DETECTION OF FAULTS IN THREE PHASE INDUCTION MOTORS USING WAVELET PACKET ANALYSIS

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Abstract. *The motors can be exposed to different types of aggressive environment and inappropriate operation which can lead to a motor breakdown. Different internal motor faults (e.g., short circuit of motor leads, low insulation, ground faults, worn out/broken bearings, broken rotor bars) are expected to happen sooner or later. Several faults can be avoided if the application, work condition and origin of the faults are understood. In terms of electric motors, the reliability has been growing constantly due to the importance of their applications and of the technological progress. This work proposes the application of the Wavelet Packet analysis for the detection and diagnosis of inter-turn short circuits, as this represent most of the electric faults that happen in the motors. The results showed that the multi-resolution Wavelet Packet approach is sensitive to asymmetries caused by this fault. Therefore the technique can be included in maintenance programs.*

Keywords*: predictive maintenance, three-phase induction motors, Wavelet packet analysis.*

1. INTRODUCTION

Electrical machines are susceptible to faults which, depending on their kind, can lead to material, financial and social damage. Among all existing electromechanical systems, one can notice a numerical supremacy of electrical motors that are used to run, for example, gearboxes, pumps, compressors, etc.

This large dependence on electrical motors inside an industry plant requires these machines to be reliable as much as the maintenance program dedicated to them. 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, what allows the maintenance engineer to plan a corrective action preventing the foreseen fault. This can be done if the application, work condition and origin of the faults be understood, 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: Maier (1989), Finley and Burke (1994), Almeida (1996), Joksimovic *et al.* (1999), Joksimovic *et al.* (2000), Finley *et al.* (2000), Benbouzid (2001), Lamim Filho *et al.* (2001), Brito (2002), Benbouzid and Kliman (2003), Lamim Filho (2003), Henao *et al.* (2003), Lamim Filho *et al.* (2004), Baccarini (2005), Silva (2006), Lamim Filho *et al.* (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).

Different internal motor faults (e.g., short circuit of motor leads, inter-turn 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, under load) 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 and Rittenhouse (1988), LaForte *et al* (1988), Schump (1989), Tavner and Penman (1989), Trutt and Cruz (1993), Mishra *et al.* (1999), Benbouzid *et al.* (1999), Riley *et al.* (1999).

These faults are of a transient nature that can be represented by impacts, shocks and other short duration events. A proper tool to deal with this sort of events is the Wavelet Packet Transform (WPT). Its multi-resolution decomposition of a signal makes it efficient to detect transient effects on a time frequency analysis, like those caused by inter-turn short circuits.

Liu and Huang (2005) showed that the electromagnetic torque signal of a 4 pole induction motor suffers disturbances detectable by Wavelet Packet decomposition.

This work puts together the magnetic flux technique and the Wavelet Packet analysis approach for the detection and diagnosis of the short circuit between spirals fault as this represent most of the electric faults that happen in electrical motors, Brito (2002), Baccarini (2005), Lamim Filho (2007). This paper goes to show that magnetic flux is also very sensitive to asymmetries caused by different stages of the fault, from its very beginning.

For a better understanding of the relationship fault/signal, 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 test, Fig. 1, was assembled in the Laboratory of Vibrations and Mechanical Projects of the FEM-UNICAMP-Mechanical Project Department.

