A REVIEW ON FAULT DIAGNOSIS OF INDUCTION MACHINES

C. J. VERUCCHI[†], G. G. ACOSTA[†‡] and F. A. BENGER[†]

[†] Grupo INTELYMEC – Facultad de Ingeniería – Universidad Nacional del Centro de la Provincia de Buenos Aires, Argentina.
[‡] Consejo Nacional de Investigaciones Científicas y Técnicas – CONICET, Argentina.
gerardo.acosta@ieee.org

Abstract - Different alternatives to detect and diagnose faults in induction machines have been proposed and implemented in the last years. These new alternatives are characterised by an on-line and non-invasive feature, that is to say, the capacity to detect faults while the machine is working and the capacity to work sensorless. These characteristics, obtained by the new techniques, distinguish them from the traditional ones, which, in most cases, need that the machine which is being analysed is not working to do the diagnosis. The main purpose of this article is to revise the main alternatives in the detection of faults in induction machines and compare their contributions according to the information they require for the diagnosis, the number and relevance of the faults that can be detected, the speed to anticipate a fault and the accuracy in the diagnosis.

***Keyword* – Induction machines. Fault detection and diagnosis.**

I. INTRODUCTION

Induction electric machines with squirrel cage are the most used in modern industry due to the low cost, strength, and economical maintenance. In this kind of machines, there are often electric and mechanic faults (Bonnet *et al.,* 1988, 1992; Benbouzid, 2000). The most important ones can be found in bearings or shafts, winding stators and bar rotors. The first ones can lead, in many cases, to eccentricities in the rotor which have a relatively slow evolution. This, through an anticipated detection, helps to prevent irreversible damage not only in the machine but also in the production process of which they are set. Faults in winding stators consist in: contacts between wires and the motor frame, loops of the same coil, coils of the same phase or of different phases. Faults in winding stators can have a fast evolution so their detection is more difficult. However, through on-line diagnostic routines, it is possible to detect them at the beginning and, in that way, the complete wear and tear of the winding can be prevented. Finally, faults in shorting bars of the rotors consist generally in breakings or fissures that can extend to neighbouring bars or damage winding stators when there are strains or the fault affects the ferromagnetic plates which form the core. These faults are slow and can be early detected.

In general, it can be confirmed that about 40% of the faults of this kind of machines corresponds to flaws in bearings, 30 or 40% to stator faults, 10% to faults in the rotors, and the remaining ones are a consequence of a great variety of other faults (Motor Reliability Working Group, 1985). These figures were set through the analysis of a group of machines which had a great variety of powers. Besides, in high power machines, rotor faults are the ones that occur most frequently and become the most relevant ones. Taking into account that motors of high power are precisely the ones that need special attention because of their high price, the faults in these rotors are extremely important.

II. TRADITIONAL TECHNIQUES TO DETECT FAULTS IN MACHINES.

Traditionally, techniques such as the measure of the tangent of the delta angle, the measure of the polarization index or the measure of the insulating strength with the use of a megohmmeter to establish dielectric features in the insulators of electric winding machines (Wiedenbrug, 2001). All of them are characterized by the capacity to submit the winding insulator to a voltage above the nominal.

In this way, fault currents can be measured and the dielectric capacity of the insulating material can be settled. The impulse testing has become commonly used recently (Wiedenbrug *et al.,* 2003). It consists in the use of high tension pulses on the windings of a machine and the analysis of a transitory response. As a result, a fault in a winding stator can be found when there are differences among the responses of each coil or phase in the machine.

All these techniques are very effective and are capable of establishing the estate of the insulator and estimate its useful life. However, its use is quite limited because the diagnostic has to be done with the machine out-of-service.

With respect to fissures or cuts in bar rotors, the detection was done through the study of motor vibrations or observing fluctuations of low frequence in stator currents. In both cases, the fault must be found in an advanced estate to be seen ostensibly.

Bearing faults are generally detected by the study of vibrations. If an accelerometer is used, it is possible to control the intensity and frequence of vibrations in the motor. From this, the possible abnormal behaviors can be established (McCully and Landy, 1997).

III. METHODS OF ON-LINE FAULTS DETECTION

A. Obtaining the frequency spectrum of the stator current (MCSA)

The stator current in induction machines has generally got harmonics due to the fact that the disposition of the windings in the slots is not perfectly sinusoidal but stepped, to the imperfections or irregularities which occurred in the manufacture of the motor and to the possible harmonic components which are in the power supply. If there is a short circuit in any of the stator coils, either between coils or loops of the same phase or between coils of different phases, the configuration of the revolving magneto motive forces is affected and, as a consequence, the harmonic components of the stator currents have their amplitudes affected. Taking this into account, and checking the frequency spectrum of the stator currents regularly, it is possible to detect small short circuits and prevent further consequences. The frequencies affected by this type of faults can be calculated as follows according to (Thomson and Ferger, 2001):

$$f_f = f_1 \cdot \left[k \pm n.\frac{(1-s)}{p} \right], \tag{1}$$

with $k = 1$, 3 y $n = 1$, 2, 3 , ... ($2.p\text{-}1$) and where f_1 is the frequency of the power supply, s, the slip of the motor and p the number of pair of poles.

