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# A review on location, detection and fault diagnosis in induction machines

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***Abstract***

: In this work a careful review describing different types of failures in electrical machines, their characteristic signals generated and diagnosis methods is performed. Additionally, a comparison of the advantages between the known failure detection methods based on the information required for diagnosis, the occurrence and importance of failures detection, the effectiveness for anticipating a malfunction or failure and the final diagnosis accuracy is also made. Particularly, this review will help to provide a straightforward up date about the most recent work and research in this field.

*Keywords:* Induction machines, type of failures, characteristics signal generated, failure detection methods, and diagnosis methods.

## 1. Introduction

Failures in induction machines (IN), in most cases, do not appear untimely manner but rather develop gradually along the time instead as a sudden failure. This makes possible to detect a failure during the earlier stages before its consequences become catastrophic. In recent decades new techniques for faults detection have been developed leading to more accurate diagnoses. [1] The most applied techniques to identify failures are those involving vibration analysis (MVA), current spectral analysis (MCSA), analysis of axial leakage flux (AF) and the most recent models combining failure simulation and application of artificial neural networks (ANN).

Except vibration analysis, has not been widespread application of these diagnostic techniques in IM at the industry level, with many of them in experimental phase, however, is of great interest deepen their study and theoretically ahead to conventional methods in the ease of application and its sensitivity for the detection of faults. Monitoring of IM can significantly reduce maintenance costs (corrective) and the risk of unexpected failures to allow early detection of potentially catastrophic damage.

## 2. Electrical Machines Faults

Several surveys [2], [3], [4] have found the most common failure mechanisms in IM´s (figure 1). These have been classified according to the main components of a machine: faults related to stator, rotor, bearings and other faults.

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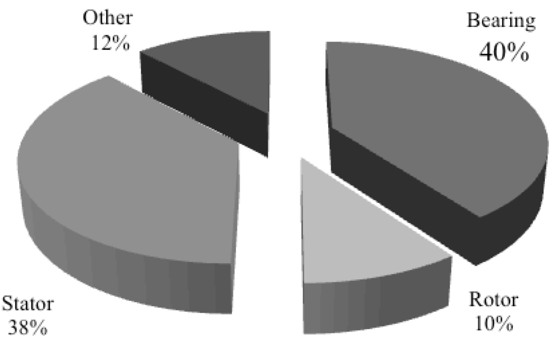


**Fig. 1.** Types of EM faults. Source: Sing ML, WL Soong & Ertugrul N., http://adelaide.academia.edu

It is known that failures depend on the type of electric machine, working conditions, where are located, as well as the duty cycle to which they are subject.

### A. Bearing failures

Most of electrical machines use ball bearings (or simply bearings) for rotating motion and are one of the most common causes of failures. A bearing is a mechanical device that reduces friction between a rotating shaft and the other parts attached to it. Ball bearings are contained by two rings, an inner ring which is strongly attached to the shaft, and an outer ring attached to the bearing bracket, as well as a set of rolling elements that can be balls, rollers or cones, located between both rings thus generating the rotation [5].

Failures in the inner ring, outer ring or rolling elements (balls) will produce a characteristic and unique vibration frequency of the components of the machine. Under normal operating conditions, bearings will fail due to wear or material fatigue. Before bearings start to fail there will be an increase in machine vibration as well as in acoustic noise levels. The vibration frequencies depend on both the geometry of the bearings and shaft speed [2], [4]. Although more than 40% of the electrical machines faults are related to ball bearings, this behavior can be erroneously attributed to rotor asymmetries [5].

**B. Failures in stator or armature**

Almost 40% of all reported IM´s failures fall into this category [6]. Stator winding faults are often caused by insulation failure between two adjacent turns in a coil. This is called a turn-to-turn fault o shorted turn. The resultant induced currents produce overheating and cause imbalance over the machine magnetic field. If this phenomenon is not detected, the local overheating will cause damage to the stator insulation and a catastrophic failure may occur. To prevent this to happen, temperature sensors should be installed at strategic locations on stator.

There is an expression that allows us to find the characteristic frequency of the short circuits.

$$f_{cc} = f_1 \left\{ \frac{n}{p} ( 1 - s ) \pm k \right\} \tag{1}$$

where:

$f_{cc} =$ characteristic frequency of the component produced by the short circuit;
$f_1 =$ frequency of power electric supply;
$n = 1, 2, 3, \dots$ ;
$k = 1, 3, 5, \dots$ ;
$p =$ number of pairs of poles;
$s =$ sliding.

Standard procedures, such as IEEE 275 reveal that exceeding 10°C the permitted limit temperature of insulation the useful life of machine is reduced to half [7], [8]. The imbalanced magnetic field can also result in an excessive vibration that might cause premature bearing failure.