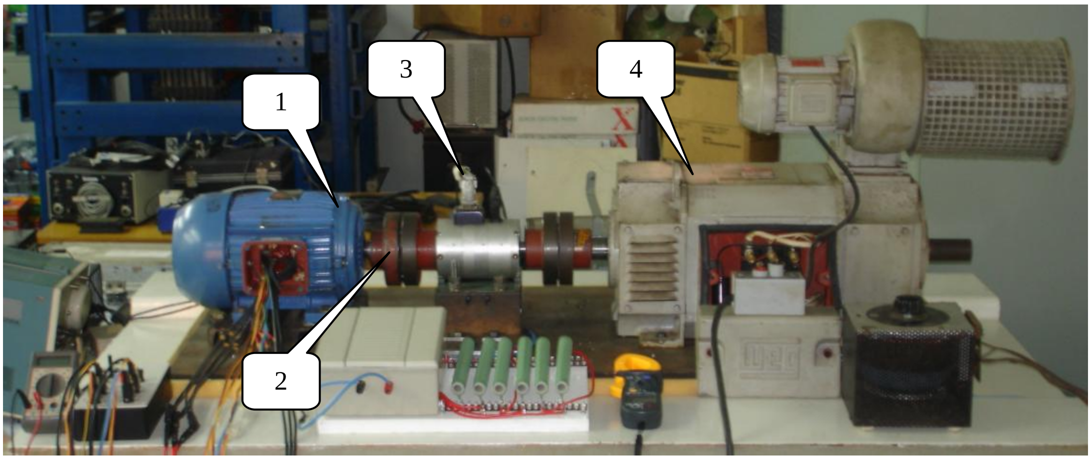


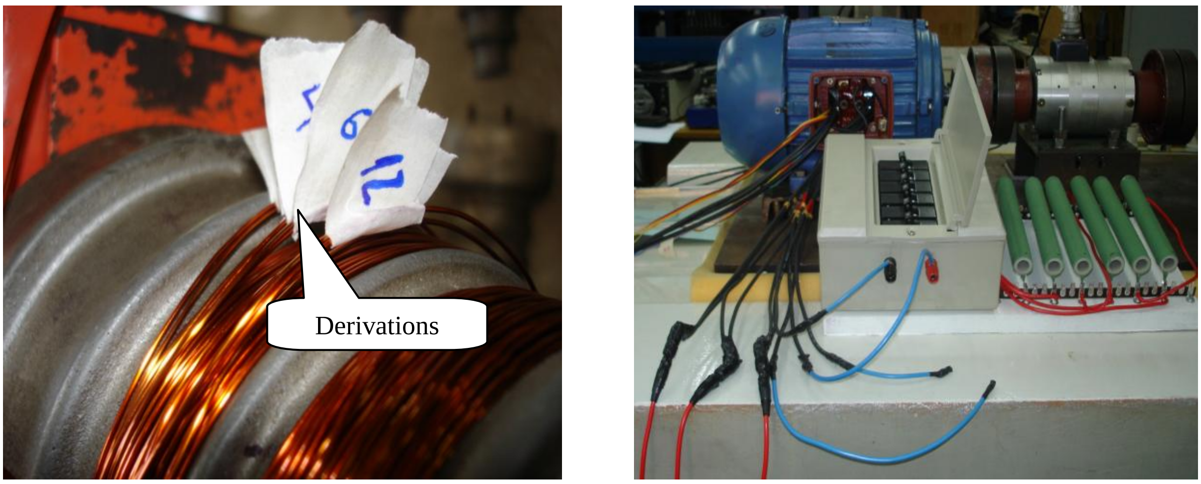
Figure 1. View of the experimental setup.

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, shown in 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 around 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.

Thus 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 will serve as a magnetic flow sensor the recoiling of the induction motor was necessary. 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 insertion of two or three more spirals in its compartment.

This way, during the recoiling and after making the process of isolation of the main coiling, three new coils were inserted inside the induction motor, each of them containing three turns with wire diameter equal to 16 AWG, which started to be part of the magnetic circuit of the machine. 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 shown in Fig. 3.