It is important to highlight that, as it is shown in (1), the affected components are part of the slipping and so, the frequence in which they are present depends on the load state of the motor.

In the same way, the variation of the range of the harmonic components which are affected by a fault depends on the motor load, so, it is convenient to make a comparison for states of similar loads.

The incidence of a fault on each harmonic component varies from one motor to the other and depends mainly on the characteristics of the state. The harmonic components cannot only increase but also reduce its value, in some cases.

The example in Fig. 1 shows a comparison between the spectrum of frequencies in a motor of 3 HP, 380 V, 50 Hz and four poles in normal conditions, and the spectrum of the same motor with one of its coils in short circuit. (The current in the loop in short circuit was limited to the same value as the nominal motor current.) According to Fig. 1, in a motor with no load the most important components in which the fault occurs are at about 25 and 75 Hz approximately, as it is shown in the figure.

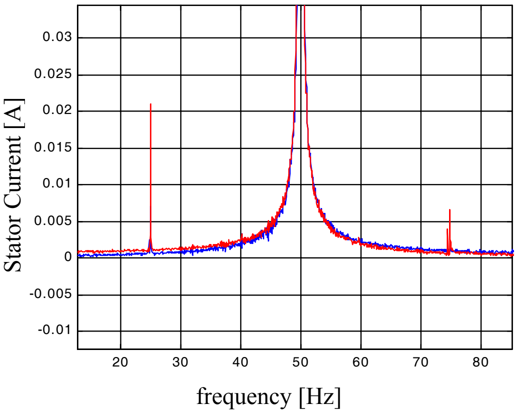


Figure 1: Comparison between the frequency spectrum of a motor in normal state (blue) and a short circuit in a coil (red).

In relation to rotor faults, the breaking of one of its bars or short circuit rings, turns the rotor into an unbalanced three-phase circuit (Filippetti *et al.*, 1998). That unbalance appears with the circulation of a current of inverse sequence. As a consequence, there is a magnetic field which turns the other way about in which the rotor turns, with a speed of:

$$\omega_{CGI} = -s.\omega, \tag{2}$$

where ω_{CGI} shows the speed of the inverse revolving field with respect to the rotor and s the slipping per unit. The speed of the inverse revolving field with respect to the stator is:

$$\omega_{CGI}^{s} = -s.\omega + (1-s)\omega = \omega - \omega_0, \tag{3}$$

where:

$$\omega_0 = 2s\omega \tag{4}$$

This new revolving field causes a new torque on the rotor, in a frequence:

$$f_0 = 2sf \cdot \tag{5}$$

where f is the frequence of the net. This torque also causes an oscillation in the rotor speed, and its amplitude depends on the coupling inertia. These oscillations affect the stator currents on which the so called nominal bands are induced with the frequencies:

$$f_S = (1 \pm 2s) f \cdot \tag{6}$$

These side bands allow a clear identification of the rotor, the frequencies in which they appear are part of the rotor slipping and its amplitude strongly depends on the state of the load. An exact diagnostic requires the motor to be over half of its nominal load. Some loads that have an oscillating torque (as compressors) can cause lateral bands similar to the ones caused by a fault and interfere in the diagnostic.

The eccentricities in the rotor, moreover, cause harmonics to frequencies calculated by (Thomson *et al*, 1999):

$$fexc = fs.\left[1 \pm m.\left(\frac{1-s}{p} \right) \right], \tag{7}$$

with m = 1,2,3... and where: $fexc$ is the frequence of the affected harmonics because of a fault, s is the slipping, p the number of pair of poles and fs the frequency in the power net .

Finally, some research shows the capacity of this technique to detect faults caused in the bearings (Schoen *et al.*, 1995). A fault in any revolving element of the bearing causes vibrations to the frequence:

$$f_b = \left(\frac{pd}{bd} \right).frm.\left[1 - \left(\frac{bd}{pd}.\cos(\beta) \right)^2 \right], \tag{8}$$

where n is the number of revolving elements, $f_{rm,}$ the revolving speed in turns per second, pd is the half diameter of the bearing , bd is the diameter of each ball and β is the contact angle of the balls with the race of the bearings. These vibrations in the machine rotor are harmonic components in the stator current and, in this way, the fault can be identified.

