Review Diagnosis Methods of Induction Electrical Machines based on Steady State Current

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Abstract. This paper reviews the main techniques of a diagnostic fault for an induction electrical machine, based on the on-line analysis of machines in steady state. It is focused in broken bar and eccentricities failures of an induction machine. In this paper, FFT of stator current, of instantaneous power and Hilbert Transform of the instantaneous current are compared. Experimental results are obtained on a 1.1-kW three-phase induction motor with a one broken bar.

Key Words: MCSA, FFT, Hilbert Transform, Diagnosis, Broken Bars, Eccentricity.

1. Introduction

Nowadays three-phase induction motors are used in a wide variety of industrial applications. They are the most used kind of electrical machines, for their reliability and simplicity of construction. But they are subjected to failures, due to operating conditions or inherent to the machine itself by construction. In an industrialized nation motors can consume between 40 to 50 % of all the generated capacity of that country [1]. Failure surveys [2], [3] have reported that percentage failure by components in induction motors is typically

- Stator Faults (38%)
- Rotor Faults (10%)
- Bearing balls Faults (40%)
- Others Faults (12%)

There are more causes, such as environmental, duty, the installation, etc that it is possible to accelerate motor failure and shorten engine life. Due to these motors are so widespread, failure in one of them can lead to critical situations. For this, in the last decade has been invested in maintenance plans.

There are many published techniques and commercially available tools to monitor induction motors to improve the reliability of the motors [4]. Traditionally motors are supervised by measuring noise, vibration and temperature but the implementation of the systems to measure these quantities are expensive and they don't allow the discrimination between all types of faults. For this reason, recently other electrical magnitudes are used to monitoring the motor, such as a stator current motor, or instantaneous power.

Detection of faults in steady state have focused extensive research effort over the past decade, and Motor Current Signature Analysis (MCSA) has become one of the most extended methods for motor diagnostic. It requires just the measurement of one stator current, it is non-invasive, it can identify different simultaneous failures, and of course it is on-line method, which can be applied without perturbing the installation operation conditions. The existence of frequency components dependent of the type of the motor's fault in the stator line current is used to detect the faults in the machine has been applied to detect broken rotor bars [5]. These frequency components are also presented in the speed and torque signal [6] or axial flux leakage [7].

Other way to detect failures is the application of the MCSA method in transient state (TMCSA) adds a new dimension to the spectral analysis, the time, which can greatly enhance the reliability of the diagnosis process. Time-frequency analysis of the stator currents has been used to detect induction motor faults such as broken rotor bars [8] , [9], stator short circuits [10], eccentricities [11], insulation problems [12], power faults [13], and also to develop sensorless speed measurement systems [14].

The analysis of the motor current in the time-frequency plane state increases the dimensionality of the detection process, so traditional indicators for quantifying the fault are not long valid for TMCSA, so new indicators must be defined.

The paper is structured as follows: in section II the frequency of the characteristic harmonic of a baroken bar and eccentricity fault is described. In section III the Motor Current Signature Analysis is introduced. Section IV it is compared Fast Fourier Transform versus Hilbert Transform. In section V the experimental results are presented. Section VI presents the conclusions.

2. Frequencies Characteristic of each type of fault

Normally, each type of fault produces a characteristic frequency in the stator current. This paper will focus on broken bar rotor and eccentricities faults. But it does not mean that the methods or techniques shown in this paper are not valid or extensible for other types of faults.

A. Broken Bars

Breakages in the rotor cage winding introduce a distortion in the airgap field that produces sideband components f_b in the line current spectrum around the fundamental and around other harmonics caused by non ideal winding distribution [7], at frequencies given by:

$$f_b = \left(k/p\left(1-s\right) \pm s \right) f_1 \quad where\ k/p = 1,3,5... \qquad (1)$$

where f_1 is the supply frequency, s is the rotor slip and p the pole pairs number.

