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Modelling and Detection of Broken Rotor Bars Fault Using Fast Fourier Transform and Time-Frequency in Induction Motor

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Abstract-The detection of electrical and mechanical faults in induction machine by analysis of stator current methods has been widely explored. These techniques have become the reference method for faults diagnosis and are called Motor Current Signature Analysis (MCSA); the methods are based on Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) are applied to detect the broken rotor bars fault in induction motor from a spectral analysis of the stator current. These techniques are effective for the stationary signal processing. The analysis and fault signature of the machine is performed in healthy and faulty states. Simulation and experimental results are presented for the diagnosis of the broken bars faults at the rotor level.

Keywords: Induction machine (IM), fault detection, diagnosis, Analysis, broken bar, FFT, STFT.

1. INTRODUCTION

THE INDUCTION motor is certainly the electric machine most frequently used in industry, especially if it is the squirrel cage motor; because of its robustness, the ease with which it can start [1]. However, the inductions machines are often subjected during their operation to several constraints of different kinds (excessive heating, magnetic fatigue caused by the electromagnetic forces and environmental stresses that the rotor must undergo during its usual use). The accumulation of these constraints causes defects in the different parts of the machine such as broken bar rotor, inter-turn short-circuits, eccentricity, etc..,[2].

The diagnosis methods are many and varied; they correspond to the diversity of the problems encountered. There are two approaches: approach without model [3] and model approach [4], [5]. In this article, we are interested in the first approach.

This article expects on the diagnosis the faults of broken bar; on the analysis of the stator current (MCSA: Motor Current Signature Analysis) show that in addition to the information contained in the spectra; motor current signature analysis (MCSA) this approach assumes that each type of fault is characterized by its own spectral signature [6].

This method has some advantages such as simplicity of current measurement and relies on simple signal processing techniques, for example, the Fast Fourier transforms (FFT) and Short Time Fourier Transform (STFT) for detecting the presence of the broken bars faults of the motor in different states (healthy and faulty) of the induction machine. This technique utilizes results of spectral analysis of the stator current (precisely, the supply current) of an induction motor to spot an existing or incipient failure of the motor or the drive system [7], [8].

2. FAST FOURIER TRANSFORM FFT

The failure of the induction machine causes the appearance and the modification of harmonics at the level of the spectra of the signals. The monitoring by the spectral analysis technique of the signals thus consists of perform a simple Fast Fourier Transform $x(f)$ of a continuous signal over time, which allows describing any signal by its frequency spectrum expressed by:

$$x(f) = \int_{+\infty}^{-\infty} x(t) e^{-j2\pi f \cdot t} dt \tag{1}$$

The analysis of a signal is a known interval, which generates the need to choose a weighting window for the analysis (Blackmann window, Hanning, Hamming…), plus the size of the window that will influence the resolution.

In addition, the size of the window will have an influence on the maximum possible resolution. Indeed, the frequency accuracy depends on the sampling frequency and the number N of samples: $\Delta f = \frac{f_s}{N}$

3. SHORT TIME FOURIER TRANSFORM STFT

The Short Time Fourier Transform (STFT) is a time–frequency analysis technique, it is a development that extends the standard Fourier Transform technique for analyzing non-stationary signals; Fourier transforms are applied to short windows of data represented in the time domain.
The time-frequency distribution, called Short Time Fourier Transform is defined by:

$$F(f,b) = \int_{-\infty}^{+\infty} x(t) h(t-b) e^{-2\pi f t} dt \tag{2}$$

Therefore, the STFT decomposes the signal into the temporal domain into two dimensions time and frequency (f,b). The module of this plane that is the square of the amplitude of the STFT $\left|F(f,b)\right|^2$ is called the spectrogram.
The time and frequency resolution of the spectrogram is limited by the Heisenberg-Gabor inequality given by [9]:

$$\Delta f . \Delta t \geq \frac{1}{4\pi} \tag{3}$$

With Δt and Δf are respectively the temporal resolution and the frequency resolution and are defined by:

$$\Delta t = \sqrt{\frac{1}{E}\int (t - t_c)^2 \left|x(t)\right|^2 dt} \quad (4)$$

$$\Delta f = \sqrt{\frac{1}{E}\int (t - C_t)^2 \left|X(f)\right|^2 dt} \quad (5)$$

With E is the energy of the signal, C_f and C_t respectively correspond to the time and frequency center of the energy.

