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EMBEDDED SYSTEMS FOR DETECTION OF FAULTS IN INDUCTION

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Abstract. *Electric motors account for 95% of primary source movement of industrialized nations. 90% of these are three-phase induction motors (TIM), virtually present in all industries, triggering mechanisms that can present unbalance, misalignment, among others. Due to its importance in the productive sector, it is important that they are properly monitored in order to avoid interruptions in production and operational disasters. This work aims to study and develop an embedded system to diagnose broken bar fault and dynamic eccentricity in the induction motor making through current signature analysis (MCSA). The embedded system must be able to perform real-time monitoring of the TIM, allowing decisions to be made before the full equipment breakdown. The installation of the system in the motor should be completely non-invasive and can be performed while the motor is running. In addition, the embedded system performance studies will be performed to verify the processing latency and study the feasibility of integrate the embedded system on a wireless sensor network for fault diagnosis.*

Keywords: *Fault analysis , embedded systems, current signature analysis*

1. INTRODUCTION

In mechanical maintenance, it is considered as an equipment failure the situation in which the equipment cannot be used or cannot maintain an adequate quality production. In this case, the failure is considered a situation in which the equipment does not fulfill its function. Fault refers to a condition of the equipment, different from the condition it was designed for (a crack, for example), that may be or maybe not cause a failure on the equipment. In this case, the fault is considered equipment's disability, although, it does not necessarily ceases to fulfill the function for which it was designed for (Fujimoto, 2005).

The electrical motors are manufactured for a wide range of application, such as: pump driver, compressors and cargo handling. The Industrial engines are usually driven by electrical motors that can, with its use, present fault indications, which usually are classified according its location. The most commons faults are: stator failure, failure of the rotor and on the bearing. Theses faults are mechanicals by nature, however they may present a behavior variation on the electrical variables of the motor and can occur due to external situation, such as productions and assembly errors, or due to its incorrect operation (Reis, 2010).

The presence of any kind of fault in induction motor, for example, may cause interaction flux changes between the stator and the rotor, resulting in changes on the stator current, voltages, magnetic field, machine vibration, operation temperature, audible noises, among others (Reis, 2010). The faults can be subdivided according its internal source (rotor faults, broken bars, air-gap eccentricity, damaged bearings, misalignment, etc.) or external (mechanical overload, pulsing load, phase imbalance, undervoltage, overvoltage, etc.) (Lamim Filho, 2012).

Fault detection in electrical motor have been widely discussed over the last decades until today, the subject offers outstanding contributions in relation to more efficient monitoring by current signature analysis. Such as, failure investigation in the rotor bars (Didier *et al.*, 2007); unbalance detection, and misalignment (static and dynamic eccentricity) in the machine coupling (Dorrell et al., 1997); and bearing failures (Schoen *et al.*, 1995).

Traditionally, the energy and fault detection monitoring in industrial systems is s conducted offline or through wired networks. The connection of cables and sensors usually have a higher cost than the cost of the sensors themselves (Lu e Gungor, 2009). Besides the high cost, the approach wired offers little flexibility, making deployment and maintenance of the system difficult. In this context, wireless networks present a series of advantages over wired networks such as the ease and speed of implementation and maintenance, and lower cost. (GOMES, 2013). Moreover, wireless sensor networks (WSN) allow self-organization and local processing capability. Therefore, these networks appear as an advantageous and inexpensive solution to build monitoring industrial control systems (Chafik, 2014, 2013 Wan, 2013).

However, the use of WSN in developing automation systems for industrial environments, presents a number of challenges that must be overcome. Wireless networks have an unreliable communication, which can be aggravated by noise and interference in the communication spectrum band (Gomes, 2012). Studies on the application of WSN in industrial environments, aimed at replacing wired systems have been widely explored in recent years

This study presents an embedded system to determine dynamic eccentricity faults in industrial electric motors, with communication through a wireless sensor network. Fault detection results are sent to a base unit for real-time monitoring. Thus, preventive action can be taken where adverse conditions are detected.