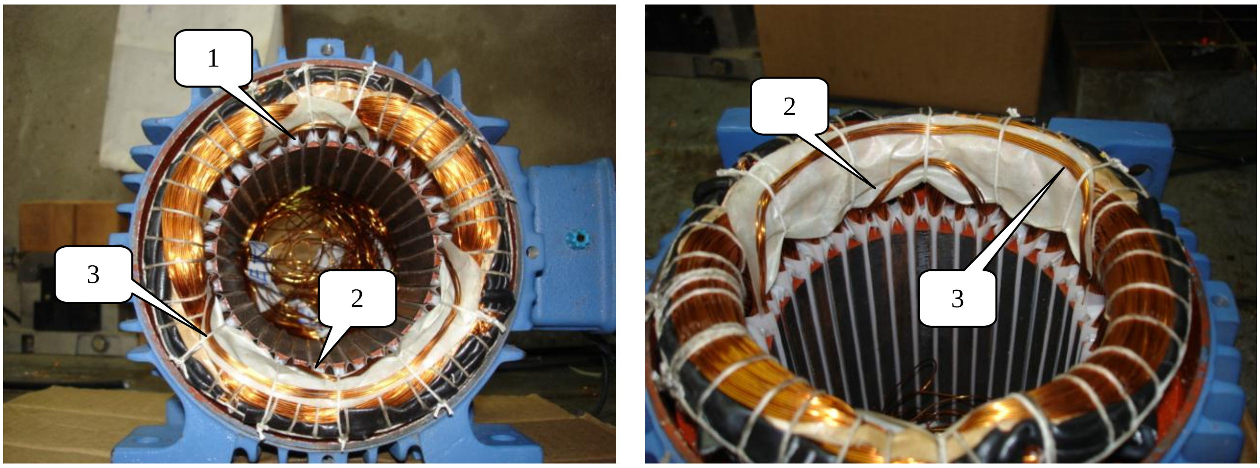
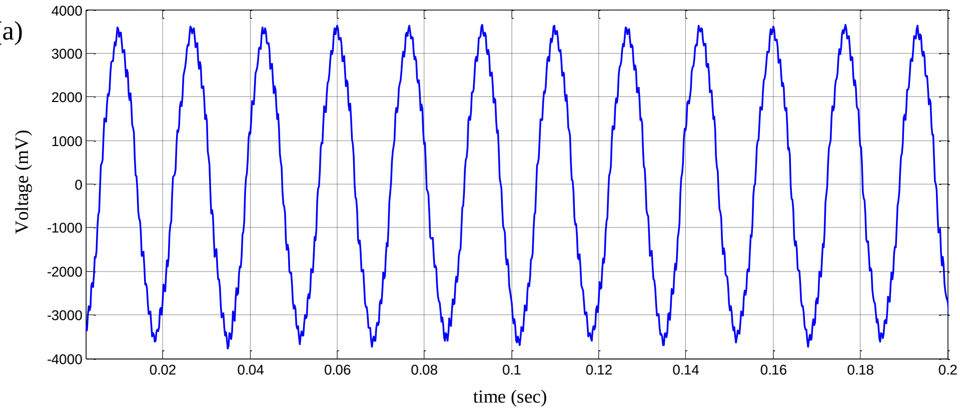


Figure 3. Internal Flux Sensor: Coils 1, 2 and 3 (left) and details of the Coils 2 and 3 (right).

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 Fig. 4 the voltage signals of the coils 1, 2 and 3 are shown. Lamim (2007) stated that only coil 3 is sensitive to the introduced levels of short circuit. For this reason coil 3 is the only one that will be monitored for the detection of faults in this work.

(a)



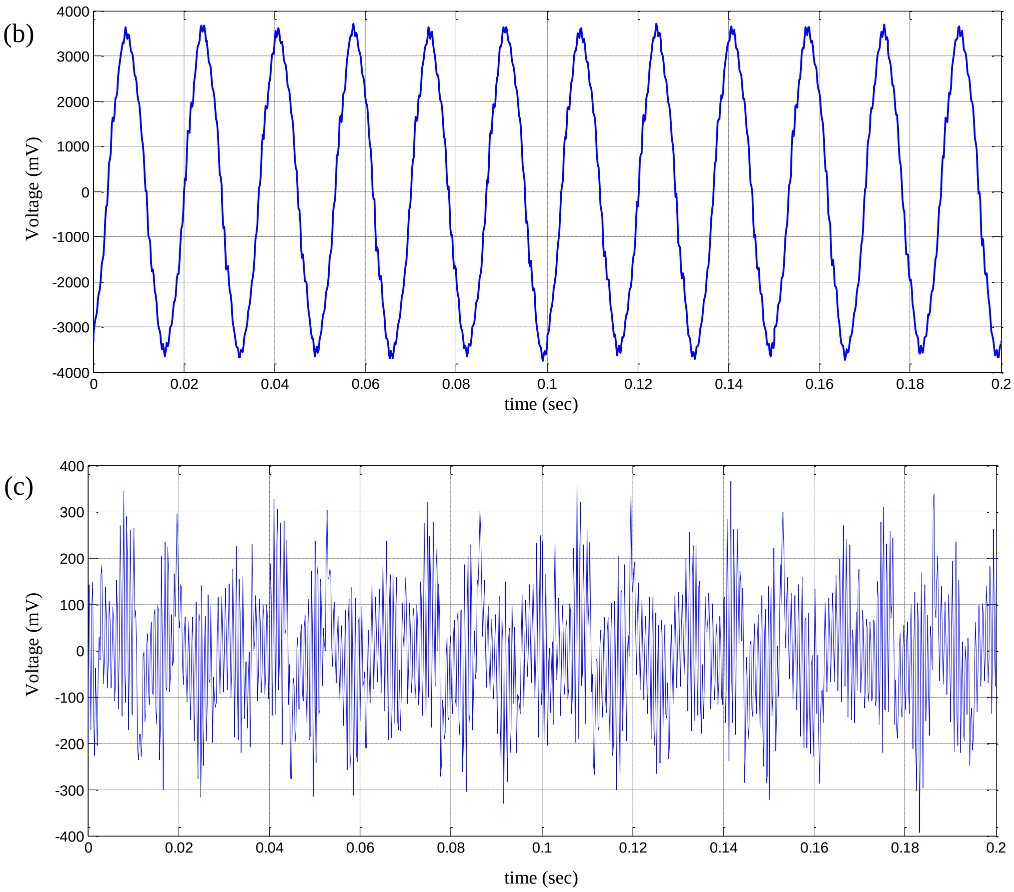


Figure 4. Signal of the sensor: coil 1(a), coil 2 (b) and coil 3 (c).