The left sideband harmonic (LSH) is obtained by substituting k/p=1 in (1); this component produces oscillations in the rotor speed, originating a new family of fault related components [15], with frequencies given by:

$$f_b = (1 \pm 2 \cdot k \cdot s) \cdot f_1 \qquad k = 1,2,3.... \qquad (2)$$

The diagnosis indicator in this case is particularly simple: the value of this modulus harmonics marks the presence or absence of the fault.

B. Eccentricities

Rotor eccentricity can result from a variety of sources such as design features, manufacturing tolerances, and operation conditions. The rotor may be positioned slightly off center in the stator bore. Eccentric rotor running of induction motors can result sufficient to increase in the unbalanced magnetic pull to cause stator-rotor contact [16]. Four types of Eccentricities can be identified via MCSA:

1) Static Eccentricity

Static eccentricity is characterized by a displacement of the axis of rotation, which can be caused by a certain misalignment of the mounted bearings or the bearing plates or stator ovality. Since the rotor is not centred within the stator bore the field distribution the air gap is no longer symmetrical. The non-uniform airgap gives rise to a radial force of electromagnetic origin, called unbalanced magnetic pull (UMP). This produces distortion frequencies given by:

$$f_{static} = \left[\left((k \cdot N) \cdot \left(\frac{1-s}{p} \right) \pm \upsilon \right) \right] \cdot f_1. \qquad (3)$$

where k is a positive constant or cero, N is the number of slots machine and v is the harmonic order.

2) Dynamic Eccentricity

Dynamic eccentricity appears when the stator bore axis does not match with rotor bore axis. This kind of eccentricity may be caused by a bent shaft, mechanical resonances, bearing wear on movement. Therefore, the non-uniform airgap of a certain spatial position is sinusoidal modulated and results in an asymmetric magnetic field. This produces distortion frequencies given by (n_d is a positive integer):

$$f_{dinamica} = \left[\left((k \cdot N \pm n_d) \cdot \left(\frac{1-s}{p} \right) \pm \upsilon \right) \right] \cdot f \qquad (4)$$

3) Mixed Eccentricity

This eccentricity is the combination of static and dynamic eccentricity. It causes characteristic sideband currents in the current spectrum given by:

$$fl = |f_1 \pm k \cdot f_r| \quad \rightarrow k = 1,2,3 \qquad (5)$$

where f_r is the mechanical frequency.

4) Axial Eccentricity

This eccentricity appears when there are varying of the eccentricities along the axis of the rotor. Therefore, the axis of rotor rotation is not parallel to the stator axis and has different eccentricity in each section of the machine.

3. Motor Current Signature Analysis (MCSA)

MCSA has become one of the most extended methods for motor diagnostic. Also it requires only one measurement of stator current, it is non-invasive, it can identify different simultaneous failures, and being an on-line method, it does not perturbed process the installation operation conditions. MCSA is based on the detection of specific current harmonics, with frequencies that are characteristic of each type of fault.

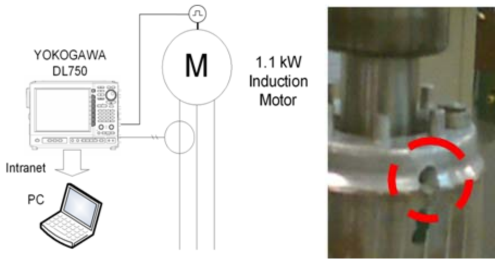

Figure 1. Experimental Test Bench

One of the simplest ways of performing MCSA is to sample the stator current of a phase during a fixed time, Figure 1, with the motor running at constant speed, and then to obtain the frequencies spectrum, using for example the Fast Fourier Transform (FFT) to analyze the spectrum and decide the existence of the fault. In this way the monitored characteristics can be used to predict the need for maintenance before breakdown occurs.

In the other hand, today there are industrial equipment similar than power analyzer that capture the stator current of the machine and make the diagnostic of the motor as shown in Figure 2.

