DETECTION OF STATOR WINDING FAULTS IN SIX POLES INDUCTION MOTOR USING AN INTERNAL FLUX SENSOR UNDER DIFFERENT LOADS

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***Abstract**. In this work is presented the implementation of a special flux coil sensor inside the six poles three-phase induction motor under different loads (80, 90 and 100% of load). This sensor is sensitive to electromagnetic field and is used for detection and diagnosis electrical faults. It was established the relationship between the main electrical faults (inter-turn short circuits and unbalanced voltage supplies) and the signals of magnetic flux in order to identify the characteristic frequencies of those faults. The experimental results shown the efficiency of the flux coil sensor developed and the strategies for detection, diagnosis and monitoring tasks. The results were undoubtedly impressive and the system developed can be adapted and used in real predictive maintenance programs in industries.*

***Keywords**: Fault detection, flux coil sensor, three-phase induction motors, inter-turn short circuits, unbalanced voltage supplies.*

1. INTRODUCTION

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, 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, Lamim Filho (2007). 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, (Brito, 2002, Baccarini, 2005, Liang, 2003 and Silva, 2006).

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, Brito (2002). In terms of electric motors, the reliability has been growing constantly due the importance of their applications and of the technological progress, (Dymond et al., 2007, Gojko, 2000, Henao et al., 2003, Joksimovic et al., 2000).

In this work is presented the detection and diagnosis of the inter-turn short circuits in stator windings and unbalanced voltage supplies using magnetic flux in six poles three-phase induction motor under different loads (80, 90 and 100 % of load). 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. The results showed the efficiency of the proposed sensor and made possible the distinction between the analysis of short circuit and unbalanced voltage.

2. INTERNAL 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 (± 10V) by the boards and sign collectors found at the market. The visualization of the points where the coils were inserted in six poles motors is showed in Fig. 1.

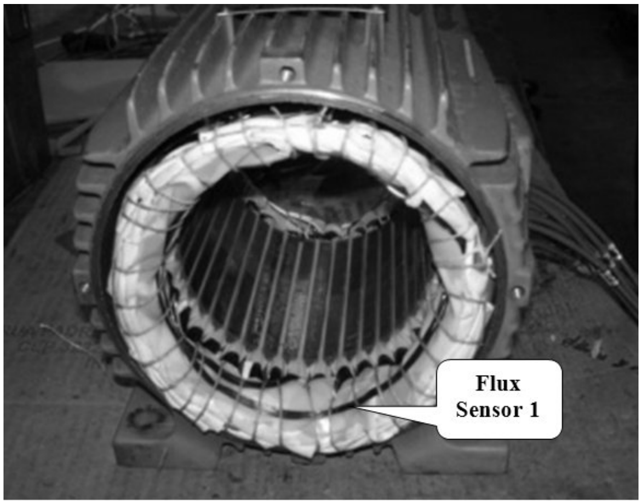

Figure 1. Internal Flux Sensor in six poles motor.

2.1. Signals of the Sensors

The equations which describe the general induction machine with *m* stator circuits and *n* rotor bars can be written in the matrix form (Lamim Filho, 2007):

$$[U_s] = [R_s][I_s] + \frac{d[\psi_s]}{dt} \tag{1}$$

$$[U_r] = [R_r][I_r] + \frac{d[\psi_r]}{dt} \tag{2}$$

$$[\psi_s] = [L_{ss}][I_s] + [L_{sr}][I_r] \tag{3}$$

$$[\psi_r] = [L_{rs}][I_s] + [L_{rr}][I_r] \tag{4}$$

Where U is the phase voltage, R is the resistance, I is the electrical current, ψ is the flux concatenated and L is an inductance, being the sub written *s*, and *r* the stator and rotor, respectively.
For a symmetrical squirrel-cage machine $[U_r] = [0]$ e $[L_{rs}] = [L_{sr}]^T$, *and, also,*

$$[U_s] = [u_{s1} \;\; u_{s2} \;\; u_{s3} \;\; \cdots \;\; u_{sm}]^T \tag{5}$$

$$[I_s] = [i_{s1} \;\; i_{s2} \;\; i_{s3} \;\; \cdots \;\; i_{sm}]^T \tag{6}$$

$$[I_r] = [i_{r1} \;\; i_{r2} \;\; i_{r3} \;\; \cdots \;\; i_{rm}]^T \tag{7}$$

For the three-phase induction machine, with the rotor and stator coiling, Fig. 2, the vectorial matrices could be written to the stator voltage considering internal flux sensor 1 as follows:

