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STUDY USING INDUCTION MOTORS AS TRANSDUCERS FOR DEGRADATION DETECTION ON THE SURFACE OF GEARS

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Abstract. *This paper proposes an investigation into the use of electrical variables of induction motors, for the detection of faults distributed in gear, seeking to an alternative solution to the vibration signals. Specifically, from the acquisition of voltage, electric current and rotor speed, we intend to examine the expression of Motor Current Signature Analisys (MCSA), Extend Vector Approach Park (EPVA), Torque Signature Analysis (TSA) and Instant Power Signature Analysis (IPSA) in the presence of a fault by applying the Fourier analysis. Based on the understanding the behavior and limitations of applied electrical signals and processing techniques, we intend to propose an appropriate strategy for monitoring the main flaws in such mechanism, comparing the operations in good and bad conditions. Experimental results are presented comparing the signals from vibration and electric motor, evaluating the fault detection efficiency in a wide range of speed and machine load, and in varying degrees of severity of the failure.*

Keywords: *Gearbox, Failure, Detection, Induction Motor, Degradation the Surface.*

1. INTRODUCTION

The maintenance has a representative space in the costs of large industrial corporations and for this reason is constant research topic to improve their efficiency and minimize consequence (Garcia and Savi, 2005). For industry, prevent the stop of production for malfunctions in equipment signifies highest rate of the production line availability, and reduced maintenance costs (Araújo, 2011).

A recent strategy being investigated for detection of faults in electric motors coupled to mechanisms is the motor current signature analysis, which has already been successfully applied to condition monitoring of induction motor and in bearings (Kar and Mohanty, 2006). Second Benghozi, et al. (2012), as it is not necessary to the mechanism being diagnosed by fixing mechanical sensors for data collection, this strategy is particularly useful in places where the usual methods such as the implementation of accelerometers for monitoring vibration signals are inadequate or non-viable like equipment in deep wells in the oil industry, or where there may be risk of contamination and/or changes in sensitivity due to prolonged exposure to certain working conditions. The hypothesis is that a given failure of an engine coupled to an electric motor is presented as a harmonic component in current stator.

Kia, Henao and Capolino (2007) present a mathematical description based on the observation of the spectrum (FFT) for distributed fault current in a gearbox, gear wear observed by simulations and experimental results. In Kia, Henao and Capolino (2008) the authors reported a template for extension of gear trains, applying the Hilbert transform.

Kia, Henao and Capolino (2012) performed the simulation a dynamic model for the electromechanical assembly created in order to compare different strategies for the diagnosis of wear of the tooth surface. The sound pressure diagnostic capabilities and vibrations are analyzed by the envelope technique, and current signals of the coupled induction motor stator are analyzed by the current power spectrum density, which performs the signal energy distribution in relation to frequency using a high-resolution acquisition system and Welch technique.

In Feki, Clerc and Velex (2012) simulated results from analytical model are presented to illustrate the possibility of detection of distributed faults (spalling) in teeth of a gear box (helical gears, shafts and bearings) coupled to a motor induction (model *dq*) for the stator current measurements. In Feki, Clerc and Velex (2013) researchers apply through simulations, the Park vector technique the analytical model.

Kia, Henao and Capolino (2013) presented experimental results of wear in a gearbox using electromagnetic torque analysis and SCSVIF (Vector Space Stator Current Instantaneous Frequency) induction motor. In Kia, Henao and Capolino (2015) a new theoretical model of wear is simulated and validated by experimental results through SCSVIF.

The majority of studies on the wear detection gearbox were conducted using simulated results because aims to solve the theoretical foundation in the vibrational effects on the electric motor current. Despite the mathematical modeling of electromechanical assembly has been an important achievement in relation to knowledge of the vibrational effects, a coherent estimation of mechanical parameters which primarily reflect the rigidity of the teeth, such as variations due to the formation of cracks, limiting the outcome.