**C. Broken rotor bars and failures in the rings**

The detection of this type of fails is important because the fracture of one his bars or one of their rings, converted the rotor in a three phase circuit (3ϕ) imbalance [5], [9]. Such an imbalance is manifested by circulation of negative sequence currents. As a result, are set a magnetic field that rotates in the opposite direction to the direction of rotation of the rotor, this rotating field causes a new pair of the rotor, at a frequency:

$$f_0 = 2 . s . f_1 \tag{2}$$

This torque, in turn, causes an oscillation in the rotor speed, whose amplitude depends on the coupled inertia. Such variations affect the stator currents, about which are induced the so-called sidebands, given to the frequencies:

$$f_s = ( 1 \pm 2 . s) . f_1 \tag{3}$$

These sidebands allow clearly identify faults in the rotor, the frequencies that to manifest are a function of the motor slip and its amplitude is strongly dependent the state of the load. A correct diagnosis requires at least that the engines are finding by above half of its rated load. Some loads that present pulsating torques (such as the compressors) can cause sidebands similar to those produced by a failure and interfere with the diagnosis [5], [9].

**D. Failures related to eccentricity**

Eccentricity occurs when the rotor is not well aligned within the stator thus producing a non-uniform air-gap between both pieces. This can be caused by defective bearings or manufacturing faults. The variations of the air-gap disturb the magnetic field distribution within the motor producing a net magnetic force on the rotor in the direction of the smallest air-gap. This so called ‘imbalanced magnetic pull’ can cause mechanical vibration.

All fault detection techniques require prior knowledge of the IM’s behavior by measuring the appropriate data in order to distinguish normal operation conditions from failure conditions.

## 3. Off-line monitoring

Off-line methods are typically more direct and accurate, [10], [11], [12], [13]. The user does not need to be an expert in IM but only have basic knowledge in electrical machines for testing. This is one of the main drawbacks compared to the monitoring methods online. An advantage of off-line monitoring is that they can carry out meaningful tests after manufacture of the unit and a test device can be used for several different machines thereby saving costs.

**A. Winding Resistance/DC Conductivity Test**

With the winding resistance test simply checked if there is an imbalance between the resistances of the windings of the stator. Therefore a well defined DC current is injected and the voltage drop across the winding is measured. If the resistance in one of the windings is lower than in the other windings, this is an indicator of some shorted turns in the winding [12]. This method has no predictive character since it can only detect a fault when it has already occurred.

**B. Insulation Resistance (IR) / Megohm Test**

The Insulation Resistance test, also called Megohm test, is probably the most widely used test for assessing the phase to-ground insulation of the stator insulation system [12], [14], [15]. It has been developed in and used since the early 20th century. The testing method can be applied to all machines and windings except for the rotor of a squirrel cage induction motor.

During the test the motor frame is grounded and a specified test voltage is applied to the motor terminals. Ideally, the measured resistance should be infinitely large. Since there is always a small leakage current present, the value of the insulation resistance can be determined by measuring the leakage current. If the value is too low this indicates that there might be a problem with the insulation.

The voltages to be applied and the insulation resistances to be expected are specified by different standards like IEEE 43-2000, NEMA MG-1-1993 and EASA technical manuals. One of the drawbacks of this method is that the measurement strongly depends on the temperature at which the test is done. In order to compensate for that there are methods for converting the IR value to a standard temperature [12].

**C. Polarization Index (PI)**

The PI test is a variation of the IR test and is performed at the same voltage level. The PI test measures the groundwall insulations ability to polarize. This is done by measuring the

IR after one minute and after ten minutes and calculating the ratio of those two values. Usually the polarization index should be “high” if the insulator is in a good condition [12], [15], [16]. The minimum acceptable values of the PI are determined by different standards like IEEE 43-2000.

The current between the copper of the windings and the stator core consists of different components: a capacitive current, conduction current, surface leakage current and absorption current. The ones that are of interest are the conductive and the leakage current. The capacitive current decays quickly. It has been shown empirically that the absorption current is first very high and vanishes after approximately ten minutes. Thus the PI value shows us how large the leakage and conductive currents are compared to the absorption current. If the PI ratio is close to one this indicates that there might be a problem with the insulation condition.

An advantage of the PI test compared to the IR test is its insensitivity to the temperature at which the test is performed.

**D. DC High Potential Test (DC Hi-Pot)**

The DC High Potential Test shows the groundwall insulations ability to withstand high voltages without exhibiting large leakage currents or even breaking down. The voltages applied are substantially above the normal operation voltages. If the insulation is able to work under those conditions, it is very likely that under normal operating conditions there won’t be any major problems that will cause the insulation to fail in the near future [12], [15]. The magnitude of the test voltage and the way the test should be conducted are again described by various standards like IEEE 95, IEC 34.1 or NEMA MG-1.

