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# Comparing MCSA with Vibration Analysis on Rotating Electrical Machines to Detect Broken Bars — A Case Study

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***Abstract*— Anomalies in operation of the rotating electrical machines modify harmonic content of motor supply current. Motor electrical current signature analysis (MCSA) is sensing an electrical signal containing current components. In this work, by introducing progressive failures to a healthy motor, we investigated the efficacy of motor current signature with vibration- analysis to detect broken bars on rotating electrical machines. Our results demonstrate the advantages and disadvantages of both methods from a practical point of view in the detection of broken bars.**

***Keywords*— *broken bar; fault; induction motor; vibration; MCSA***

## I. Introduction

Induction motors are an important source of power for installed machinery, mainly due to their robustness, reliability, reduced operational cost, and ease of maintenance [1, 2, 3, 4, 5]. They consume about 85% of the power used in Brazilian industrial plants and for power of up to 500 hp, the most commonly used rotor is the squirrel-cage type [6, 7]. The occurrence of broken bars in induction motors is one of the major causes of production process failure and interruption, accounting for approximately 10% of these occurrences [8, 9, 10]. This type of failure is more common in large motors that operate under heavy load cycles and are subject to large inertia, and because of their high cost, often do not have immediate substitutes. Therefore, they are considered to be critical machinery in the production process. Some defects originate in the manufacturing process and can remain hidden for some time before gradually developing into more apparent problems [6, 4].

In this context, maintenance systems become important as they directly influence the availability of plant equipment. These systems often rely on predictive maintenance techniques in which variables are monitored as reference parameters for subsequent analysis [9, 11]. This has been a reliable approach for providing an indication of the condition of rotating electrical machines. In fault monitoring systems, it is also important that detection occurs in the early stages of fault development when the associated damage can be more easily reversed and to allow more scope in corrective intervention schedules [12, 13].

As such, there have been a rich and wide variety of investigations regarding the detection of motor failures, as well as studies that combine monitoring methods with diagnostic techniques, such as motor current signature analysis (MCSA) and vibration analysis. Antonino-Daviu et al. [14] developed a reliable indicator for detecting the severity of non-adjacent broken rotor bars in induction motors. Siddiqui et al. [6] used transformative techniques for detecting broken rotor bar faults in induction motors. Pires et al. [8] conducted motor square current signature analysis in the diagnosis of induction motor rotors. Wang et al. [15] also studied diagnostic techniques for broken rotor bars in induction motors. Historically, vibration-monitoring techniques have been used widely for diagnosing broken bars in induction motors but as reported by Naha et al, 2016 [5], in recent years, current detection methods have become popular. In this work, we develop an analysis method that combines MCSA and vibration techniques for the detection of broken bars in rotating electrical machineries.

## II. Motor Current SignatureAnalysis

In this approach, detection is performed by an activation check of the frequencies of specific lateral bands around the fundamental frequency associated with this particular fault. The difference between the lateral range and the fundamental frequency depends on the slip of the motor and these differences are generally small. Therefore, adequate frequency resolution is an important criteria when evaluating the spectrum amplitudes of the side bands, without which the evaluated spectrum will not be sufficiently sensitive to detect faults.

The spectral analysis approach is based on the fact that whenever a motor experiences a change in its mechanical or electrical characteristics due to some anomaly, one of its frequency spectrum components will also be altered. This analysis tool is based on the Fourier theorem, which established that any periodic function in the time domain can be decomposed into a series of pure sine waves with distinct and multiple frequencies of the fundamental signal frequency called the harmonics, which constitute the signal frequency spectrum [16].

According to the authors in [2], faults are indicated not only by variations in the amplitudes of the spectral components but mainly their frequencies, by which the spectra indicate which part of the equipment is deteriorating. As explained in [5], the cage rotor bars form parallel paths joined at the ends by short rings. The stator poles divide the rotor bars into parallel circuits equal in number to the number of stator poles. So, a two-pole winding divides the rotor into two parallel circuits that continuously move around the rotor cage. Any broken bars in the rotor alter this current distribution, and the author in [7] explains that the effect of a broken bar can be decomposed by the superposition of the two configurations. The configuration of a machine in perfect condition superimposed onto a machine with a current source of the same amplitude flowing through a broken bar, but with opposite direction, results in zero current through the bar in question. Figure 1 shows the current distribution in a rotor.