3. GENERAL CONSIDERATIONS ON SHORT CIRCUITS

According to Gupta and Culbert (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 :

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

Where t is the time, θ_r is the angle of rotor position, ω_1 is the main 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, flows a current of the same frequency and amplitude phase shifted by $p.2\pi/n$, where p is the number of pole pairs. This loop produces its own MMF which has the following shape (Gojko and Penman, 2000):

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

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

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

Equation (4) clearly shows that MMF waves exist only for the cases $v = p$, $v + p = \pm \lambda n$, and $v - p = \pm \lambda n$, $\lambda = 1, 2, 3 \ldots$. As v can only be 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:

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

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.

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

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 $(1 \pm \lambda n(1 - s)/p)f_1$ (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 Eq. (5) and Eq. (6) (Gupta and Culbert, 1993).

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

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

So 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 and Culbert, 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.

4. WAVELET PACKET TRANSFORM

A wavelet is a short wave of oscillatory nature and finite energy. Differently from other signal analysis techniques, as the Fourier Transform which decompose the signal as if it was the result of a summatory of sinusoidal waves of different frequencies, the Wavelet Transform understands the signal as displaced and scaled versions of an original wavelet, called mother wavelet.

Wavelet Transform might be applied either continuously (Continuous Wavelet Transform) or discretely (Discrete Wavelet Transform). The Continuous Wavelet Transform carries problems such as redundancy and hard implementation, while the discretization of the wavelet in a dyadic scale makes both computational implementation and data analysis easy.

The Discrete Wavelet Transform is defined by:

$$DWT(j,k) = \int_{-\infty}^{+\infty} x(t)\cdot\psi^{*}{}_{j,k}(t)dt,\ j \text{ e } k \in Z \tag{8}$$

Where $\psi_{j,k}(t) = \frac{1}{\sqrt{2^j}}\cdot\psi\left[\left(t-k2^j\right)/2^j\right]$ are orthogonal wavelet functions of orthonormal basis $L^2(R)$.

Mallat (1989) developed the Multiresolution Analysis (MRA), showing that a signal can be decomposed into two components, approximation and detail, and also rebuilt through them. Approximation and detail can be interpreted respectively as a low-pass filter and a high pass filter. This means that approximation holds low frequency contents of the original signal and detail holds high frequency contents of the original signal. Approximation can then be decomposed again into new approximation and detail components. This standard can be followed through j decomposition levels. Then approximation and detail in the j-th level are defined as A_j and D_j. Each vector A_j holds $N_t/2^j$, where N is the length of the original signal s and provides information about a frequency band with a range of $[0,F_S/2^{j+1}]$, where F_S is the sampling frequency of the signal (Nikolaou and Antoniadis, 2001).

Wavelet Packet Transform (WPT) is a generalization of the Discrete Wavelet Transform. In this kind of wavelet analysis, not only the approximations are decomposed into other components, but also the details are, what gives refined information about every frequency band. Equation (9) and Eq. (10) define a sequence of functions where $W_0 = \phi(t)$ is the scale function, $W_1(t) = \psi(t)$ is the mother wavelet function and n is the wavelet location in a specific level. After j WPT decompositions, signal data is equally distributed into 2^j frequency bands.

$$W_{2n}(t) = \sqrt{2}\sum_{k=0}^{2N-1} h(k)\cdot W_n(2t-k) \tag{9}$$

$$W_{2n+1}(t) = \sqrt{2}\sum_{k=0}^{2N-1} g(k)\cdot W_n(2t-k) \tag{10}$$

Figure 5 pictures a diagram of the example of the decomposition process on a signal with 5 kHz of sampling frequency where each block is a coefficients vector $\boldsymbol{c}_{j,n}$. This diagram is called Wavelet Packet Tree.