The major problem with the Hi-Pot test is that it can be destructive in case of an insulation breakdown even though the machine might still have been able to operate for a long time. A breakdown usually results in a costly repair of the machine.

**E. AC High Potential Test (AC Hi-Pot)**

The principle of the AC Hi-Pot test is similar to the one in DC Hi-Pot testing. Instead of a DC voltage an AC voltage of 50 or 60 Hz is applied to the groundwall insulation. Sometimes a test frequency of 0.1 Hz can be employed [3], [17].

The AC Hi-pot test basically has all the features described in the DC Hi-pot test. The main difference between AC and DC is the voltage distribution. In the DC case the amount of voltage dropped across an element depends on its resistance (resistivity). In the AC case the voltage distribution depends on the capacitance of the element (dielectric constant).

**F. Surge Test**

About 80% of all electrical failures in the stator originate from a weak turn-to-turn insulation [12], [18]. None of the tests described above is capable to directly measure the integrity of the turn insulation though. By applying a high voltage between the turns the surge test is able to overcome this limitation and provides precious insight into the condition of the turn-to-turn insulation [12], [15].

The principle of surge testing is to apply a short current pulse with a fast rise time to the windings of the stator. By Lenz’s Law there is a voltage induced between the adjacent loops of the winding. If the voltage is too high for the insulation there will be an arc developing. This process can be detected observing the impulse response of the motor which is also called “surge waveform”.

In praxis a capacitor is charged up to a specified voltage level and subsequently discharged in one of the motor windings. In a first order approximation the capacitor and the motor present a RLC-series circuit. If there is a short between the turns of the insulation due to a deteriorated winding, a change in the frequency and the magnitude of the impulse response can be observed.

By applying voltages that are significantly higher than during operation a weakness in the insulation can be found that is not apparent under rated conditions. The recommended test-voltages can be found in IEEE 522, NEMA MG-1.

**G. Other Test Methods**

Some other offline-tests that should just be mentioned here are the Offline-Partial-Discharge test, [15], [19], which is only applicable to medium and high voltage machines, the Dissipation-Factor test, [15], [20] and the Inductive-Impedance test [15].

## 4. On-line monitoring

The on-line monitoring is generally preferred on application shaving a continuous process, such as petrochemical, water treatment, management of materials, etc. The main advantage is that a machine will not does not have to be taken out of service. As a result, the normal operation condition can be evaluated while the motor is running. Also predictive maintenance is easier because the machine is under constant surveillance so an incipient failure can be detected immediately and actions can be programmed to avoid larger process downtimes. A disadvantage is that monitoring on-line techniques often require installation of additional equipment which must be installed on each machine. Compared to off-line tests the on-line tests exhibit more difficulty or even impossible to detect some failures in processes [6], [10]-[12], [15] [17], [21]. However, many non-invasive methods without sensors have been recently developed using forms of electrical signals, for example, current and voltage signals in such a manner that the monitoring equipment can be located in the motor control center or within devices of control in the motor, as well as on the IM groups.

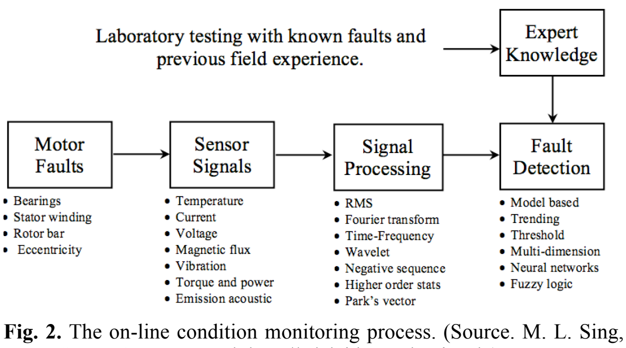


**Fig. 2.** The on-line condition monitoring process. (Source. M. L. Sing, W. L. Soong & N. Ertugrul, http://adelaide.academia.edu)

Figure 2 shows a block diagram of the general approach about on-line condition monitoring. Each of the blocks will be discussed in turn in this paper. Starting from the left, common IM faults are shown. The next block show different types of sensors can be used to measure signals to detect these faults. Various signal processing techniques can be applied to these sensor signals to extract particular features which are sensitive to the presence of faults. Finally, in the fault detection stage, a decision needs to be made as to whether a fault exists or not.

**A. Temperature monitoring**

Constant monitoring of machine temperature and its behavior along the time can be used by maintenance personnel to draw conclusions about the current condition of insulation [6], [8], [12], [14], [15], [18], [22], [21],. In many machines the temperature is monitored and the machine shuts down if it exceeds a certain temperature. Temperature sensors can be embedded within the stator, the stator core, the frame, or even might be part of the cooling system. Different types of temperature sensors such as temperature resistance (RTD) or thermocouple detectors can be used.