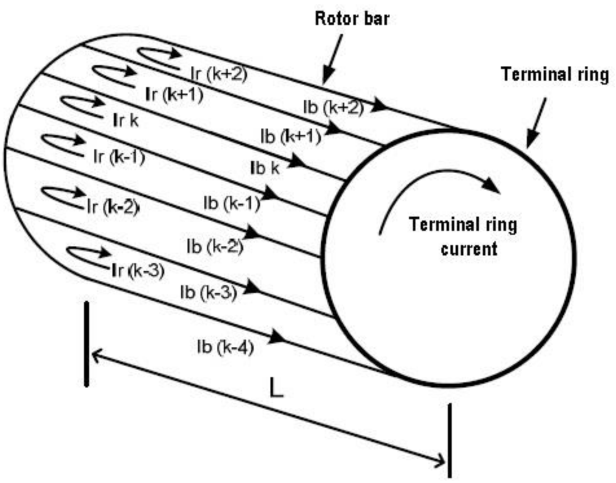


Fig. 1. The current distribution in a rotor.

If there is only a forward rotating field at a slip frequency relative to the rotor, the cage winding is symmetrical. Where rotor asymmetry occurs, then there will be a resultant backward rotating field at a slip frequency relative to the forward rotating rotor. As a result, relative to the stationary stator winding, this backward rotating field at a slip frequency relative to the rotor induces a voltage and current in the stator winding at a frequency given by (1).

$$f_{bb} = (1-2s)\,f_0 \quad \text{Hz} \tag{1}$$

This is referred to as a twice-slip-frequency sideband due to broken rotor bars, where $s$ is the motor slip and $f_0$ is the frequency of the power grid to which the motor is connected. Therefore, there is a cyclic variation in the stator current that causes a torque pulsation at the twice-slip-frequency ($2sf_0$) and a corresponding speed oscillation, which is a function of the drive inertia. This speed oscillation can reduce the magnitude of the ($(1-2s)\,f_0$) sideband, but an upper sideband current component at ($(1+2s)\,f_0$) is induced in the stator winding due to the rotor oscillation. This upper sideband is also enhanced by the third harmonic of the flux. Broken rotor bars, therefore, result in current components being induced in the stator winding at frequencies given by (2).

$$f_{bb} = (1\pm 2s)\,f_0 \quad \text{Hz} \tag{2}$$

From (1) and (2), we have a method that is relatively dependent on slip ($s$), which must be accurately determined to prevent false interpretations. Variations in the load are also undesirable, as explained in [4], which can introduce inaccuracies in the determination of the lateral frequencies. In high-efficiency motors with very low slip, this method can also present difficulties since the lateral frequencies would be very close to the fundamental ($f_0$) value, which can make it difficult to detect faults in their initial stages [17].

Although widely used and accepted as a standard method, the spectral analysis approach involves challenges that have yet to be completely resolved and continues to yield inconsistent results with respect to the detection of broken half bars, non-adjacent broken bars, rotors with ventilation ducts, and false diagnoses in motors with low slip and variations in load, among others [18, 19].

## III. Motor Vibration Analysis

In a motor with broken bars, the current in the failed bar will be less than that in the adjacent bars, so the failed bar will contribute less torque when it passes the poles of the stator winding, thereby creating a vibration [20]. Predictive maintenance by vibrational spectrum analysis is based on the assumption that the frequency at which vibrations occur indicates which part of the machine is deteriorating [21].

The induction motor in a failure condition produces vibration components, which are related to the frequency source and speed of rotation. These vibrations are due to induced electromagnetic forces. Ruptured bars generate an asymmetry condition that produces a counter rotating field (at slip frequency) relative to the rotor. This field rotation interacts with the stator field to produce torque and a velocity oscillation with a frequency of $2sf$. The oscillation velocity with the frequency $2sf$ modulates the rotation frequency as two side bands appear around the rotation frequency $f_m$ in the vibration spectrum. These components increase in amplitude as the imbalance in the rotor circuit increases. Equation 3 describes the frequency of broken bars in an induction motor.

$$f_{bbv} = (f_m \pm 2 f_o s) \qquad \text{Hz} \tag{3}$$

Where:

$f_m$ : Rotation frequency.

$f_o$ : Frequency of the power grid.

$s$ : Slip frequency.

