Induction Motor's Rotor Faults Diagnosis at Variable Speed Using an STFT-MLA Combination

A. F. Aimer, A. H. Boudinar, M. E. A. Khodja and A. Bendiabdellah

Abstract—Induction motor diagnosis during speed variation is very difficult since the analyzed stator current become non-stationary; thus, the fault frequency signatures are impossible to determine. The use of the Short Time Fourier Transform (STFT) technique solves in part this problem. Indeed, the analysis of the signal on windows of short duration makes it possible to avoid the non-stationarity properties of the signal. Unfortunately, this technique has a poor frequency resolution when the chosen window duration is too short thus making the diagnosis unreliable. In this paper, the Maxima's Location Algorithm (MLA) is associated with STFT to improve the efficiency of this technique. Experimental results on the rotor faults diagnosis during speed variations are presented in this paper to show the performances of this new approach.

Index Terms—Induction motor, Rotor faults diagnosis, Time-Frequency Analysis, STFT, MLA

1 Introduction

INduction motors represent more than 80% of the electrical machines in industry. This interest is due to its simple and robust structure, its efficiency and its low manu-facturing cost [1]. In addition, the latest advances in power electronics and control circuits allow the use of the induction motor in different variable speed applications. Nevertheless, several faults can appear in the induction motor, which reduces its performance. These faults can, at worst, cause the complete shutdown of the electric drive. As a result, special attention is paid to the detection and diagnosis of the various faults that can appear in the induction motor [2]–[4]. The stator current analysis by the Power Spectral Density (PSD) estimation based on the Fourier transform calculation is the most used technique in diagnosis procedures because of its speed and simplicity. Unfortunately, during variable speed operation, the induction motor signals become non-stationary. In this case, the conventional PSD gives only a time average of the spectral content of the stator current without giving any precision on the possible changes of frequency over time. As a result, the information regarding frequency localization over time is lost using the conventional PSD. To resolve this problem, researchers focused on the application of techniques based on time-frequency representation. Indeed, Gabor's work in the 1940s laid the foundation for a new type of analysis called Short Time Fourier Transform (STFT). He was the first to imagine a local Fourier transform based on a windowing of the analyzed signal to observe frequency variations over time. This transformation requires dividing the signal into consecutive short segments and then calculating the Fourier transform of each segment [5]. The idea is to introduce a local frequency parameter so that the Fourier transform will be applied to the signal through a sliding window on which the signal is considered stationary. This transform represents the results in three dimensions, the signal description is carried out in the time-frequency plane composed of spectral properties as a function of time [6], [7]. The main disadvantage of this transformation is its limited Time-Frequency resolution. Indeed, it is impossible to have a perfect location in both time and frequency. In other words, if the temporal support of the sliding window is small the frequency localization is bad and vice versa. To overcome this problem, several approaches are developed based on STFT. In [8], a technique combining the Hilbert transform and the neural networks is proposed to improve the frequency resolution of the STFT. Another approach inspired by STFT is introduced in [9] where the authors use a technique called SFFT (Short Frequency Fourier Transform). Also, other Time-Frequency methods such as Wigner-Ville Dis-tribution [10] or Wavelets Transform [11]–[14] are proposed to improve the time-frequency resolution but in spite of the computation time which will make it difficult to apply these techniques in an online diagnosis. In this paper, we propose to associate an algorithm called MLA (Maxima's Loca-tion Algorithm) [15] with STFT. Indeed, this algorithm allows us to show only the frequencies likely to bring useful information on the existence of a possible fault. In this way, we will have a clearer and faster Time-Frequency representation of the stator current while improving the spectrum resolution for fault detection purposes. To verify the effectiveness of the proposed STFT-MLA combination, we apply this approach in the rotor faults diagnosis of an induction motor running at variable speed. Indeed, several experimental tests will be carried out in order to illustrate the merits of the proposed

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Manuscript received January 10, 2018; revised February 28, 2018; accepted March, 10, 2018.

STFT-MLA combination.

