DETECTION OF LOW INSULATION AND UNBALANCE VOLTAGE IN THREE PHASE INDUCTION MOTORS USING VIBRATION ANALYSIS

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Abstract. *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, low insulation, 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, under load) are expected to happen sooner or later. 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. 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. In terms of electric motors, the reliability has been growing constantly due the importance of their applications and of the technological progress. This work proposes the application of the vibration analysis for the detection and diagnosis of the low insulation between turns and unbalance voltage, and these represent most of the electric faults that happen in the motors. The results showed the efficiency of the vibration technique and their relevance to detect and diagnose faults in induction motors. In this way it's possible to include it in a maintenance programs.*

Keywords*: three-phase induction motors, vibration analysis, predictive maintenance*

1. INTRODUCTION

Induction motors are used worldwide as the workhorse in industrial applications. Such motors are robust machines used not only for general purposes, but also in hazardous locations and severe environments Lamim Filho (2007). General purpose applications of induction motors include pumps, conveyors, machine tools, centrifugal machines, presses, elevators, and packaging equipment. On the other hand, applications in hazardous locations include petrochemical and natural gas plants, while severe environment applications for induction motors include grain elevators, shredders, and equipment for coal plants Lamim Filho (2007), Silva (2006).

Predictive maintenance program must include several techniques of monitoring of electrical motor’s condition. Among these techniques, probably the two most classic ones are related to the electric current and vibration analysis Lamim Filho (2007). Unfortunately, in both cases inherent drawbacks make difficult their use in loco on industry plants. According to published surveys Benbouzid (2003), Baccarini (2005), induction motor failures include bearing failures, inter-turn short circuits in stator windings, and broken rotor bars and end ring faults.

Bearing failures are responsible for approximately two-fifths of all faults. Inter- turn short circuits in stator windings represent approximately one-third of the reported faults. Broken rotor bars and end ring faults represent around ten percent of the induction motor faults, Lamim Filho (2007).

In the last twenty years several researches have been developed seeking the detection and diagnosis of faults in three-phase induction motors Trutt (1993), Almeida (1996), Brito (2002), Henao (2003), Baccarini (2005), Lamim Filho (2007), Nakamura (2008). However, one of the researchers' difficulties is to distinguish faults as: inter-turn short circuits, unbalanced voltage supplies and rotor eccentricity, Lamim Filho (2007), Silva (2006).

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

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, Benbouzid (2003), Baccarini (2005), Lamim Filho (2007).

If the incipient faults or the gradual deterioration are not detected, they can provoke the breakdown 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.

In this work is presented the detection and diagnosis of the inter-turn short circuits in stator windings and unbalanced voltage supplies using vibration analysis techniques, and these represent most of the electric faults that happen in the motors, Benbouzid (2003), Brito (2002), Lamim (2004).

For a better understanding of the relationship failure/sign, the accomplishment of experiments controlled in an experimental bench is indispensable. At this way, several experimental tests were done at the Laboratory of Vibration and Control of UNICAMP (University of Campinas). An experimental bench was set up, where its robustness guaranteed the repeatability of the tests (inter-turn short circuits and unbalanced voltage supplies) under the same conditions and full load. The results showed the efficiency of the vibration technique and their relevance to detect and diagnose faults in induction motors. In this way it's possible to include it in a maintenance programs.