This research aims to experimental detection as well as the presentation of wear severity degree in a gearbox through the investigation of electrical variables that similarly the stator current, may be sensitive to vibrational effects, such as the Extend Vector Approach Park, the Instant Power Signature Analysis and the Torque Signature Analysis as alternative sources of information by analyzing vibration signals.

2. ANALYSIS OF DAMAGE IN GEARBOXES

The American Association of Gears Manufacturers (AGMA) classifies 20 sports faults in gears in various categories. However, the basic categories were: overload, flex fatigue in the tooth root, contact fatigue, wear (abrasion, adhesion, cavitation, etc.) and scuffing (Koda, 2009).

Second Norton (2004) fatigue is responsible for ninety percent of faults by mechanical causes. Second Dudley (1994), the contact fatigue is largely responsible for breaks in industrial gears. However, Alban (2002), the most common failure mode is the gear ratio of flexion fatigue. Sousa (2010) explains that in reality this dichotomy is due to failure frequency be related to the criteria for calculation and the safety factors used favoring only one type of fatigue.

The process of as a fault in the mechanism coupled to an electric motor can be monitored by analyzing the signatures of the current signals may be represented in Fig. 1.

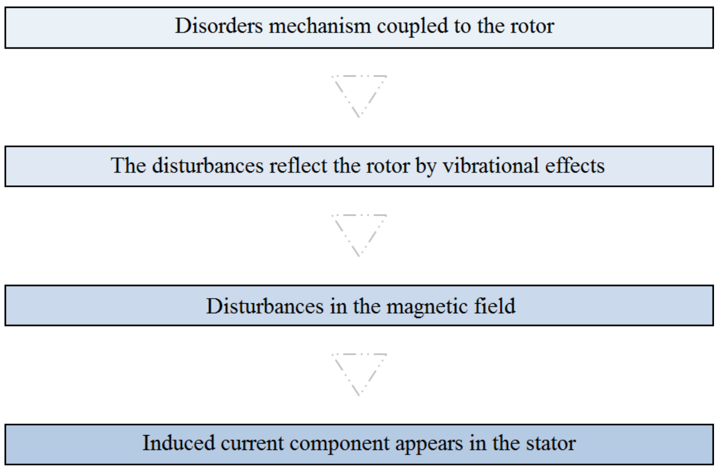

Figure 1. The process by which the mechanical problems can be monitored by analysis of the signatures of engine electrical signals. Adapted from Bonaldi (2005).

In Eq. (1) Kia, Henao and Capolino (2007) suggest the set of frequencies that may arise due to a malfunction in gear.

$$
\begin{aligned}
f_{BL_{pin}} &= f_{a\,lim} \pm m.f_{pin} \\
f_{BL_{cor}} &= f_{a\,lim} \pm n.f_{cor} \\
f_{BL_{pin/cor}} &= f_{a\,lim} \pm m.f_{pin} \pm n.f_{cor} \\
f_{BL_{eng}} &= f_{a\,lim} \pm q.f_{eng} \\
f_{BL_{pin/eng}} &= f_{a\,lim} \pm m.f_{pin} \pm q.f_{eng} \\
f_{BL_{cor/eng}} &= f_{a\,lim} \pm n.f_{cor} \pm q.f_{eng} \\
f_{BL_{pin/cor/eng}} &= f_{a\,lim} \pm m.f_{pin} \pm n.f_{cor} \pm q.f_{eng}
\end{aligned}
\qquad (1)
$$

Where f_{alim} is the motor supply frequency in Hz; m, n and q are the orders of the harmonics (m, n and $q=1,2,3,...$); f_{pin} is the rotor speed of the pinion in Hz and f_{cor} is the rotor speed crown in Hz.