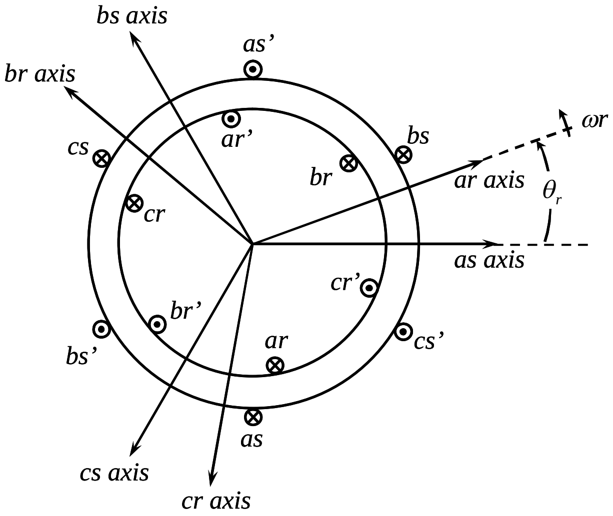

Figure 2. Representation of the three-phase machine, Krause (1986).

$$\left[U_{abc1s}\right] = \left[R_{abc1s}\right]\left[I_{abc1s}\right] + \frac{d\left[\psi_{abc1s}\right]}{dt} \tag{8}$$

$$\left[\psi_{abc1s}\right] = \left[L_{ss}\right]\left[I_s\right] + \left[L_{sr}\right]\left[I_r\right] \tag{9}$$

where U is the stator phase voltage, R is the resistance, I is the electrical current, ψ is the flux concatenated and L is an inductance, being the sub written s, r, and 1 the stator, rotor and internal flux sensor 1, respectively.

With the coils insertion in the stator, the concatenated flux ψ_{as} could be written as follows:

$$\psi_{as} = L_{asas}i_{as} + L_{asbs}i_{bs} + L_{ascs}i_{cs} + L_{asar}i_{ar} + L_{asbr}i_{br} + L_{ascr}i_{cr} + L_{as1s}i_{1s} \tag{10}$$

The concatenated flux ψ_{bs} and ψ_{cs} could be written in the same way as the flux ψ_{as}. From the same principle we have the flux ψ_{1s} for the internal flux 1.

$$\psi_{1s} = L_{1s1s}i_{1s} + L_{1sas}i_{as} + L_{1sbs}i_{bs} + L_{1scs}i_{cs} + L_{1sar}i_{ar} + L_{1sbr}i_{br} + L_{1scr}i_{cr} \tag{11}$$

Considering that do not exist voltages applied in the internal flux sensor 1 and that the currents $i_{1s} = 0$, consequently the concatenates fluxes ψ_{as}, ψ_{bs} e ψ_{cs} are not modified, remaining the model of the induction motor, described by (1)-(4), unchanged. For the internal flux sensor 1, we have:

$$\left[U_{1s}\right] = \frac{d\left[\psi_{1s}\right]}{dt} \tag{12}$$

According to Gupta (1993), 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.

These frequency components in $(1 \pm \lambda n(1 - s)/p)f_1$, where $\lambda = 1, 2, 3, \ldots$, n is the number of slot or rotor bar, s is the rotor slip and f_1 is the line frequency, 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. EXPERIMENTAL TESTS

The experimental test, Fig. 3, was assembled in the Laboratory of Vibration and Control of the FEM-UNICAMP-Mechanical Project Department.

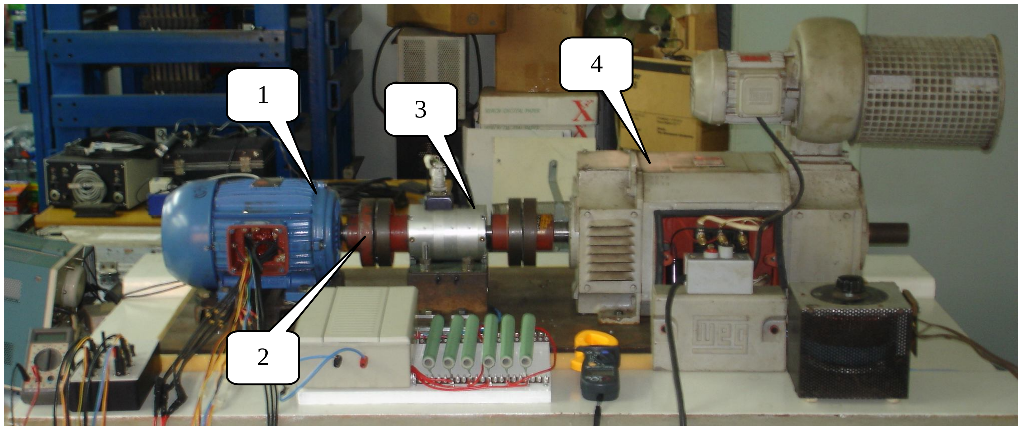

Figure 3. View of the experimental setup.