2. EXPERIMENTAL TESTS

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

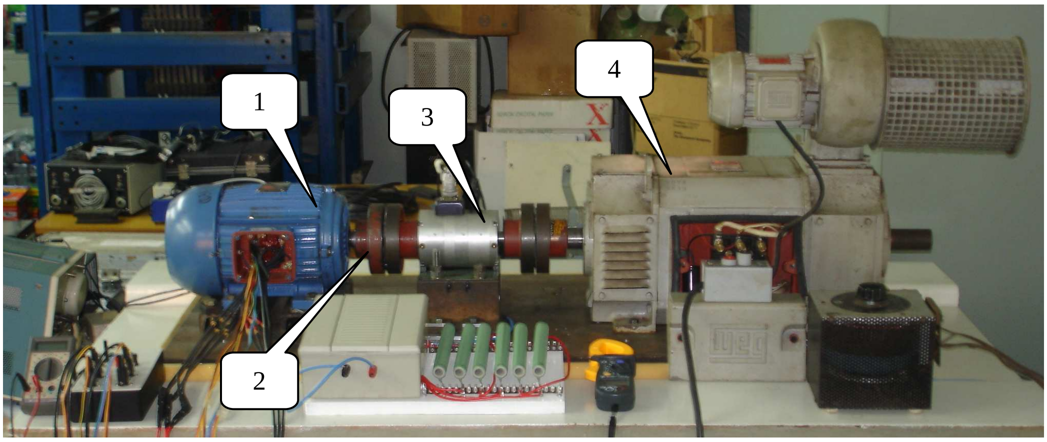


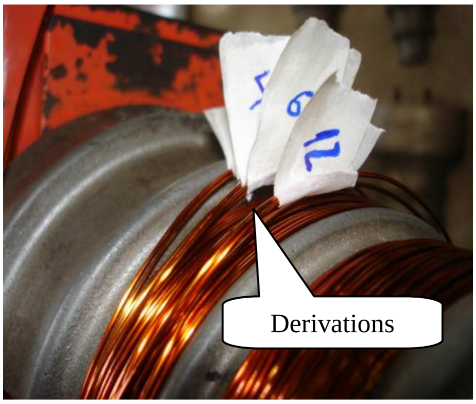
Figure 1. View of the experimental setup.

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, Ip/In 7,5, IP 55, 13,8 A.

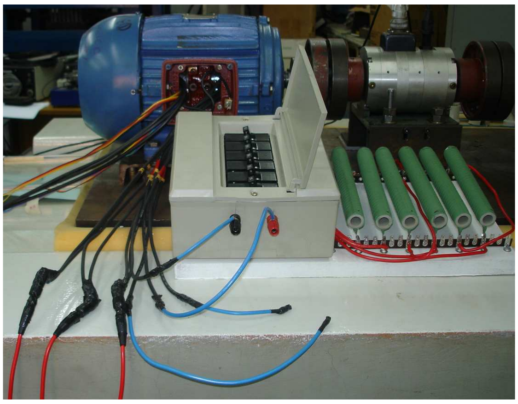
A CC generator [4] feeding by the bank of resistance is used as a load system. Varying the excitement current of the CC generator field, it is obtained, consequently, the variation of the motor load.

The generator is connected to the electric motor through flexible couplings [2] and a torquimeter [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 1 Ω, 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.

The stator winding arrangement is illustrated in Figure 3.