In the same way, fissures in the external runaway cause vibrations in the following sequence:

$$f_o = \left(\frac{n}{2}\right).frm.\left[1-\frac{bd}{pd}.\cos(\beta)\right]. \tag{9}$$

They appear in the stator current through components at frequencies:

$$\left|f \pm k.f_o\right|. \tag{10}$$

Fissures or flaws in the interior runaway of a bearing cause vibrations at a frequence given by:

$$f_i = \left(\frac{n}{2}\right).frm.\left[1+\frac{bd}{pd}.\cos(\beta)\right] \tag{11}$$

and they are seen as components in the current stator frequencies given by:

$$\left|f \pm k.f_i\right|. \tag{12}$$

It is important to point out that for this type of faults, the use of the harmonic spectrum of the stator current has been implemented in laboratory tests with intentional faults. Unlike the other faults, there still haven't been informed enough cases in industrial applications to support the capacity of diagnosis of this technique.

B. Complex Park Vector (CPV)

The well-known Park transformation allows showing the variables of a three-phase machine through a system of two quadrature shafts and as Milanez and Emanuel (2003) show, they are a measuring and diagnostic tool in electric three-phase systems. The components of the stator current in a reference system formed by two octagonal shafts which are fixed to the stator (shafts *D* and *Q*) are obtained by the following reports:

$$i_D = \sqrt{\frac{2}{3}}.i_A - \sqrt{\frac{1}{6}}.i_B - \sqrt{\frac{1}{6}}.i_C, \tag{13}$$

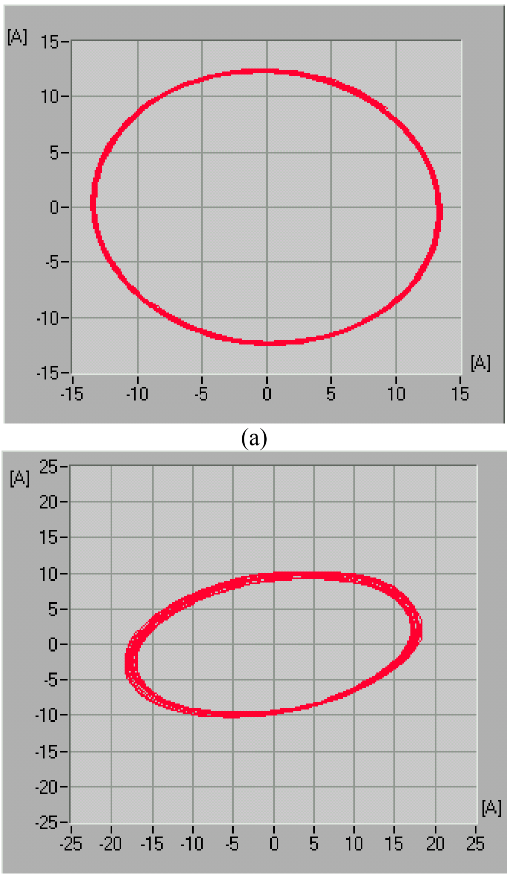
$$i_Q = \sqrt{\frac{1}{2}}.i_B - \sqrt{\frac{1}{2}}.i_C, \tag{14}$$

where i_A, i_B e i_C are the currents of the phases A, B, and C of the stator. In normal conditions, when a motor without faults works through a three-phase system of sinusoidal currents, balanced and of positive sequence, the components of the Park vector form a circle centered in the origin of the plane *D-Q* with a constant radius, as it is shown in Fig. 2.a. In case of a short circuit in winding stators the motor behaves as an unbalanced load and the stator currents stop being a balanced system. Such unbalances cause an oscillation in the radius of the Park vector and turn into elliptical shapes. Figure 2-b shows the results obtained in a motor with two coils of the *a* phase (over 16), in short circuit. The bending on the main shaft of the ellipsis shows the phase in which the fault occurred (Acosta *et al.*, 2002).

Another way of finding a fault consists in watching the value that the radius of the vector takes through time (Cruz and Cardoso, 2001). As the radius moves between its minimum and minimum value twice in each cycle of the power net, its analysis in Fourier series, shows a component in twice the frequency of the power net. The amplitude of this component shows the relevance of the fault. In Fig. 3 is shown the example of a machine with faults in the stator coils.