In an induction motor with $p$ poles, the rotation frequency is slightly lower than $\frac{2 f_0}{p}$. By looking at the spectrum of the vibration signal, we can determine the exact mechanical frequency $f_m$ and its harmonics. The resolution of the frequency $\Delta f$ in a spectrum calculated by the fast Fourier transform (FFT) is reciprocal at sampling time T. This resolution is constant across the spectrum. Thus, it is preferable to consider higher-order speed harmonics to more precisely determine slip. The harmonic of $f_m$ is near to and on the left side of $2 f_0$ in the vibration spectrum, and the exact slip can be given by the following [22]:

$$s = \frac{(2.f_0 - p.f_m)}{2.f_0} \tag{4}$$

## IV. Experimental Setup

In the experimental setup, we used a three-phase induction motor with a squirrel-cage rotor, manufactured by WEG Industries, with a power of 0.5 cv, 230/380 V, 1750 rpm, and four poles. We acquired the stator current using a current sensor, with a 30-A AC/DC range, a transformer ratio of 100 mV/A, and a frequency range of 0–20 kHz. We used an integrated electronics piezoelectric (IEPE), three-axis, 10-mV/g accelerometer with an integrated amplification circuit to generate the mechanical vibration of the induction motor.

To record the vibration and current signals, we used a National Instruments USB 6009 data acquisition device, with a USB communication interface, a 14-bit differential and 13-bit single-ended analog/digital converter, and a sampling rate of 48 kS/s. Figure 2 shows the experimental setup we used in the practical experiments. Figure 3 shows photographs of the rotor rupture bars we used in testing, with Fig. 3(a) showing a healthy rotor, 3(b) a rotor with one broken bar, 3(c) a rotor with two broken bars, and 3(d) a rotor with three broken bars.

### A. *Data Acquisition algorithms*

In frequency domain analysis, we examine the signal (current and vibration) and separate the signal energy into various frequency bands. We used this frequency domain or spectral analysis of the vibration signal or current to identify failures in the induction motor. The advent of FFT computational techniques have facilitated and enhanced the efficiency of spectral analysis. In the analysis and diagnosis of faults, the bands of components with high and low frequencies in the vibration spectrum and current are of interest. We implemented our data acquisition algorithm in the software LabVIEW.

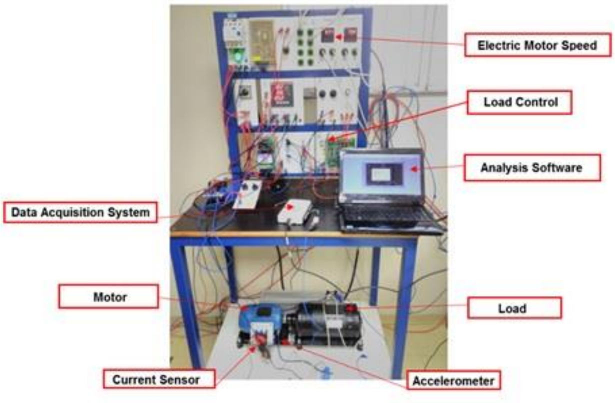


Fig. 2. View of experimental setup


Fig. 3. Rotors: a) healthy; b) one broken bar; c) two broken bars, and d) three broken bars.

### B. *Stator Current Spectrum*

To verify the efficiency of the feature extraction method, we conducted several tests under different loads in healthy rotors and in faulty rotors with broken bars. In each case, we transformed the stator current into the frequency domain for MCSA.

Figure 4 shows the stator current spectrum for a healthy motor at 95% of the rated load and a motor speed of 1,738 rpm. The amplitude of the left broken-bar frequency component is 55 dB lower than that of the grid frequency (60 Hz), and that of the right broken-bar frequency component is 60 dB lower.

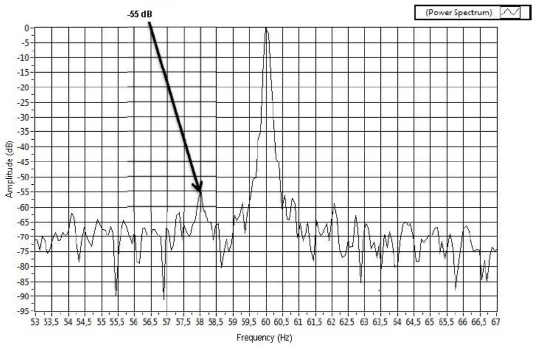

Fig. 4. Current spectrum for a healthy motor.

Figure 5 shows the stator current spectrum for one broken bar at 95% of the rated load and a motor speed of 1745 rpm. We analyzed and extracted the fault frequency components (left broken-bar frequency) at 57.50 Hz and the right broken-bar frequency at 62.50 Hz. The amplitude is 40 dB lower than that of the grid frequency and the amplitude frequency of the left broken-bar component is 55 dB lower.