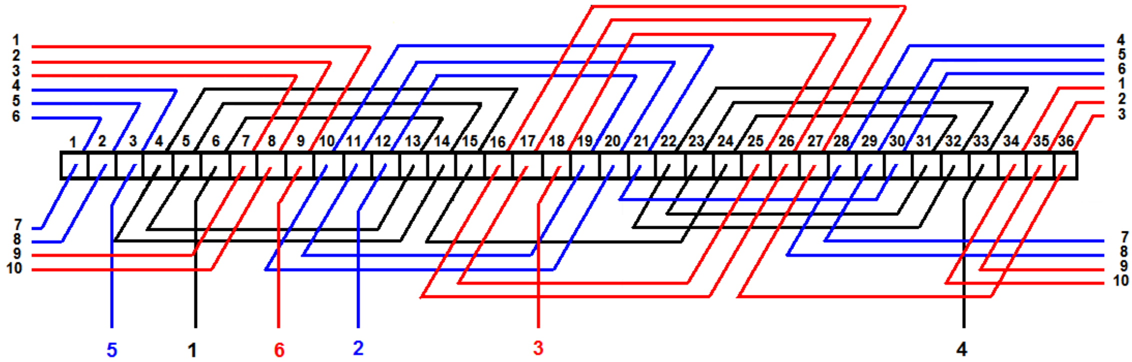
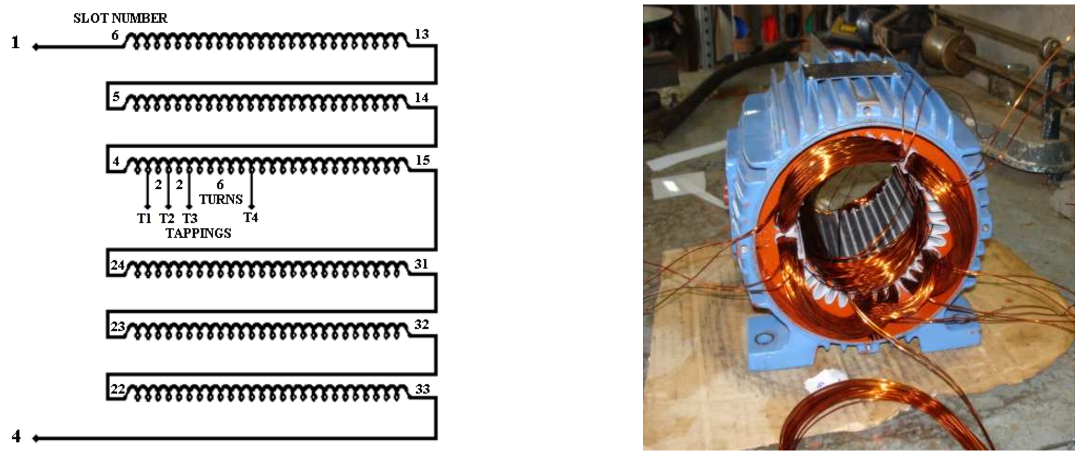


Figure 3 - Stator winding arrangement.

The location of the tappings for one of the motor phases (phase A) and the stator windings is shown in Fig. 4.

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



(a) Location of the tappings for motor phase A (b) Details of the stator windings

Figure 4. Stator windings.

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.

The excitement for unbalance phase was obtained inserting a changeable resistance in series with one of the phases of the electric motor supplying, Fig. 5.

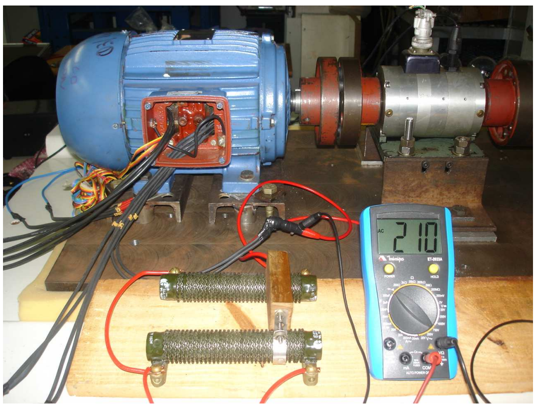


Figure 5. Excitement for unbalance phase.

3. GENERAL CONSIDERATIONS

The factors that affect the behavior of the induction motors can be grouped into problems of electric or magnetic origin and problems of mechanical origin. Because of the importance of understanding the sources of disturbances for the diagnosis of failures, several studies have been conducted in order to identify possible frequencies deterministic, Baccarini (2005), Lamim Filho (2007).

3.1. General Considerations on Unbalanced Voltage Supplies

Thus, for the study after it was used as a reference the following works, Almeida (1996), Baccarini (2005).

When an electric current through a conductor immersed in a region of magnetic field the driver suffers a force action described by (1), Sen (1997):

$$F = \vec{i} \times \vec{B}\, l \tag{1}$$

Where $\vec{i}$ is the vector of electric current, $\vec{B}$ is the vector of flux density and l is the length of the stator.

If the three-phase stator winding of the induction motor is fed by balanced sinusoidal voltage, is produced in the air gap a magnetic field which has sinusoidal distribution in the space and rotates with synchronous speed n_1 while the rotor spins with velocity n. The difference between the two speeds is called slip speed.

The fundamental space component of the resulting wave of the flux air gap turns on the rotor with a speed of slipping sn_1 and induces electromotive force (EMF) of the slip frequency sf in the rotor circuit. These electromotive forces generate currents of slip frequency in the bars in short-circuiting of the rotor.