Some authors propose the use of the Park vector method (Cardoso and Saravia, 1994) to detect eccentricities in the rotor. In this case, what is obtained is a double circle with the centers displaced, as it is shown in Fig. 4. This is because the geometric locus of the vector shows a complete circle for each cycle of the net. In machines with more than one pair of poles, the circles that correspond to different angular positions of the rotor are overlapped. In a four pole machine, for example, the vector will present a circle for each half rotor turn. If the gap of the machine is not the correct one due to eccentricities, two consecutive circles will not match exactly and the difference between both will show a faulty state. A way of finding the relevance of the fault, consists in calculating the enclosed areas in each circle and get the difference between both.

Finally, faults in shorting bars are present when there is an overlapping of concentric circles with an oscillating radius as it is shown in Fig. 5. This is the case of a rotor with 3 cut bars, over a total of 58 working at half load. The frequency with which the current stator vector moves between its maximum and minimum radius is the same as *2.s.f* and it can be seen in the frequency spectrum of the radius in the vector.



(a)

(b)

Fig. 2. Geometric locus of the Park vector. b) normal working conditions, b) coils in short circuit.

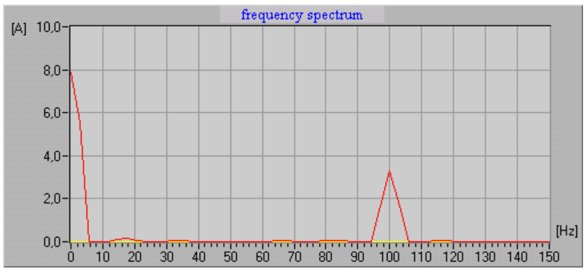


Fig. 3. Harmonic analysis of the vector Park module.

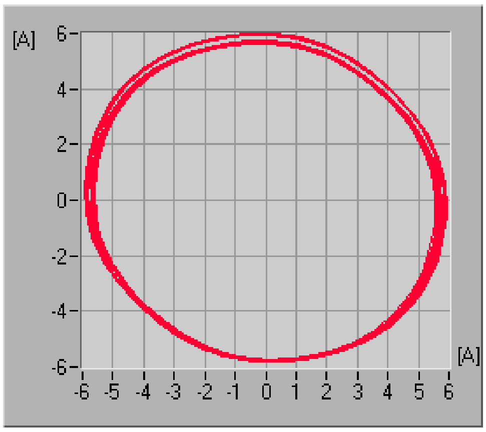


Fig. 4. Geometric locus for the Park vector currents for eccentricities of the rotor.

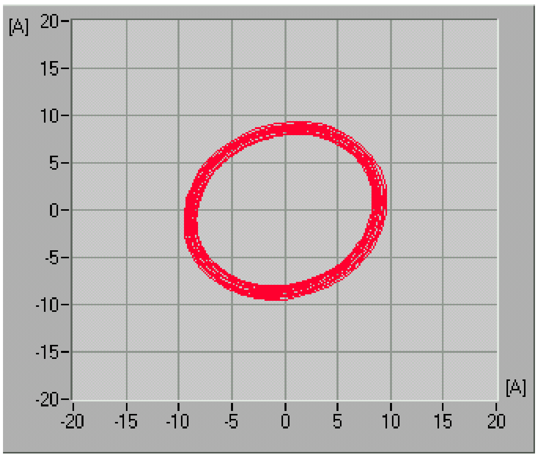


Fig. 5. Geometric locus for the Park vector currents for two cut bars and ½ of the nominal load.

C. Axial flow (AF)

In any induction machine, even in normal working conditions, there are small unbalances in the currents. These appear due to manufacture imperfections and the unbalances of the power net. This causes negative current sequences in the rotor and, besides, the unbalance of the currents on the end of the coils cause a flow in the axial side of the motor. This flow, which is the result of the stator currents, has the same harmonics as those, and as a consequence, it allows identifying the faults. A coil placed on the end of the motor in a concentric way with its shaft, allows seeing the axial flow and diagnosing faults (Penman *et al.*, 1994). So, through the analysis of the frequency spectrum of the axial flow of the motor, short circuits in the winding stator, eccentricities and cut bars in the rotor can be detected.

D. Torque harmonics analysis (THA)

The harmonic analysis of the full power used by the motor, of some of the partial powers or electric torque, allows to detect some of the faults that occur most frequently in induction machines (Trzynadlowski and Ritchie, 2000; Verucchi, 2005).