4. MODEL OF INDUCTION MACHINE WITH BROKEN ROTOR BARS FAULTS

Parameter estimation is based on the simulation of a continuous state-space model of induction motor. This model assumes sinusoidal magneto-motive forces, non-saturation of magnetic circuit, and negligible skin effect.

The Figure 1. illustrate the conventional modeling of the rotor by elementary dipoles with a broken bar.

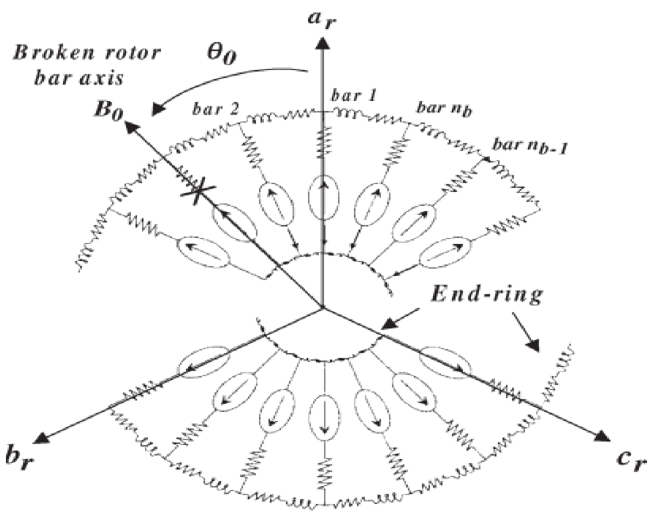


Figure 1 Broken rotor bar representation

The faulty model for the broken rotor bars of the induction motors with the equivalent resistance is illustrated in Figure 1.

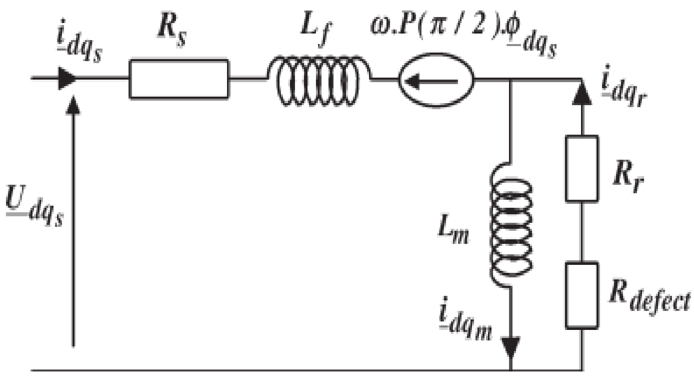


Figure 2 Model of machine with broken rotor bars fault

The model of a three-phase induction motor in the reference frame (d-q) related to the rotor is:

$$\begin{cases} \dot{x}(t) = A(w).x(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{6}$$

With:

$$x = \begin{bmatrix} i\,ds & i\,qs & \phi_{dr} & \phi_{qr} \end{bmatrix}^T, u = \begin{bmatrix} U\,ds \\ U\,qs \end{bmatrix},$$

$$y = \begin{bmatrix} i\,ds \\ i\,qs \end{bmatrix}, \; B = \begin{bmatrix} L_f^{-1} & 0 \\ 0 & L_f^{-1} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \; C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$A(W) = \begin{bmatrix} -(R_s + R_{eq})L_f^{-1} & w\,r & R_{eq}L_m^{-1}L_f^{-1} & w\,rL_f^{-1} \\ -w\,r & -(R_s + R_{eq})L_f^{-1} & w\,rL_f^{-1} & R_{eq}L_m^{-1}L_f^{-1} \\ R_{eq} & 0 & R_{eq}L_m^{-1} & 0 \\ 0 & R_{eq} & 0 & -R_{eq}L_m^{-1} \end{bmatrix}$$

$$R_{eq} = R\,r + \frac{\alpha}{1-\alpha} Q(\theta 0) R\,r,$$

$$Q(\theta 0) = \begin{bmatrix} \cos(\theta 0)^2 & \cos(\theta 0)\sin(\theta 0) \\ \cos(\theta 0)\sin(\theta 0) & \sin(\theta 0)^2 \end{bmatrix} \text{and } \alpha = \frac{2}{3}\eta_0, \; \eta_0 = \frac{3n_{bc}}{n_b}$$