Recently a lot of work related to machine´s temperature estimation techniques has been reported. The capability of measuring even small changes in temperature allows the detection of potential problems in insulation at earlier stages and therefore can be used to schedule maintenance before a major breakdown may occur [12].

**B. Condition monitoring and tagging compounds**

The monitoring of machine conditions with tagging compounds has been used in motor monitoring for over 30 years. These monitors can be described as “smoke detectors”, [8], [12], [15]. Tagging-compounds are paints that emit particles with unique chemical properties at high temperatures. These particles can be easily detected by monitoring, indicating if a certain temperature is reached by the motor. Basically these unique particles appear and are detected when the winding is at very high temperature and insulation system is close to failure.

**C. Leakage currents**

This is a non-invasive monitoring method based up on measurement of the differential leakage of currents through the ground conductor [12]. The method is useful to find out the condition of the insulation system allowing the calculation of an equivalent capacitance between phase to ground and phase to phase as well as a dissipation factor. The continuous measurement and determination of these values allows drawing conclusions about the general condition of insulation system as well as its behavior through time. An increase or decrease of capacitance and dissipation factor provides an indication about the cause of deterioration. Although this method is able to detect changes on the insulation system phase-ground and phase-to-phase it provides no indications of deterioration of insulation between turns.

**D. High frequency impedance/Turn to turn capacitance**

A non-invasive monitoring system using high-frequency response of the motor is presented by [12], [15], [18], [21]. This system is capable of perceiving the deterioration of turn-to-turn insulation by detecting small changes in capacitance between each turn of stator winding. This method shows that when the turn to turn capacitance of the stator winding changes the impedance spectrum also changes as an effect of the system aging. Because it is not possible to use impedance analyzer in an on-line test, it is suggested to insert a small high-frequency signal in the stator winding. Its frequency should be closer to the series resonance frequency of the system. The machine flux caused by the HF signal introduced can be measured by a magnetic probe in the vicinity of the machine. The change in the phase time delay between the HF signal and the measured flux is used as an indicator of change in the resonance frequency and the capacitance between turn-to-turn, which is caused by the deterioration of insulation.

To determine the status of insulation, the impedance response is compared to a response recorded after that the motor has been manufactured or the dissipated power through insulation is calculated and compared against a target value, which can be determined by historical data of similar motors.

**E. Sequence components**

According to the theory of symmetrical components [23], all 3ϕ (three-phase) system imbalanced can be decomposed into two 3ϕ balanced systems of different sequence plus a set of equal-phase phasors. The first systems are called positive and negative sequence systems while the last one is called the zero-sequence system. Thus, from the complex values 3ϕ of voltages and currents the components sequence systems can be calculated by the following relationships:

$$\begin{bmatrix}\overrightarrow{V_0}\\ \overrightarrow{V_1}\\ \overrightarrow{V_2}\end{bmatrix} = \frac{1}{\sqrt{3}}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & \vec{a} & \vec{a}^2\\ 1 & \vec{a}^2 & \vec{a}\end{bmatrix}\cdot\begin{bmatrix}\overrightarrow{V_A}\\ \overrightarrow{V_B}\\ \overrightarrow{V_C}\end{bmatrix} \quad (4)$$

$$\begin{bmatrix}\overrightarrow{I_0}\\ \overrightarrow{I_1}\\ \overrightarrow{I_2}\end{bmatrix} = \frac{1}{\sqrt{3}}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & \vec{a} & \vec{a}^2\\ 1 & \vec{a}^2 & \vec{a}\end{bmatrix}\cdot\begin{bmatrix}\overrightarrow{I_A}\\ \overrightarrow{I_B}\\ \overrightarrow{I_C}\end{bmatrix} \quad (5)$$

The subscripts $A$, $B$ and $C$ refer to each of the phase components of the actual system, while 0, 1 and 2 indicate the components of the zero-sequence, positive and negative systems, respectively, and the constant $\vec{a}$ is given by:

$$\vec{a} = e^{j2\pi/3} \quad (6)$$

The relationship between the sequence currents and voltages are determined by sequence impedance positive, negative and zero:

$$\begin{bmatrix}\overrightarrow{V_0}\\ \overrightarrow{V_1}\\ \overrightarrow{V_2}\end{bmatrix} = \begin{bmatrix}Z_0 & 0 & 0\\ 0 & Z_1 & 0\\ 0 & 0 & Z_2\end{bmatrix}\cdot\begin{bmatrix}I_0\\ I_1\\ I_2\end{bmatrix} \quad (7)$$

Taking separately each of these systems it can be defined the parameters $Z_0$, $Z_1$and $Z_2$. This equation is valid only for perfectly symmetrical machines. For a machine with asymmetries a coupling between components of positive and negative sequence is set introducing new terms in this equation [18].