2. TESTING WORKBENCH

In Figure 1 is shown a workbench designed and built in the laboratory to perform tests of mechanical failures. The workbench consists basically in a Three-Phase Induction Motors (TIM) with its drive system, the load control system comprising a DC generator; and electrical and mechanical measuring instruments. The workbench contains an induction motor [5], triggered via frequency inverter [7] and coupled to the torque transducer [3]. The DC generator [2] has in his armor terminal a resistors bank to dissipate the energy generated by the movement. The DC generator field winding is fed through a rectifier circuit with a variable voltage [1].

Figura 1. Workbench

The projected workbench is able to apply a known constant load to the TIM axis, easily ranging from zero to torque values above the nominal. The TIM is driven, in addition to the direct starting, by frequency inverter, so one can vary the motor power supply frequency, thus changing the low speed to high speed.

The installation of the embedded system is relatively simple, it must be installed on the switchboard where the motor drive is. It is possible, thereby, measuring the voltage and electric current input, without the need to install anything directly on the motor.

Initially, the voltage and electric current are acquired and converted to a digital data. After the conversion, data processing is performed and failures, if present, are diagnosed. The results are sent to a central station via a wired or wireless interface.

Internally the device consists of three circuits: a power supply board, sensor and signal conditioning board, and the main one, the conversion, data processing and transmission of signals board (PCPD). The simplified schematic of the embedded system, designed in the laboratory, is illustrated and shown in Figure 2.

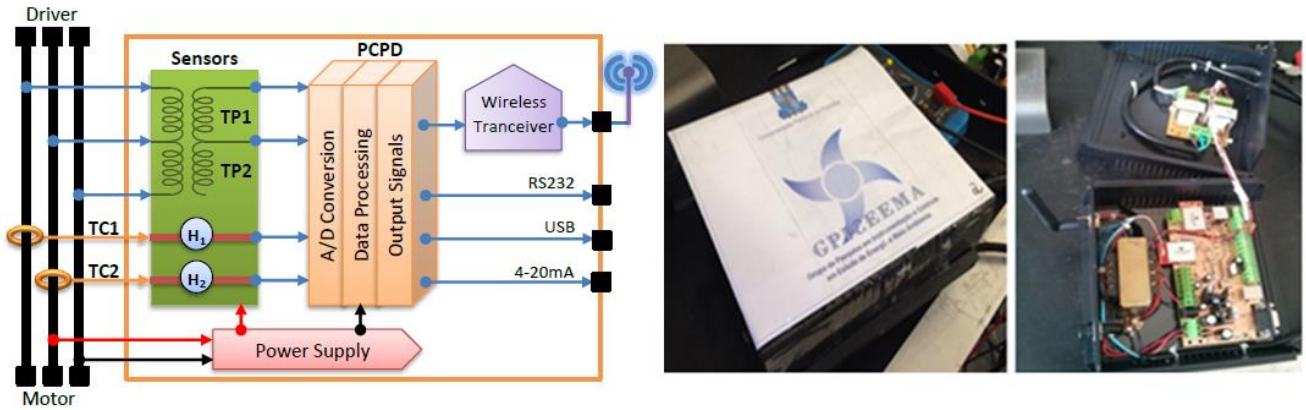


Figura 2. Diagram and Picture of embedded system

The Figure 3 illustrates in detail the bottom of the system. The toroidal transformer [2] reduces the 380V voltage to 9 V, in the electronic board this voltage is rectified and used for power all the electronics. In the microprocessor board [4] is possible to see two transceivers RF [3], USB interface [7], RS-232 interface [8], and communication through the RJ-12 plug [5] for in-circuit programming the microcontroller. The sensor board sends measured values to the microcontroller A / D converter, responsible to perform calculations for diagnostic and transmit the desired signal using the wired communication or wireless transceivers [3] with the aid of an antenna external [1].