The faults were inserted in a three-phase motor [1], WEG (FH 88747), squirrel cage rotor, 5 CV, 1730 rpm, 220 V, 60 Hz, 6 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. Those derivations were disposed externally and linked in series (two each time) with a resistance bank 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.

The location of the tappings for one of the motor phases (phase A) 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.

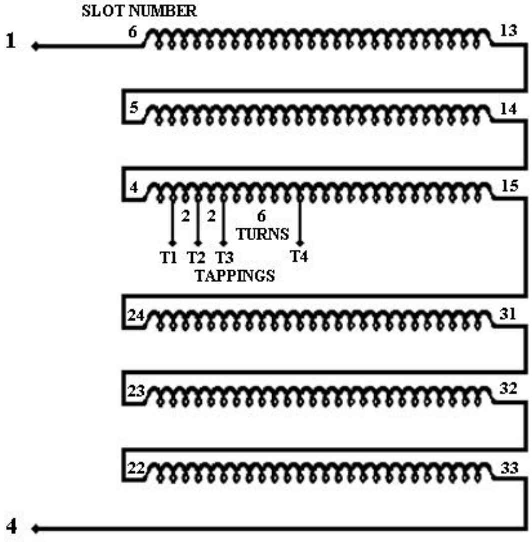

Figure 4. Stator windings: Location of the tappings for motor phase A.

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.

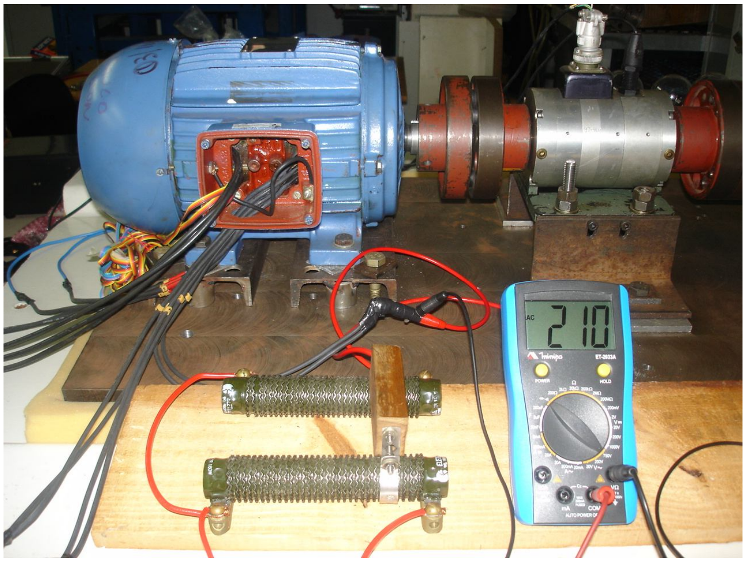

Figure 5. Excitement for unbalance phase.

3.1. Experimental Results

It has been acquired 60 spectra in a series of 20 tests for each excitement (without fault; two, four, eight and ten turns short circuits; 210 V and 200 V unbalance phase) and randomly repeated under the same load conditions (80, 90 and 100 % of load).

The board NI-6251BNC 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 internal flux sensor 1 were submitted to an anti-aliasing filter with 2 kHz of cut-off frequency. The Matlab software was used for the implementation of the algorithm of data acquisition and diagnosis of faults.

According to Lamim Filho (2007) 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.

In the spectra of magnetic flux of the figures above, it can be clearly observed the harmonics of dependent frequencies of the line frequency, $f_l = 60Hz$. Also, there are harmonics of the main frequency of slot harmonic frequencies $(1 \pm \lambda n(1 - s)/p)f_l$, to $\lambda = 1$, $n = 44$, $s = 0.045$, $p = 3$ and $fl = 60$ $(900.2 Hz)$, for the six poles motor.

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

The spectrum of the magnetic flux for the six poles motor working with full load in the condition without fault, ten turns short circuited and unbalanced phase 200 V is showed in Fig. 6. The dB reference is 1 V.