$\Omega = \frac{w\,r}{P}$: is mechanical speed of the motor.

n_{bc} and n_b represent the number of broken bars and the total number of bars in the rotor respectively.

θ_0 : an absolute localization of the faulty winding according to the first rotor phase.

The expression of the torque is defined by:

$$T_e = p(i_{qs} \cdot \phi_{dr} - i_{ds} \cdot \phi_{qr}) \tag{7}$$

5. SIMULATION AND EXPERIMENTAL RESULTS

The motor under test experimental is 3 kW, 220/380V, 50 Hz, two pole, Squirrel-cage induction motor with 28 rotor bars, a DC generator acts as a load.

This study investigated the accuracy of common signal processing namely, window Fourier analysis and wavelet for stator winding diagnosis in induction machine. The current signal from health condition and with fault analyzed. The primary current was measured during the steady-state working of a motor. Fluctuations in current waveforms were then analyzed by FFT and STFT using the MATLAB Toolbox. In the experiments, the data acquisitions used are the voltage and stator current. The signals were connected to the computer by using DSpace (1104) for a data acquisition-board.

In the experimental analysis, in order to wait good results and not to miss important information, it is important to take the acquisition information correctly. The motor current data was sampled at 10 kHz, i.e., 100,000 samples was obtained at a measured time of 10 s. All the signal processing was performed using MATLAB software.

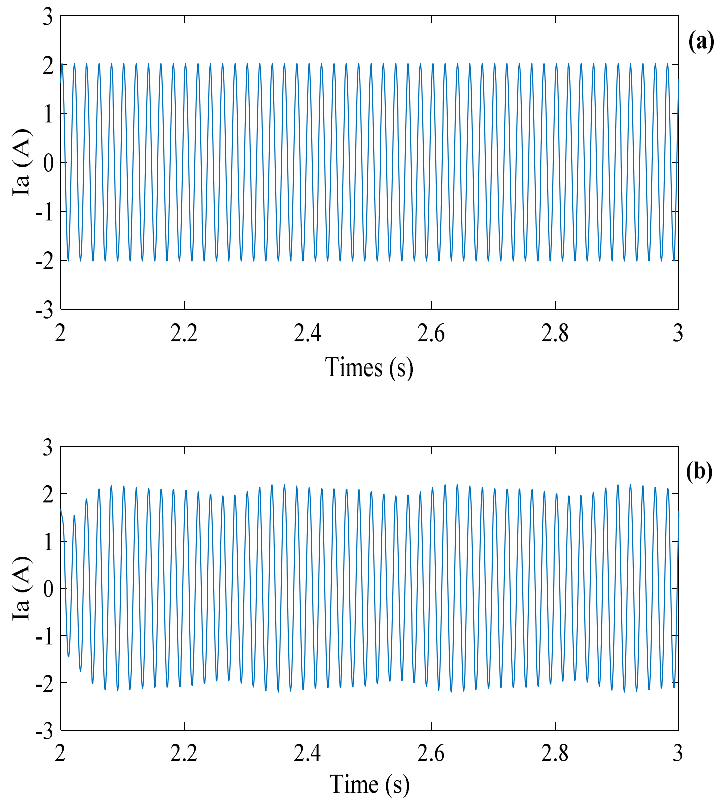


Figure 3 Evolution of stator currents in steady state: (a) Healthy machine, (b) Machine with two broken rotor bars

By analyzing the Figure 3 where we present the evolution of the stator current of the induction machine (healthy and two broken bars), visualizing a modulation and increase in the case of two broken bars, the rotor fault induces a very slight amplitude modulation in the case of a broken bar as shown in Figure 3b.