2 Short Time Fourier Transform Analysis

2.1 Rotor faults frequency signatures

Induction motor's broken rotor bars is one of the most commonly studied faults in laboratory because of its simplicity of implementation. This fault induces changes in the stator currents and therefore causes the appearance of characteristic harmonics in this signal spectrum. Indeed, during the appearance of a broken bar fault, flux harmonics are produced and induce current harmonics in the stator winding at frequencies [4]:

$$f_c = (1 \pm 2ks) f_s \tag{1}$$

where f_s, f_c are respectively, supply frequency and broken rotor fault frequency, s is motor slip and $k = 1, 2, 3, \ldots$

2.2 Short Time Fourier Transform

The time-frequency distribution, called Short Time Fourier Transform or STFT, is defined by [16]: STFT is made up of the Fourier Transform of $x(\tau)h^*(\tau - t)$ obtained by weighting $x(\tau)$ by the window $h^*(\tau - t)$ which is nothing else than a sliding analysis window located around t and that we slide by varying the parameter τ.

Associate with $h(\tau)$, the family of functions depending on the parameters $t$and f, defined by:

$$STFT_x(t, f) = \int_{-\infty}^{+\infty} x(\tau)h(\tau - t)^* e^{-j2\pi f\tau} d\tau \tag{2}$$

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Associate with $h(\tau)$, the family of functions depending on the parameters t and f, defined by:

$$h_{t,f} = h(\tau - t)^* e^{-j2\pi f\tau}, \qquad (t, f) \in \Re^2 \tag{3}$$

We introduce the terms $STFT_x(t, f)$, are commonly called projections of $x(\tau)$ on the functions system $h_{t,f}$. If h is the rectangle function with support T, the STFT consists of taking the FT from a succession of signals equal to x on the support $h^*(\tau - t)$ and equal to zero elsewhere.

We will start the calculation by the discrete time signal $[x_n = x(nT)], T > 0$. We take $h_n = h(nT)$ we consider N is the number of samples in the analysis window. Finally, we introduce a discretization of the frequency f. $STFT$ is then defined by the set of numbers $X_(k, n)$calculated as follows [16]:

$$X_{k,n} = \sum_{l=0}^{N-1} x_{l+k} h_l^* e^{-j2\pi l \frac{n}{N}} \quad k \in \mathbb{Z}, \quad n = 1, 2, \cdots \tag{4}$$

As for the FT (Fourier Transform), the method of zero padding makes it possible to improve the frequency resolution. The principle of this method consists in completing by M zeros a set of N samples so that $M + N$ is a power of 2 and thus makes it possible to perform the computations using the FFT (Fast Fourier Transform) algorithm using the $N + M$ points.

2.3 Heisenberg-Gabor Uncertainty Principle

This inequality, also called Time-Frequency inequality, is based on Heisenberg's uncertainty relations in quantum mechanics. The combination with Heisenberg's work for the Fourier transform was achieved by Dennis Gabor in 1946.

We consider the finite energy signal $x(t)$ centered in time and frequency around zero. Gabor defined time duration Δt and frequency band Δf as [5]:

$$\Delta t = \frac{1}{E_x} \int_{-\infty}^{+\infty} t^2 \mid x(t) \mid^2 dt \tag{5}$$

$$\Delta f = \frac{1}{E_x} \int_{-\infty}^{+\infty} f^2 \mid X(f) \mid^2 df \tag{6}$$

where E_x represents the signal's energy given by the Parceval's expression:

$$E_x = \int_{-\infty}^{+\infty} \mid x(t) \mid^2 dt = \int_{-\infty}^{+\infty} \mid X(f) \mid^2 df \tag{7}$$

The inequality of Heisenberg-Gabor is then written:

$$\Delta t \cdot \Delta f \geq \frac{1}{4\pi} \tag{8}$$

It expresses the fact that the duration-band product of any signal is bounded below for a time duration Δt and a frequency band Δf. In other words, the greater the resolution in frequency, the lower the resolution in time and vice versa.

The Short Time Fourier Transform is subject to this uncertainty due to the use of the Fourier transform. This phenomenon requires finding the right time-frequency compromise adapted to the case considered by setting the correct window width.

The Gaussian window has the best time-frequency location. Indeed, it checks the following equality:

$$\Delta t \cdot \Delta f = \frac{1}{4\pi} \tag{9}$$

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

3 Maxima's Location Algorithm

To improve the resolution of the stator current time-frequency representation (ob-tained from the STFT), we associate with the STFT a Maxima's Location Algorithm (MLA) on a well-defined frequency band [17]. Indeed, the MLA algorithm locates the maximum harmonic numerically in the chosen frequency band corresponding to the harmonic characterizing the rotor fault.

