

PREDICTIVE MONITORING OF INDUCTION MOTORS VIA MAGNETIC FLUX ANALYSIS

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Abstract. *The diagnosis of defects with the analysis of magnetic flux has been considered for equipment manufactures of the machine monitoring area. However, this technique has not been deep for researches. Through preliminary studies already some advantages have been found in relation to the conventional techniques of current analysis, as for example, not necessity of knowledge of the motor load, the number of bars and slots for the detection of turn-to-turn short circuit in the stator. This work considers the exploration of this technique for the detection of electric faults in three-phase induction motors. Theoretical and practical aspects, as well advantages and advantages of the method considered are discussed from the application of this method in the diagnosis of faults introduced in a workbench of tests, composed by an electric motor of 5 CV, 4 poles and controlable mechanical load.*

Keywords: *three-phase induction motors, magnetic flux, predictive maintenance*

1. INTRODUCTION

A modern predictive maintenance program for electric motors must include several monitoring techniques in order to observe their operational performance parameters, such as temperature, electric current, flux, torque, etc. Concerning these techniques, probably the two most classic ones are related to electric current and vibration analysis.

Unfortunately, in both cases inherent drawbacks make their use in loco on industry plants difficult. As there is a large range of possible fault sources and abnormal machine use conditions (such as broken rotor bars, unbalanced voltage supplies, inter-turn short circuits conditions, etc.) the determination of the real machine problem is difficult.

Machinery monitoring manufactures proposed the diagnosis of these excitation sources by analyzing the equipment magnetic flux.

In the last twenty years several researches have been developed seeking the detection and diagnosis of faults in three-phase induction motors Almeida (1996), Joksimovic (1999), Finley (2000), Brito (2001), Benbouzid (2001), Benbouzid (2003) Lamim Filho (2003), Henao (2003), Lamim Filho (2004), Baccarini (2005), Silva (2006), Lamim Filho (2006), Lamim Filho (2007). However, one of the researchers' difficulties is to distinguish faults as: inter-turn short circuits, unbalanced voltage supplies and rotor eccentricity, Lamim Filho (2007).

The detection of faults through the comparison of spectra of magnetic flux when they are still in development phase makes possible to the maintenance engineer to plan a corrective action regarding the foreseen fault.

The motors can be exposed to different types of aggressive environment and inappropriate operation. Different internal motor faults (e.g., short circuit of motor leads, interturn short circuits, ground faults, worn out/broken bearings, broken rotor bars) along with external motor faults (e.g., phase failure, asymmetry of mains supply, mechanical overload, blocked rotor, underload) are expected to happen sooner or later Altug *et al.* (1999). Beside it, the degradation of the electric motors isolation can be accelerated if the motor operates in aggressive environments, turning it still more susceptible to incipient faults Boothman *et al.* (1974), Cambrias (1988), LaForte (1988), Schump (1989), Tavner e Penman (1989), Mishra *et al.* (1999), Benbouzid (1999), Riley *et al.* (1999).

If the incipient faults or the gradual deterioration are not detected, they can provoke the break down of the motor causing damages and upsets. Several faults can be avoided if the application, work condition and origin of the faults be understood, Lamim Filho (2007). In terms of electric motors, the reliability has been growing constantly due the importance of their applications and of the technological progress.

This work considers the exploration of the magnetic flux technique for the detection and diagnosis of the short circuit among spirals fault and this represent most of the electric faults that happen in the motors, Brito (2002), Baccarini (2005), Lamim Filho (2007).

For a better understanding of the relationship fault/sign, the accomplishment of experiments controlled in an experimental bench is indispensable. This way, several experimental tests were done at the Laboratory of Vibrations of UNICAMP (State University of Campinas). An experimental bench was set up, where its robustness guaranteed the repeatability of the tests (short circuit among stators spirals) under the same conditions.

The results were undoubtedly impressive and in a near future the system developed can be adapted and used in real predictive maintenance programs in industries.

2. EXPERIMENTAL TESTS

The experimental tests, “Fig. 1”, was assembled in the Laboratory of Vibrations and Mechanical Projects of the FEM-UNICAMP-Mechanical Project Department.