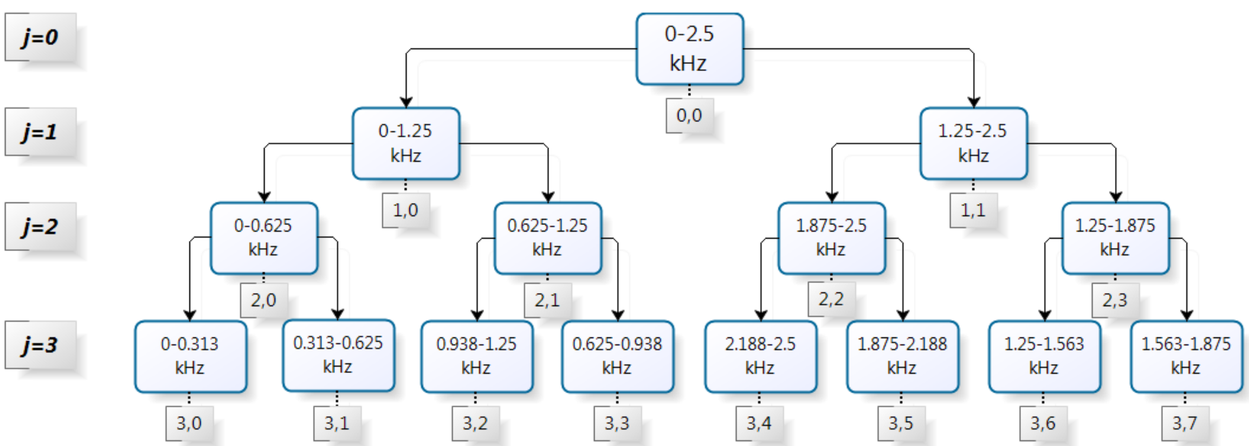


Figure 5. Diagram of an example of a 3 levels Wavelet Packet Transform decomposition

Notice in Fig. 5 that the frequency order of the terminal nodes (each $\boldsymbol{c_{3,n}}$ vector) of a 3 levels WPT increases unexpectedly. Before decomposing a frequency band, the signal within it is downsampled to eliminate redundant information between resultant decomposed bands. This means that low-pass filters may carry information about high frequency content of the signal due to frequency folding (Nikolaou and Antoniadis, 2001). Consequences of this inversion are then carried along to any decomposition level above the 3rd level.

Another useful characteristic of the WPT is the compression of data. For example, a signal with $N_t = 1024$ points subjected to a $j = 3$ levels WPT has a resultant $\boldsymbol{c_{3,0}}$ vector holding $N_t/2^j = 128$ points. That is an important feature in predictive maintenance, because it makes possible to retain information only on the signal frequency band where the frequencies of faults appear (Reis *et al.*, 2009). This way, these frequencies can be held inside specific nodes which can be analyzed with a suitable method.

Liu and Huang (2005) propose a method based on eigenvalues and eigenvectors evaluation to detect the energy inside each terminal node relative to total energy. For this, they define Eq. (11).

$$E_m = \sum_{n=0}^{2^j-1} \left| c_{j,n}(t) \right|^2 \tag{11}$$

Where E_m is energy eigenvalue of each frequency band, $m = 0, 1, 2 \ldots 2^j\text{-}1$, j is the decomposition level and $c_{j,n}(t)$ is the amplitude of the WPT coefficient in each discrete point of the corresponding frequency band.

The eigenvector is then given by Eq. (12).

$$T = \left[\frac{E_0}{E}, \frac{E_1}{E}, \ldots, \frac{E_{2^j-1}}{E} \right] \tag{12}$$

Where $E = \left(\sum_{m=0}^{2^j-1} \left| E_m \right|^2 \right)$.

5. 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 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 signals of coils tension implemented were sampled with 5 kHz of sampling frequency and submitted to an anti-aliasing filter with 2 kHz of cut frequency. This means that the first WPT decomposition will be done on a signal in the $j = 0$ level ranging from 0 to 2.5 kHz, as $[0,F_S/2^{j+1}] = [0,5/2^{0+1}] = [0,2.5]$ kHz.

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

According to Baccarini (2005), there 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 section 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 $(1 \pm \lambda n(1 - s)/p)f_1$. Hence a substantial change in the energy distribution to the Wavelet Packet Tree terminal nodes containing the frequency components of interest can be expected.

To avoid a high concentration of energy in the first node due to the presence of the 60 Hz line frequency, the original signal was submitted to a high-pass filter with a cut frequency of 1 kHz.