2.1. Extend Park's Vector Approach (EPVA)

The advantage of an EPVA technique resides in the fact of fundamental component of the motor supply is automatically subtracted spectrum by transforming Park, causing the characteristics of components and demodulated faults appear highlighted. The Park vector components of the electric current as a function of the supply current are given by:

$$i_{sd}^{s} = \sqrt{2/3}\,i_{s1}^{s} - 1/\sqrt{6}\,i_{s2}^{s} - 1/\sqrt{6}\,i_{s3}^{s} \quad (2)$$

$$i_{sq}^{s} = 1/\sqrt{2}\,i_{s2}^{s} - 1/\sqrt{2}\,i_{s3}^{s} \quad (3)$$

The Park vector module is given by:

$$EPVA = \sqrt{(\mathrm{i}_{\mathrm{sd}}^{\mathrm{s}})^2 + (\mathrm{i}_{\mathrm{sq}}^{\mathrm{s}})^2} \quad (4)$$

where i_{s1}^{s}, i_{s2}^{s} and i_{s3}^{s} are the three-phase currents; i_{sd}^{s} and i_{sq}^{s} are the transformed two-phase currents.

2.2. Instantaneous Power Signature Analysis (IPSA)

The power provides more information than the single current, this is because the normal engine operating condition is affected by both the current waveform as the phase difference between current and voltage. The total instantaneous power of a healthy induction motor can be calculated by Eq. (5) using the three measured voltages and currents.

$$p_{tot} = v_{s1}^{s} i_{s1}^{s} + v_{s2}^{s} i_{s2}^{s} + v_{s3}^{s} i_{s3}^{s} \quad (5)$$

where v_{s1}^{s}, v_{s2}^{s} and v_{s3}^{s} are the three-phase voltages.

2.3. Torque Signature Analysis (TSA)

The stator flux is calculated by integrating the electromotive force (EMF) by the method presented by Freitas et. al. (2011), which is the voltage measured at the terminals of the machine subtracted from the voltage drop in the stator resistance.

$$\lambda_{sd}^{s} = \int \left(v_{sd}^{s} - R_s i_{\mathrm{sd}}^{\mathrm{s}} \right) dt \quad (6)$$

$$\lambda_{sq}^{s} = \int \left(v_{sq}^{s} - R_s i_{\mathrm{sq}}^{\mathrm{s}} \right) dt \quad (7)$$

Estimated flux is used together with the measurement of the stator current to calculate the electromagnetic torque as Eq. (8).

$$c_e = P\left(i_{sq}^{g} \lambda_{sd}^{g} - i_{sd}^{g} \lambda_{sq}^{g} \right) \quad (8)$$

where λ_{sd}^{s} and λ_{sq}^{s} are the components of the electromagnetic flux.

3. EXPERIMENTAL RESULTS

The experimental system of Fig. 2 was developed and projected to in the laboratory validation and motor performance tests, torque and for simulation of mechanical failure, both in loading and in the induction motor. It is composed of an induction motor three phase Siemens 2 HP (1,5kW), 8,6 N.m, 4-pole, 3,64A / 380V and can be connected by a frequency inverter (variable speed) or power directly (with variable speed the load due to slipping).

The motor when actuated transmits the speed to the gears and those for a mechanical brake through a timing belt and pulleys. The brake can be adjusted by imposing a desired load to the engine. The torque on the motor shaft can be estimated by the mechanical model of the experimental system and strain gages signal.

Voltage sensors (voltage transformers) provide a signal proportional to supply voltage and current Hall effect sensor provides a voltage signal proportional to the stator current. These signals are provided to the A/D converter, which performs sampling and transmit the information from the sensors to the computer where they can be viewed or stored.

The A/D converter is multifunction data acquisition module, NI USB-6211 has 16-bit resolution and can work with a sampling rate of up to 250 ksamples/s. This module provides 16 analog inputs; four lines of digital input; four lines of digital output; programmable levels of acquisition per channel, with voltages ranging from ± 0,2V to ± 10V and two counters or timers. From the signals obtained from the A/D converter are carried out analyzes of failures by a code in LabVIEW™.