The currents of the rotor in the slip frequency generate a magnetomotive force (MMF), whose fundamental spatial also moves at the speed of slip on the rotor.

But superimposed on this rotation is the mechanical rotation of the motor n. Thus, the speed of the rotor field in the space is the sum of these two speeds, Baccarini (2005).

Considering, first, failures in the rotor, the influential frequencies in the circuit are: line frequency f, frequency of rotation of the rotor f_r and frequency of slipping f_2 ($f_2 = sf$).

Doing the analysis for uniform air gap (infinite number of slots) and purely sinusoidal current, the expression of the force will have two components of the frequency of slipping, but outdated of the angle θ, as shown in (2), Baccarini (2005):

$$F_{rotor} = k \sin(s\omega_1 t)\sin(s\omega_1 t - \theta) \tag{2}$$

Doing the decomposition of the multiplication of sine, we have:

$$F_{rotor} = \frac{k}{2}\left[\cos\theta - \cos(2s\omega_1 t - \theta)\right] \tag{3}$$

Where $2s\omega_1 t = 2\omega_2 t = 2(2\pi f_2)t$.

The Equation (3) shows that the force generated has a constant part and a variable part with $2sf$, that is, twice the frequency of slipping. As the irregularities are attributed to the rotary engine, the unbalance caused by MMF will unbalance the forces on both sides of the rotor causing vibration. The vibrations induced in the frame of the engine are subject to the instantaneous angular position of the rotor. Multiplying (3) by the $\cos\omega$, where ω is the motor speed, there is the radial projection of the rotational forces in the frame of the engine:

$$F_{rotor} = \frac{k}{2}\left[\cos\theta\cos\omega t - \cos(2s\omega_1 t - \theta)\cos\omega t\right] \tag{4}$$

The Equation (4) is the expression of a modulation in amplitude with carrier, where the carrier is the rotation of the motor and the modulation signal is twice the frequency of slipping.

Due to AM modulation the mechanical vibration in the frame has the same harmonic of the rotational force and, in its spectrum; the component in the frequency of the rotor has side bands spaced with twice the frequency of slipping.

If the defects are located on the stator, the resulting forces do not turn and has the following shape:

$$F_{stator} = k\sin(\omega_1 t)\sin(\omega_1 t-\theta) \tag{5}$$

$$F_{stator} = \frac{k}{2}\left[\cos\theta - \cos(2\omega_1 t-\theta)\right] \tag{6}$$

The resulting vibration has a constant component and another one alternated in twice the frequency of the line. The frequency of rotation of the rotor and slip are also involved in the process, and can cause modulations around twice the frequency of the line, Almeida (1996).

3.2. 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 :

$$\begin{aligned} &F_{loop1}(t,\theta_r) = \\ &= \sum_{v=1}^{\infty}\left[K_v\cos(v\theta_r + s\omega_1 t) + K_v\cos(v\theta_r - s\omega_1 t)\right] \end{aligned} \tag{7}$$

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.

$$K_v = \frac{2}{v\pi}\left(1-\frac{1}{n}\right)\sin\left(v\frac{\pi}{n}\right)I_{r\max} \tag{8}$$

Equation (7) 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):

$$\begin{aligned} &F_{loop2}(t,\theta_r) = \\ &= \sum_{v=1}^{\infty}\left[K_v\cos\left(v\theta_r + s\omega_1 t - (v+p)\frac{2\pi}{n}\right) + \right. \\ &\left. + K_v\cos\left(v\theta_r - s\omega_1 t - (v-p)\frac{2\pi}{n}\right)\right] \end{aligned} \tag{9}$$

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

$$\begin{aligned} &F_r(t,\theta_r) = \\ &= \sum_{i=0}^{n-1}\sum_{v=1}^{\infty}\left[K_v\cos\left(v\theta_r + s\omega_1 t - i.(v+p)\frac{2\pi}{n}\right) + \right. \\ &\left. + K_v\cos\left(v\theta_r - s\omega_1 t - i.(v-p)\frac{2\pi}{n}\right)\right] \end{aligned} \tag{10}$$

