

# Rotor Failure Diagnosis of Induction Motors by Wavelet Transform and Fourier Transform in Function of the Load

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**Abstract.** This paper presents two diagnostic methods for the online detection of broken bars in induction motors with squirrel-cage type rotors. The wavelet representation of a function is a new technique. Wavelet transform of a function is the improved version of Fourier transform. Fourier transform is a powerful tool for analyzing the components of a stationary signal. But it is failed for analyzing the non-stationary signal whereas wavelet transform allows the components of a non-stationary signal to be analyzed. In this paper, our main goal is to find out the advantages of wavelet transform compared to Fourier transform in rotor failure diagnosis of induction motors.

## Introduction

Induction motors with a squirrel-cage rotor are widely used in many industrial processes, and they play important roles in various processing industries [1, 2]. Despite their low cost, from the reliability and robustness viewpoint, induction motors are prone to failure owing to their exposure to a variety of harsh environments and incorrect operating conditions or manufacturing defects. If not identified in time, these failures and gradual deterioration can lead to motor disruption and increase electricity consumption. It is known that early fault detection of induction machines can not only minimize damage and reduce energy consumption but also prevent the spread of failure or limit its escalation in terms of severity. Therefore, diagnostic or engine condition monitoring systems received considerable attention over the past 10 years [3, 4, 5]. Failure of the bars of squirrel-cage rotors rarely causes immediate failure, especially in large multi-pole motors (slow speed). However, if a sufficient number of rotor bars are broken, the motor cannot start because it cannot develop sufficient torque. Thus, the presence of broken rotor bars directly affects the energy efficiency of an industrial plant.

For the purposes of this study, it is considered that there are two methods for analyzing the stator current of a squirrel-cage rotor induction motor: (i) Fourier Transform (FT) and, (ii) Wavelet Transform (WT).

## Fourier Transform (FT) versus Wavelet Transform

The wavelet transform is often compared with the Fourier transform. Fourier transform is a powerful tool for analyzing the components of a stationary signal (a stationary signal is a signal where there is no change in the properties of signal). For example, the Fourier transform is a powerful tool for processing signals that are composed of some combination of sine and cosine signals (sinusoids) [6].

The Fourier transform is less useful in analyzing non-stationary signal (a non-stationary signal is a signal where there is change in the properties of signal).

Wavelet transforms allow the components of a non-stationary signal to be analyzed. Wavelets also allow filters to be constructed for stationary and non-stationary signals [7, 8]. The Fourier transform shows up in a remarkable number of areas outside of classic signal processing. Even taking this into account, we think that it is safe to say that the mathematics of wavelets is much larger than that of the Fourier transform. In fact, the mathematics of wavelets encompasses the Fourier transform. The size of wavelet theory is matched by the size of the application area. Initial wavelet applications involved signal processing and filtering. However, wavelets have been applied in many other areas including non-linear regression and compression. The main difference is that wavelets are well localized in both time and frequency domain whereas the standard Fourier transform is only localized in frequency domain. The Short-time Fourier transform (STFT) is also time and frequency localized but there are issues with the frequency time resolution and wavelets often give a better signal representation using Multiresolution analysis [9].

### Spectral Analysis

Spectral analysis refers to the representation of current signals in the frequency domain. The Fourier transform (FT) defines that a periodic waveform in the time domain can be represented by a weighted sum of sines and cosines. The same waveform can then be represented in the frequency domain as an amplitude–phase pair for each frequency component.

Spectral analysis of stator current using the fast Fourier transform (FFT) is applied to the diagnosis of rotor bar rupture. According to [3], in a three-phase induction motor with a squirrel-cage rotor, the rotor bars break or crack in the rotor ring termination bars, disturb the magnetic flux, the rotor frequency, thus, altering the motor current spectrum.

