Asynchronous Motor Rotor Faults Detection and Location using the Short Time Fourier Transform Approach

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Abstract – *Recent advances in the field of power electronics and control circuits, have contributed to the increasing use of induction machines in electrical systems. The use of induction machines is mainly due to their robustness, their power/weight ratio and their low cost of manufacture. Still, various defects may appear in such machines. The Power Spectral Density (PSD) based on the Fourier Transform (FT), is used as a method of analysis for many years for its simplicity and its relatively low computing time. However, it is ineffective in faults detection in the case of a small slip (harmonics too near to the fundamental). In addition, the fact that this method is based on the calculation of the FT, implicitly implies that the spectral properties of the signal are stationary. With the development of variable speed applications, the spectral characteristics of the stator current become non-stationary and the spectra are much richer in harmonics. To resolve these problems, we used in this paper, a time-frequency representation called Short Time Fourier Transform or STFT, giving therefore, additional information on changes of the frequencies with time in the case of a stator current signal. Several simulations are achieved in the aim of validating our approach.*

***Keywords**: Induction motor, fault diagnosis, time-frequency, broken rotor bars, signal modeling.*

I. Introduction

These Due to its simple technology, the induction motor is widely used in most electric drives, especially for constant speed applications. Advances in power electronics associated with modern controls techniques have led to wide variable speed applications of these motors. Thus, growing interest is being given for fault detection and condition monitoring of induction machines.

Fault detection in electrical machinery has been the subject of research and industrial achievements in recent years. There are several types of diagnosis techniques; the vibration analysis is the oldest and most used one [1], [2], [3], but this is mainly used for mechanical faults detection. Another technique based on the analysis of stator current; is also being used increasingly in recent years. This is called Motor Current Signature Analysis or MCSA, its particularity is that the stator current contains significant information on almost all the faults that can appear on the induction motor [4], [5], [6].

In most cases, induction motor operates directly from the mains and runs in steady state conditions with known loads.

The development of technology and the advances in variable speed drives have given another dimension to various problems including non stationary condition of measurable signals, disruptions and distortions caused by power converters, etc. [7].

The power spectral density or PSD of the stator current, based on the Fourier transform (FT) is the most currently tool used by researchers and industrials [8]. This is justified by its simplicity, the low cost of current sensors and the rich harmonic content of stator current.

However, this technique has several disadvantages which are due to the problem of frequency resolution. Indeed, the calculation of the FT introduces a smoothing effect and a side effect. These effects are reflected by the appearance of sideband lobes in the stator current spectrum and reduce the analysis efficiency [9].

To analyze a signal, it is interesting to have a main lobe as narrow as possible and sideband lobes of very low amplitude. Two advantages impossible to achieve simultaneously. However, it is possible to reduce the amplitudes of sideband lobes by replacing the rectangular window by a smoother and seamless window.

The PSD finds difficulties in detecting faults with a small motor slip (harmonics close to the fundamental). Since it is based on the FT, implicitly implies that the spectral properties of the signal are stationary. In addition, the modulus of the FT of a signal provides only a time average of the spectral content of the signal without giving details on possible changes in frequency with time. Therefore, information regarding the location of the frequencies with time can not be determined from the Fourier transform. To overcome these constraints, we use a time-frequency representation. Indeed, the Gabor works in the 40s have conducted to the foundations of a new type of analysis called Short Time Fourier Transform or STFT.

He was the first to imagine a local Fourier transform based on a windowing signal analysis to observe changes in frequency with time. This transformation requires the division of the signal in consecutive short segments and then calculates the Fourier transform of each segment.

The idea is to introduce the local frequency parameter so that the Fourier transform is applied to the signal through a sliding window on which the signal is approximately stationary. This method represents the results into three dimensions; the description of the signal is carried out in the time-frequency plan composed of spectral characteristics as a function of time [10].

In this context, this paper focuses on the application of the Short Time Fourier Transform in detecting and locating induction motor faults. To this end, the STFT is evaluated and used for the analysis of stator current in the presence of faults close to the fundamental. The results of simulations will illustrate the merits of the technique and its validation.

II. Stator current signature analysis

The stator current spectral analysis is the most commonly method used in recent years, because the resulting spectrum contains a source of information on most faults that may appear on an induction machine.

Induction motor broken rotor bars is considered among the most common fault studied because of its simplicity of implementation. This fault induced changes in the stator current spectral component and thus the appearance of sideband frequencies in the current spectrum produced by the magnetic field anomaly of the broken rotor bars [7].

Indeed, broken rotor bars give rise to a sequence of sidebands given by:

$$f_c = (1 \pm 2ks) f_s \qquad (01)$$

Where: f_s is the supply frequency and f_c the sideband frequencies associated with the broken rotor bars, s is the motor slip and k = 1, 2, 3…

III. Time-frequency analysis

The Fourier transform is expressed by the following equation [11]:

$$FT_x(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \qquad (02)$$

We define the power spectral density or PSD as the square modulus of the Fourier transform, which is thus independent of the signal phase. Therefore, any information on the frequency changes with time variation is lost in the PSD [8], [10], [13].