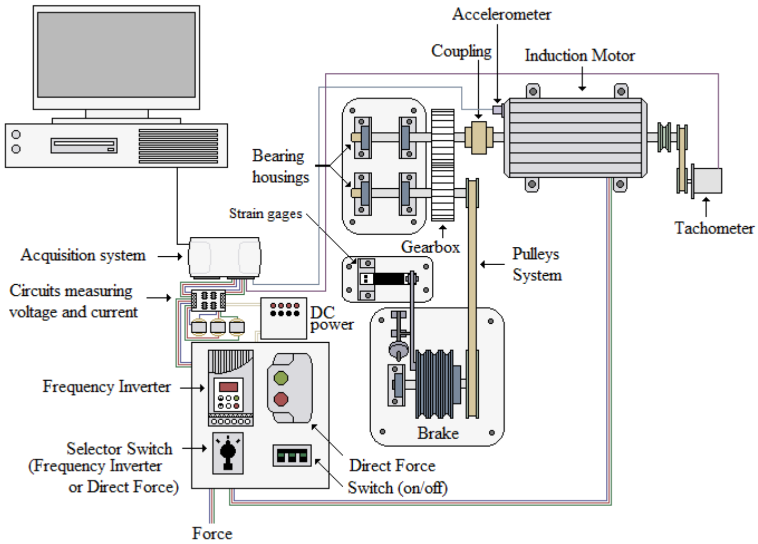

Figure 2. Schematic of the experimental test system.

Distributed faults were obtained by natural wear in approximately 6 hours of operation without lubrication and at high speed, with the range of measurements chosen by the significance of the changes in the spectra. The tests were applied to observe the behavior of vibration signals and some electrical variables at significant stages of direct drive wear or training with frequency inverter with 20Hz, 40Hz and 60Hz, the conditions in empty and load.

The results presented in the frequency region of force some sidebands, or where demodulating the natural frequencies of the axes of gears, with minor changes in some tests, but are not as compared with the observed changes in a localized fault. In meshing region is possible to observe a gradual increase in noise during the malfunction process of formation, being more severe in drives with load, showing at random some peaks related to the frequency of meshing and their bands or the frequency of meshing in relation the frequency of the force and their bands.

Some cases have emerged expressive and random peaks at frequencies related to the power of harmonic meshing in the region. In trials with a frequency inverter, just the drive with 60Hz presented the significant noise rise, suggesting that the lower speeds the vibrational effect is smaller, and this effect is most evident in the charged state.

During the experiments the vibration signals, current, voltage and input shaft speed were sampled at 30 kHz, and processed using 60.000 points. Fig. 3 shows the fault of the formation of stages in the case under load.

(a) **(b)** **(c)**

Figure 3. Stages of formation of wear load: (a) no fault, (b) failure after 3 hours of operation, and (c) failure after 6 hours of operation.

In direct drive power, all variables were sensitive to wear showing significant peaks with and without load. Using an inverter, the drive with power at 20 Hz and 40 Hz only the current and the Extend Vector Approach Park showed peaks representative the malfunction in the load condition. In no-load operation all signs showed some changes with 3 working hours, but at low levels imposing imprecise about the possibility of using them for a diagnosis. In tests with 6 working hours levels of the changes were larger.

The formation of wear occurred with all direct force fed with estimated load in 5 N.m. The formation of wear test lasted 6 hours with acquisition of the signals in the states of the gearbox no fault, worn after 3 hours and after 6 hours wear. Initially, the speed measured by the tachometer indicated 1791,89 RPM. Therefore, no fault analysis provided the characteristic frequencies: f_{pin}*=29,88 Hz*, f_{cor}*=14,94 Hz* e f_{eng}*= 687,24 Hz*.

The set of frequencies after 3 working hours showed no change, however, there was an increase in the effect due to the torsional vibration frequency distribution throughout. In Fig. 4 presents the vibration spectral and electric current in the region between 0 and 200Hz, compared to the state no fault and wear after 3 hours of operation. The vibration spectrum presented the appearance frequency of meshing (687,24Hz). The power spectrum shows an increase in noise, and the emergence of the sidebands of the relative frequency of meshing/power (747,24Hz) for the first components (m=1) of the pinion frequency: 657,12Hz e 777,12Hz.