The MLA algorithm:

1. Acquisition of stator current for a given phase.
2. PSD Estimation by Periodogram technique.
3. Choice of the frequency band where the frequencies signatures faults can appear.
4. Localization of the maximum harmonics in the selected frequency band.
5. Verification if the localized harmonics correspond to the faults frequencies signatures obtained by calculation.

Fig. 1. Experimental bench description.

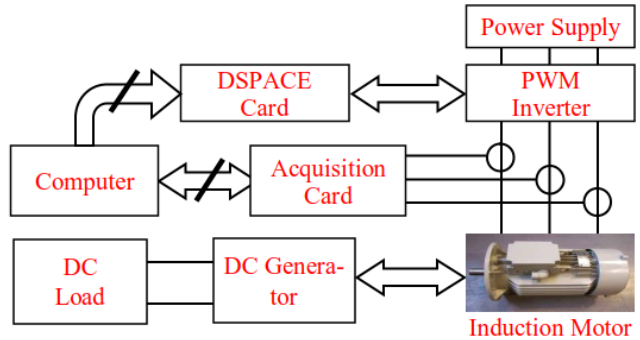

Fig. 2. Diagram of the experimental setup.

Fig. 3. Squirrel cage rotor with two broken bars.

4 The STFT-MLA Combination Principle

The broken rotor bar diagnosis using the proposed approach in this paper, using the association of STFT with the MLA on a given frequency band is defined as follows [17]:

❶ Digitization of the phase stator current $i_s(t)$.
❷ Choice of the analysis window $h(t)$ to be apply the STFT.
❸ Calculation of the stator current segment $i_h(t) = i_s(t)h(t - \tau)$ for a given temporal position (τ).
❹ Calculation of the current segment's spectrum $i_h(t)$.
❺ Determination of the frequency band where the fault signature is likely to ap-pear. This band depends on the programmed supply frequency.
❻ Application of the MLA Algorithm only on the chosen frequency band.
❼ Localization the searched fault signature.
❽ Repeat steps 3 to 7 according to the temporal position of the window $h(t)$.
❾ Display results.

5 Experimental Results

The induction motor used in our tests is a three-phase squirrel cage fed by a three-phase inverter (SEMIKRON AN-8005) and coupled to a DC generator used as a load. The motor parameters are: 3kW, 1410 rpm, 4 poles. As shown in Fig. 1, the measurement chain consists of three Hall effect current sensors and one acquisition card. The bench is connected to a computer for viewing, processing the measured signals as well as generating the control signals necessary for the inverter control. These control signals are obtained using a Space Vector PWM (Pulse Width Modulation) through DSPACE card 1104. The block diagram of this measurement bench is illustrated in Fig. 2. In addition, a tachometer is used to measure the mechanical speed of our motor. All acquisitions were made with a data acquisition time of 20 seconds with a sampling frequency of 3 kHz, which gives us a frequency resolution of $0.05Hz$. The broken rotor bars fault studied in this paper is created artificially by drilling a $3mm$ hole on two rotor bars to simulate a real rotor fault. Fig. 3 shows the rotor with two broken bars used in these tests. Thus, the induction motor used for our experimental tests has a faulty rotor. This motor is fed by a three-phase inverter according to the following operating modes:

- Supply frequency of $50Hz$ corresponding to a programmed speed $1500rpm$.
- Supply frequency of $30Hz$ corresponding to a programmed speed$900rpm$.
- Supply frequency varying from $30Hz$ to $50Hz$ corresponding to a variable programmed speed from $900rpm$to $1500rpm$.

5.1 Motor operation with rotor fault and a supply frequency of $50Hz$

In this first operation mode, we will analyze the stator current in the case of two broken bars and a supply frequency of 50Hz delivered by the inverter. Fig. 4 and Fig. 5 illustrate respectively, the stator current spectrum obtained by the conventional STFT and the proposed STFT-MLA. From Fig. 4, the conventional STFT shows only the supply frequency (50Hz) but fails to detect the rotor fault signature despite that the supply frequency of the inverter does not change. However, in Fig. 5, the proposed combination STFT-MLA shows in addition to the fundamental (50Hz), the frequency signatures: (47.5Hz and 52.5Hz) characterizing the rotor fault. Comparing these results with (1), it can be concluded that these two frequencies represent the broken rotor bars signature for a motor slip of 2.5%. These first results obtained show the power of the STFT-MLA combination in the detection of this type of fault compared to the conventional STFT for a stationary operating regime.