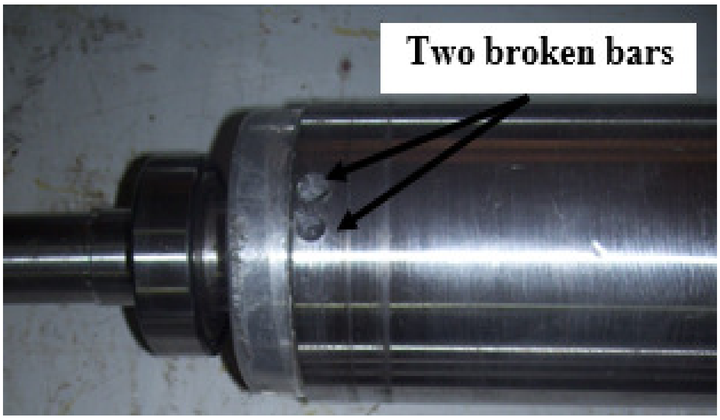


Figure 4 Rotor of induction motor with broken rotor bars

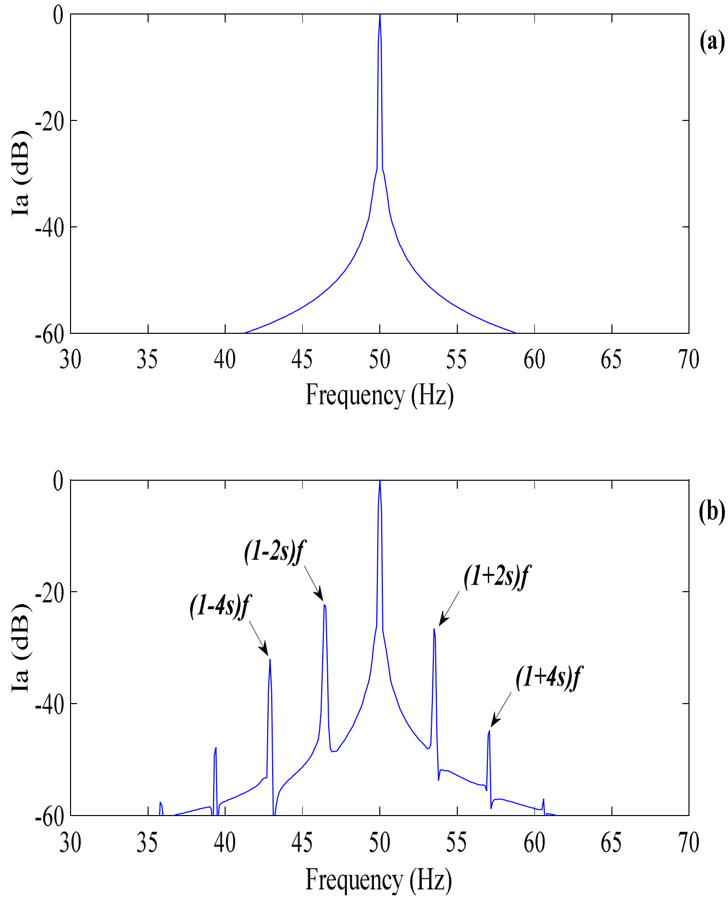
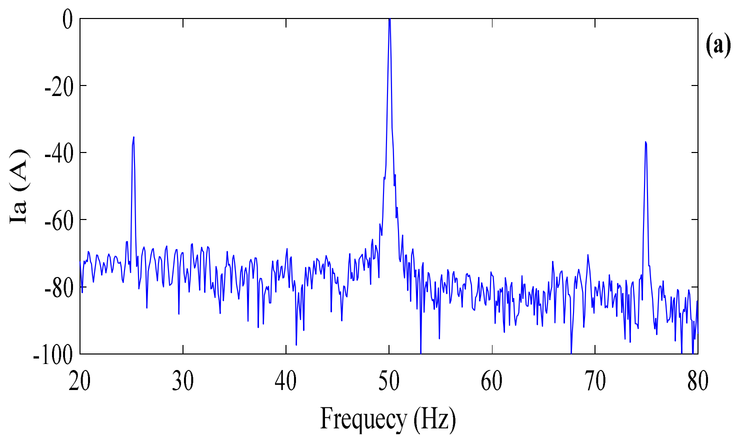