Partial powers have, in a rotor fault, components of the frequence *2.s.f* and side bands about the double of the red frequency. These components, absent in normal conditions, can detect and specify the relevance of the fault. So, the total power will be affected by a component of the frequency *2.s.f.*

The electric torque showed by the motor can be estimated by the flow bonds and stator currents (Vas, 1990):

$$T_{est}(t) = \frac{p}{3}\cdot\left[\lambda_{ds}(t).i_{qs}(t) - \lambda_{qs}(t).i_{ds}(t)\right], \qquad (15)$$

where T_{est} is the electrical estimated torque, p the number of poles, and λ_{ds}, λ_{qs}, i_{ds} e i_{qs} the flow bonds and currents in *d-q* respectively. The flow bonds can be obtained through voltages and stator currents.

$$\boldsymbol{\lambda}_s(t) = \int_0^t \left[\mathbf{v}_s(t) - R_s.\mathbf{i}_s\right]dt + \boldsymbol{\lambda}_s(0), \qquad (16)$$

where R , is the stator resistance, and the voltages and currents are shown in the shape of spatial vectors:

$$\mathbf{v}_s(t) = v_{ds}(t) + j\ v_{qs}(t), \qquad (17)$$

$$i_s(t) = i_{ds}(t) + j\ i_{qs}(t). \qquad (18)$$

As the motor speed is practically constant, it can be said that the electric torque has the same components as the power, and therefore, it can be used to detect faults.

On the other hand, short circuits in the stator, can be detected in the power and in the torque through components at the double of the supply frequency.

E. Impedances of inverse sequence (IIS)

Depending on the theories of symmetric components, all three-phase unbalanced system can turn into two three-phase unbalanced systems of different sequence plus a group of monophasic phasors. The former are systems of direct and inverse sequence and the latter, a system of zero sequence. So, with the complex values of voltages and the currents of a three-phase system, the components of the sequence systems can be found starting from the relation given by the Eqs. (19) and (20) (Nasar, 1991).

$$\begin{bmatrix}\mathbf{V}_0\\ \mathbf{V}_1\\ \mathbf{V}_2\end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\ 1 & \mathbf{a} & \mathbf{a}^2\\ 1 & \mathbf{a}^2 & \mathbf{a}\end{bmatrix}\begin{bmatrix}\mathbf{V}_A\\ \mathbf{V}_B\\ \mathbf{V}_C\end{bmatrix} \qquad (19)$$

$$\begin{bmatrix}\mathbf{I}_0\\ \mathbf{I}_1\\ \mathbf{I}_2\end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\ 1 & \mathbf{a} & \mathbf{a}^2\\ 1 & \mathbf{a}^2 & \mathbf{a}\end{bmatrix}\begin{bmatrix}\mathbf{I}_A\\ \mathbf{I}_B\\ \mathbf{I}_C\end{bmatrix} \qquad (20)$$

The sub indexes *A, B, and C,* refer to each one of the components of the phase of the real system, while *o, 1, and 2,* show the components of the systems of zero sequence, direct and indirect respectively. The constant **a** is given by:

$$\mathbf{a} = e^{j.2.\pi/3} \tag{21}$$

The relations between the sequence currents and voltages are determined by the impedances of direct, inverse and zero sequence as follows:

$$\begin{bmatrix} \mathbf{V}_0 \\ \mathbf{V}_1 \\ \mathbf{V}_2 \end{bmatrix} = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{22}$$

Taking separately each one of the systems, the impedances of direct, inverse and zero sequence can be defined. In the case of induction motors, taking into account that they are generally connected in triangle, or in star with a disconnected center, the component of the zero sequence is null. In this way, the asynchronic motor will be identified by the impedances of direct and inverse sequence as follows:

$$Z_1 = \frac{V_1}{I_1} \tag{23}$$

$$Z_2 = \frac{V_2}{I_2} \tag{24}$$

It is important to highlight that Eq. (22) is valid for symmetric machines only. In a machine with asymmetries there is a coupling between the components of direct and inverse sequence that brings new conclusions to this equation. In small unbalances, however, the coupling is unnecessary in own components and so, simplification (22) can be used.

While the impedance of the direct sequence is independent of the load state of the motor, the impedance of the inverse sequence is practically independent and very susceptible to short circuits in winding stators. Consequently this one is the most suited for the diagnosis of this kind of fault.

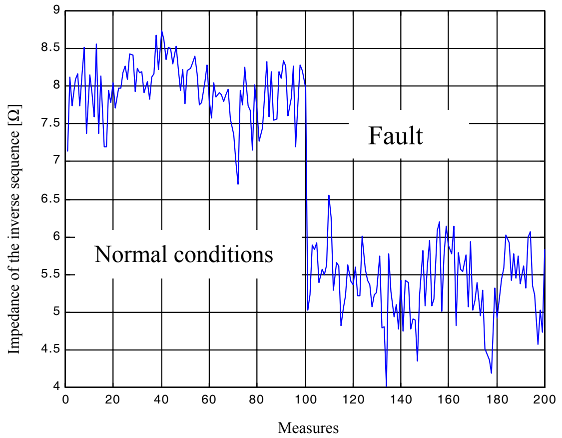


Fig. 6: Impedance values calculated in normal conditions and with a fault with 0.4 % of unbalance in the power.