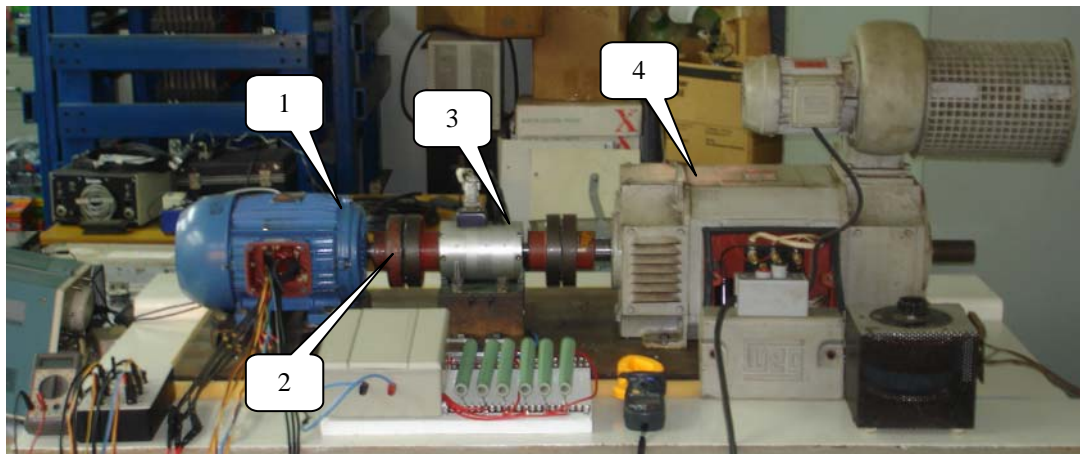


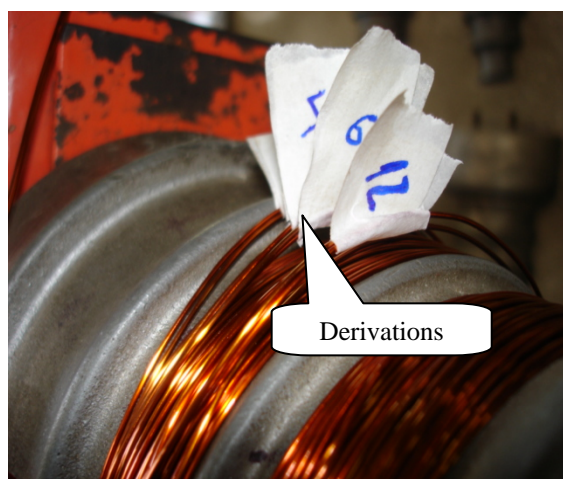
Figure 1. View of the experimental setup.

The faults were inserted in a three-phase motor [1], WEG (FH 88747), squirrel cage rotor, 5 CV, 1730 rpm, 220 V, 60 Hz, 4 poles, category N, 44 bars, 36 slots, SKF 6205-2Z bearing, ID-1, frame 100L, class of insulation B, FS 1,15, I_p/I_n 7,5, IP 55, 13,8 A.

A CC generator [4] feeding by the bank of resistance is used as a load system. Varying the excitement current of the CC generator field, it is obtained, consequently, the variation of the motor load.

The generator is connected to the electric motor through flexible couplings [2] and a torque meter [3] that could guarantee the same operation condition in all the accomplished tests.

To simulate a low isolation, among spirals from a same phase it was extracted four derivations in a coil, “fig. 2a”. Those derivations were disposed externally and linked in series (two each time) with a resistance bank, “fig. 2b”, of 1Ω , 100 Watts (each one) connected in parallel and added to the circuit in order to control the current intensity of short circuit in approximately 10 A, always staying the nominal load of the motor.



(a) Derivations in a coil



(b) Resistance bank

Figure 2. Recoiling of the induction motor.

Each coil is constituted by 26 turns with the diameter wire equal to 16. As each phase is formed by 6 coils, so the total of turns for each phase is equal to 156.

Therefore the configuration allows to analyze low isolation (short circuit) among, at least, two turns and, in the maximum, 10 turns for the phase A corresponding to the percentages of 1,2% (2/156) and 6,4% (10/156) of low isolation.

2.1. Flux sensor

A transducer is characterized by a capable device to respond to the physical phenomenon, or stimulus, and convert its magnitude in a known electric sign, proportional to the stimulus amplitude. The transducers are also known as signs converter.

For the implementation of the proposed transducer that it will serve as a magnetic flow sensor was necessary the recoiling of the induction motor. Starting from the several visual inspections done inside the electric machines, it was noticed that in most of the motors there is a space in the slots of the stator capable to endure the insert of more two or three spirals in its compartment.