Several works such as [2, 3, 4] have used fast Fourier transform (FFT) for spectral analysis of stator current to diagnose broken rotor bars. From these works, internal faults of broken rotor bars may be detected in the stator current spectrum according to Eq. 1. Here,  $f_0$  is the supply frequency and  $s$  is the slip  $s = (n_s - n) / n_s$ ;  $n_s$  is a constant (synchronous speed) and  $n$  is machine speed.

$$f_{brb} = f_0 \cdot \left[ k \left( \frac{1-s}{p} \right) \pm s \right] \quad (1)$$

On the whole, owing to rotor asymmetry, the following frequencies appear in the spectra of different signals:  $(1 \pm 2ks)f_0$  in the stator current and instantaneous power signals,  $(2k - 1)sf_0$  in the rotor current signal,  $2ksf_0$  in the velocity and torque signals, and  $ksf_0$  in the axial flux signal, where  $k = 1, 2, 3, \dots$

Broken bar failures can be diagnosed by determining the sidebands of twice the slip frequency ( $2sf_0$ ) on the fundamental supply frequency of the motor ( $f_0$ ) from the stator current spectrum. As the number of broken bars increases, the difference in the amplitudes (dB) of the sidebands around the frequency ( $f_0$ ) decreases. The smaller the difference, the greater is the number of broken or cracked bars. This occurs because of a non-uniform magnetic flux [5]. With the Fast Fourier Transform method, the presence of broken bars is indicated by an amplitude difference of less than 40 dB between the fundamental frequency and the sideband frequencies.

### Wavelet Analysis

Wavelet Transform has been applied in various branches of science owing to their peculiar characteristic of detailing signal specific points [9, 10]. In applications where very-high-precision frequency analysis is required, the traditional Fourier transform (FT) does not yield satisfactory

results and does not possess the ability to drill regions of interest in the signal. In terms of methods for detecting broken bars in a squirrel-cage rotor, wavelets, which use the startup current of the motor, are very effective. During motor startup, the speed varies from zero to near synchronous speed. Thus, using a steady state current, failure may not be detected at a fixed frequency, as in traditional FT method. Failure varies within the frequency spectrum, and using the FT method, it is impossible to detect any broken rotor bar. By contrast, Wavelet Transform allows for the decomposition of a signal into different frequency components, thus allowing for the study of each component separately in its corresponding scale. Therefore, WT is a powerful tool in such cases.

Wavelet Transform can be applied continuously as continuous Wavelet Transform (CWT) or discretely as wavelet discrete transform (DWT). According to [7, 8], with multi-resolution analysis (MRA), a Wavelet-based technique, a signal can be decomposed and reconstructed by means of two components: approximation and detail, where approximation can be interpreted as a high-pass filter and detail as a low pass filter. This means that the approximation contains the low-frequency information of the original signal and detail contains the high-frequency information.

Determining a suitable wavelet type and number of level is very important in analysis of signals. Different types of wavelets and levels performed and which type of wavelet and level give the maximum efficiency is selected. The Daubechies - 44 orders, wavelet discrete transform (DWT) was applied to the stator current. The stator current signals are decomposed into eight different levels.

### Experimental set up

For validating the developed method that uses FT and WT, several tests were performed with a 4-pole, 3-phase, 60 Hz, 1.5 kW, 220/380 V (rated voltage), 1750 rpm (rated speed), and 28-rotor-bar induction motor. Fig. 1(a) shows the experimental setup. The load was a 2 kW DC machine with a rated speed of 1800 rpm and rated voltage of 220 V. To demonstrate the application of the both techniques, we performed an analysis of different signals collected from rotor bar breakages, which were forced in the laboratory by opening the motor and drilling holes in different bars, Fig. 2(b).