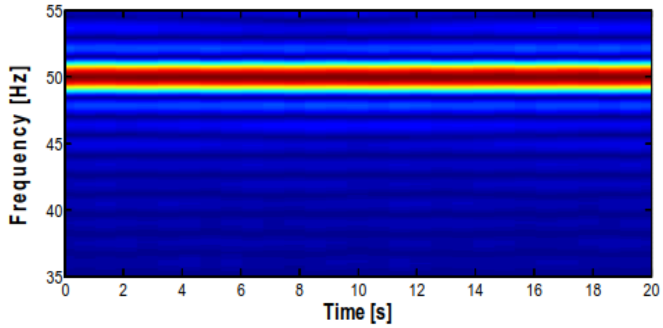

Fig. 4. Conventional STFT for a rotor fault (inverter's supply frequency of 50Hz).

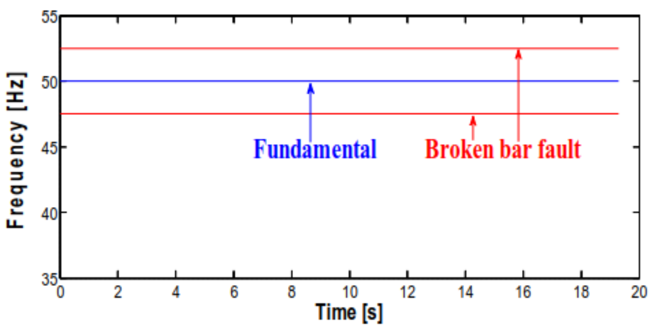

Fig. 5. Proposed STFT-MLA for a rotor fault (inverter's supply frequency of 50Hz).

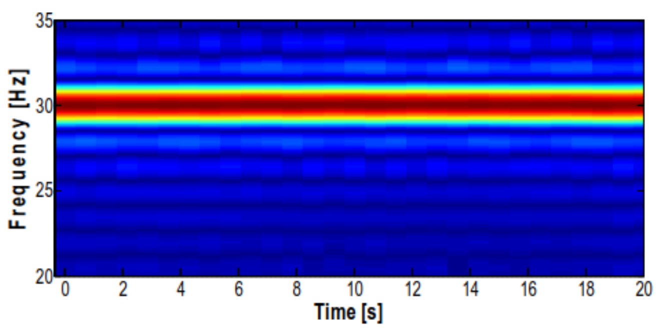

Fig. 6. Conventional STFT for a rotor fault (inverter's supply frequency of 30 Hz).

5.2 Motor operation with rotor fault and a supply frequency of $30Hz$

In this second operation mode, the motor is fed by inverter with a supply frequency of 30Hz and a rotor fault of two broken rotor bars. The stator current spectrum for this operating mode obtained by the conventional STFT is shown in Fig. (6). From Fig.(6), the conventional STFT detects only the fundamental frequency at 30 Hz. The fault frequency signature is still difficult, even impossible, to show with this conventional approach. On the other hand, the proposed combination of the STFT with the MLA detects the fundamental (30Hz) and two harmonics at frequencies: 27.9Hz and 32.2Hz as shown in Fig. (7). These harmonics represent the signature of the broken rotor bars fault for a supply frequency of 30Hz and a motor slip of 3.5% using (1). A slight difference is observed between the detected

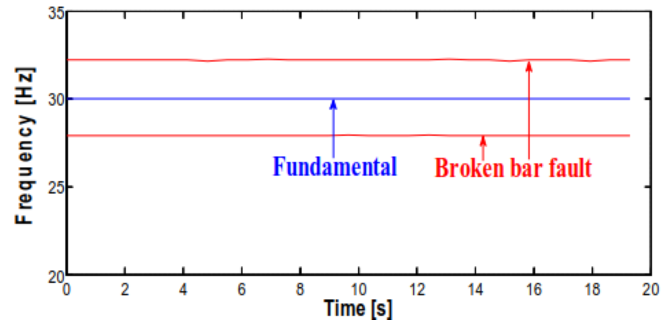

Fig. 7. Proposed STFT-MLA for a rotor fault (inverter's supply frequency of 50 Hz).