At this way, during the recoiling and after making process all the and isolation of the main coiling, three new coils were inserted, and each of them each containing three turns with diameter of the wire equal to 16 AWG, inside the induction motor and that started to be part of the magnetic circuit of the machine. And these coils were totally isolated of the main circuit. The signs were monitored through an oscilloscope, guaranteeing that the tension levels were inside the allowed band (± 10 V) by the boards and sign collectors found at the market. The visualization of the points where the coils were inserted is showed in Fig. 3.

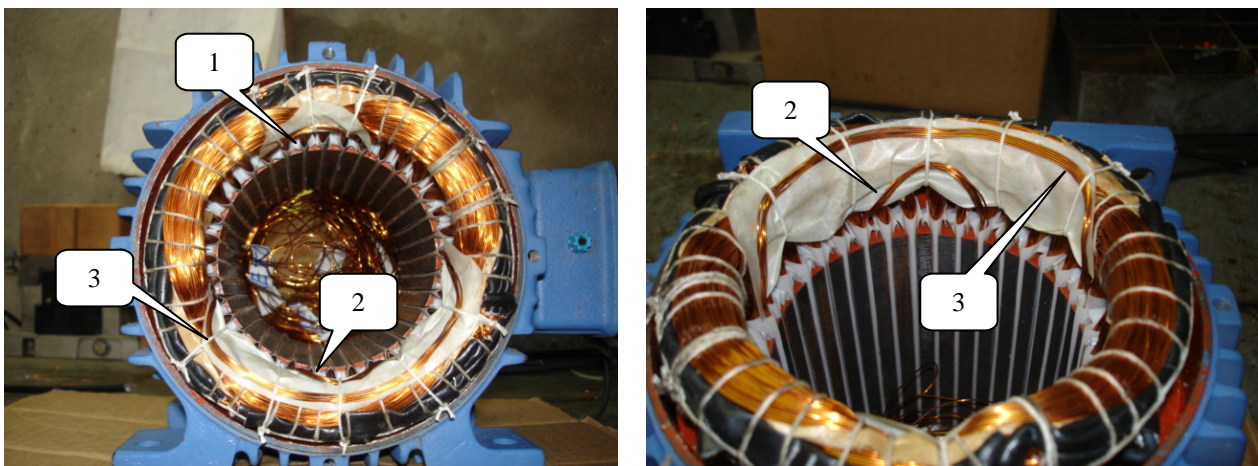


Figure 3. Internal Flux Sensor: Coils 1, 2 and 3 (left) and details of the Coils 2 and 3 (right).

For future comparisons these coils will be a reference during the whole text: coil 1, coil 2 and coil 3 as showed in Fig. 3.

Measuring and comparing the spectrum of the induced tensions in coils 1, 2 and 3 we have the real working condition of the electric motor to be analyzed. In Figure 4 the voltage signals of the coils 1, 2 and 3, that it will be monitored in order to detection faults, is showed.

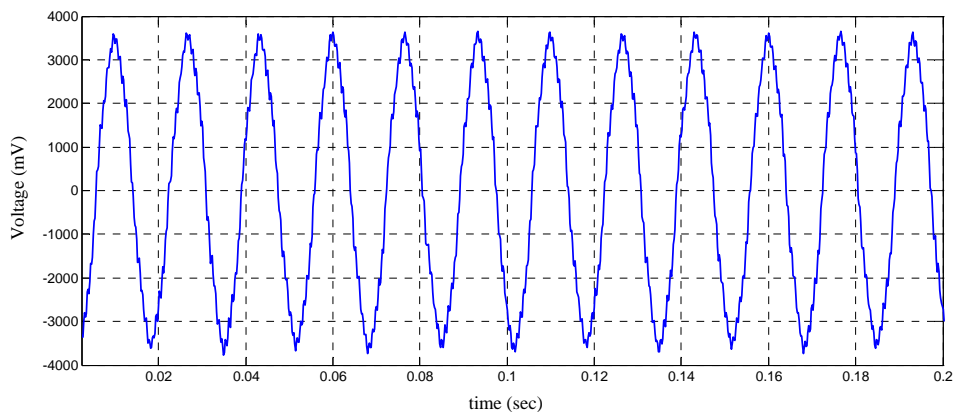


Figure 4. Signal of the sensor: coil 1.