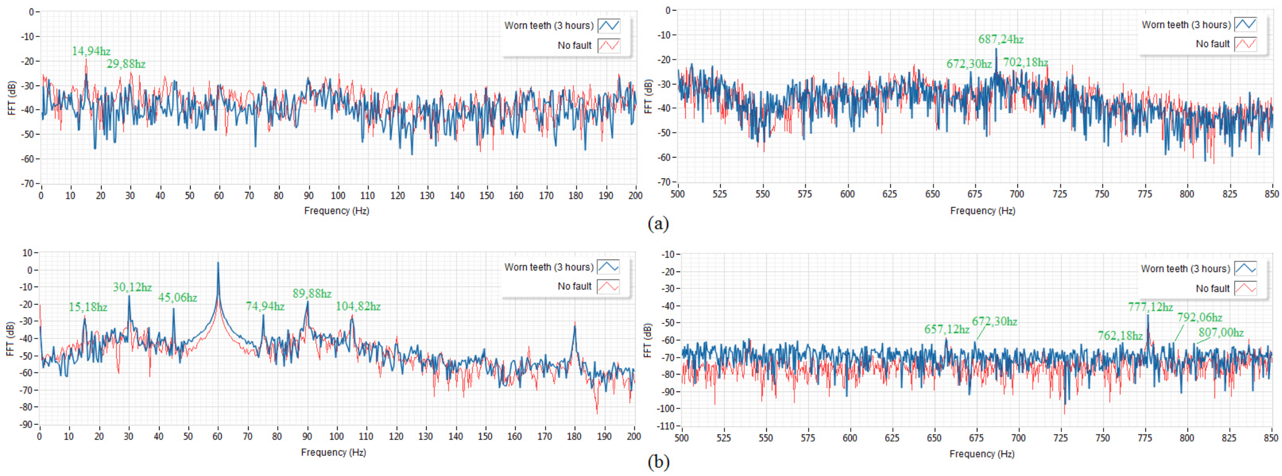

Figure 4. Spectrums no fault and worn after 3 working hours load of the signs of: (a) vibration and (b) electric current i_{s1}.

The wear after 3 and 6 hours of operation, the speed measured by the tachometer indicated 1792,82 RPM. The analysis provided the frequencies set: f_{pin}=29,90 Hz, f_{cor}=14,95 Hz e f_{eng}= 687,70 Hz. In Fig. 5 presents the vibration spectra and comparing the electric current state with wear after 3 and 6 hours of operation. Vibration spectra show the meshing frequency (687,70Hz) and left sidebands 657,60Hz and 642,65Hz. Current spectra show an increase of noise and features relative frequencies in 732,75Hz; 747,70Hz; 777,60Hz; 792,55Hz e 822,45Hz, and roughly observed and the onset of meshing frequency.