In order to detect this disturbance, coil 3 magnetic flux signals for the motor working with 100% load were decomposed through WPT and then the energy eigenvalue of each frequency band was read.

The chosen wavelet family was Daubechies 12 and the signals were decomposed into 8 independent frequency bands, after a 3 level decomposition.

Table 1 shows the energy eigenvalues for the following conditions: without fault, two turns short-circuited, four turns short-circuited, eight turns short-circuited and ten turns short-circuited.

Table 1. Energy eigenvalues for each node according to the motor condition

Node	Without Fault	2 Turns Short-Circuited	4 Turns Short-Circuited	8 Turns Short-Circuited	10 Turns Short-Circuited
1	8.2659E-07	1.81E-07	1.81E-06	4.78E-07	3.12E-06
2	2.95E-06	1.93E-06	5.09E-06	3.72E-06	8.66E-06
3	0.445321979	0.477759103	0.512249955	0.599512003	0.646611248
4	0.00282238	0.002593866	0.002578886	0.002487767	0.003331997
5	0.00272195	0.003034271	0.003511412	0.008157405	0.011853491
6	0.009345366	0.008437011	0.007401782	0.007967406	0.008702463
7	0.893025735	0.876638541	0.857325159	0.799119129	0.761467338
8	0.06395828	0.05624936	0.050197501	0.043101777	0.042825781

The change in energy eigenvalue with the evolution of the fault is clearly shown in Fig. 6.