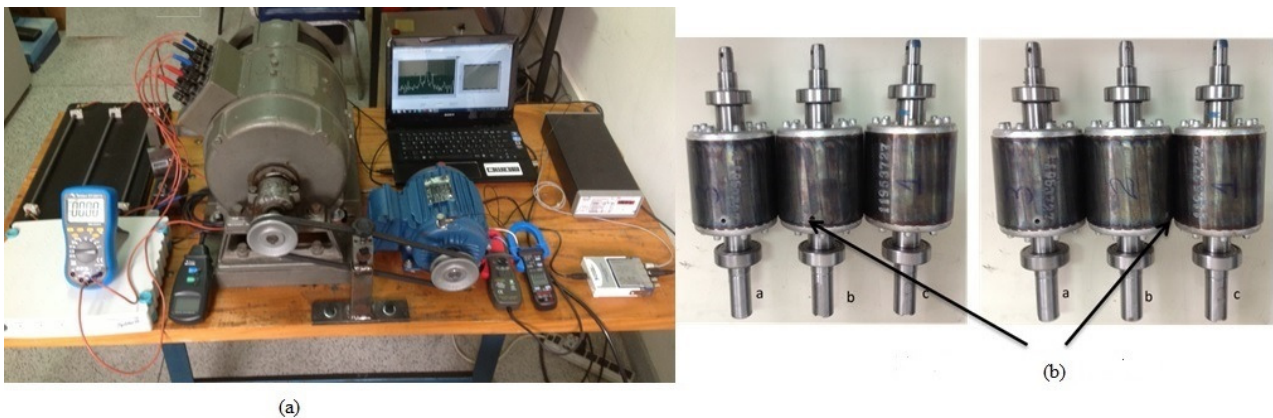


Figure 1- (a) Experimental set up for 1,5 kW motors test. (b) Rotor bar breakages.

### Experimental results with FT

Fig. 2 shows the current spectrums of the laboratory motor obtained using FT. The fundamental frequency  $f_0$  (60 Hz), the right fault frequency component  $(1+2s)f_0$  is 62, 53 Hz, and the left fault frequency component  $(1-2s)f_0$  is 57, 47 Hz can be seen in the figure. Fig. 2(a) shows the spectrum of the motor with a healthy rotor at 60% of the nominal load. The sideband frequencies are 60 dB lower than the fundamental frequency. Fig. 2 (b) shows the spectrum of the motor with 1 broken bar in the rotor at 60% of the nominal load. The sideband frequencies are 40 dB lower than the fundamental frequency.

In the test with 1 broken rotor bar without load, at 0 % of the nominal load, Fig. 3, the traditional FT method based on Fourier analysis is not valid because the slip  $s$  is very low and the components of the right and left fault sideband overlap with the fundamental frequency  $f_0$ . Therefore, the resultant amplitude does not accurately indicate the motor condition.

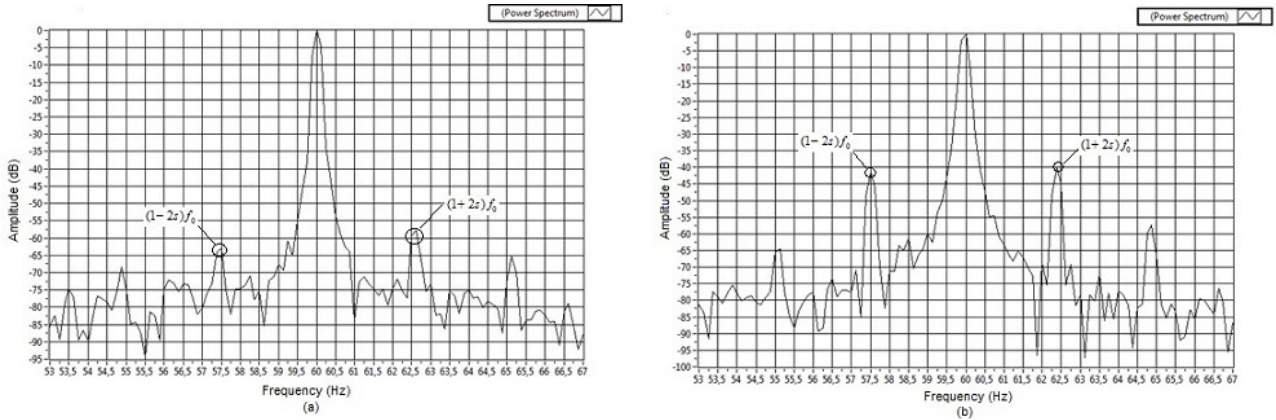


Figure 2- Spectrum of current: (a) loaded healthy motor, (b) loaded motor with one broken bar