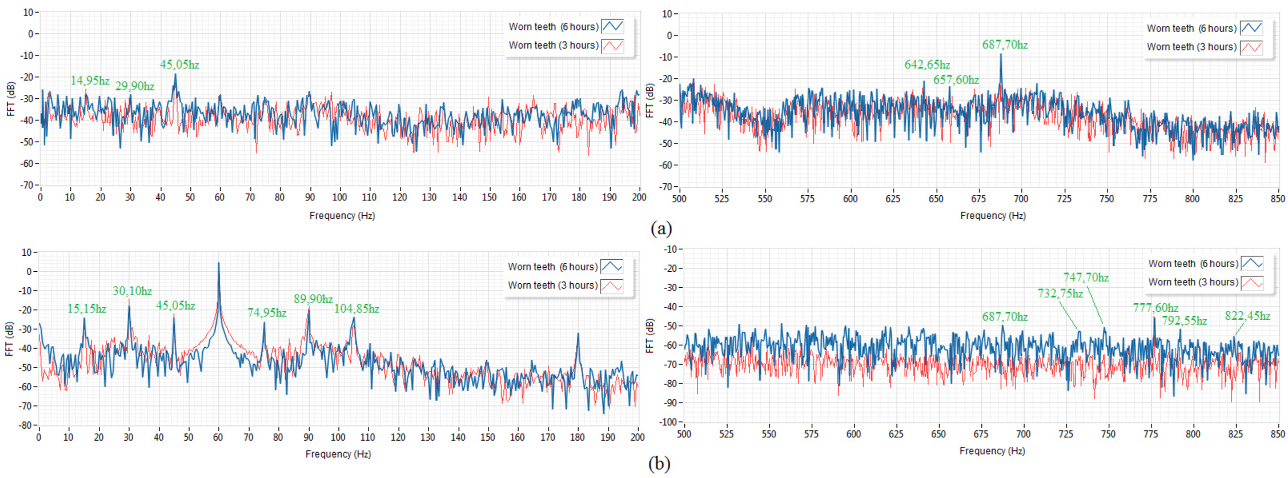

Figure 5. Spectrums worn after 3 and 6 hours of operation with the signal charge (a) vibration and (b) electric current i_{s1}.

Fig. 6 presents the wear spectra after 3 and 6 hours of operation. The spectra show a significant increase in noise, and the emergence of characteristic frequencies on randomly.

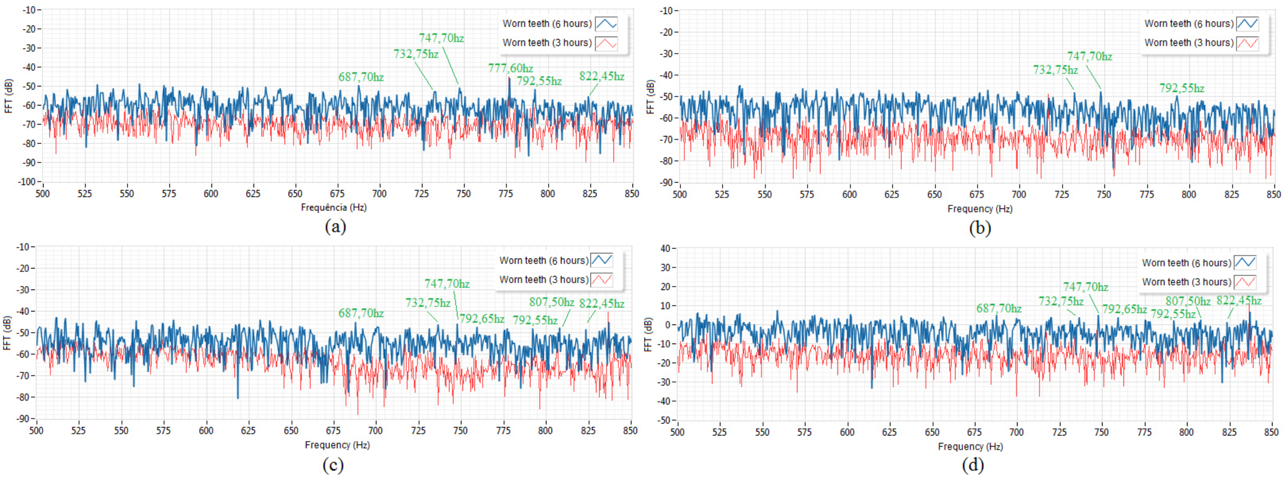

Figure 6. Spectrums worn after 3 and 6 hours of operation with the load signal (a) electric current i_{s1}, (b) EPVA, (c) TSA and (d) IPSA.