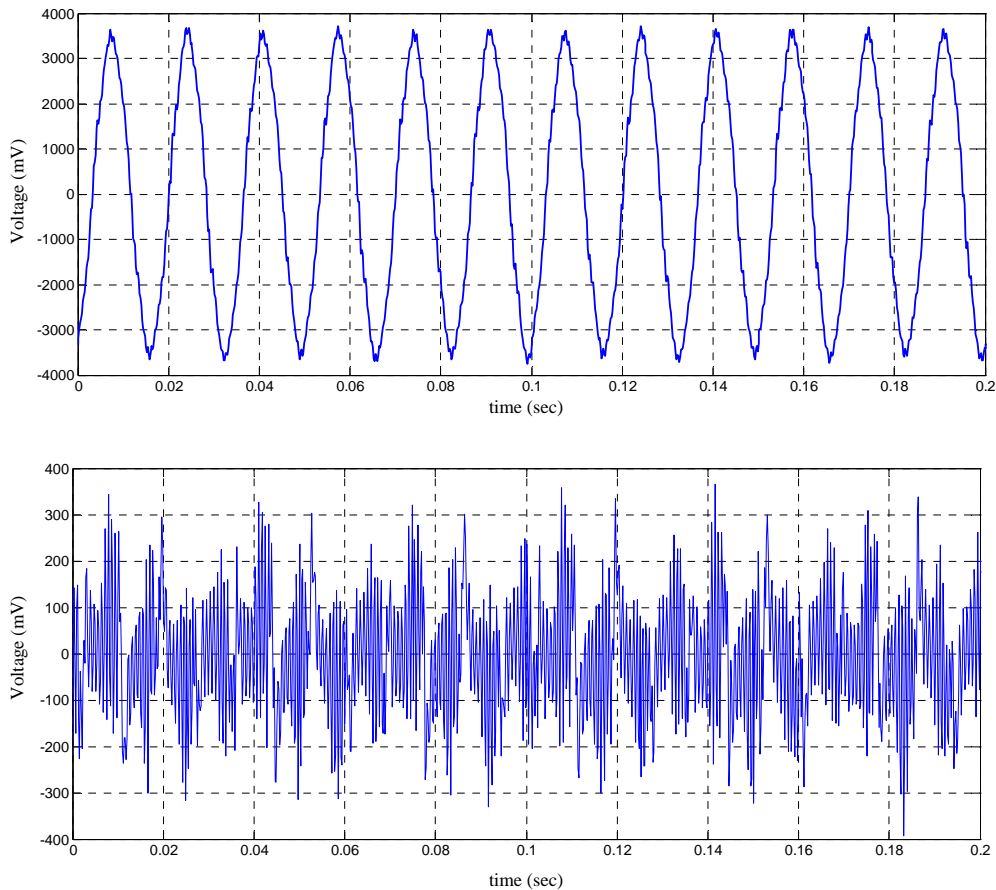


Figure 4 (continuation). Signal of the sensor: coil 2 (top) and 3 (bottom).

3. GENERAL CONSIDERATIONS ON SHORT CIRCUITS

According to Gupta *et al.* (1993), for three-phase motor with n bars, the magnetomotive force (MMF) frequency generated by the current that runs through a rotor cycle with maximum amplitude $I_{r\max}$ can be found by :

$$\begin{aligned}
 F_{loop1}(t, \theta_r) &= \\
 &= \sum_{v=1}^{\infty} \left[K_v \cos(v\theta_r + s\omega_1 t) + K_v \cos(v\theta_r - s\omega_1 t) \right]
 \end{aligned} \tag{1}$$

Where t is the time, θ_r is the angle of rotor position, ω_1 is the mains angular frequency and s is the rotor slip.

$$K_v = \frac{2}{v\pi} \left(1 - \frac{1}{n} \right) \sin \left(v \frac{\pi}{n} \right) I_{r\max} \tag{2}$$

Equation (1) is derived in the rotor reference frame. In the neighboring rotor loop, which is shifted by $2\pi/n$ rad in space, a current of the same frequency and amplitude but phase shifted by $p.2\pi/n$ flows, where p is the number of pole pairs. This loop produces its own MMF which has the following shape, Gojko *et al.* (2000):

$$\begin{aligned}
 F_{loop2}(t, \theta_r) &= \\
 &= \sum_{v=1}^{\infty} \left[K_v \cos \left(v\theta_r + s\omega_1 t - (v+p) \frac{2\pi}{n} \right) + \right. \\
 &\quad \left. + K_v \cos \left(v\theta_r - s\omega_1 t - (v-p) \frac{2\pi}{n} \right) \right]
 \end{aligned} \tag{3}$$