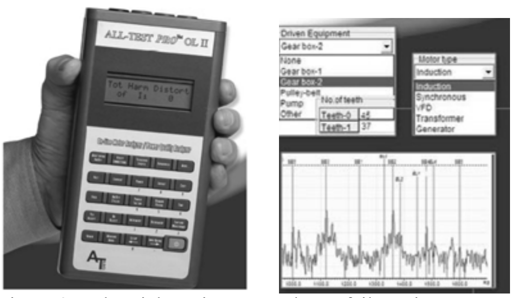
Figure 2. Industrial Equipment to detect failures in motors.

4. Current Analysis Methods.

Frequency information is extracted of one stator current of a phase, measured during a fixed time via any of the following techniques:

A. Fast Fourier Transform (FFT)

Fourier analysis is very useful for many applications where the signals are stationary, as in diagnostic faults of electrical machines [17]. FFT is used to detect eccentricity and broken bars; it is shown in Figure 3.

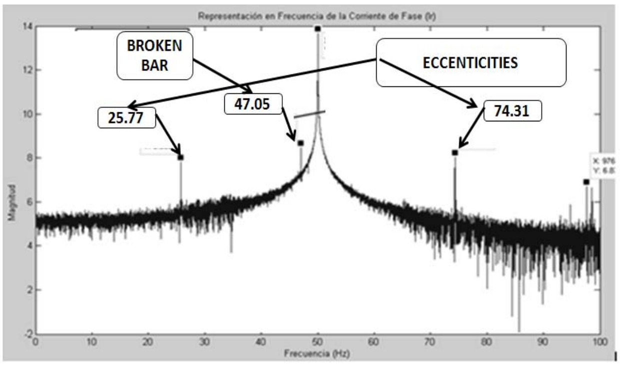

Figure 3. Spectrum (FFT) of the phase current of the machine with a broken-bar and static eccentricity.

However, the application of this method on an industrial environment has some drawbacks or practical limitations:

- Spectral leakage: it is due to use of a finite-time window. The energy of the mains frequency spreads over the rest of the frequencies and can hide the sideband components [18]. Alternative methods for the monitoring of the machine conditions use multiple inputs voltage and current signals, in order to generate quantities with better separation between the frequencies of interest: the instantaneous phase's power [19], the total input power [20], the current Park's Vector [21], the air-gap torque [15], the three phase stator current envelopes [22], the Concordia stator mean current [23], the swing angle [24] and others.
  Spectral leakage has a special adverse impact to detect broken bar failure or other type of fault which characteristic frequency is near the frequency fundamental when the machine operates at low slip. In Figure 4, it is represented the spectrum of the current and the spectrum of the instantaneous power for a machine with a broken bar and its slip is about 3.33%. For this case, the spectrum phase current is able to detect the broken bars faults, but for minor slips is probably not detected.
  For this reason, it is possible used the instantaneous phase power spectrum that separated the frequency to the main frequency.

- Need a high frequency resolution: frequency resolution is the frequency separation between two adjacent bins in the spectrogram. Diverse techniques can improve the frequency resolution without increasing the measurement time [25].

- Varying load conditions: if the load varies during the sampling time, the sideband frequencies, which depend on the slip. This change can invalidate a detection process.

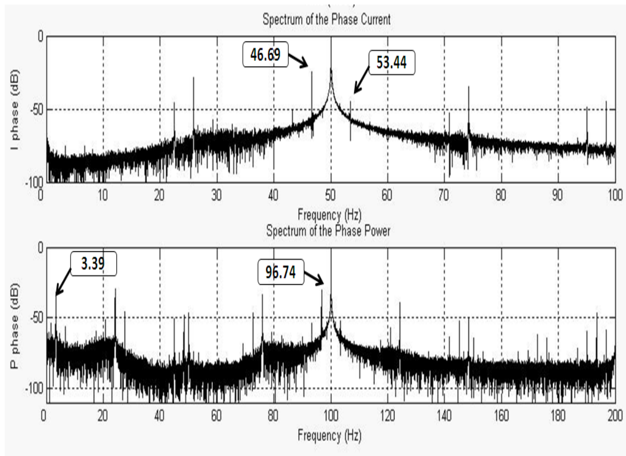

Figure 4. Top.-Spectrum (FFT) of the phase current and Down.-Spectrum (FFT)of instantaneous phase power of the machine with a broken-bar under 3.33% slip.