The time-frequency distribution, known as Short Time Fourier Transform or STFT is defined by [11]:

$$STFT_x(t, f) = \int_{-\infty}^{+\infty} x(\tau) h(\tau - t)^* e^{-j2\pi f\tau} d\tau \qquad (03)$$

$$STFT_x(t, f) = \int_{\Re} X(\theta + f) H^*(\theta) e^{-j2\pi\theta t} d\theta \qquad (04)$$

The second expression of the $STFT_x$ is obtained from the classical properties of the FT: conservation of the scalar product, shift properties and transformation of a normal product into a convolution one.

The STFT is constituted by the FT of $x(\tau)h^*(\tau - t)$ obtained by weighting $x(\tau)$ by the window $h^*(\tau - t)$ which is a short time analysis window localized around t and that shifts by varying the parameter t.

Join to $h(\tau)$, the family of functions depending on two parameters t and f, defined by [14]:

$$h_{t,f}(\tau) = h(\tau - t) e^{j2\pi f\tau}, \qquad (t, f) \in \Re^2 \qquad (05)$$

The numbers $STFT_x(t, f)$ are commonly called projections of $x(\tau)$ on the function's system $h_{t,f}$. If h is the rectangle window of T support, the STFT consists in taking the FT of a sequence of signals equal to x on the support and zero elsewhere.

We begin by the discrete-time signal [$x_n = x(nT)$], $T>0$. Let $h_n = h(nT)$ and N the number of samples in the analysis window. Finally, we introduce a discretization of the frequency variable f.

The STFT is then defined by the entire numbers $X_{k,n}$ calculated as follows [15]:

$$X_{k,n} = \sum_{\ell=0}^{N-1} x_{\ell+k} h_\ell^* e^{-j2\pi\ell T\frac{n}{N}}, \; k \in \mathbb{Z}, \; n = 1,2,\ldots \qquad (06)$$

As for the FT, the zero-padding technique allows the improvement of the frequency resolution. The principle of this method is to complete by M zeros a set of N samples so that $M + N$ is a power of 2 and thereafter can perform calculations using the Fast FT algorithm using the $N + M$ points.

When $M = N$, the method use the Discrete FT algorithms that are being made to calculate $2N$ points from the spectrum, from only N points of the signal [15].

IV. Heisenberg-gabor uncertainty principle

The uncertainty principle, also called time-frequency inequality, is based on the uncertainty relationships established by Werner Heisenberg in quantum mechanics. The analogy with the work of Heisenberg for the Fourier transform was made by Dennis Gabor in 1946.

Let us consider the finite energy signal $x(t)$, centered in time and frequency around zero. Gabor defines the duration Δt and the spectral band Δf as follows [14]:

$$\Delta t = \frac{1}{E_x}\int_{-\infty}^{+\infty} t^2 |x(t)|^2 dt \quad (07)$$

$$\Delta f = \frac{1}{E_x}\int_{-\infty}^{+\infty} f^2 |X(f)|^2 df \quad (08)$$

Where E_x is the energy of the signal given by the Parceval relationship:

$$E_x = \int_{-\infty}^{+\infty} |x(t)|^2 dt = \int_{-\infty}^{+\infty} |X(f)|^2 df \quad (09)$$

Therefore, the time-frequency inequality is defined by [12]:

$$\Delta t \cdot \Delta f \geq \frac{1}{4\pi} \quad (10)$$

It expresses the fact that the duration-band product of a signal is lower bounded for a Δt duration and a Δf spectral band. The STFT is subject to the uncertainty principle due to the use of Fourier transform.

This issue requires the search for the right time-frequency compromise suitable to the case considered in determining the correct window width.

Gaussian window has the best time-frequency localization. Indeed, it verifies the following equality [14]:

$$\Delta t \cdot \Delta f = \frac{1}{4\pi} \quad (11)$$

Finally, the choice of the window is important because it represents another compromise (comparable to the time-frequency compromise) between the main lobe width and the amplitude of the sideband in the frequency domain.

V. Simulation results and discussion

To simulate the presence of a rotor fault in a squirrel cage induction machine with a motor slip **s** = 5%, we construct the signal of stator current as follows:

$$x(t) = 5\sin(2\pi f_s t) + 0{,}066\sin(2\pi f_{c1} t) + 0{,}068\sin(2\pi f_{c2} t) + b(t) \quad (12)$$

With: $b(t)$ a signal that represents the white noise introduced by using the concept of the SNR. The SNR being the Signal to Noise Ratio given by the following equation:

$$SNR = 10\log_{10}\frac{P_s}{P_b} \quad (13)$$

Where P_s and P_b are, respectively, the signal and noise powers. The supply frequency used is equal to $fs = 50Hz$. The sideband frequencies of broken rotor bars are calculated by equation (1).