Figure 6 shows an example of application (Verucchi *et al.*, 2004), where there are consecutive measures of the impedance of the inverse sequence of the motor, first in normal conditions and then with a minor fault in one of the stator coils. The accuracy with which the value can be measured depends on the unbalance level of the power.

A better solution shown in (Kohler *et al.*, 2002; Sottile *et al.,* 2002), suggests to take into account mutual terms of (22). As these values are independent from the slipping of the motor, this technique needs to count with a great variety of values for the different slippings. With that data the value of the inverse current sequence can be calculated and then compared with its mean value. An important difference between both currents shows a fault in the winding stator.

F. Artificial neural networks (ANN)

Tallam *et al.* (2000, 2002, 2003) suggests using artificial neural networks to detect short circuits in winding stators in induction machines. This consists in using a model, based on the voltages of indirect and inverse sequence used on the motor and the direct current sequence consumed, which is capable of establishing the value of the component of the inverse sequence of the current. Then, when this estimated value is compared with the measured one, it is possible to determine abnormalities.

The strategy of the diagnosis consists in, once the ANN has been trained for working conditions without faults but with different load states and unbalances in the power lines, comparing its prediction with the current value of the inverse sequence calculated by the measure of the currents of each phase of the motor as Fig. 7 shows.

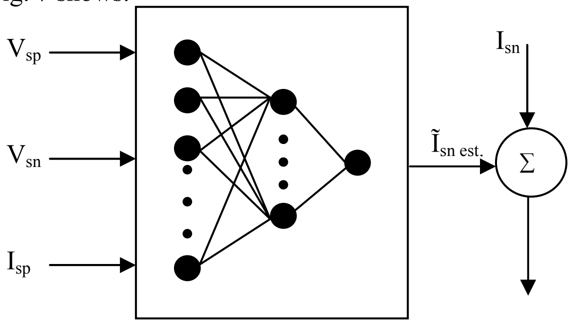


Fig. 7: Diagram of the net used.

Figure 8 shows the results obtained in computer simulations. The mathematic model of the motor used for simulations is completely accurate and is based on the theory developed by Luo *et al.* (1995). In this case, there is a motor of 3 HP, 380 V y 50 Hz with 4 loops of one of its winding stators in short circuit. This figure shows the error which comes up when comparing the current of the inverse sequence estimated by the neural network and the measure, for normal working conditions and the simulated fault.

To adjust the parameters of the neural network (weights) during the training process, the gradient of the error is evaluated between the out desired and the obtained one. A feed-forward neural network (FFNN) is employed (Haykin, 1999). To stop the process from getting trapped in a part of the error function, a time dependent term is added (memory effect in the change of the previous step).

Figure 9 displays a comparison of the error estimated for the healthy/sound motor and with faults of different intensities (obtained with different limited resistance values in the loop in short circuit). So, it is possible to prove that the fault indicator increases with the importance of the fault.

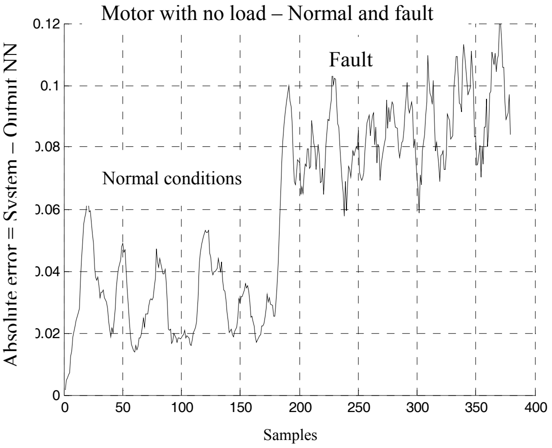


Figure 8: Fault indicator. Motor with no load.

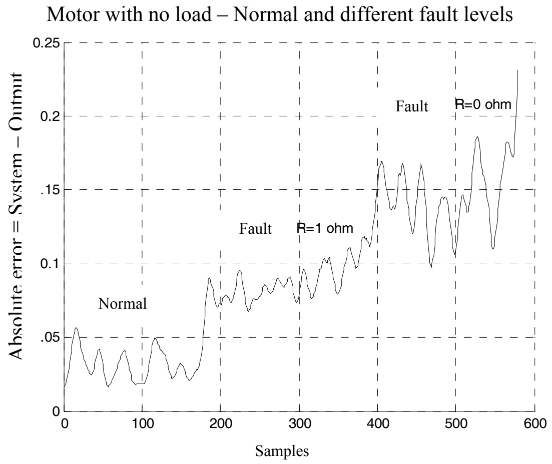


Figure 9: Fault indicator. Motor with no load and different fault levels.