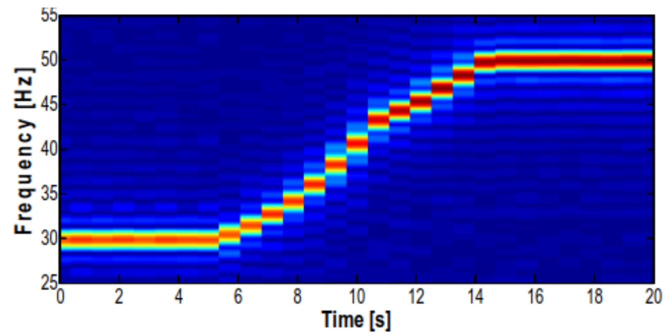

Fig. 8. Conventional STFT for a rotor fault (inverter's supply frequency variation from $30Hz$ to $50Hz$).

frequency $(32.2Hz)$ and the theoretical frequency $(32.1Hz)$. This difference is due to the variation of the motor slip during the test and also to the frequency resolution.

5.3 Motor operation with rotor fault and a supply frequency variation from $30Hz$ to $50Hz$

The aim of this last case is to show the power of the proposed combination STFT-MLA in the detection of broken rotor bars fault with speed variation. For this, the motor is fed by an inverter with a variation of the supply frequency from 30Hz to 50Hz. The stator current spectrum obtained by conventional STFT for this operation mode is illustrated in Fig. 8. According to this figure, the conventional STFT still fails to detect the fault signatures or its evolution as a function of the variation of the supply frequency. The only information obtained with this classical approach is the time duration of the evolution of the supply frequency. Indeed this duration is of [0s - 5s] for 30Hz. Then a variation of the frequency from 30 Hz to 50 Hz is observed on approximately 9s. Finally, the supply frequency of 50 Hz remains constant from $[15sto20s]$. Moreover, the proposed approach based on the combination of the STFT and the MLA makes it possible to visualize the temporal evolution of the fundamental, which indicates the instants of variation of the supply frequency, in other words of the speed, as shown in Fig. (9). In addition, this new approach allows us to detect the rotor fault frequency signa-tures and also its temporal evolution as a function of the applied supply frequency. Note that the difference between the fundamental and the fault signature is $2.1Hz$ for a supply frequency of 30Hz and 2.5Hz for a supply frequency of 50Hz. This

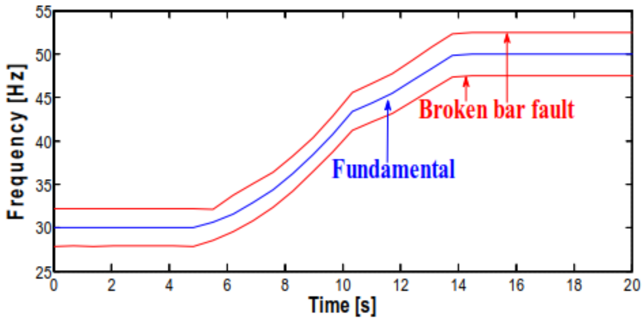

Fig. 9. Proposed STFT-MLA for a rotor fault (inverter's supply frequency variation from $30Hz$ to $50Hz$).

difference found for both supply frequencies is the same as both previous operating modes, which shows that this signature represents the broken rotor fault signature. The obtained results for this last operation mode clearly show the effectiveness of the proposed STFT-MLA combination in the fault detection during the variation of the supply frequency, in other words of the programmed speed.

5.4 Conclusion

A new Time-Frequency transform is presented in this paper. Indeed, a combination between the STFT and the MLA algorithm is used in order to obtain a simple and reliable method that can detect the induction motor rotor faults during a speed variation regime. The obtained results in this paper show the performances of this proposed method compared to the conventional STFT method in the detection of broken rotor bars fault of an induction motor with a supply frequency variation, in other words, a speed variation. Through the experimental results obtained, we can notice the superiority of the proposed STFT-MLA method compared to the conventional STFT and its efficiency in the induction motor diagnosis.

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