Equation (10) clearly shows that MMF waves exist only for the cases $v = p$, $v + p = \pm\lambda n$, and $v - p = \pm\lambda n$, $\lambda = 1, 2, 3\ldots$. 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:

$$
\begin{aligned}
& F_r(t,\theta) = \\
& = F_{r1}\cos\left(\left(1-\lambda\frac{n}{p}(1-s)\right)\omega_1 t + (\lambda n - p)\theta\right) + \\
& + F_{r2}\cos\left(\left(1+\lambda\frac{n}{p}(1-s)\right)\omega_1 t - (\lambda n + p)\theta\right)
\end{aligned}
\tag{11}
$$

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. (12).

Multiplying Eq. (11) and Eq. (12) 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.

$$
\begin{aligned}
& F_{r\mu}(t,\theta) = \\
& = F_{r\mu 1}\cos\left(\left(1-\lambda\frac{n}{p}(1-s)\right)\omega_1 t + (\lambda n - \mu p)\theta\right) + \\
& + F_{r\mu 2}\cos\left(\left(1+\lambda\frac{n}{p}(1-s)\right)\omega_1 t - (\lambda n + \mu p)\theta\right)
\end{aligned}
\tag{12}
$$

From Eq. (11) and Eq. (12) it is clear that besides the EMF at the base frequency additional EMFs will appear only at rotor slot frequencies $(1 \pm \lambda n(1 - s)/p)f_1$ (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 (11) and (12).

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

$$
F_{add}(t,\theta) = \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} F_{addk}\cos(\omega_1 t - k\theta)
\tag{13}
$$

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 $(1 \pm \lambda n(1 - s)/p)f_1$, 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 60 spectra of magnetic flux and vibration in a series of 10 tests for each excitement (without fault; two, four, six and ten turns short circuits; unbalance phase) 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 analogical 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 magnetic flux and vibration were submitted to an anti-aliasing filter with 2.5 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 3.1 and 3.2 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 in two times the line frequency and $(1 \pm \lambda n(1 - s)/p)f_1$. The spectrum of vibration for the motor working with 100 % load in the condition without fault is showed in Fig. 6.

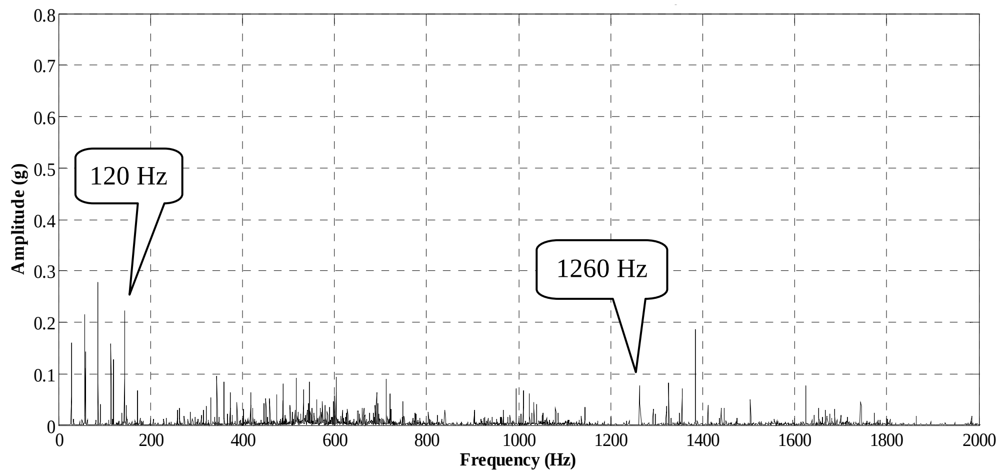


Figure 6. Vibration spectrum without fault with the machine operating at rated speed and rated load.

The spectrum of the vibration for the motor working with 100 % load and two turns short circuited is showed in Fig. 7.