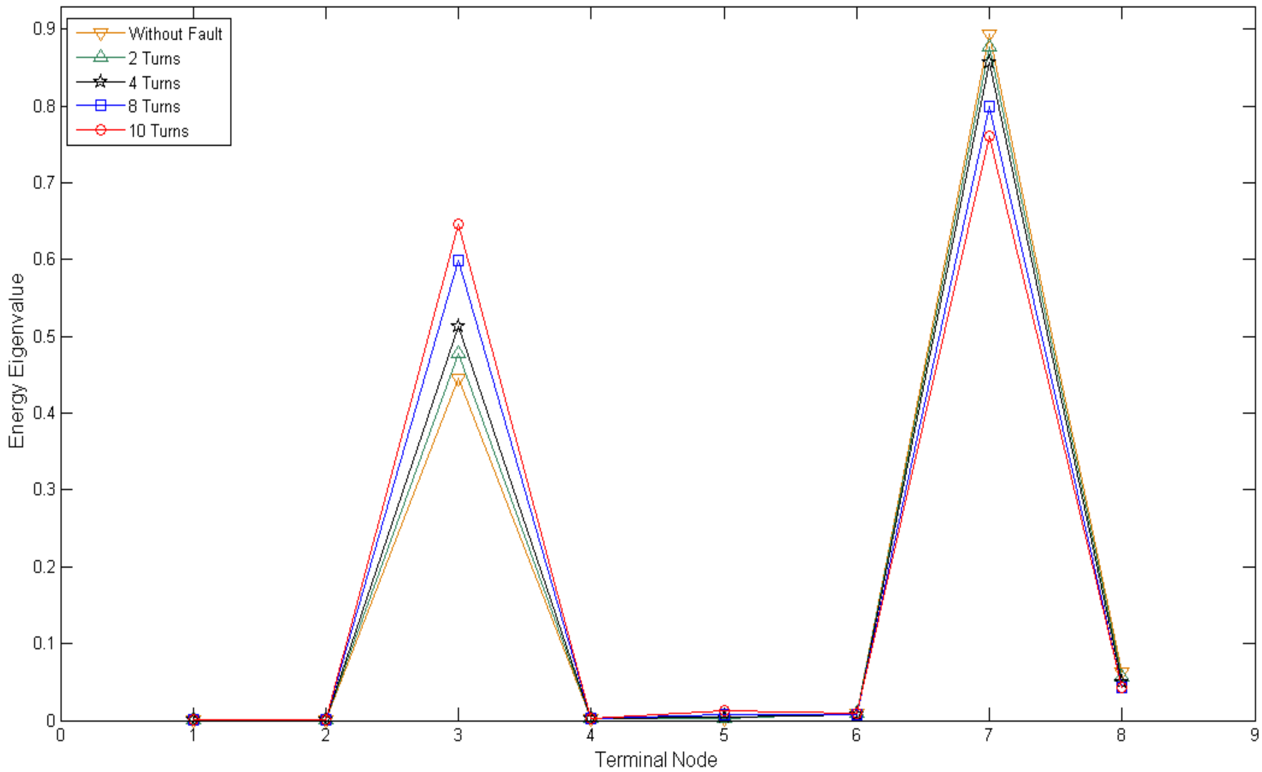


Figure 6. Graph for energy eigenvalues in each node for different conditions

It can be noticed that relative energy has a rise on 3rd and 7th frequency bands, which range respectively from 937.5 to 1250 Hz and from 1250 to 1562.5 Hz, as it can be seen in Fig. 5. These bands contain 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). Besides, they contain the 19th and 21st harmonics (1140 and 1260 Hz) of the line frequency, as according to Lamim (2007) are the most excited by the presence of short-circuits and can be pointed as the characteristic frequencies of the fault for the specifications of the tested induction motor. Nandi and Toliyat (2000) also point out the presence of the 21st harmonic when there is a stator fault.

6. CONCLUSION

Wavelet Packet Transform analysis proved to be an efficient tool for the detection of inter-turn short circuits as the change in relative energy for the bands containing the characteristic frequencies behaves in a foreseeable way. It is sensitive to changes in the magnetic flux caused by this kind of fault and can be followed gradually since lower levels that represent only low insulation until higher levels that 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 to show that magnetic flux on a induction motor also suffers asymmetries detectable by the application of an energy method aided by Wavelet Packet Transform decomposition.

This study is important 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 analysis techniques in electric motors by the real time analysis of relative energy distribution in each frequency band. 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.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Almeida, M. T., 1996, “Análise de vibrações na manutenção preditiva de motores elétricos”, Technical report, Fupai.

Altug, S., Chow, M. Y.H. and Trussell, J., 1999, “Fuzzy Inference Systems Implemented on Neural Architectures for Motor Fault Detection and Diagnosis”, IEEE Transaction on industrial electronics, Vol. 46, No. 6, pp. 1069-1079

Baccarini, L. M. R., 2005, “Detecção e Diagnóstico de Falhas em Motores de Indução”, Belo Horizonte, Faculdade de Engenharia Elétrica, Universidade Federal de Minas Gerais, 179 p. Tese (Doutorado).

Benbouzid, M. E. H. and Kliman, G. B., 2003, “What Stator Current Processing-Based Technique to Use for Induction Motor Rotor Faults Diagnosis?”, IEEE Transaction on Energy Conversion, v.18 (2), pp. 1078-1084.

Benbouzid, M. E. H., Vieira, M. and Theys, C., 1999, “Induction motor’s faults detection and localization using stator current advanced signal processing techniques”, IEEE Transaction on Power Electronics, v.14 (1), pp. 14-22.

Benbouzid, M.E.H., 2001, “A Simple Fuzzy Logic Approach for Induction Motors Stator Condition Monitoring”, IEEE Trans. Industrial Electronics, pp. 634-639.

Boothman, D. R., Elgar, E. C., Rehder, R. H. and Woodall, R. J., 1974, “Thermal tracking - A rational approach to motor protection”, IEEE Transaction on Power Apparatus and Systems, Sept./Oct., pp. 1335-1344.

Brito, J. N., 2002, “Development of a Hybrid Neural/Expert System to Diagnose Faults in Induction Motors”, Campinas, Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, 214 p. Tese (Doutorado).

Cambrias, S., and Rittenhouse, S. A., 1988, “Generic guidelines for the life extension of plant electrical equipment”, EPRI - Electric Power Research Institute.

Finley, W. R. and Burke, R. R., 1994, “Troubleshooting motor problems”, IEEE Transaction on Industrial Applications, v.30 (5), pp. 1383-1397.

Finley, W. R., Howdowanec, M. M., and Holter, W. G., 2000, “Diagnosing motor vibration problems”, In Pulp and Paper Industry Technical Conference, 2000. Conference Record of 2000 Annual, pages 165–180, June 2000.

Gojko, M. J., and Penman, J., 2000, “The Detection of Inter-Turn Short Circuits in the Windings of Operating Motors”, IEEE Transaction on Industrial Electronics, v.47 (5), pp. 1078-1084.

Gupta, B. Y. and Culbert, I. M., 1993, “Assessment of insulation condition in rotating machine stators”, IEEE Transaction on Energy Conversion, v.7 (3), pp. 500-505.

Henao, H., Demian, C., and Capolino, G. A., 2003, “A frequency-domain detection of stator winding faults in induction machines using an external flux sensor”, Industry Applications, IEEE Transactions on, 39(5):1272 – 1279, Sept.-Oct. 2003.