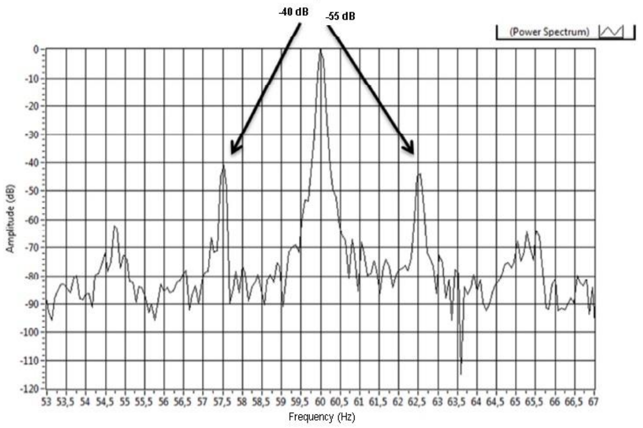


Fig. 5. Current spectrum for one broken bar**.**

Figure 6 shows the stator current spectrum for two broken bars at 85% of the rated load and a motor speed of 1746 rpm. We analyzed and extracted the fault frequency components of the left broken-bar frequency at 57.50 Hz and the right broken-bar frequency at 62. 50 Hz. The amplitude is 35 dB lower than that of the grid frequency and the amplitude of the left broken-bar component is 40 dB lower.

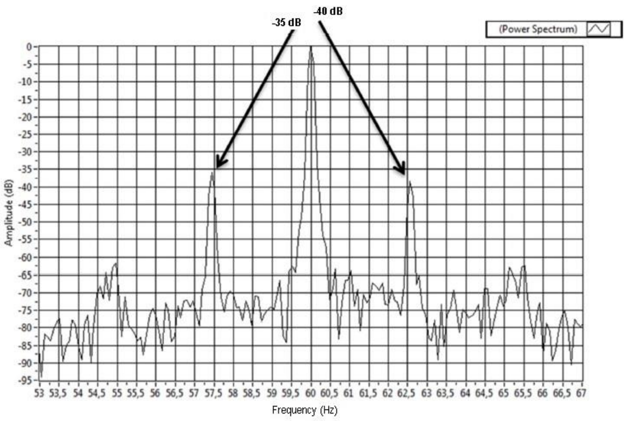


Fig. 6. Current spectrum for two broken bars.

*C. Vibration Analysis*

In the broken bar cases, there is an oscillation speed with the frequency $2sf_0$, which modulates the rotation frequency, so that two lateral bands $f_m \pm 2sf$ appear around frequency $f_m$. To determine the values of $f_m$ and $s$ more precisely, we can check the higher-order harmonics of the rotation frequency. In vibration spectra, the P-th harmonic (P = 4 poles) $4.f_m$ is near and to the left side of $2.f_0$, and the slip ($s$) can be given by (5).

$$s = \frac{(2.f_0 - 4.f_m)}{2.f_0} \tag{5}$$

Figure 7 shows our first data results using the vibration spectrum method. The slip calculated by Eq. 5 is equal to 0.0247 and the motor rotation frequencies ($f_m$) are 29.26 Hz. The harmonic frequencies $4\times f_m$ and $2\times f_0$ are, respectively, 117.04 Hz and 120 Hz.

In Fig.8, the power spectrum of the two sidebands, i.e., $(f_m - 2sf_0)$ of 26. 30 Hz and $(f_m + 2sf_0)$ of 32. 94 Hz near $f_m$, are well below −60 dB, which indicates that there are no broken-bar faults.