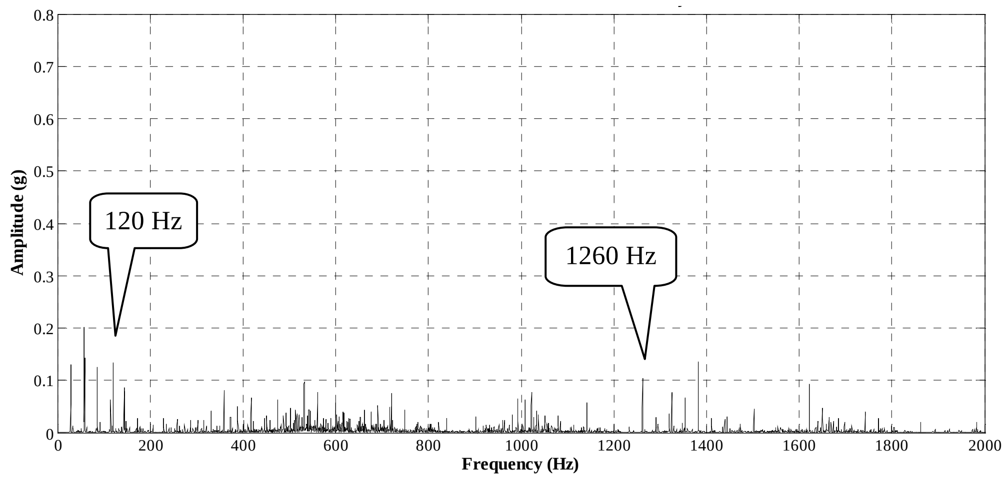


Figure 7. Vibration spectrum with two turns short circuited.

The spectrum of the vibration for the motor working with 100 % load and four turns short circuited is showed in Fig. 8.

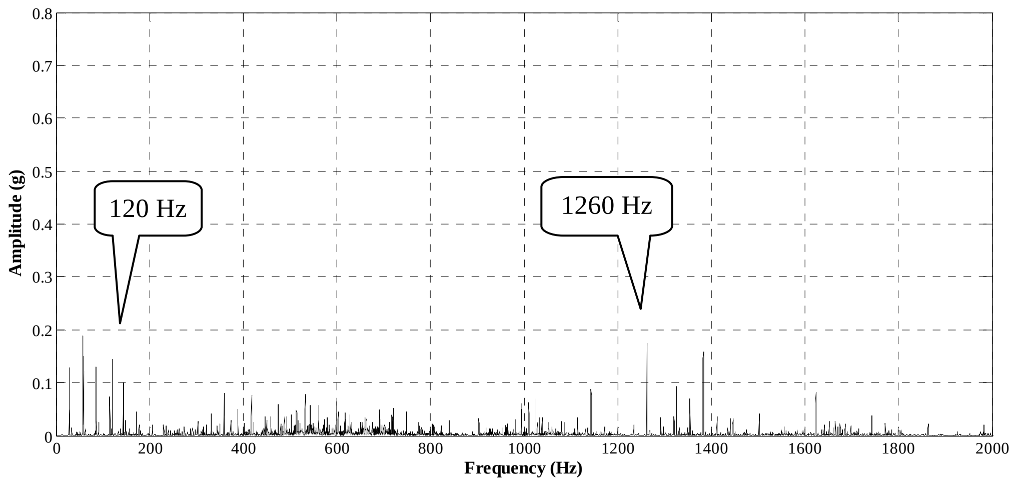


Figure 8. Vibration spectrum with four turns short circuited.

The spectrum of the vibration for the motor working with 100 % load and six turns short circuited is showed in Fig. 9.