The total rotor MMF is the sum of the MMFs of all the rotor loops and it is given by:

$$\begin{aligned}
 F_r(t, \theta_r) &= \\
 &= \sum_{i=0}^{n-1} \sum_{v=1}^{\infty} \left[K_v \cos\left(v\theta_r + s\omega_1 t - i.(v+p)\frac{2\pi}{n}\right) + \right. \\
 &\left. + K_v \cos\left(v\theta_r - s\omega_1 t - i.(v-p)\frac{2\pi}{n}\right) \right]
 \end{aligned} \tag{4}$$

Equation (4) clearly shows that MMF waves exist only for the cases $v = p$, $v + p = \pm \lambda n$, and $v - p = \pm \lambda n$, $\lambda = 1, 2, 3 \dots$. As v can be only a positive integer, it follows that only for $v = p$ and $v = \lambda n \pm p$ MMF waves exist. Therefore, apart from the basic harmonic of MMF for $v = p$ which is the armature reaction to the basic harmonic of MMF from the stator side, there exists the so-called rotor slot harmonics of order $\lambda n \pm p$ (space harmonics). These MMF waves have the following shape when observed from the stator side:

$$\begin{aligned}
 F_r(t, \theta) &= \\
 &= F_{r1} \cos\left(\left(1 - \lambda \frac{n}{p}(1-s)\right)\omega_1 t + (\lambda n - p)\theta\right) + \\
 &+ F_{r2} \cos\left(\left(1 + \lambda \frac{n}{p}(1-s)\right)\omega_1 t - (\lambda n + p)\theta\right)
 \end{aligned} \tag{5}$$

It can be shown in a similar manner that higher frequency rotor currents, which are a result of higher harmonic flux density waves from the stator side, produce MMF waves which have a similar shape given by Eq. (6).

Multiplying Eq. (5) and Eq. (6) MMF waves with constant air-gap permanent, the flux density waves of the same shape will be obtained. Flux-density waves will induce electromotive forces (EMFs) in the stator windings and these EMFs will generate currents.

$$\begin{aligned}
 F_{r\mu}(t, \theta) &= \\
 &= F_{r\mu 1} \cos\left(\left(1 - \lambda \frac{n}{p}(1-s)\right)\omega_1 t + (\lambda n - \mu p)\theta\right) + \\
 &+ F_{r\mu 2} \cos\left(\left(1 + \lambda \frac{n}{p}(1-s)\right)\omega_1 t - (\lambda n + \mu p)\theta\right)
 \end{aligned} \tag{6}$$

From Eq. (5) and Eq. (6) it is clear that besides the EMF at the base frequency additional EMFs will appear only at rotor slot frequencies $(1 \pm \lambda n(1-s)/p)f_i$ (now, they are time harmonics). These frequency components will be prominent depending on the number of pole pairs of flux-density waves, i.e., MMF waves in (5) and (6), Gupta *et al.* (1993).

Under inter-turn short-circuit conditions a new series of MMF waves will appear, which can be described as:

$$F_{add}(t, \theta) = \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} F_{addk} \cos(\omega_1 t - k\theta) \tag{7}$$

Therefore, there exist MMF and flux-density waves at all numbers of pole pairs and in both directions of rotation. One of these waves is a wave with the same number of pole pairs as the basic flux-density wave in the machine, but with an opposite direction of rotation. This wave has no influence on the stator current spectra because it induces only base frequency current component. As previously discussed, all other waves only induce EMFs and generate currents at rotor slot harmonic frequencies. Therefore, no new frequency component appears in the stator current spectra as a result of a fault in the stator windings, only a rise in the rotor slot harmonic frequencies can be expected, Gupta *et al.* (1993).

These frequency components in $(1 \pm \lambda n(1-s)/p)f_i$, can also be excited by the phase unbalance. It is required than to identify which frequencies will be more sensitive to one or other faults. Now it is possible to make the correct diagnosis of the fault that compromises the motor function.

3. RESULTS

It has been acquired 300 spectra in a series of 50 tests for each excitement (without fault; two, four, six and ten turns short circuits) and randomly repeated under the same load conditions.

The board NI-6251 made by National Instruments was used for acquisition data. This board has 16 analog channels of entrance that can show until 200 kHz and 2 digital accountants of 24 bits each. The analogical entrances have resolution of 16 bits. The signs of coils tension implemented were submitted to an anti-aliasing filter with 2 kHz of cut frequency.