Therefore, the sideband frequencies of one broken bar are given by:

$f_{c1} = 45Hz$ and $f_{c2} = 55Hz$.

Fig. 1 shows the signal of stator current in time domain simulated with and without broken bars. We can observe the change in the form of the stator current after the introduction of the broken rotor bar fault.

In Fig. 2, the STFT of the stator current is used for the detection of harmonics corresponding to one broken bar. This simulation is done with a motor slip of 5% and SNR = 50 dB corresponding to a moderately noisy signal. The sideband frequencies of the faults are highlighted in the STFT using the three dimensional grid technique.

Fig. 3 represents the of stator current signal analysis simulation achieved by the STFT algorithm. The simulation parameters used correspond to one broken rotor bar with a motor slip of 5% and a SNR of 10 dB.

The sideband frequencies corresponding to the simulated fault are easily located for this value of the SNR which corresponds to a highly noisy signal. This verifies the robustness of the STFT against noise.

VI. Conclusion

Through this paper, accent is made on the presentation of an effective diagnostic method capable of detecting and locating the sideband frequencies of rotor faults particularly near the fundamental.

Indeed, it was used in this paper, a signal corresponding to the stator current signal in the case of a squirrel cage induction motor with one and two broken rotor bars. Therefore, an algorithm based on Short Time Fourier Transform is proposed and developed to perform a correct diagnosis and relatively precise location of the sideband frequencies of the considered fault. Several tests have been established to verify and to validate the robustness and effectiveness of our approach.

Indeed, The STFT is robust to variations of the noise and allows a clear and easy location of the faults frequencies for even low values of motor slip.

However, the STFT is limited regarding the time-frequency resolution compromise.