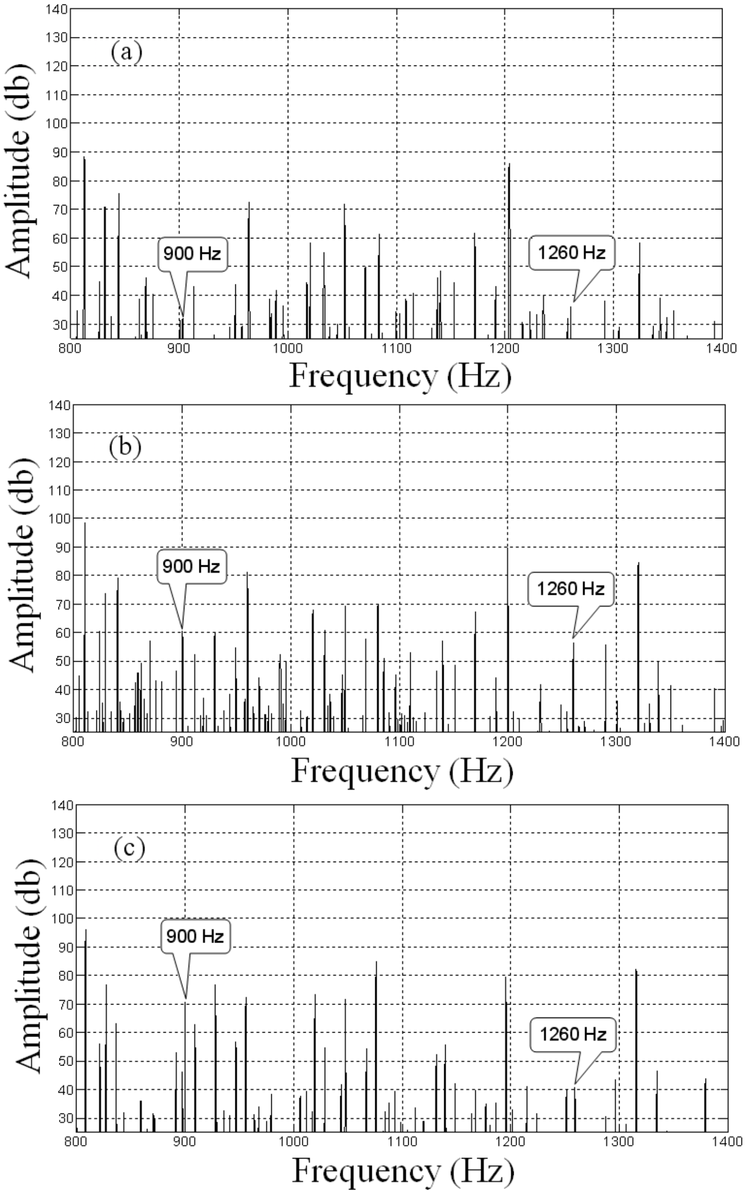

Figure 6. Flux spectrum for the six poles motor operating at nominal speed and full load; (a) Without fault; (b) Ten turns short circuited; (c) Unbalanced phase 200V.

After the comparison of more than 60 spectra of magnetic flux it was possible to verify that the harmonic *21st* (1260 Hz) of the line frequency were the most excited by the insertion of the short circuit. These harmonic will be considered until the end of the text as being characteristic of the fault frequency.

Through the analysis of item 2 it can be said that the presence of an abnormality in the rotor circuit and/or in the stator circuit will provide a disturbance 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 $(1 \pm \lambda n(1\quad s)/p)f_l$.

When comparing the spectra of Fig. 6 the visualization of the components of slot harmonic frequency, for the six poles motor, that had been most excited by the short circuit and unbalance phase. So, these harmonic will be considered as being characteristic of the fault frequency.

Fig. 7, 8 and 9 shows the tendency of introduces faults for the six poles motor working with 80%, 90% and 100% of load respectively.