The Matlab software was used for the implementation of the algorithm of data acquisition and diagnosis of faults.

According to Baccarini (2005) it might exist a running time of the motor before the short circuit between turns evolves for short circuit between phase-land and phase-phase what justifies the development of faults detection systems.

Through the analyses of item 3 it can be said that the presence of an abnormality in the rotor circuit and/or in the stator circuit will provide a riot in the magnetic flux density that crosses the air gap machine causing a modification in the reference spectrum and it can be identified through the analysis of the frequencies components $(1 \pm \lambda n(1 - s)/p)f_1$.

The spectrum of the coil 3 magnetic flux for the motor working with 100 % load in the condition without fault is showed in Fig. 5.

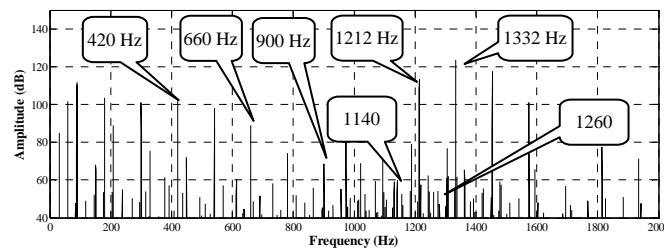


Figure 5. Flux spectrum with the machine operating at rated speed and rated load.

The spectrum of the coil 3 magnetic flux for the motor working with 100 % load and four short-circuited spirals is showed in Fig. 6.

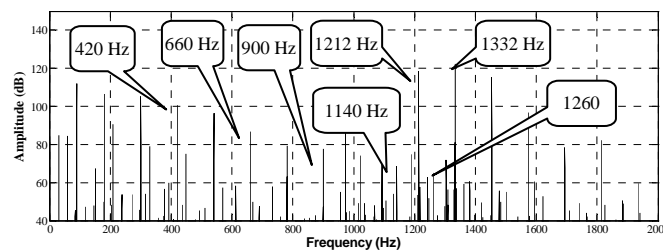


Figure 6. Flux spectrum with four turns short circuited.

In the spectra of magnetic flux of the figures above, it can be clearly observed the harmonics of dependent frequencies of the line frequency, $f_1 = 60\text{Hz}$, (420, 660, 900, 1140 and 1260 Hz). Also, there are harmonics of the main frequency of slot harmonic frequencies $(1 \pm \lambda n(1 - s)/p)f_1$, to $\lambda = 1$, $n = 44$, $s = 0,36$, $p = 2$ and $f_1 = 60$ (1212,48 and 1332,48 Hz).

With the characteristics frequencies of the electric engine, slot harmonic frequencies $(1 \pm \lambda n(1 - s)/p)f_1$ and harmonic of the line frequency $1xf_1$, $2xf_1$, $3xf_1$,..., an extremely meticulous study was carried in order to identify the main frequencies that are excited by the short circuit and unbalance phase.

According to Nandi and Toliyat (2000) the 21st harmonic (1260 Hz) is always present when there is a stator fault. After the comparison of more than 300 spectra of magnetic flux it was possible to verify that the harmonic 19th and the 21st of the line frequency were the most excited by the insertion of the short circuit. Those harmonics will be considered until the end of the text as being characteristic of the fault frequencies.

When comparing the spectra of Fig. 5 and 6 the visualization of the components of slot harmonic frequency that had been most excited by the imperfections of short circuit and unbalance phase becomes extremely difficult.

In front of such difficulty this work proposes the application of the envelope analysis, which is very used in the detection of bearings faults, visualization of the slot harmonic frequency components that had been most excited by the electrical faults.

The procedures conjunction applied to the signal, considering the envelope analysis and that will be applied in the signals of magnetic flux of this work, is shown in Fig. 7.

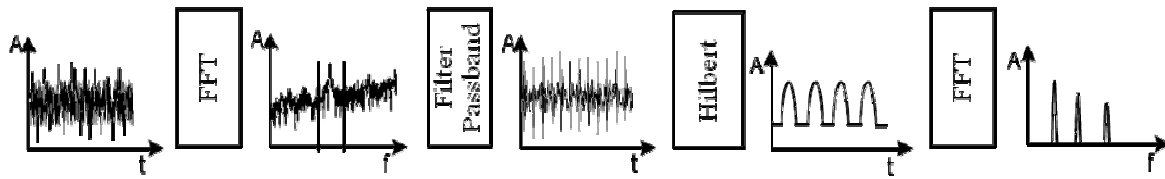


Figure 7. Envelope analysis, Bezerra (2003).