Joksimovic, G, M. Đurovic, M.D. and Penman, J., 2000, “The Detection of Inter-Turn Short Circuits in the Stator Windings of Operating Motors”, IEEE Transaction on Industrial Electronics, v.47 (5), pp. 1078-1084.

Joksimovic, G, M. Đurovic, M.D. and Obradovic, A.B., 1999, “Skew and linear rise of MMF across slot modeling-Winding function approach”, IEEE Trans. Energy Conversion, vol. 14, pp. 315–320, Sept. 1999.

LaForte, J. T., McCoy, R. M. and Sharma, D.K., 1988, “Impulse voltage withstand capability of rotating machine insulation as determined from model specimens”, IEEE Transaction Energy Conversion, v.3 (1).

Lamim Filho, P. C. M, Brito, J. N. and Pederiva, R., 2004, “Predictive Accompaniment of Three-phase Induction Motors by Magnetic Flux Analysis”, presented at III Congresso Nacional de Engenharia Mecânica, Belém - PA.

Lamim Filho, P. C. M., Baccarini, L. M. R., Brito, J. N. and Pederiva, R., 2001, “Influência do desequilíbrio de fase no comportamento dinâmico de motores de indução trifásico”, presented at Congresso Brasileiro de Engenharia Mecânica.

Lamim Filho and Paulo C. M., 2007, “On-line Monitoring of Three-phase Induction Motors”, Campinas,: Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, 140 p. Tese (Doutorado).

Lamim Filho and Paulo C. M., 2003, "Predictive Accompaniment of Three-phase Induction Motors by Magnetic Flux Analysis", Campinas,: Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas,. 105 p. Dissertação (Mestrado).

Lamim Filho, P. C. M, Brito, J. N. and Pederiva, R., 2006, "Detecção de defeitos de origem mecânica em motores de indução trifásicos através da lógica fuzzy", IV Congresso Nacional de Engenharia Mecânica, Recife - PE.

Liu, T. and Huang, J., 2005, "A novel method for induction motors stator interturn short circuit fault diagnosis by wavelet packet analysis", IEEE Trans. on Electrical Machines and Systems, v. 3, pp. 2254-2258.

Maier, R., 1989, "Protection of squirrel-cage induction motor utilizing instantaneous power and phase information". IEEE Transactions on Industry Application. v.28 (2), pp.376-380.

Mallat, S., 1989, "A theory for multi-resolution signal decomposition: the wavelet representation", IEEE Trans. on Pattern Analysis and Machine Intelligence, v.11, (7), pp. 674-693, June 1989.

Mishra, M. K., Tarnekar, S.G., Kothari, D.P. and Ghosh, A., 1999, "Detection of Incipient Faults in Single Phase Induction Motors Using Fuzzy Logic", IEEE Trans. Industrial Electronics, June, pp. 117-121.

Nandi, S. and Toliyat, H. A., 2000, "Novel Frequency Domain Based Technique To Detect Incipient Stator Inter-Turn Faults In Induction Machines", Electric Machines & Power Electronics Laboratory Dep. of Electrical Engineering, Texas A&M University.

Nikolaou, N.G. and Antoniadis, I.A., 2002, "Rolling element bearing fault diagnosis using wavelet packets", J NDT&E, v.35, pp. 197–205.

Reis, R.A., Brito, J. N. and Sousa, G. R., 2009, "Fault detection in gearbox using the wavelet transform", presented at 20th International Congress of Mechanical Engineering, Gramado – RS.

Riley, C. M., Lin, B. K., Habetler, T. G. and Kliman, G. B., 1999, "Stator current harmonics and their causal vibrations: a preliminary investigation of sensorless vibration monitoring applications", IEEE Transaction on Industry Applications, v.35, (1), pp. 94-99.

Schump, D. E., 1989, "Reliability testing of electrical motor", IEEE Transactions on Industry Application. v.25 (3).

Silva, A. M., 2006, "Induction motor fault diagnostic and monitoring methods", Thesis submitted to the Faculty of the Graduate School, Marquette University, In Partial Fulfillment of the Requirements for the Degree of Master of Electrical and Computer Engineering, 146 p, 2006.

Tavner, P. J. and Penman, J., 1989, "Condition monitoring of electrical machines", Research Studies Press Ltd. John & Sons Inc.

Trutt, F. C., and Cruz, C. S., 1993, "Prediction of electric behavior in deteriorating induction motors", IEEE Transactions on Industry Application. v. 29 (4), pp. 1239-1243.

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