Finally, Fig. 10 shows the results for an estimate of a specific fault and the different load states in the motor. In this way there is no doubt that the indicator of the relevance of the fault is independent from the load state of the motor. This is very important because it allows detecting faults in different load states, and that is a restriction for other methods.

The method shows a great capacity to detect this type of faults and it also has the capacity to detect early faults. The training of the net is done off-line and can be a bit difficult. To assure that the ANN is capable of estimating the inverse sequence current accurately, it must be trained with a great variety of unbalances in the net and load motor states. Although in many applications the machine works in predictable load conditions and tension unbalances, the training off-line method will not be able to estimate the behavior in far conditions during the training step. So, Tallan *et al.* (2002) present a series of alternatives, as in the continuous training, which makes the model better but is incapable of detecting faults which occur in a slow way.

Other alternatives by the same authors consist in the use of a dynamic database that has only got the working conditions found recently, and can be modified on-line. When the size of the database reaches its limit, some data vectors have to be eliminated to set the size of the database constant, being sure that the stored data is the best to assure the red training feed forward neural network from the point of view of minimizing the estimated error. Weights need to be up dated only if a different operation occurs and the time is longer. If it is a fault, the data base increases and the "prune" of the data is delayed until the situation is verified. Another alternative by the same authors is a combination between the previous one and the on-line training, using two sets of weights, so it will be fast enough to detect early faults and recognize a new working condition.

Table I

Technique	Required measured	Application	Main advantage	Main drawback
MCSA	One stator current	- Rotor broken bar - Stator winding turn-fault - Air gap eccentricity	- Low Cost - It is non-invasive.	- Without capability of diagnosis for some motor charge states. -Fault symptoms (frequencies) vary from one motor to another.
CPV	Two stator currents	- Rotor broken bar - Stator winding turn-fault - Air gap eccentricity	- Operation simplicity - It is non-invasive.	- Network unbalances are interpreted as faults.
AF	Axial flux	- Rotor broken bar - Stator winding turn-fault - Air gap eccentricity	- Low Cost	- It is invasive.
THA	Two stator currents and two stator voltage	- Rotor broken bar - Stator winding turn-fault - Mechanical faults in load	- Mechanical Faults Detection. - It is non-invasive.	- It is not effective to detect short-circuits.
IIS	Two stator currents and two stator voltage	- Stator winding turn-fault	- Incipient Faults Detection. - It is non-invasive.	- It requires great measure precision.
ANN	Two stator currents and two stator voltage	- Stator winding turn-fault	- Incipient Faults Detection - Easily to adapt to each motor - It is non-invasive.	- It requires a training period. - It is not effective in unforeseeable motor charge states.

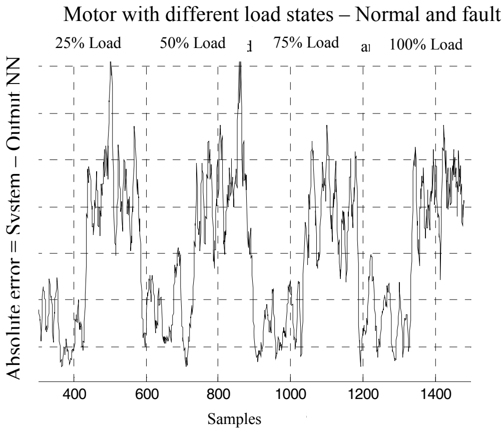


Figure 10: Fault indicator. Healthy/sound and faulty motor with different load states.

G. Expert systems

Taking into account the different detection and techniques proposed, expert systems have been developed to manage the diagnosis process. This expert system take into consideration the outcome of different techniques from the analysis of the acquired variables of the motor and work out conclusions employing rules developed from empirical knowledge (Acosta *et al.*, 2006; Bellini *et al.*, 2000).

IV. DISCUSSION

As it has been shown, there are many tools to detect and diagnose faults in induction machines on-line. The use of each technique in particular has a direct relation to the information that can be obtained from the motor (current, tension, flow bonds, and others). Each mentioned technique has its pros and cons in relation to the fault to be detected, the needed information for the diagnosis and the load type applied to the motor.

The technique based on the study of the frequency spectrum of the stator currents is easy to implement in most of the cases. In fact, with only amperometric pincer it is possible to know the current of any phase of the motor and have enough information to do the diagnosis. This technique is very effective to detect cut bars in the rotor. The side bands that appear in that fault in the supply frequency, allow identifying the fault easily. It is important to point out that the diagnosis has to be done with the motor working at least with half of its nominal load and it is more effective when the load of the motor is bigger. A short circuit in the stator of an induction machine can be detected by the use of this technique. In this case, however, the frequencies in which the faults appear vary from one motor to the other and the identification becomes more difficult. Due to the fact that these faults have a rapid evolution, the frequency with which the diagnosis is greater than the one used to detect fault bars, a fault with a much slower evolution.