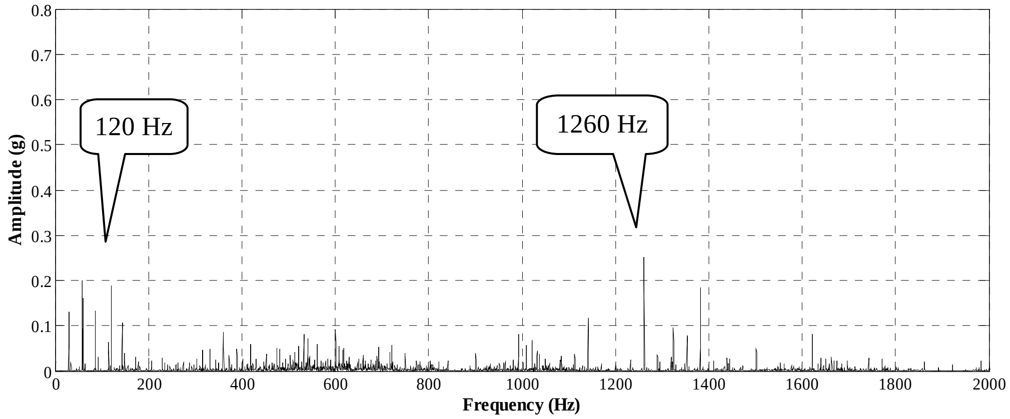


Figure 9. Vibration spectrum with six turns short circuited.

The spectrum of the vibration for the motor working with 100 % load and ten turns short circuited is showed in Fig. 10.

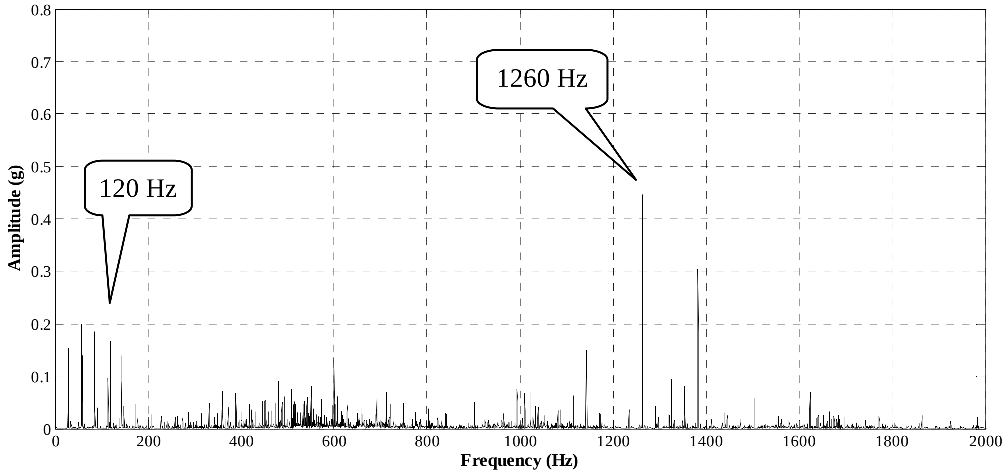


Figure 10. Vibration spectrum with ten turns short circuited.

The spectrum of the vibration for the motor working with 100 % load and unbalance phase (Vab = 210 V, Vbc = 210 V e Vca = 220 V) is showed in Fig. 11.

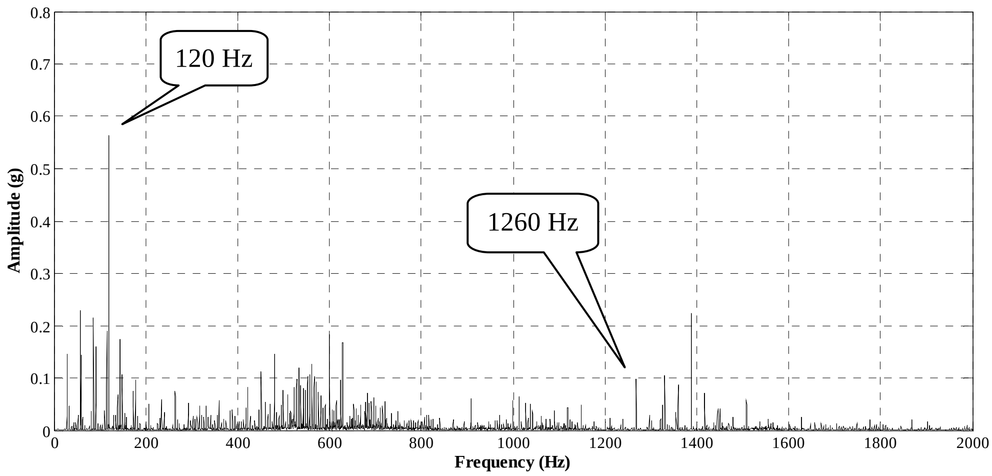


Figure 11. Vibration spectrum with unbalance phase.