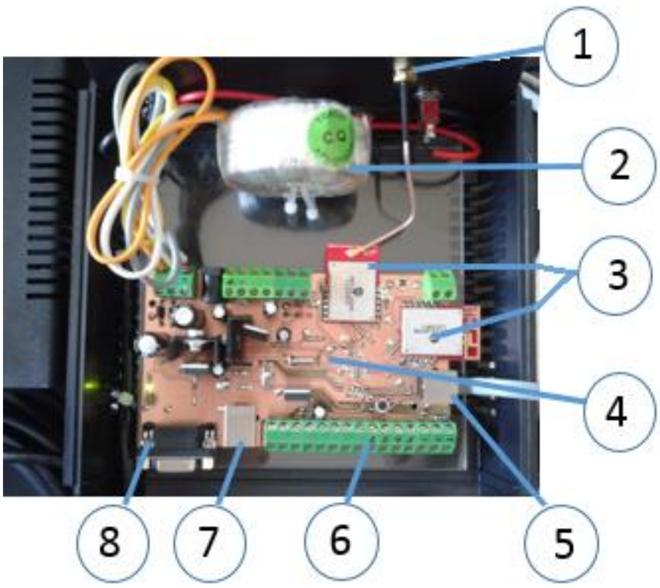


Figura 3. Embedded systems SEMMIT in details.

3. FAULT DETECTION METHOD FROM THE ANALYSIS OF STATOR CURRENT

The Motor Current Signature Analysis, MCSA is a non-invasive technique for problems diagnostic problems induction motors. It consists in current signal the use of spectrum one of the stator phases and a standard procedure for analysis of specific harmonics. When a fault is in development, the current frequency spectrum becomes different from the motor spectrum when in good operating conditions. Such failures modulate the motor air gap and produce harmonic frequencies in the self-inductance and mutual inductance of the machine. Once the flux oscillates only at the power frequency, theses harmonics inductances result in sidebands to the frequency line (7).

Dynamic eccentricity failures is undoubtedly the major cause of vibration in rotating machinery. This phenomenon is characterized by the existence of mass imbalances in relation to the axis of rotation. Such imbalances are inevitable caused by asymmetries, tolerances and deviations in shape, in addition to the imperfections of the raw material and assembly. The resultant vibration is predominantly radial, strong component one times the rotation frequency (1 x fr) with stable phase. The two bearings are phased to the static unbalance and out of phase for dynamic unbalance (9).

The presence of static or dynamic eccentricity can be easily detected by the use of MCS technique. The equation that describes the frequency components of interest for the failure detection is given by:

$$f_e = f\left[(kR \pm n_d)\frac{(1-s)}{p} \pm v\right] \quad (1)$$

Wherein nd is the eccentricity order, assuming values to nd = 0 to the situation of static eccentricity and nd = 1, 2, 3… to the dynamic situation, f is the fundamental supply frequency, R is the rotor slot number, s is the slip, p is the pole-pairs number, k is a constant, and v is the harmonic order present in the motor supply (v = v = ±1, ±3, ±5…). However, if static and dynamic eccentricities coexist, it can be observed components near the fundamental frequency.

$$f_1 = |f \ \pm k.f_r|, \quad k = 1,2,3,\ldots \quad (2)$$

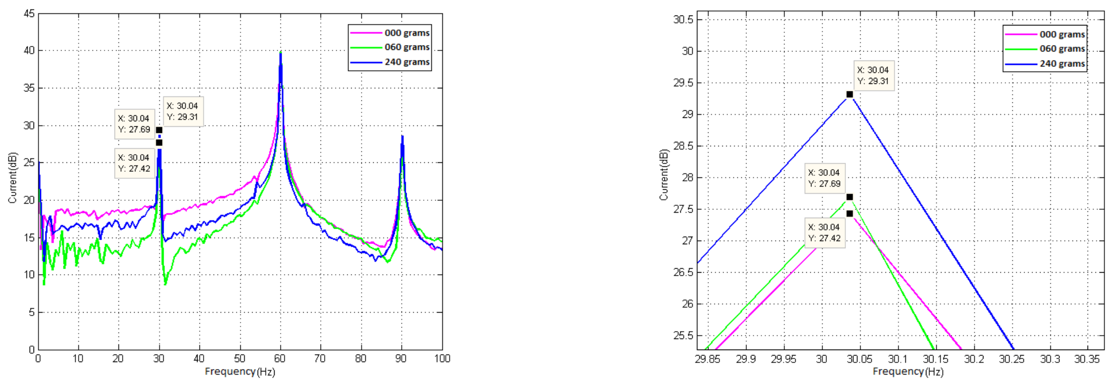
Wherein f is the supply fundamental frequency, and fr is the rotor frequency. For dynamic eccentricity fault analysis, one calculates the harmonic frequency on the dynamic eccentricity by using Equation (1), considering k = 0, nd = ± 1 and v = 1. The severity of failure is classified from the harmonic amplitude, in dB, located in the motor current signal spectrum.