- Confusing mechanical frequencies: induced by the load can be avoided with no-load test, but in this case for example the characteristically frequencies of the broken bars are very close to the main frequency and more probably get buried by spectral leakage.

B. Hilbert Transform(HT)

Hilbert Transform (HT) is a well-known signal analysis method, used in different scientific fields such as signal transmission [26], also to diagnostic faults in electrical machines [27].

The HT of a real signal *x(t)*, such as the phase current, is used to emphasize its local properties. Mathematically it is defined as the convolution with the function 1/t, as follows [28]:

$$HT(x(t)) = y(t) = \frac{1}{\pi t} * x(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (6)$$

The divergence at $t=\tau$ is allowed for by taking the Cauchy principal value of the integral. Coupling the *x(t)* and its HT, the so called Analytic Signal (AS) $\vec{x}(t)$ is created

$$\vec{x}(t) = x(t) + j\,y(t) = a(t)e^{j\theta(t)} \qquad (7)$$

Where

$$a(t) = \left[x^2(t) + y^2(t)\right]^{1/2} \quad \theta(t) = \arctan\left(x(t)/y(t)\right) \qquad (8)$$

a(t) is the instantaneous amplitude of $\vec{x}(t)$, which can reflect how the energy of *x(t)* varies with time, and *θ(t)* is the instantaneous phase of $\vec{x}(t)$.

Three key properties of the HT and the AS that give a more physical insight about it are:

- The HT of a trigonometric function *x(t)* is a version of itself with a 90º phase shift: sins are transformed to cosines and vice versa. The spectrum of a Hilbert transformed series has the same amplitudes and frequencies contents as the original data, but the phase of each frequency component is shifted by 90º.

- The AS $\vec{x}(t) = x(t) + j\mathrm{HT}(x(t))$ has a one-sided Fourier transform, that is, its negative frequencies are 0. It retains the positive frequency content of the original signal while zeroing negative frequencies and doubling the DC component.
- The low frequencies of the original signal are in the amplitude $a(t)$, and the high frequencies in the phase $\theta(t)$ of the AS.

The variable used to diagnose the fault is the alternating component of the modulus of the AS of the phase current, $I_{hilbert}$. It is generated from the values of the phase current, i_{phase}, with a simple line of code:

$$I_{Hilbert}=\mathrm{abs}(\mathrm{hilbert}(i_{phase}))-\mathrm{mean}(\mathrm{abs}(\mathrm{hilbert}(i_{phase}))) \quad (9)$$

In Figure 5, it is compared the spectrum and the spectrum of analytical signal of the phase current of the machine with a broken bar under 3.33% slip, for demonstrate the validity of the analytical signal method.
The Spectrum of AS phase current results more clearly than Spectrum of the phase current. Also it is eliminate the mainly frequency.

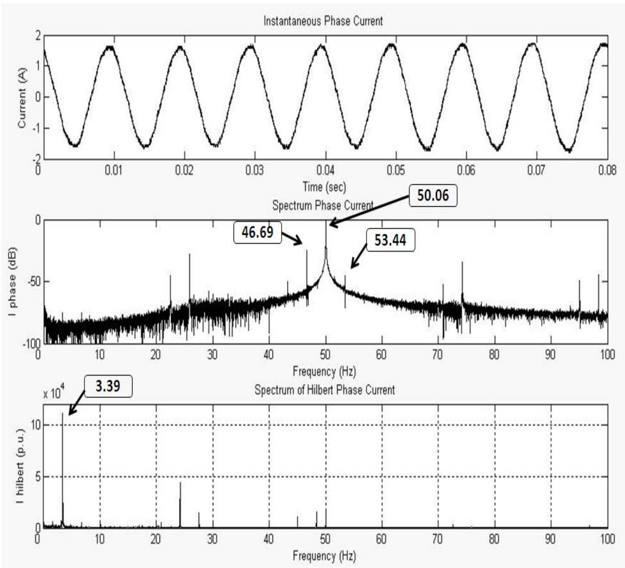

Figure 5. Top.- Instantaneous Phase Current. Medium.-Spectrum (FFT) of the phase current and Down.- Spectrum (FFT)of Analytical Signal of phase current of the machine with a broken-bar under 3.33% slip.