In this way, after the application of the envelope analysis in the band of frequency from 700 to 2000 Hz, there is the spectrum of flux in low frequency where the slot harmonic frequency components become extremely easy to be visualized and comparative ones with the others.

The spectrum of coil 3 magnetic flux, after the application of the envelope analysis for the motor working with 100 % load in the condition without fault is shown in Fig. 8.

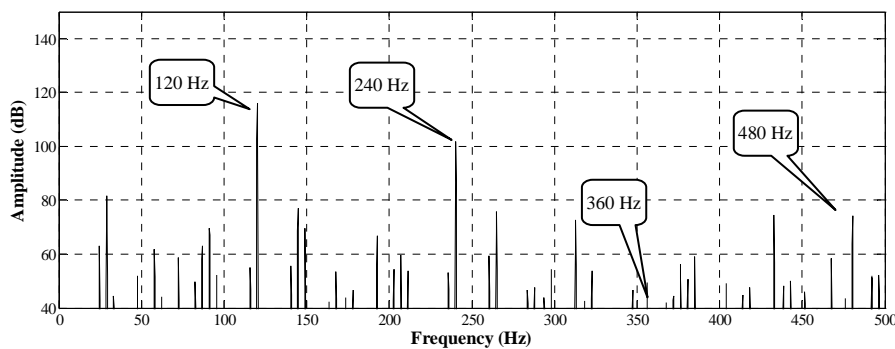


Figure 8. Flux spectrum with the machine operating at rated speed and rated load.

The spectrum of coil 3 magnetic flux, after the application of the envelope analysis, for the motor working with 100 % load and four turn-short-circuited is showed in Fig. 9.

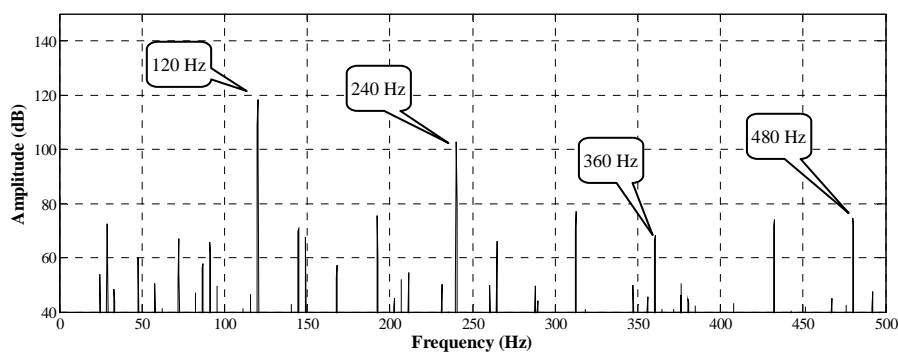


Figure 9. Flux spectra with the machine operating at rated speed and rated load.

In the spectra of magnetic flux of the figures above, the demodulation of the components of slot harmonic frequency can be observed clearly (120, 240, 360 and 480 Hz).

After the comparison of more than 1000 spectra of magnetic flux it could be verified that the components of frequencies demodulated in 360 and 480 Hz had been excited by the insertion of the short circuit and unbalance phases.

So, these harmonics will be considered as being characteristic frequencies for identification of the short circuit and unbalance phase and will be referenced as being 6th demodulated harmonic and 8th demodulated harmonic.

For the coils 1, 2 and 3 the graphs of tendency are shown in Fig. 10, respectively. It was consider the means of the amplitudes of the characteristic frequencies of the fifty tests carried through in the situations without fault, two turns short circuit (sc), four turns short circuit, six turns short circuit, ten turns short circuit and unbalance phase with 100% of load.