4. RESULTS

Will present and discuss the first experiments for analysis of dynamic eccentricity faults in induction motors using the MCSA technique. The failure detection processes presented in this paper were carried out online and offline. Electrical current, voltage, and rotor speed were acquired through Hall Effect sensors, power transformers and encoder, respectively.

For the data obtained in the time domain was used Fast Fourier Transform (FFT) to allow the analysis in the frequency domain. The tests were divided regarding the presence of mechanical coupling, load, and weights inserted into the motor shaft (dynamic eccentricity). For analysis of this type of failure, one calculates the frequency of the harmonics caused by the dynamic eccentricity using equation (1), considering k=0, nd = ±1 e v =1. Then it is identified the severity of the fault from the harmonic amplitude, in dB, on the left sideband motor current signal spectrum.

The first experiment (Figure 4) was performed with the motor coupled to the mechanical system and a load, 0 Nm, applied on the motor shaft for unbalance three conditions (0, 60, 240 grams). The eccentricity level observed for a frequency calculated in 30.04 Hz was, 27dB, 42 dB, 27.69dB and 29.31dB for 0, 60 and 240 grams of mass inserted on the side of the motor shaft, respectively.



(a) (b)

Figura 4. (a) Mechanical System Coupled– Load: 0 Nm – Mass coupled to axis: 00g; 60g; 240g (b) Plot Detail

In the experiment with the motor coupled to the mechanical system with DC generator and a load of 10 Nm applied to the motor shaft for two unbalance conditions (Figure 5), t eccentricity level observed for a frequency calculated 30.77 Hz was 20.88dB and 23.96 dB for 240 and 360 grams of mass applied to the motor shaft, respectively.

Tests were also carried out with the engine idling (Figure 6). The eccentricity level observed for a frequency calculated 30.04 Hz was 18.33 dB and 22.08 dB for 10 and 40 grams of added mass on the side of the motor shaft, respectively.

Also load variation tests were performed as illustrated in Figure 7. Carrying a mass of 60 grams unbalancing the motor shaft and a load applied of 0, 10 and 25 Nm, the eccentricity level observed was 19.88 dB, 23.56 dB and 25.36 dB for frequencies of 30.77 Hz, 31.5 Hz and 25.36 Hz, respectively.

The firsts online acquisitions experiments (Figures 8 and 9) were performed with the engine coupled to the mechanical system and a load applied to the motor shaft of 0 Nm to 20Nm with a 50 grams unbalance condition in the motor shaft. In Figure 9a the eccentricity level observed at a frequency of 29.33 Hz was 0.1992 A and 2.326 A for the fundamental frequency of 58.65 Hz. In the Figure 9b for a load of 20 Nm applied to the motor shaft and the unbalance condition of 50 grams. The eccentricity level observed at a frequency of 29.33 Hz, was 0.09333 A and 5,635 A for the fundamental frequency of 58.65 Hz.