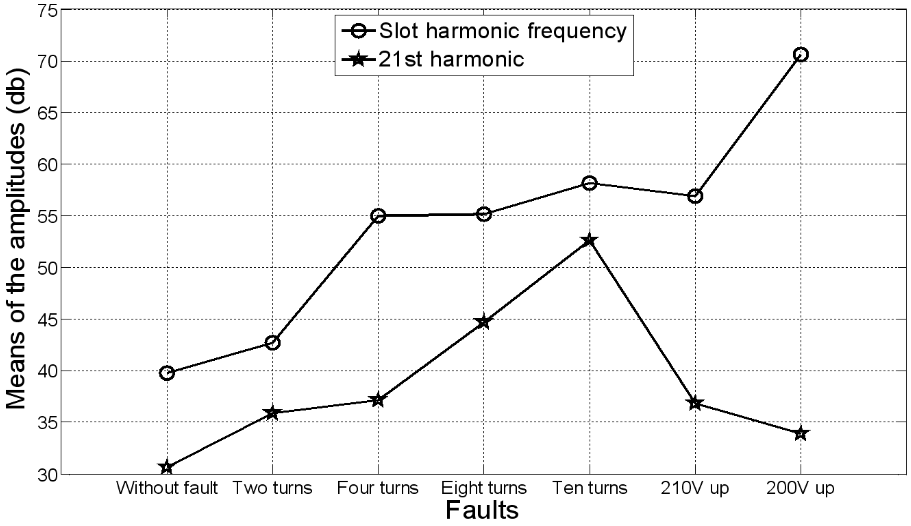

Figure 7. Tendency of introduces faults for the six poles motor with 80% of load.

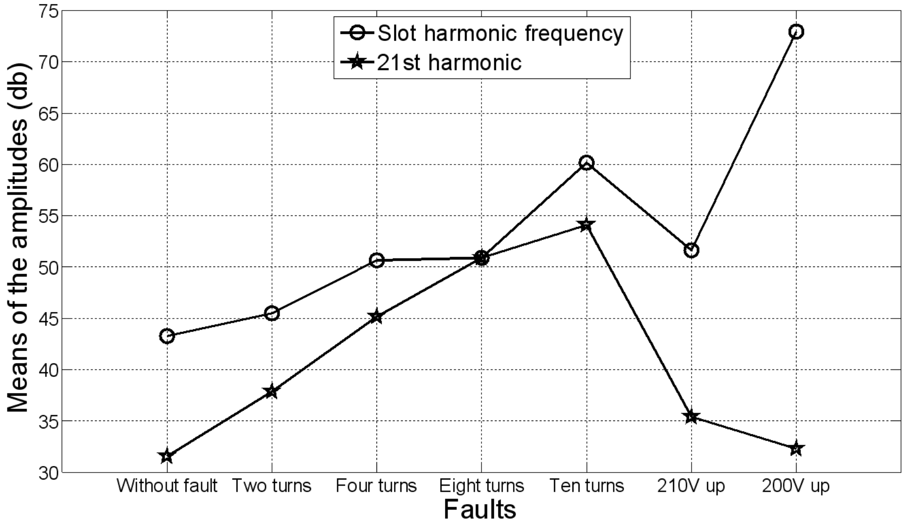

Figure 8. Tendency of introduces faults for the six poles motor with 90% of load.

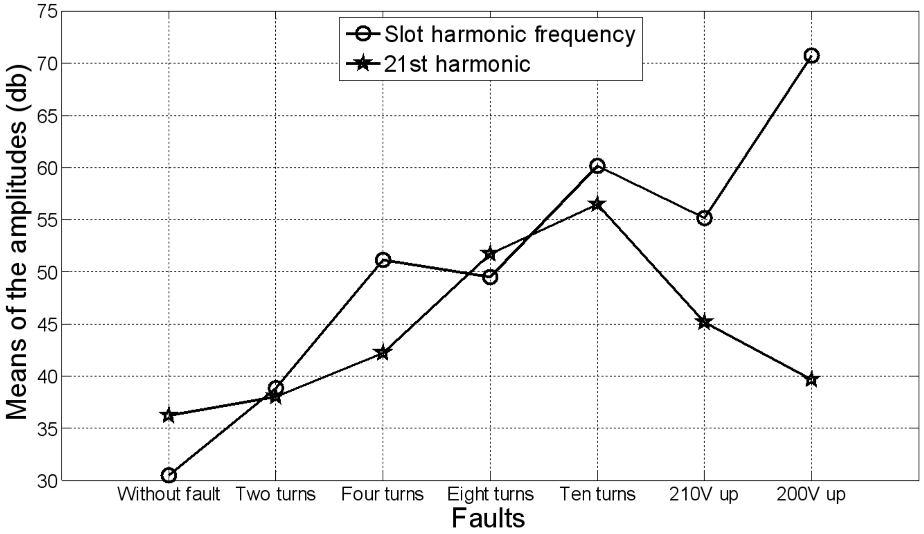

Figure 9. Tendency of introduces faults for the six poles motor with 100% of load.

4. CONCLUSION

It was observed through the spectra of magnetic flux, that all tests had a good repeatability. 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 some of the main electric origin faults (short circuit and unbalance phase) and the determination of characteristic frequencies for each one.

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 analysis techniques in electric motors by the spectral analysis 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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