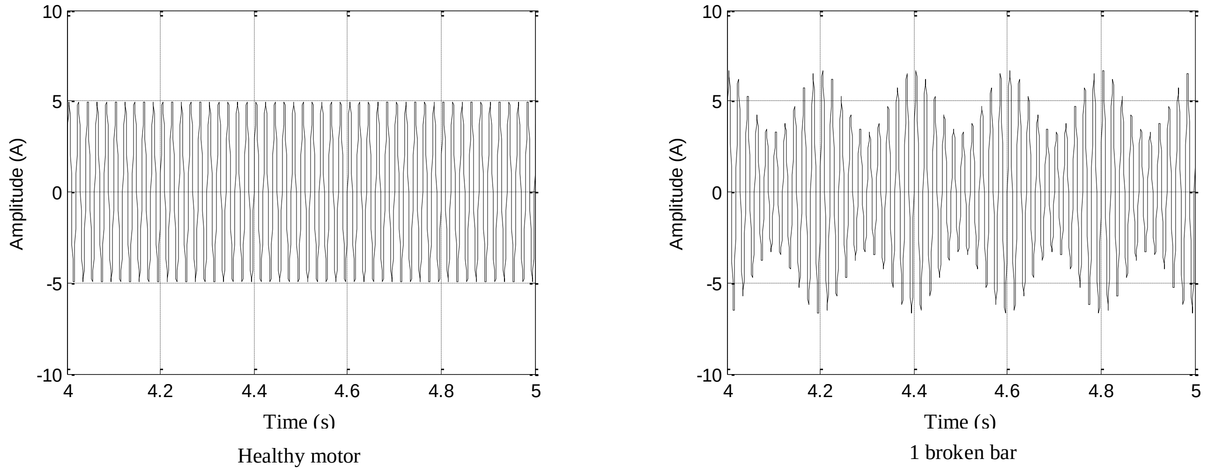

Fig. 1. Stator current signal in time-domain for healthy and faulty cases

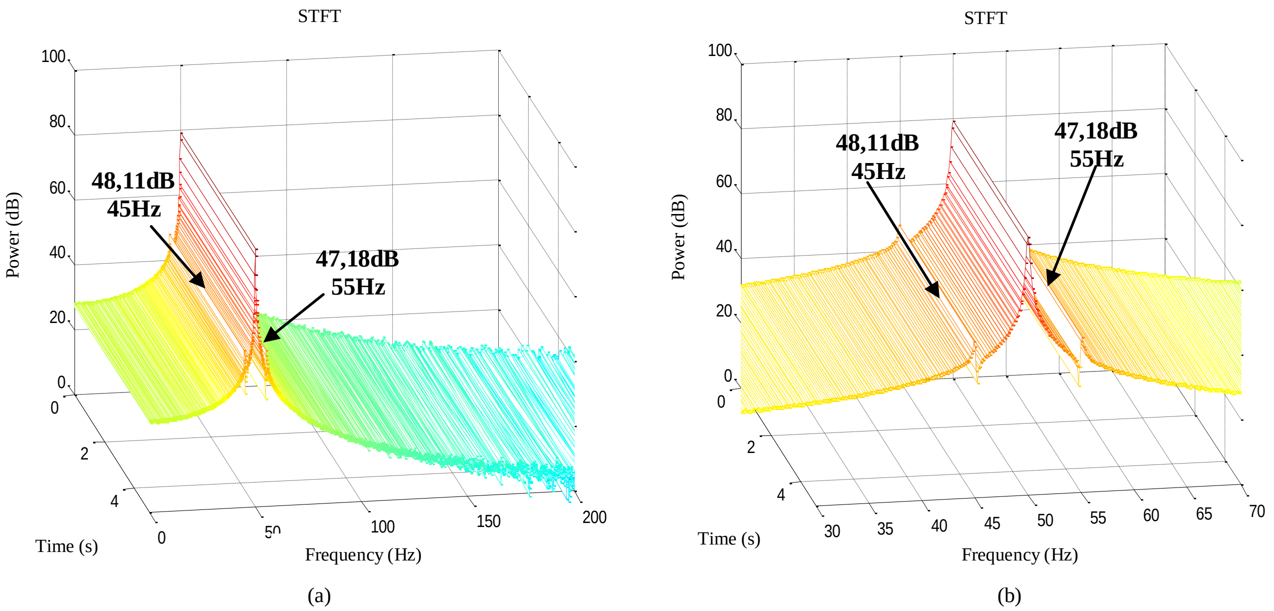

Fig. 2. Stator current analysis by STFT for one broken bar, a motor slip of 5 % and an SNR=50 dB: (a): without zoom (b): with zoom

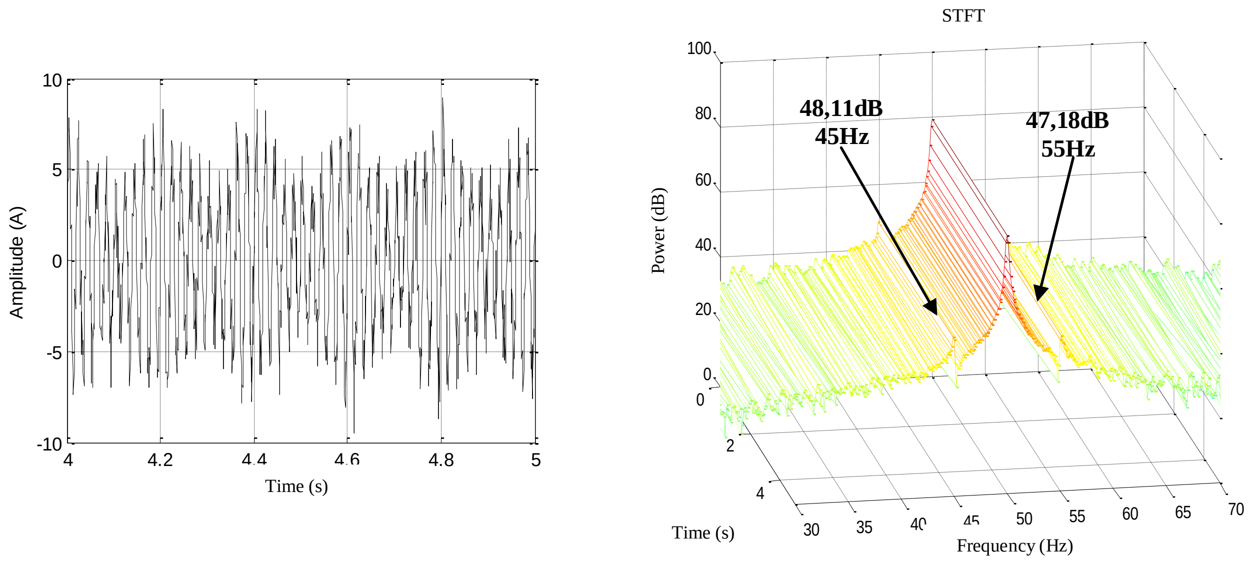

Fig. 3. Time-domain representation and STFT analysis of a stator current for one broken bar, a motor slip of 5 % and an SNR=10 dB.

Indeed, since the STFT is based on the calculation of the FT, it is subject to the Heisenberg-Gabor uncertainty principle, which notices the impossibility of obtaining a good resolution in both time and frequency planes.

Finally, it should be noted that this work constitutes a first step in analyzing non-stationary signals, through which, we have validated the effectiveness of our approach in the case of stationary signals.

In this context, two perspectives should be considered for this work: extending the diagnosis to the transient state (case of load changes) to solve the non-stationary problem observed in the variation of load of the induction machine and the experimental validation of this approach.

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