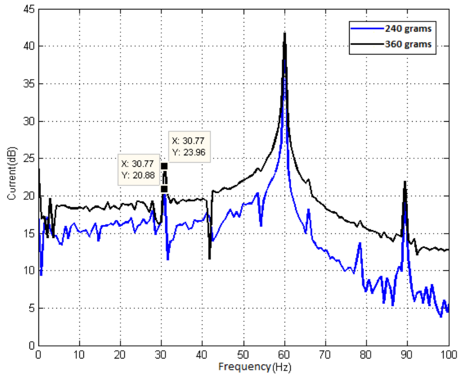


Figura 5. Mechanical System Coupled
Load: 10 Nm - Weight: 240 e 360g

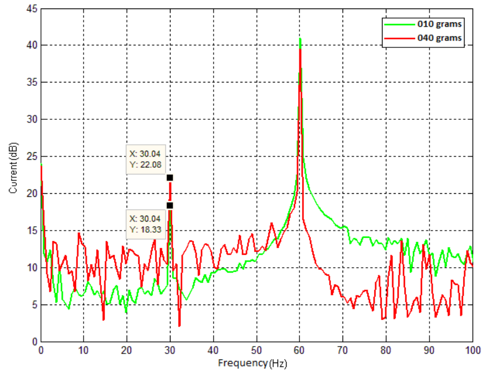
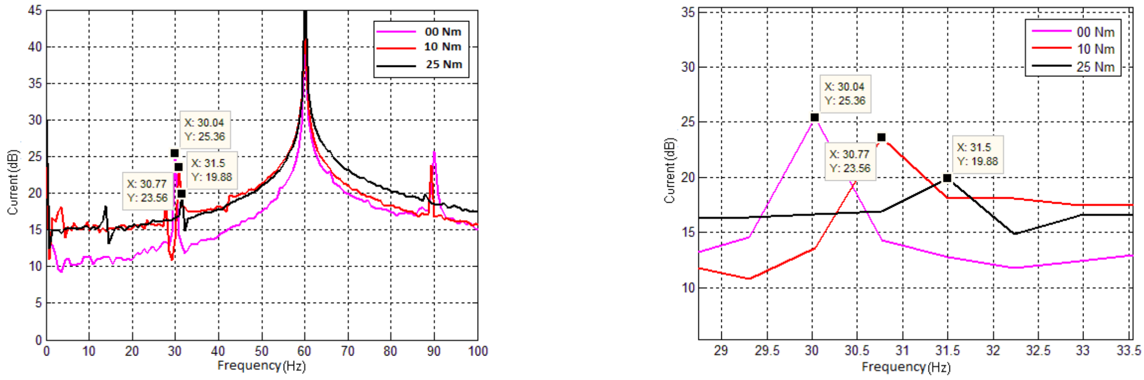


Figura 6. Motor no load- Weight: 10 and 40g

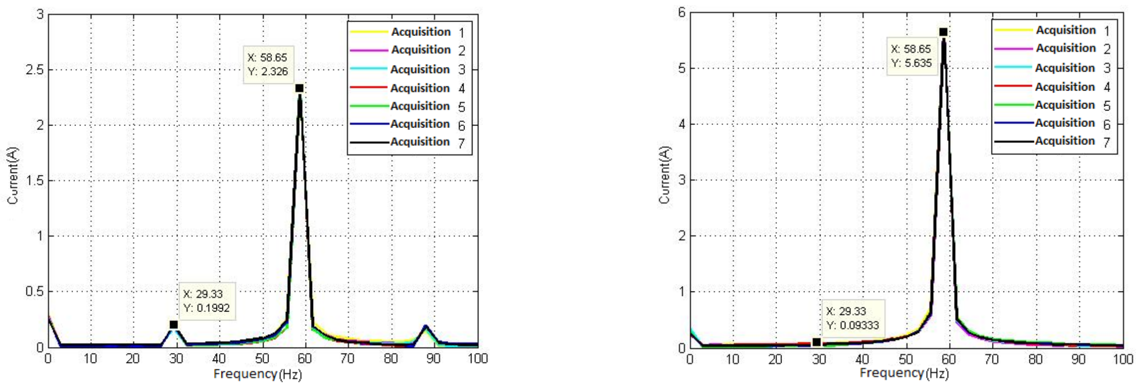
In Figure 9, the same test is illustrated with the eccentricity level in dB. As can be seen it was obtained an eccentricity level of -7,008dB and -10,92dB (29,33Hz), absence (Figure 9a) and presence (Figure 9b) load (20Nm), respectively, and the fundamental frequency (58,65Hz) in 3,621dB unloaded and 7,509dB load.