The detection of eccentricities in the shaft of the rotor can be done by the analysis of the spectrum of frequencies of the stator current, the frequencies at which these frequencies are present are independent of the number of poles of the motor and of the slipping, so its use is not so simple to implement and systematize. Finally, its practical application is not usual in abnormalities in tracks or balls in the bearings. However the application of this technique has already started and the results have been promising.

With this kind of fault, the harmonic components of the stator current are higher. Then, faster and more expensive equipment is required to obtain useful date. Besides, to identify these frequencies, it is necessary to know the manufacturing features of the bearings, number of rotating elements, support angles on the tracks, ... It must be taken into account that for this type of faults, the technique based on the analysis of the motor vibrations has been widely used for decades with very encouraging results.

The technique based on the following of the Park vector however, needs simultaneous information of the three stator currents. In the case of faults in the winding stator, the module of the Park vector has a component at vary low frequencies (*2sf*). This makes the component easier to identify. The same as in the case of the study of the frequency spectrum of the stator current, the diagnosis is highly conditioned by the load state of the motor, and is more effective when the motor has a load nearer to the nominal value. To detect short circuits in the stator this technique presents itself twice the frequency of the net, so the diagnosis is simplified. The power in the unbalances, on the other hand, affects the diagnosis, and important unbalances can be seen as a fault. Eccentricities in the shaft of the rotor can be identified with this technique only in the case of machines with more than two poles.

The spectral analysis of the axial flow of the motor can be used successfully in some cases. Although the method is not totally non-invasive because it requires the use of a sensor on the back part of the motor, it has advantages with relation to the study of stator currents to detect cut bars in the rotor and short circuits between loops. In motors of half power it is more complex to detect the stator currents and in those cases, it is easier to use a coil of axial flow. This technique has been successfully tested even with motors that work with frequency variations (Henao *et al.*, 2003).

The following of the torque of the motor, has some disadvantages in relation to the previous techniques (Verucchi *et al.*, 2003). On the one hand, the variables allow an easier identification of the harmonic components when a fault appears, and on the other hand, they are capable of detecting faults in the mechanic transition system of the motor and even in the same load (Bellini *et al.*, 2003). These techniques are more complex to implement due to the fact that they require sensing the stator currents and the voltages applied in the motor.

The measuring of the impedance of inverse sequence is more effective to detect short circuits between loops in the winding stator. To implement it, it is necessary to measure the currents and the voltages applied to the motor, and besides, the power net must show a minimum unbalance to allow measuring precisely the impedance of inverse sequence. When the direct, inverse and mutual impedances are measured, it is possible to establish accurate and trustful fault indicators. The use of this technique, however, is complicated as it requires a wide range of values that must be estimated for different load states of the motor.

The use of neural networks for fault detection and diagnosis in induction machines has a promising future. Good results have been obtained mainly in the detection of short circuits in winding stators. However, the application of this technique needs a training period and a constant control of the electric variables of the motor.

In Table I, a summary of de most outstanding features of each technique is presented for a more clear comparison.

V. CONCLUSIONS

The main techniques to detect faults in induction machines have been briefly presented taking as reference works from different authors and our own experience. The comparison among these techniques shows that the most appropriate solution for each case is given by the importance of the machine that is going to be supervised (the control of a higher and lower number of variables and the implementation of supervisory systems is subject to economic issues), the quantity and kind of fault to detect and the service of the motor (the possibility to do regular off-line diagnosis, the possibility of the operators to have access to the place where the motor is installed, etc.)

The frequency within which each diagnosis has to be done, basically depends on the faults to detect. Faults such as fissures in rotor bars have generally got a slow evolution while others, such as short circuits in the stator can evolve quickly.

It is important to point out that many of the above mentioned techniques need that the motor is working with a determined load level when the diagnosis is carried out. It is also important, in many cases, to carry out regular measures and compare the results. As a matter of fact, the analysis of the frequency spectrum of the stator, for example, is effective if the harmonic levels are compared with the ones obtained with the motor working without a fault.

Lastly, it is emphasized that the non-invasive methods of fault detection have evolved fast in the last years and the tendency shows that their use in the practice will go on increasing. Nowadays, an important number of researchers have devoted to the development of new alternatives in this field, and in many industries they have started to implement diagnostic routines based on some of the previously mentioned techniques.

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