The observation of the load worn (3,5 N.m) and driven by inverter at 60Hz speed measured by the tachometer indicated 1766,10RPM and the fault was 1768,20RPM. The analysis provided the undamaged frequency set: f_{pin}= 29,41Hz, f_{cor}=14,70Hz e f_{eng}= 676,45Hz; and fault: f_{pin}= 29,45Hz, f_{cor}=14,73Hz e f_{eng}= 677,30Hz.

Fig. 7 shows the spectra of electric current, Extend Vector Approach Park, the Torque Signature Analysis and Instant Power Signature Analysis respectively. The assay showed a significant increase 60Hz noise and the onset of meshing frequency and thus motor power-related frequency.

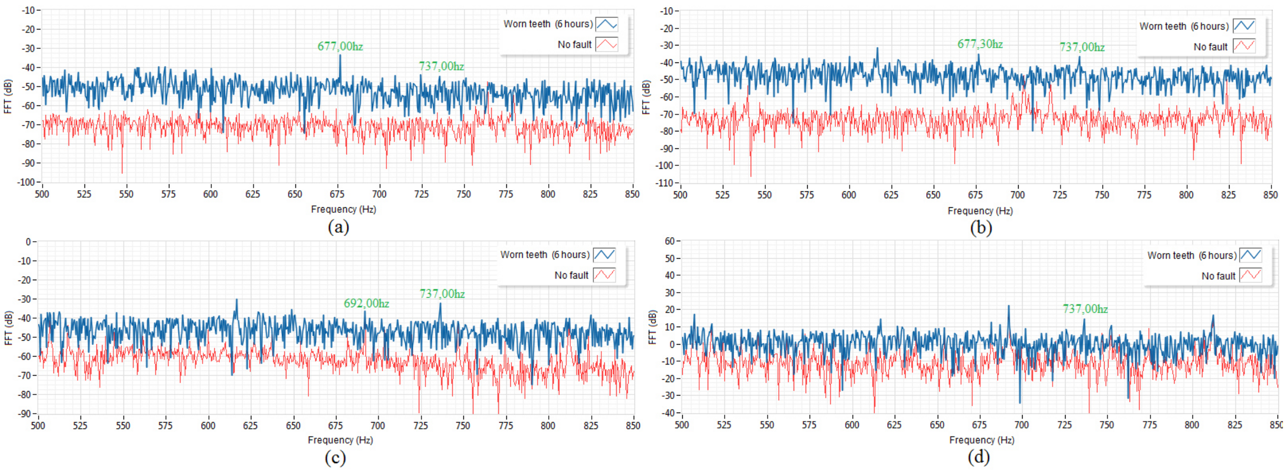

Figure 7. Spectrums in the regions of meshing no fault and tear load after 6 hours and driven in the 60Hz signal (a) electric current, (b) EPVA, (c) and TSA (d) IPSA.

4. CONCLUSIONS

This study investigated the behavior of electrical signals from an induction motor distributed in the presence of faults in a gearbox. The techniques associated with the analysis of vibration signals and electrical variables were verified in experiments where the wear on the surfaces of the teeth was induced and its worsening obtained naturally.

The distributed faults are relatively easy to be observed in the FFT due to noise causing vibrational effect on the spectra giving the appearance of significant frequency, but the randomness in which these frequencies appear difficult diagnosis using an automated search algorithm frequencies and amplitudes. It was observed that the amplitude of components of interest is proportional to the severity of the distributed fault.

The electrical variables were sensitive to faults in the applied drive meshing speeds. The drive through the inverter has increased the level of existing noise of torsional vibration in the drive only at 60Hz, providing little influence in 20Hz and 40Hz. All tested motor electrical variables were change by malfunctions, apparently being the Torque Signature Analysis less sensitive and the Instant Power Signature Analysis affected by increased amount of noise in drives per drive.

The results represent a good start in order to get a remote and automatic detection of faults in the set gear coupled to induction motors, to be a credible alternative to vibration analysis. As future work, the combined application will be investigated between wavelet decomposition, information measures and intelligent systems for classification of moderate adhesive wear, severe and excessive.

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