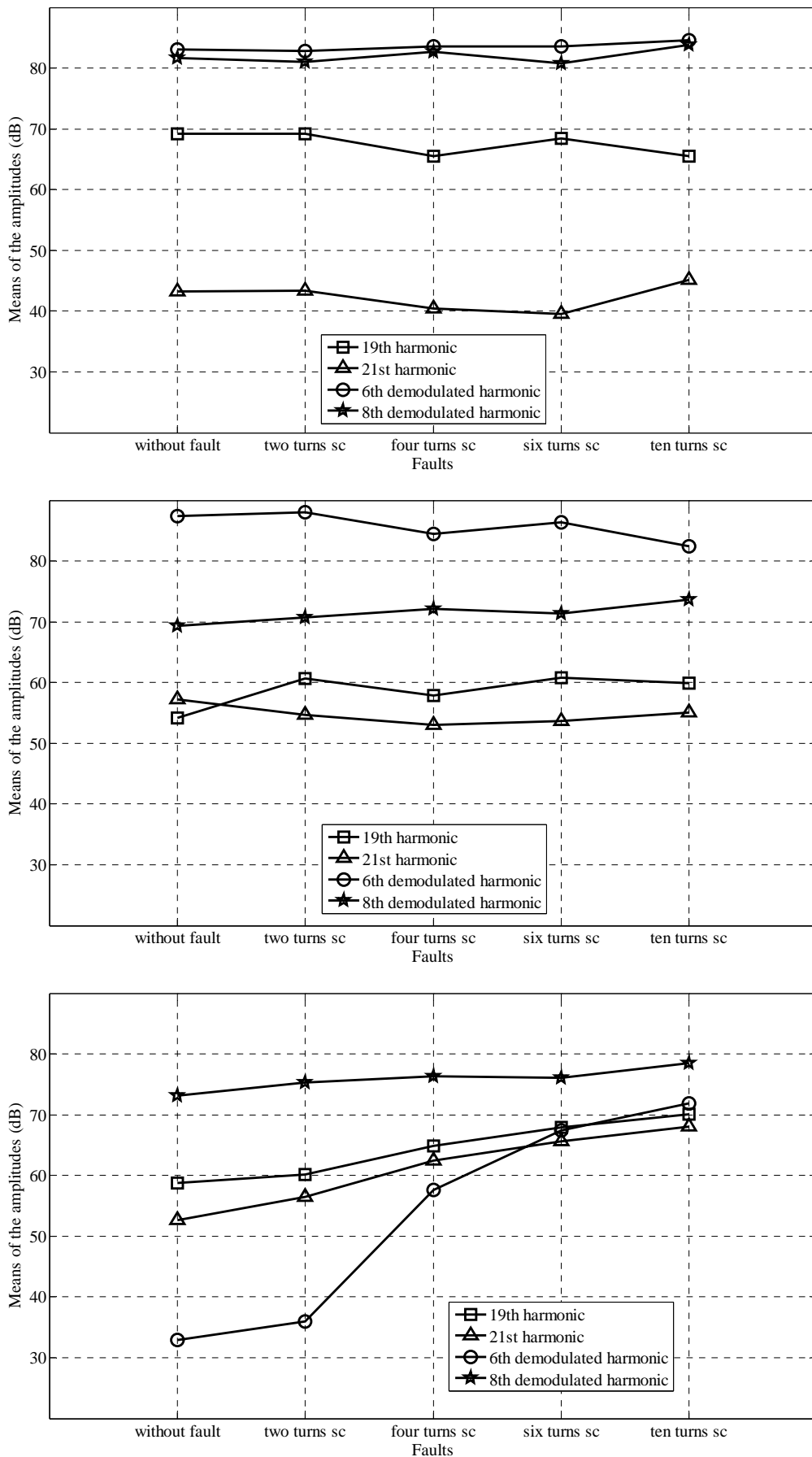


Figure 10. Tendency of introduced faults: coil 1(top), 2 (middle) and 3 (bottom).

4. CONCLUSION

For the analysis of the short circuit only the coil 3 was sensitive to the introduced levels. The coil 3 presented more parameters of analyses, turning the problem identification most visible.

For the short circuit fault it could be observed the same behavior. It can be followed gradually since lower levels that represent only low insulation until higher levels. They can be considered highly harmful to the good machine functioning.

It must be highlighted that one of the most important contributions of this work is the relationship between the signals of magnetic flux and of the main electric origin fault (short circuit) and the determination of characteristic frequencies.

This study is an important contribution mainly if we consider the prices of the implemented sensor that could be hundreds of times cheaper than a commercial sensor. Another advantage in a near future is the substitution of the conventional analyses techniques in electric motors by the spectral analyses in real time. Beside it, using this new magnetic flux sensor, we have the possibility to share it with any signals analyzer or data acquisition boards found in the market.

The results were undoubtedly impressive and the system developed can be adapted and used in real predictive maintenance programs in industries.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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