Figure 5 Simulation spectrum of stator current of phase A in steady state: (a) Healthy machine, (b) Machine with two broken rotor bars



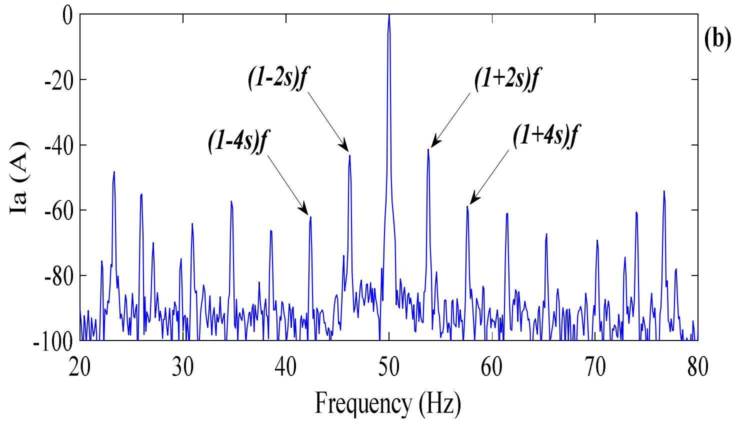


Figure 6 Experimental spectrum of stator current of phase A in steady state: (a) Healthy machine, (b) Machine with two broken rotor bars

Figure 5 and Figure 6 illustrates the result of the stator current analysis extracted in simulation and in experimental results for the machine at healthy and two broken rotor bars.

The spectral analysis of the stator current identifies its additional components that appear in default situation as Figure 6b and shows the frequency spectrum of the stator current around the network frequency of 50 Hz that is at [10]:

$$f\ defect = \left(1 \pm 2ks\right)f \tag{8}$$

Where $f\ defect$ are the sideband frequencies associated with the broken rotor bar, k = 1, 2, 3…, f is supply frequency of the machine, and s is the fractional slip of the motor.

The degree of severity of the amplitudes of the defect lines $(1 \pm 2ks)f$ show the existence of the broken two bars in Fig. 6, it is also remarked that the calculated frequencies are almost similar from the deduced ones in the experimental (Tab. I).

TABLE I. FREQUENCIES AND MAGNITUDE OF STATOR CURRENT SPECTRUM CASE OF FAILURE OF TWO BROKEN BARS

s=0.04	$(1-4s)f$	$(1-2s)f$	$(1+2s)f$	$(1+4s)f$
$f_{calculated}$ (Hz)	42	46	54	58
$f_{deduced}$ (Hz)	42.4	46.2	53.8	57.6
Magnitude (dB)	-62.08	-43.21	-41.41	-58.86