*a. Negative sequence current* ($I_2$) The monitoring of the negative sequence current for fault detection is the subject of several papers [12], [14], [16], [18], [24].

If there is an asymmetry introduced by a turn-to-turn fault the negative sequence component will change and can thus be used as an indicator for a fault. The major problem with this method is, that not only a turn-to-turn fault contributes to the negative sequence components, but also supply voltage imbalances, motor and load inherent asymmetries and measurement errors have an effect on this quantity.

The methods suggested [25] and [26] account for those non-idealities by using the negative sequence voltage and impedance and a database.

*b. Sequence Impedance Matrix.* The calculation of the sequence impedance matrix under healthy conditions is the basis of an approach that is presented in [11], [12], [13], [16], [18], [27]. A library of the sequence impedance matrix as a function of the motor speed for a healthy machine is used during the monitoring process. The method is not sensitive to construction imperfections and supply unbalances, since they have been taken into account during the construction of the library.

Another robust method with high sensitivity using the sequence component impedance matrix is introduced in [28]. It uses an off-diagonal term of the sequence component impedance matrix and is immune against supply voltage unbalance, the slip-dependent influence of inherent motor asymmetry and measurement errors.

*c. Zero sequence voltage ($V_0$).* A method utilizing the zero sequence voltage is proposed in [29]. The algebraic sum of the line-neutral voltages is used as an indicator for a turn fault. Ideally this sum should be zero. The sensitivity is improved by filtering the voltage sum to get rid of higher order harmonics. It is pointed out that the method is not sensitive to supply or load unbalances. In order to take inherent machine imbalances into account different procedures are suggested. The main drawback of this procedure is that the neutral of the machine has to be accessible.

## 5. Signal forms analysis

*A. Current spectral analysis (MCSA).*
Current spectral analysis constitutes a complement for diagnosis when using MVA because of their inherent limitations in detecting earlier electrical problems such as air-gap eccentricity, short circuits on stator winding´s turn to turn or rotor broken bars. The stator current on IM´s generally contains harmonics because the arrangement of the windings in the slots is not perfectly symmetrical, and the signal is not sinusoidal but staggered due to imperfections during fabrication and also to harmonic components present in the power supply. If a short circuit occurs on some stator windings, either between windings or turns of the same phase or between different phase windings, the configuration of the rotating magnetomotive force is affected. As a consequence, harmonic components of the stator currents will also be affected on their amplitudes [3], [6], [8], [11]-[14], [18], [22], [24], [30], [32]-[45]. By taking this into account it is possible to detect small short-circuits to prevent unwanted consequences by conducting regular monitoring of frequency spectrum of stator currents.

It is important to notice that the affected components are a function of the slip; therefore the observed frequency depends on the machine load. The amplitude variation of harmonic components is affected not only by the fault but also by the load on the motor. So it is convenient to perform comparisons under similar loads.

The incidence of a fault on each harmonic component varies from one machine to another and depends primarily on the characteristics of the winding. In some cases the value of some components can be reduced as a result of a failure. Unfortunately these components vary under different load conditions and are also sensitive to the inherent asymmetry of the motor and imbalances of power supply.

**B. Park's vector (CPV)**
Park's transformation relates 3ϕ machine variables to a two axes in a quadrature system. Continuous monitoring of spatial phasor resulting of applying Park's transformation can be employed for diagnostic purposes. [2], [3], [6], [9], [11], [13], [16], [20], [27], [34], [36], [37] [46], The components of the stator current in the direct-axis and quadrature ($D$y $Q$) fixed to the stator are obtained by means of the following relationships:

$$I_D = \sqrt{\frac{2}{3}} . I_A - \sqrt{\frac{1}{6}} . I_B - \sqrt{\frac{1}{6}} . I_C \quad (8)$$

$$I_Q = \sqrt{\frac{1}{2}} . I_B - \sqrt{\frac{1}{2}} . I_C \quad (9)$$

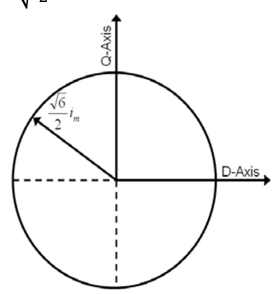


**Fig. 3.**Park's vector for a healthy machine. (**Source:** Puche, R., 2008.)

Under ideal conditions, when a 3ϕ system machine without failure is powered with a sinusoidal current and a balanced and positive sequence, the components of the CPV determine a circle centered on the origin of the plane $D - Q$ as shown in figure

3.Under these conditions the current module CPV is constant and coincides with the magnitude of Park and the radius of the circumference.