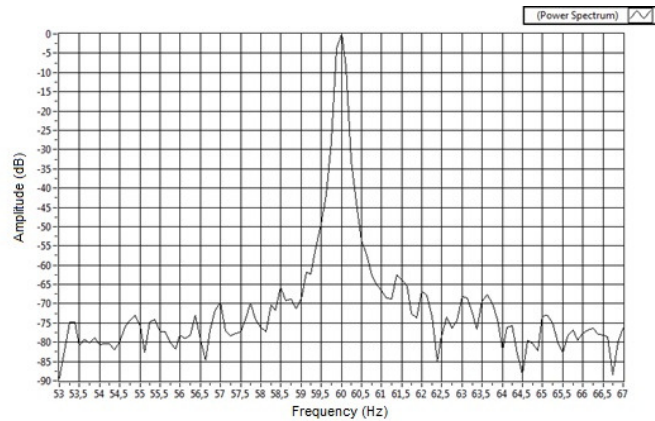
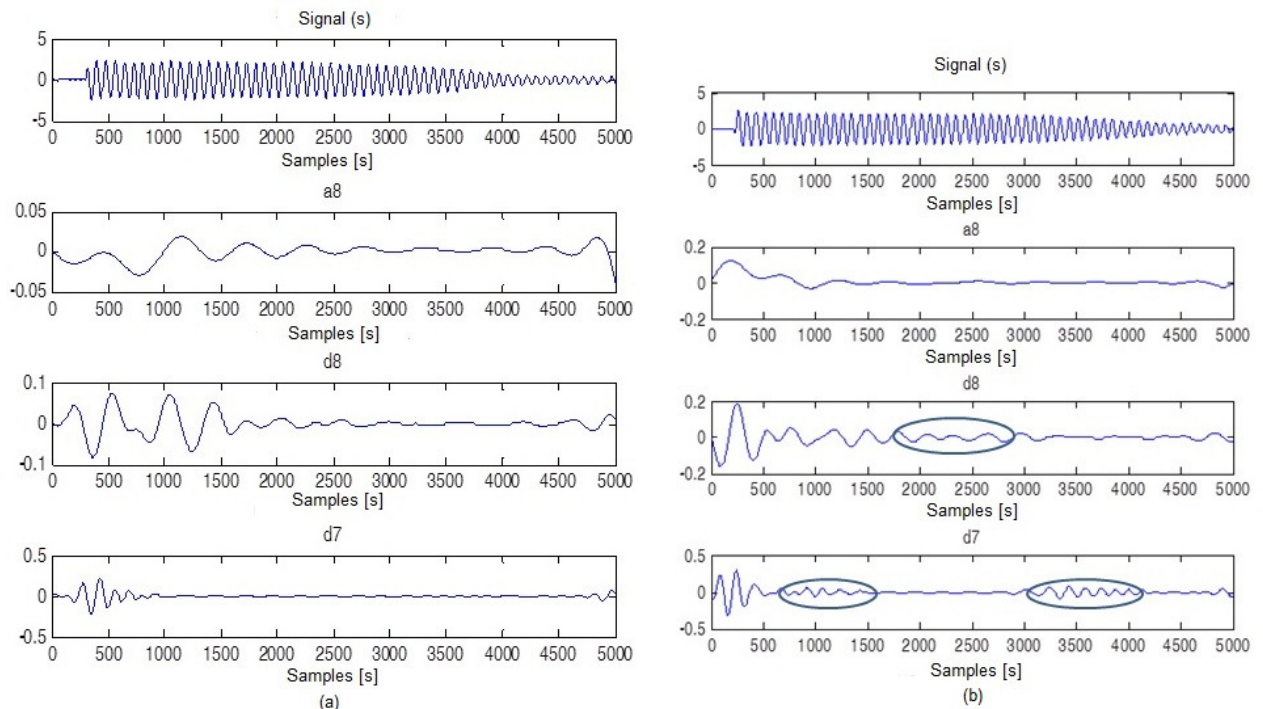


Figure 3- Spectrum of current: unloaded motor with one broken bar

### Experimental results with WT

The stator current of the induction motor was measured during stationary and non-stationary state operation of the motor at 60% of the nominal load, for the different cases tested herein. The sampling frequency used for capturing the signal was 5000 samples/s. The DWT of the stator current was obtained using the wavelet toolbox in MATLAB. 8-level decomposition was used in order to obtain the results. Daubechies-44 mother wavelet was used for analysis of the current signal.