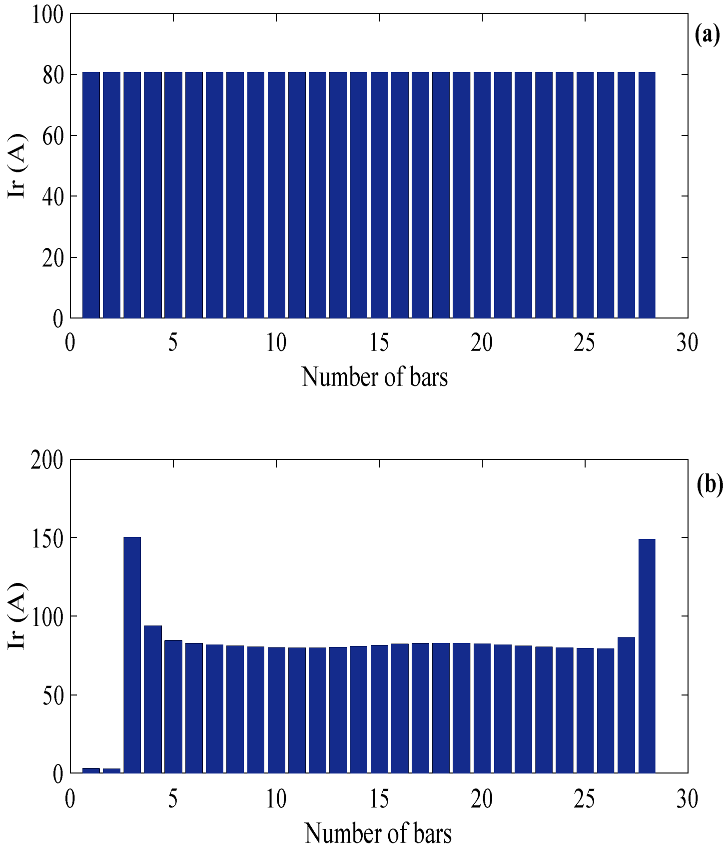


Figure 7 Effective values of the currents in the rotor bars: (a) Healthy motor and (b) motor with two broken bars (1 and 2)

Figure 7a and 7b shows the effective values of the currents in the rotor bars, before and after two broken bars. It is found that the presence of a broken bar; causes an overcurrent in the neighboring bars (bars 3 and 28).

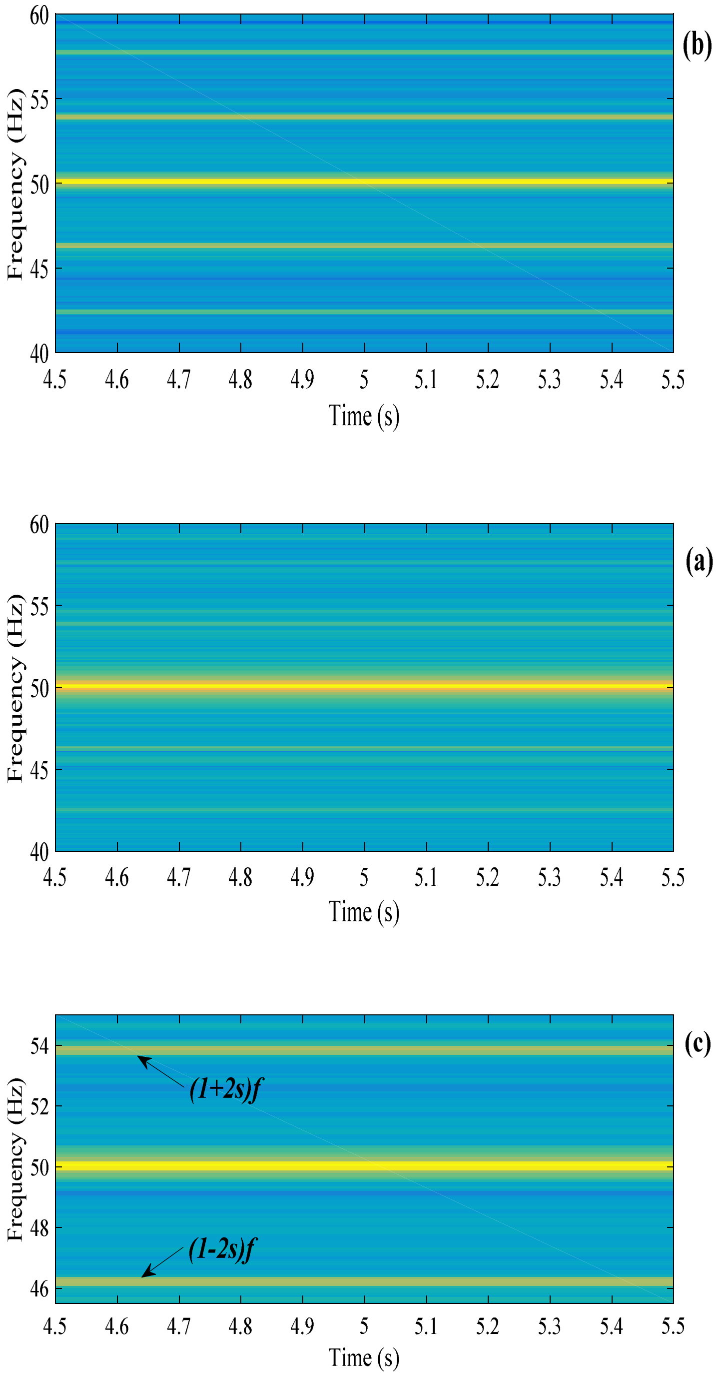
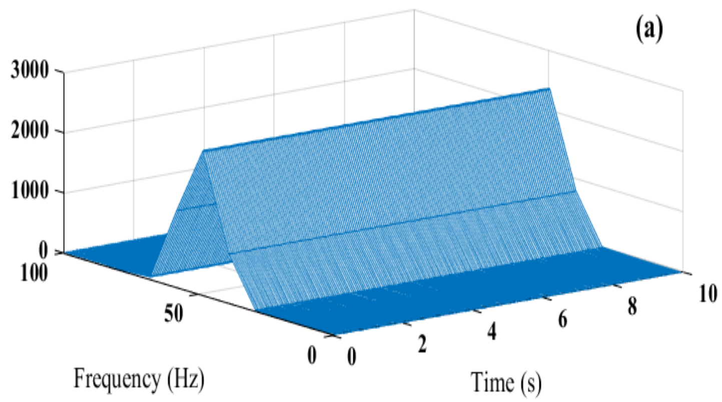