(a) (b)

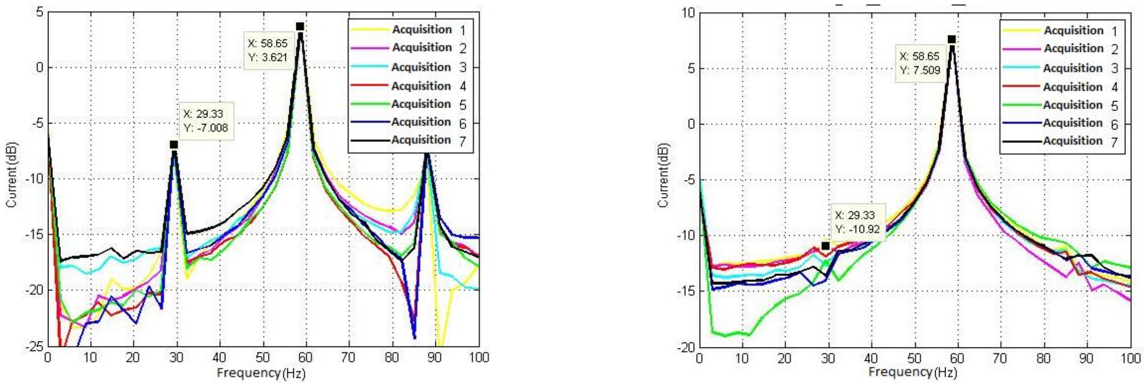
Figura 7. (a) Coupled Mechanical System Actuation
Load Variation: 00, 10 e 25 Nm – 60 grams (b) Plot Detail

In Figure 10 the online test is illustrated with the eccentricity level in dB. As can be seen there is an inconsistency between the mass applied to the shaft in the engine and the amplitude of the left sideband. This phenomenon is due to the type of coupling in which the engine is subjected, but the real reasons for getting this kind of response are still under investigation.



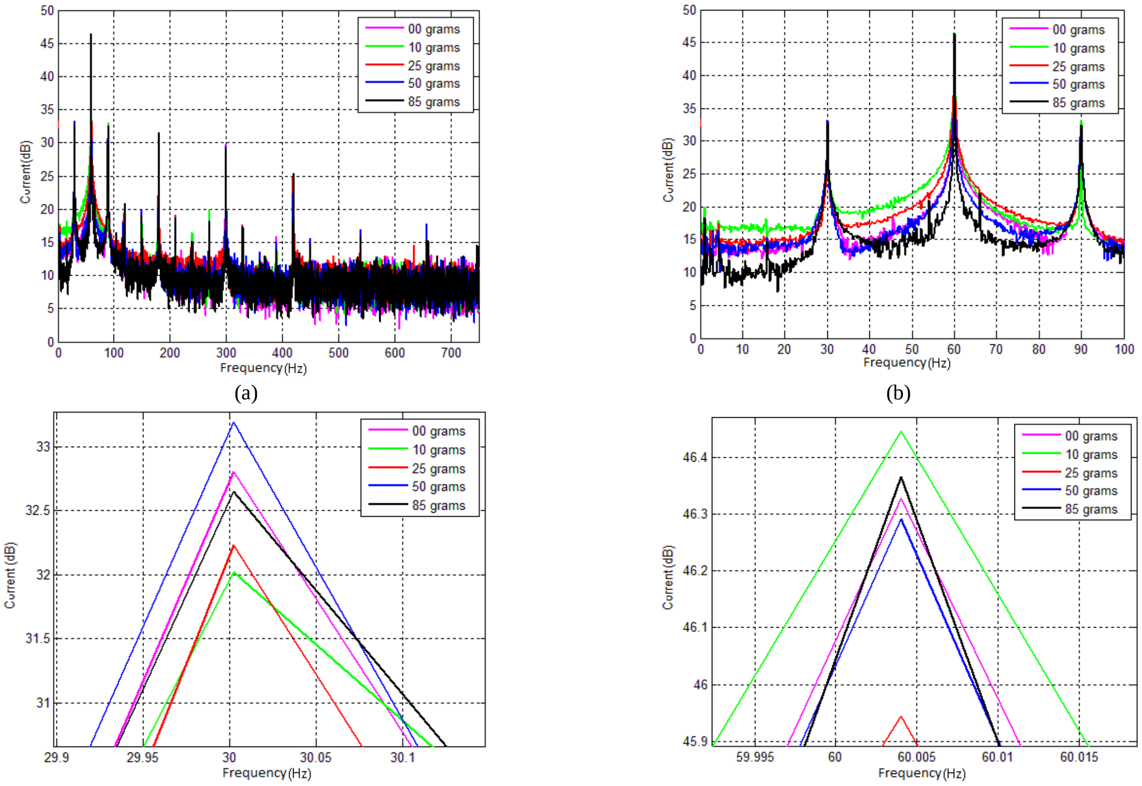
(a) (b)