The spectral analysis of the modulus of the analytic signal of the phase current, instead of the commonly used phase current analysis, has significant advantages over traditional methods:

- It is very easy to perform, requiring only just a single phase current.
- Only one fault-related frequency component appears, instead of two sidebands, which is directly located at the characteristic frequency of the fault.
- The frequency leakage due to the continuous component of the modulus can be completely avoided.
- The absence of a predominant signal corresponding to the main frequency allows the use of linear scale instead of a logarithmic.
- The frequencies that must be detected are very low, the sampling rate of the modulus of the phase current's analytic signal can be decimate prior to the generation of its spectrum.

5. Experimental Results

Through experimental test is compared the different diagnosis methods to detect faults in induction electrical machine. They have been applied to the analysis of a 1.1 kW induction motor, whose data are given in the appendix. Tests were carried out in two different conditions: healthy state and faulty condition in which a single bar was broken by drilling. In both cases, the test was performed at absolute no-load conditions, keeping free the motor shaft, to test the feasibility of the proposed method at very low slips.
Figure 6 presents three spectrums of the phase current, of the instantaneous power and the analytical signal of the phase current. The sidebands components characteristic of the broken bar condition are distinguishable only in the instantaneous power spectrum and in the analytical signal spectrum of phase current. The mainly difference between both spectrum is the form to captured the measurement as instantaneous power needed two electrical magnitudes such as phase voltage and phase current. On the other hand the analytical signal spectrum only needs the phase current.

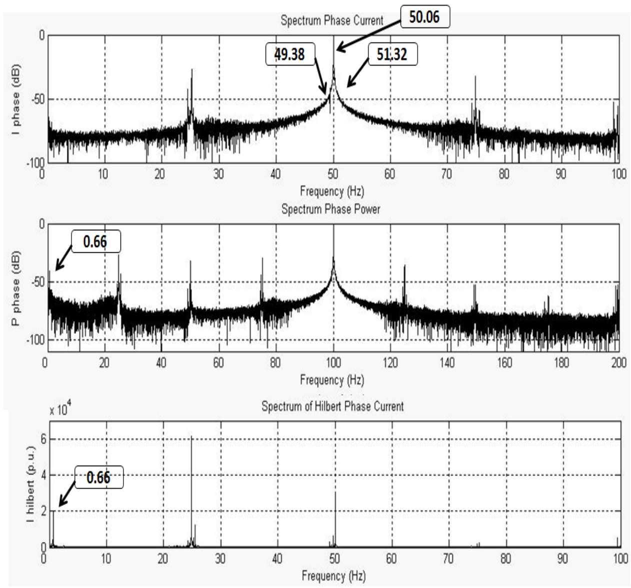

Figure 6. Top.-Spectrum (FFT) of the phase current. Middle.- Spectrum (FFT) of instantaneous phase power and Down.- Spectrum (FFT) of AS phase current of the machine with a broken-bar under 0.66% slip.

6. Conclusions

MCSA is a powerful technique for monitoring and diagnosis the electrical machines, as shown on industrial case histories. The measurement of one stator current allows the diagnosis of electrical machine without perturbing the normal operation.
Nowadays, the classical signal processing techniques, such as FFT are being extended with modern advanced

signal processing, such as the Hilbert Transform through Analytical Signal. These extend the field of application of MCSA in case that FFT of phase current not detected the fault.

In this paper, the variations of the modulus Analytical Signal of the phase current, based on the Discrete Hilbert Transform, have been used to generate the spectrum. This technique is able to accurately detect the broken bar frequencies at very low slips, uses only one of the phase currents, and needs very low storage size, which makes it very suitable to be implemented on real DSP hardware

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