When a short circuit occurs on the windings of stator machines it behaves as an imbalanced load and the currents in stator will be no longer a balanced system. In Figure 4a, is represented the current of VCP from a IM which has an asymmetric stator, it is observed that is centered at the quadrature origin $D - Q$ (as in Figure 3) but unlike this, already not be in the same plane $D - Q$,is found rotated respect to this plane through the center of coordinates itself. In Figure 4b, represented the current modulus of VCP, which is observed in sinusoidal shape and is no longer constant (as in Figure 3). The module of the circumference which forms the current VCP to represent it is constant, but as this circumference is rotated with respect to the plane $D - Q$ from the same plane module is no longer constant.

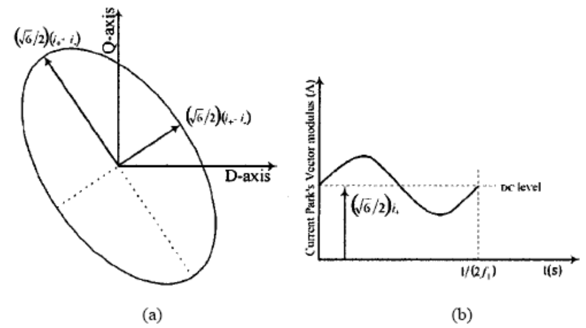


**Fig. 4**. a) Representation of current of VCP, b) Representation of module of current of VCP, both from an IM with asymmetric stator. (Source: Puche, R., 2008.)

Park's vector is used by some authors for the detection of rotor eccentricity [7], [9], [11], [13], [34], [37].

**C. Axial Leakage Flux: (AF).**

On any IM, even under normal operating conditions, small imbalances on currents occur. These imbalances arise from both manufacturing imperfections and the power electric supply. This cause the presence of negative sequence currents in the machine and the imbalance in currents in the windings heads originating a flux in the axial direction of the machine. This flux, produced by the stator currents has the same harmonics which allows identifying faults. A coil located at the end of a machine concentrically to its axis, allows measuring AF and from it, to diagnose faults [2], [6], [9], [11]-[13], [18], [24], [27], [36], [38], [48], [49],. Thus, analyzing the AF´s frequency spectrum, short circuits on the stator windings, eccentricities and rotor broken bars can be detected. This method is its strong dependence on the load driven by the motor. The highest sensitivity can be obtained at full load conditions.

**D. Torque harmonic and power analysis (THA).**

Harmonic analysis to total power consumed, partial power or electric torque, can be applied by this method allowing detection of failures that most frequently occur in IM´s [2], [6], [9], [12], [13], [26], [27], [49], [50].

Power measurement is used because power is the product of the supplied voltage times the current. Then power has a spectrum in which the fundamental frequency at 50 or 60 Hz almost vanish, appearing at 100 or 120 Hz which is the result of the product of voltage by current, while that nearly effects at 50 or 60 Hz are visible, since they are no longer masked.

When an abnormality exists in an IM such as a rotor failure, shaft misalignment, bearing breakage current variation, torque or motor speed variation, the power consumed by the IM is altered.

When a fault occurs in the rotor, partial and total power exhibit frequency components and sidebands $2sf_1$ about twice of the main frequency. Such components that are absent in normal conditions, allow to detect and weigh the severity of a failure. The total power, in turn, will be affected by means of a component to the frequency $2sf_1$.

The inner pair represents the combinate defects of all flux linkages and both the stator and rotor currents. This is very sensitive to any imbalance [2].

The instantaneous power on an IM is the sum of the products of voltage and current of each phase of the machine:

$$P = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c \tag{10}$$

The power supply voltage can be decomposed as the sum of the flux linkages:

$$v_a = \frac{d\psi_a}{dt} + r.i_a \tag{11}$$

$$v_b = \frac{d\psi_b}{dt} + r.i_b \tag{12}$$

$$v_c = \frac{d\psi_c}{dt} + r.i_c \tag{13}$$

By applying the previous formula of the voltage of each phase as the sum of flux linkage plus the resistance times the phase current. Thus the instantaneous power is given by:

$$P = \left(\frac{d\psi_a}{dt} + r\,.i_a\right).i_a + \left(\frac{d\psi_b}{dt} + r\,.i_b\right).i_b + \left(\frac{d\psi_c}{dt} + r\,.i_c\right).i_c \tag{14}$$

The flux linkage is obtained from the phase power voltage supply equation:

$$\psi_a = \int (v_a - r\,.i_a)\,.dt \tag{15}$$

$$\psi_b = \int (v_b - r\,.i_b)\,.dt \tag{16}$$

$$\psi_c = \int (v_c - r\,.i_c)\,.dt \tag{17}$$

The IM´s symmetrical inner pair calculated using the voltage and current stator is:

$$Pair\,[Nm] = \frac{P}{2.\sqrt{3}}.\langle (i_A - i_B)\int [V_{CA} - R(i_C - i_A).dt - (i_C - i_A)\int [V_{BA} - R(i_A - i_B).dt]]\rangle \tag{18}$$