Figura 8. Coupled Mechanical System Actuation– Axis Coupled Mass: 50g
(a) Load: 0 Nm **(***online***)** (b) Load: 20 Nm (*online***)**



(a) (b)

Figura 9. Coupled Mechanical System Actuation in dB– Axis Coupled Mass: 50g
(a) Load: 0 Nm **(*online*)** (b) Load: 20 Nm (*online***)**



(a) (b) (c) (d)

Figura 10. Coupled Mechanical System Actuation in dB– Axis Coupled Mass: 0, 10, 25, 50 e 85g – Load: 0Nm
(a)Current Spectrum - 0 to 750Hz; (b) Current Spectrum - 0 to 100Hz; (c) Plot Detail in 30Hz; (d) Plot Detail in 60Hz

5. CONCLUSION

In this paper the initial results were presented from the analysis of dynamic eccentricity faults in three phase induction motors. The experiments were conducted online and offline.

The embedded system (online) and instrumentation used with current sensors, voltage, rotor speed, processing and wired communication and data acquisition board (off-line), NI-DAQ, was efficient and suitable for the application, despite its limitations.

The results shown in Figure 4 with the engine coupled to the mechanical system (dc generator + torquemeter) and without applied load shown that there is a consistency between the insertion of the amplitude weights and the left sideband. However, the results with the engine coupled to the mechanical system and a 10 nm load concluded that it was possible to observe an increase of 3.08 dB by adding 120 grams of weight to the motor shaft (Figure 5). The results with the no-load motor concluded that it was possible to observe an increase of 3.75 dB by adding 30 grams of weight to the motor shaft (Figure 6). With variation of load applied to the motor shaft (Figure 7) it was observed that for the same mass (60 grams) applied to the motor shaft, there being an increased load, the left sideband amplitude decreases, while the peak of fundamental frequency increases, it is still observed a shift of the peaks from left side to right side, this means a reduction of the machine shaft rotation speed. Satisfactory results are observed. In Figures 8 and 9 the same test is illustrated with the eccentricity level in amperes and dB. As noted, for analysis in dB, an eccentricity level in -7,008dB and -10,92dB with absence and presence load (20Nm) at a frequency of 29.33 Hz, respectively, and fundamental frequency (58,65Hz) in 3,621dB without load and 7,509dB with a load, i.e., there was a reduction of 3.912 dB on the left side band. In Figure 10 (online processing) was observed an inconsistency between the mass applied to the shaft in the engine and the amplitude of the left sideband. This phenomenon is due to the type of coupling in which the engine is subjected, but the real reasons are still being investigated to obtain this type of response. A limitation of online analysis concerns the amount points (1024) used for calculating the FFT, for the analysis with embedded system the desired resolution would be obtained with 4096 points, however this amount was the maximum achieved so far due to limitations on the microcontroller memory, however, the possibility to increase the resolution using the same microcontroller is under investigation. This work is in development and has great capacity for growth. To continue working broken bars fault testing and bearing failures will be performed as well, will be implemented in dsPIC, the Wavelet Transform for the analysis and monitoring the evolution of these malfunctions.

6. REFERENCES

Almeida, M. T., Góz, R. D. S., Silva H. A., Lopes J. A. R. Análise de vibrações magnéticas em motores elétricos de indução trifásicos. Revista Manutenção, v.46, 1944.

Chafik, A. Architectures de Reseau de Capteurs pour la Surveillance de Grands Systemes Physiques a Mobilite Cyclique. Tese de Doutorado em Ciências, especialidade Automação, Análise de Sinais e Engenharia de Informática. Universidade de Lorraine. França.