Figure 8 STFT for a signal: (a) Healthy machine, (b) Machine with two broken rotor bars and (c) Zoom of STFT for a signal with two broken bars

The spectrogram of the stator current in the healthy case and with the presence of the broken bar by STFT is give in Figure 8 shows that the presence of the fault is manifested by frequency components around the fundamental as the Figure 8b and Figure 8c.



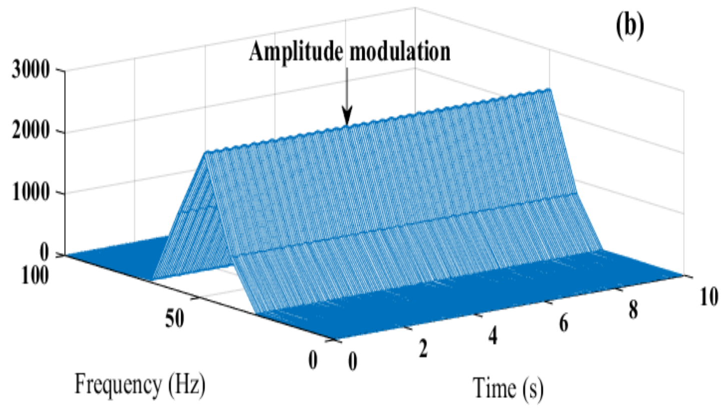


Figure 9 Spectrogram: (a) healthy machine and (b) tow broken bars

Figure 9 Illustrates results using the spectrogram. We note that this approach allows discrimination of the faulty and healthy conduction (amplitude modulation of the fundamental frequency).

6. CONCLUSIONS

In this paper, good methods for broken rotor bar detection and diagnosis in induction machine are presented. These methods are based on Fast Fourier transform and Short Time Fourier transform. The results obtained show that the FFT and the STFT can indicate the presence of the broken rotor bars fault; they are gave us a good result for detecting the failure of broken bars. The result obtained from the analysis of the stator current in simulation and experimental shows the existence of faults; the appearance of different harmonics in the spectrum and shows the efficiency of the methods used for these types of failures.

APPENDIX

FOR THE SIMULATED INDUCTION MACHINE

P_n: 3 kW
V_s: 220/380 V
f: 50 Hz

P: 1
Nr: 28
Ns: 193
Rs : 4.1Ω
Lsf : 17.5 mH
k0: 5 10^{-6} Nms^2
R_b: 74 μΩ
L_e: 0.33 μH
R_e: 74 μΩ
L_b: 0.33 μH
J: 4.5 10^{-3} Nms^2

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