Simplifying:

$$Pair\,[Nm] = \frac{P.\sqrt{3}}{6}.\langle (2i_A + i_C)\int [V_{CA} - R(i_C - i_A).dt - (i_C - i_A)\int [-V_{BA} - R(2i_A + i_C).dt]]\rangle \tag{19}$$

The traditional form of representing the equations for an IM is based on the theory of rotating fields, but they can be represented by the theory of spatial vectors $D$ (Direct)$-Q$ (Quadrature).

Applying the Park's transformation, the inner or electromagnetic torque is represented as [2]:

$$Pair = \frac{3}{2}\,.p\,.\left(\psi_D\,.i_Q - \psi_Q.i_D\right) \tag{20}$$

where:

$i_D, i_Q$ = projections of current vector on $D$ and $Q$ axes;
$\psi_D, \psi_Q$ = total flux linkage according to the $D - Q$ axes.

The derivatives flux linkage each of the $D - Q$ axes are:

$$\frac{\partial\psi_D}{\partial t} = (v_D - R.i_D).\omega_b \tag{21}$$

$$\frac{\partial\psi_Q}{\partial t} = (v_Q - R.i_Q).\omega_b \tag{22}$$

where:

$R =$ stator resistance.

By decomposing the voltage and current vectors into axes $D$ and $Q$, and integrating the flux linkage, the electromagnetic torque can be obtained.

It is assumed that motor speed is practically constant so it can be ensured that the electric motor torque has the same components as the power, and therefore it can be used to detect failures, [9], [13].

**E. Vibration Signature Analysis (MVA).**

Vibrations on machines consist of periodic oscillations and can be classified into two types: deterministic and random. The first one can always be defined by mathematical equations expressing the evolution over time. These oscillations are caused by imperfections associated with the design, manufacture and operation of the machine. On the other hand, random vibrations cannot be represented by a deterministic mathematical equation, and can only be analyzed by statistical means. These vibrations do not follow any periodic pattern and are usually caused by a force acting over a specific period of time and the disappear as they came.

Diagnostic and detection of failures can be done by measuring vibration. The vibration response as a result of a failure is recorded and analyzed, so the deterministic vibrations acquire special interest because failures produce a cyclic anomaly on vibration response. These vibrations are the consequence of such alterations and can be used for collecting useful information from a failure. When a failure begins to occur, the dynamic stress to which the machine is subjected varies, and thus also varies its vibration response. That is why it has been one of the first methods used for detection of faults.

Vibrations on an IM appear as a result of periodic forces acting between the moving parts. If a machine is well designed, and without failure, the vibration response should be reduced. However when the components of the mechanisms wear and settle, this behavior changes. When a failure starts to occur the dynamic forces acting on the machine vary, and so do too their vibratory response. Hence, this has been one of the former methods for failure detection.

Usually the most used transducers are accelerometers because they have a greater dynamic range de frequencies, robustness, reliability and small dimensions. The accelerometers produce a voltage output proportional to the acceleration undergone by the machine. When the accelerometer is subjected to vibration, its mass exerts a force on the disc or piezoelectric crystal proportional to the acceleration, thus leading to deformation of the piezoelectric element. This element produces an electrical charge directly related to its level of deformation. Finally this deformation is converted into a voltage proportional to the acceleration to that the accelerometer is subjected to.

The accelerometers that should be placed attached to the machine for measuring the vibrations produced by the rotary machine, thus it can be considered as an invasive measure because the transducer must be set and secured when installed on the machine. There are many scientific publications that use the vibration measurement to detect and diagnose faults, [5], [6], [8], [12], [18], [20], [22], [24], [26], [27], [34], [38]-[40], [43], [51]-[56].

*F. Acoustic Noise*

Under normal operating conditions IM´s might fail because of wearing down associated with their operation. When a failure begins to occur on a machine, vibration and levels of emission acoustic increase [2], [6], [11], [12], [22], [40], [52], [55], [56], [57]. The failure frequencies related to the construction of the machines themselves in such a matter that an increase of motor speed produces electromagnetic noise [6], [52], [55]. The IM´s acoustic noise spectrum is dominated by electromagnetic forces, ventilation and acoustic noise. These forces induce vibrations into the stator structure which causes the noise to spread out.