Didier, G.; Ternisien, E.; Caspary, O.; Razik, H., 2007. “A New Approach to Detect Broken Rotor Bars in Induction Machines by Current Spectrum Analysis”. Mechanical Systems and Signal Processing, vol. 21, pp. 1127–1142.

Dorrell, D. G.; Thomson, W.T.; Roach, S, 1997. “Analysis of Airgap Flux, Current, and Vibration Signals as a Function of the Combination of Static and Dynamic Airgap Eccentricity in 3-Phase Induction Motors”. IEEE Transactions on Industry Applications, vol. 33, nº 1, pp. 24 - 34.

Fujimoto, R.Y., 2005. “Diagnóstico Automático de Defeitos em Rolamentos Baseado em Lógica Fuzzy”. Dissertação de mestrado em Engenharia Mecânica, Escola Politécnica da Universidade de São Paulo, São Paulo, SP, Brasil.

Gomes, R. D., 2012. Redes de Sensores Sem Fio Aplicadas ao Monitoramento de Motores em Ambiente Industrial, Dissertação de Mestrado em Ciências da Computação. UFPB, João Pessoa, PB.

Lamim Filho, P.C.M., 2012. “Detecção de Falhas no Estator da Máquina de Indução Ttrifásica Através da Analise de Vibração e Fluxo”. In: VII Congresso Nacional de Engenharia Mecânica – CONEM, 2012, São Luiz, MA. Anais do VII Congresso Nacional de Engenharia Mecânica – CONEM 2012.

Lima-Filho, A. C.; Gomes, R. D.; Adissi, M. O.; Silva, T. A. B.; Belo, F. A.; Spohn, M. A., 2012. “Embedded System Integrated Into a Wireless Sensor Network for Online Dynamic Torque and Efficiency Monitoring in Induction Motors”. IEEE/ASME Transactions on Mechatronics , vol. 17, p. 404-414.

Lu, B., Gungor, V. C., 2009. “Online and Remote Motor Energy Monitoring and Fault Diagnostics Using Wireless Sensor Networks”. IEEE Transactions on Industrial Electronics, vol. 56, n. 11 (nov.), pp. 4651-4659.

Nandi, S.; Ahmed, S.; Toliyat, H. A., 2001. “Detection of Rotor Slot and other Eccentricity Related Harmonics in a Three Phase Induction Motor with Different Rotor Cages”. IEEE Transactions on Energy Conversion, vol. 16, nº 3, pp. 253 - 260.

Obaid, R. R.; Habetler, T. G.; Gritter, D. J., 2000. “A Simplified Technique for Detecting Faults using Stator Current in Small Induction Motors”. In Proceeding of the 35th Annual Meeting and World Conference on Industrial Application of Electrical Energy.

Reis, A.J.S., 2010. “Reconhecimento de Padrões de Falhas em Motores Trifásicos Utilizando Redes Neurais”. Dissertação de mestrado em Engenharia Elétrica. Universidade Federal do Rio Grande do Norte. Natal, RN, Brasil.

Salvadori, F., Campos, M., Sausen, P. S., Camargo, R. F., Gehrke, C., Rech, C., Spohn, M. A., Oliveira, A. C., 2009. “Monitoring in Industrial Systems Using Wireless Sensor Network With Dynamic Power Management”. IEEE Transactions on Instrumentation and Measurement. vol. 58, n. 9 (Sept.), pp. 3104-3111.

Schoen, R. R.; Habetler, T.G.; Kamran, F.; Bartheld, R. G., 1995. “Motor Bearing Damage Detection Using Satator Current Monitoring”. IEEE Transactions on Industry Applications, Vol. 31, Nº 6, pp. 1274 – 1279.

Wan, Y., Wu, W., Zhang, X., Yang, B., Gong, Z., 2013. “MRM: Wireless Sensor Network for Online Milling Roller Monitoring in Harsh Industrial Environment”. Sensors & Transducers, Vol. 155, Issue 8, August 2013, pp. 1-9.

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