According to Nandi and Toliyat (2000) the 21^{st} harmonic (1260 Hz) is always present when there is a stator fault. After the comparison of more than 100 spectra of vibration it was possible to verify that the harmonic 2^{nd} and the 21^{st} of the line frequency were the most excited by the insertion of the short circuit and unbalance phase. Those harmonics will be considered until the end of the text as being characteristic of the fault frequencies.

For the vibration analysis the graph of tendency is showed in Fig. 12. It was consider the means of the amplitudes of the characteristic frequencies of the ten 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.

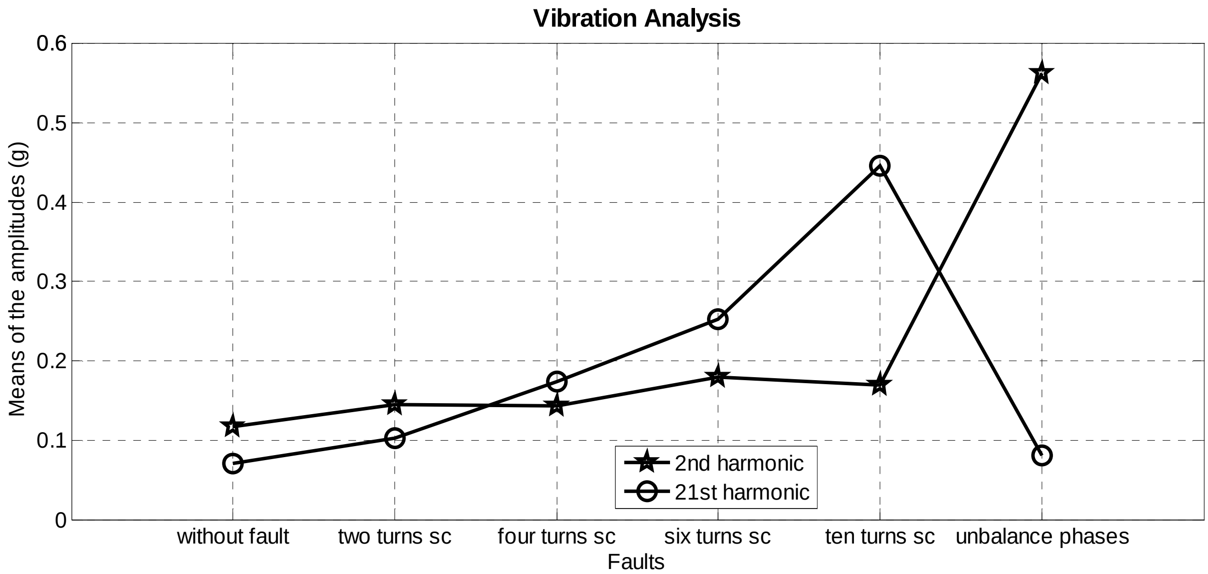


Figure 12. Tendency of introduces faults.

4. CONCLUSION

In This paper, we have discussed the use of vibration technique to detect and diagnose problems in induction motors from electrical sources (inter-turn short circuits and unbalanced voltage supplies) beyond normal condition (motor signature).

It was observed through the spectrum of vibration, that all tests had a good repeatability and that there was no change of origin to mechanical interference in the spectra of magnetic flux and vibration, ensuring a perfect analysis of the results.

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 vibration analysis with some of the main electric origin faults (inter-turn short circuits and unbalanced voltage supplies) and the determination of characteristic frequencies for each one.

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

5. ACKNOWLEDGEMENTS

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