Fig. 4(a) shows the primary current of the stator associated with the 8-level DWT of the startup current of a healthy motor under load. It can be seen that the upper level signal (a8, d8 and d7) do not show any significant variation, apart from the initial oscillations that last only few cycles. Figure 4 (b) displays the DWT analysis of the current of a loaded motor with two broken rotor bars. As shown in Figure, a significant increase with respect to the healthy state appears in the energy of the upper level signals (a8, d8 and d7). The oscillations in those signals are due to the evolution of the left sideband component during the transient. These oscillations follow a sequence that is according to the frequency evolution of the left sideband component.



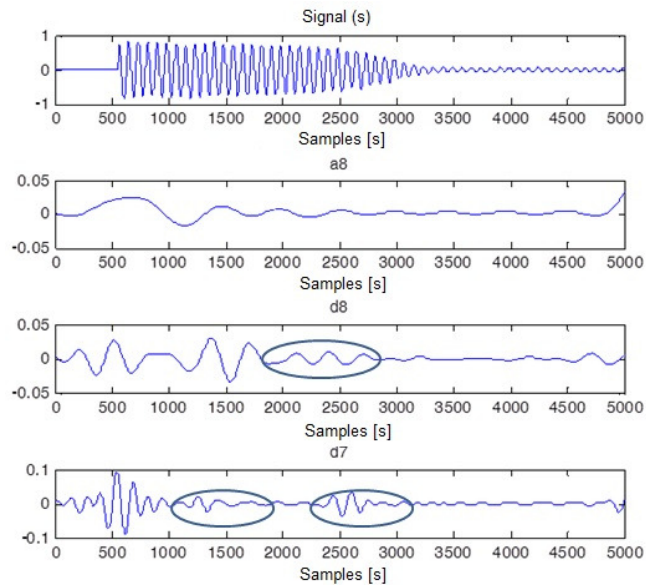
**Figure 4- 8 level DWT of the startup current : (a) Healthy motor under load, (b) Loaded motor with two broken rotor bars.**

Fig. 5 displays the DWT analysis of the current of a unloaded motor with two broken rotors bars. In this case, the application of the classical method, based on Fourier analysis, is not valid, since the slip is very low and the sideband components overlap the supply frequency component. This makes very difficult the diagnosis of the fault. Nevertheless, the upper order wavelet signals ( $a8$ ,  $d8$  and  $d7$ ) resulting from the DWT analysis of the startup current show a clear increase in their energy, if compared with the healthy state. In addition, their oscillations fit well with the left sideband frequency evolution described above. This leads to the conclusion that a bar breakage is present on the motor. This case is an example of the validity of the approach in a case when the classical method is not suitable to be applied.

## Conclusions

This work presents a comparison between two methods for the diagnosis of rotor bar faults in induction cage motors, validated and optimized. The first technique uses FT and allows for the classical detection of broken bars based on the application of the Fourier Transform to the stator current of an induction motor running in the steady state. Fault detection is achieved by studying the two sideband components (left and right) that appear around the supply frequency component. This classical approach has a few important advantages such as simplicity of data acquisition systems and required software, as well as robustness, and it has provided quite satisfactory results hitherto. However, in some cases, unloaded induction motors, for instance, the slip  $s$  is very low and the sideband components practically overlap the supply frequency. This makes it difficult to detect their presence and use them for diagnosis. The second technique is based on the use of Wavelet Transform (WT). This technique allows for the decomposition of a signal into different frequency components, thus allowing for the study of each component separately in its corresponding scale. An advantage of Wavelet Transform during signal decomposition is that it allows the user to analyze the information contained in a stationary or non-stationary signal at different time–frequency resolutions.





**Figure 5- 8 level DWT of the startup current : unloaded motor with two broken rotor bars.**

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