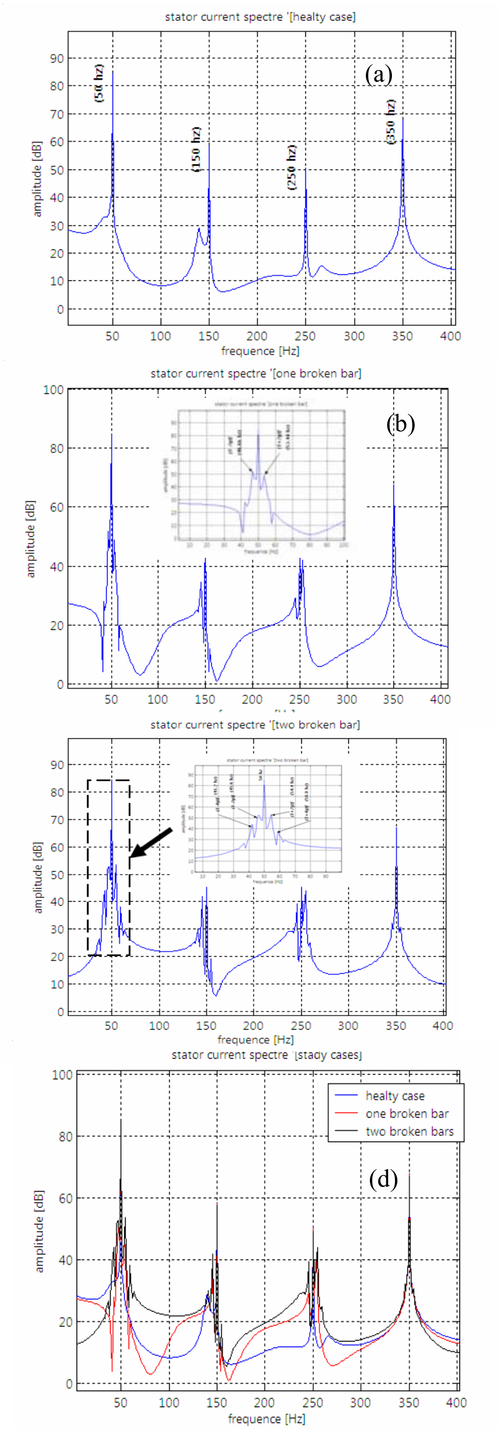

Fig. 5: Stator currents spectral analysis

5. Conclusion

The Breaking or rupture of the bars is one of the most common faults in the rotor. It reduces the average value of electromagnetic torque and increases the amplitude of oscillations, which themselves cause oscillations in the speed of rotation and also causing mechanical vibrations and thus, abnormal functioning of the machine .The large amplitude of these oscillations accelerate deterioration of the machine. In this work, the model mesh for modelling rotor was used. This model has enabled the detection of broken bars even if the induction motor is fed by a voltage inverter controlled by pulse width modulation. We only note that the known conventional relation used for diagnosis of broken bar when the motor is powered by the network is no longer valid in case the induction motor is fed by a voltage inverter. The expression in question must be corrected with an additional term in the initial expression or $(2.k - 1) f_s$.

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