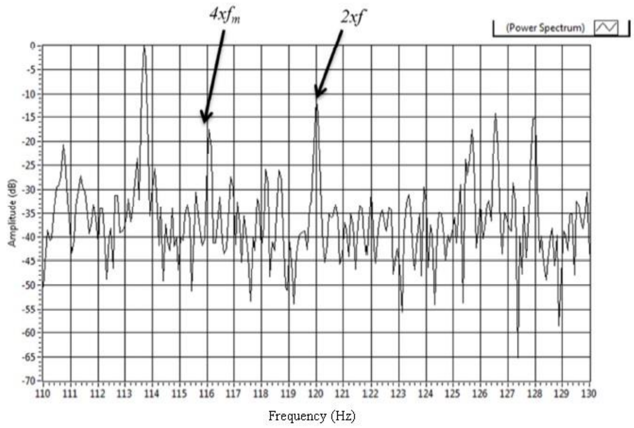


Fig. 7. Vibration spectrum for slip calculation

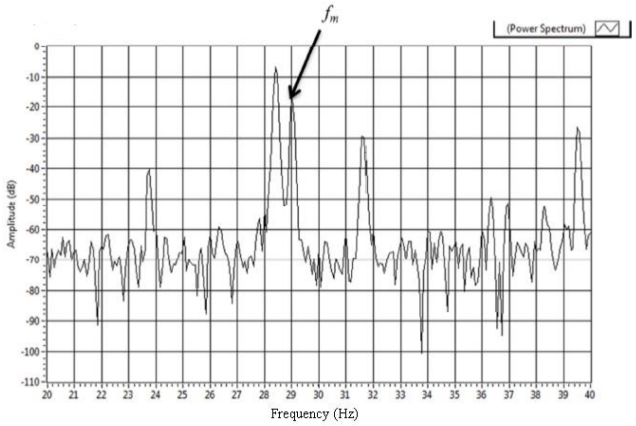


Fig. 8. Vibration spectrum for the healthy motor

Figure 9 shows the vibration spectrum for one broken bar at 90% of the rated load and motor rotation frequencies ($f_m$) of 29.26 Hz. In this figure, the power spectrum of the two sidebands $(f_m - 2sf_0)$ of 25.30 Hz and $(f_m + 2sf_0)$ of 32, 82 Hz allow us to identify with some difficulty two lateral bands near $f_m$, thereby indicating the presence of a broken bar fault.

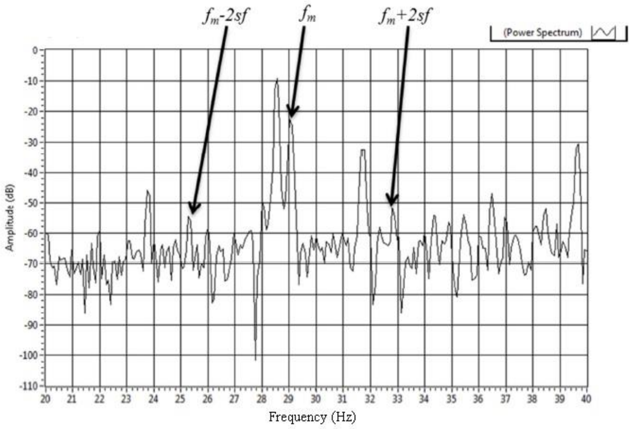


Fig. 9. Vibration spectrum for one broken bar

Figure 10 shows the vibration spectrum for two broken bars at 90% of the rated load and a motor rotation frequency ( $f_m$ ) of 29.10 Hz. In the figure, the power spectrum of the fault frequency component sidebands $(f_m \pm 2sf_0)$ are equal to 25.50 Hz and 32.70 Hz. We can see an increase in the amplitude of the lateral bands $(f_m \pm 2sf_0)$ , which indicates the presence of a two broken-bar fault.

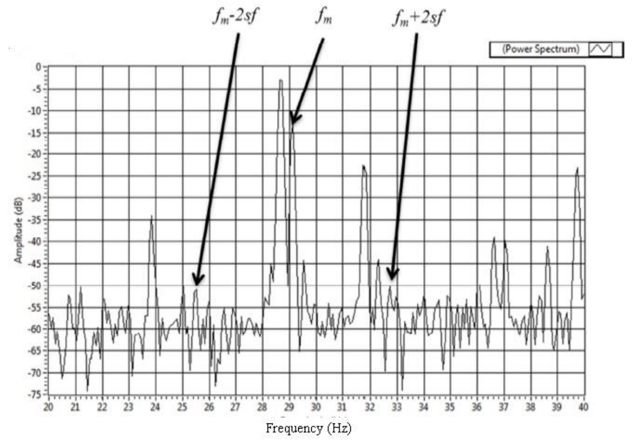


Fig. 11. *Vibration spectrum for two broken bars*

## V. CONCLUSION

In this paper, we developed and tested an analysis method that combines MCSA and a vibration-monitoring technique to study broken bars in three-phase high-performance induction motors. The combined MCSA and vibration-monitoring technique can be used to monitor non-invasive sensor signals and identify broken-bar conditions in induction motors.

We presented a detection method using stator current and vibration spectra to determine the presence of broken-bar faults in induction motors. From our analysis of these spectra, we found the detection of broken bars by signature analysis of the stator current to be more sensitive and applicable to high-performance induction motors.

In the initial stages of failure, both methods presented some difficulties in detection, in that only from the second adjacent broken bars could we verify the amplitude of the fault frequency component sidebands with sufficient clarity in both spectra. The combined method of current signature and vibration spectrum analyses can increase detection reliability since the vibration spectrum method is less sensitive to load variations, which can cause fluctuations to be reflected in the frequency spectrum that may lead to erroneous conclusions.

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