## 6. Partial discharge (PD)

A popular and reliable method for medium and high voltage machines is the method of partial discharges (PD) [6], [16]-[18], [24], [39] but this method is not applicable to low voltage machines. The test of partial discharges analyzer (PDA) was developed in 1976 and it is one of the main techniques used in hydroelectric generators machines. This test requires a small electric shock that occurs due to imperfection son insulation. When insulation deteriorates small pieces are detached from it caused by manufacturing problems or overheating thus forming air cavities spaces (or gaps) which in turn, produce electric discharges [6], [16], [17]. A damaged winding will produce 30 times or even more PD´s than a winding in good conditions. The insulation of the stator winding can be easily damaged with an on-line test PD [12].

Degradation of electrical insulation in an IM produces carbon monoxide that passes through the air-cooling circuit and can be detected by an infrared absorption technique (IR) [12].

The amplitude modulation of high frequency pulses (PWN) generates pulses of high voltage peaks leading to the breakdown of the machine insulation. Electrostatic fields surrounding opposite polarized conductors detach electrons around the gap, leaving positive-charged molecules (ionization) that produce ozone. When combined with nitrogen of the air nitrogen oxides are then produced. Corrosion attacks insulation causing degradation and eventual fracture. Tracking techniques are used to detect ozone generation [21].

## 7. Artificial intelligence

In recent years, applications of artificial intelligence (AI) methods in the field of analysis and diagnosis of electric machines have grown significantly. Methods such as expert systems, fuzzy logic and neural networks usually require a large amount of information stored as a database to describe accurately the machine operation using an AI-based logical analysis instead of the more complex deterministic mathematical analysis for decision-making.

**A. Artificial neural network (ANN)**

The Artificial neural network imitates functioning of the human brain (Figure5). The ANN´ shave been widely used for image recognition and sounds, for data and signal processing, and are a powerful tool in many fields of knowledge. The applications of ANN´s to detect faults in IM have been studied by several authors, [9], [11], [13], [16], [18], [24], [31], [36], [39], [41], [58]-[65]. A neural network is “trained” to predict a feature, the value of a variable or a characteristic of the machine from an input or initial specified value or condition. Then the estimated characteristic value is compared to the measured or real value and based on this comparison the failure diagnostic is determined.

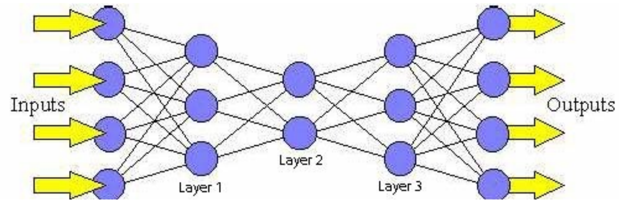


**Fig. 5**.Structure of a neural network. (Source: M. L. Sing, W. L. Soong & N. Ertugrul, http://adelaide.academia.edu.)

**B. Fuzzy logic**
This method involves making decisions on the basis of the classification of signals into a series of bands (fuzzy variables) instead of simply taking a base of normal or defective threshold. Fuzzy logic allows combining information from different signals in getting a more accurate judgment about the condition of the motor, [18], [24], [35], [36], [59], [62], [65].

**C. Expert systems**
Based on different techniques for detection and diagnosis, expert systems can be developed that, based on the analysis of the acquired variables from the motor, conclusions based on rules developed from empirical knowledge can be obtained. [9], [13], [36], [62], [65].

## 8. Results

This research describes the existing online testing methods for detection and diagnosis of failures related to induction machines.

As a result of this study a comparison of advantages and disadvantages for all diagnosis methods described above are condensed on the summary following (table I):

**Table I**. Different methods to test and monitor of failures to IM to obtained a comparison of advantages and disadvantages for all diagnosis.

| Technique | Required measured | Diagnostic Value | Advantages | Disadvantages |
|---|---|---|---|---|
| Winding resistance/DC Conductivity test | Voltage are injected and measured of the winding resistance re required | Detects shorted turns | • Easy to perform | • Only detects faults<br>• No predictive value |
| Insulation Resistance (IR) Megohm | Voltage are applied to the machine terminal and insulations resistance are measured | Find contaminations and major defects | • Easy to perform | • Results is strongly temperature depend |
| Polarization Index (PI) | Voltage and current are applied and groundwall insulations ability to polarize are measured | Find contaminations and major defects | • Easy to perform<br>• Less sensitive to temperature than IR-test | |
| DC High potential test (DC High-pot) | DC voltage are applied and and groundwall insulations (depend of the resistivity) ability to withstand high voltages without exhibit large leakage current | Finds contaminations and major defects | • Easy to perform<br>• If test does not fail the insulation is like to work flawlessly until the next maintenance period→more predictive character than IR and PI | • In case of failure repair required (destructive) |
| AC High potential test (AC High-pot) | AC voltage are applied and groundwall insulations (depend of the capacitance) | Finds contaminations and major defects | • More effective than DC High-pot | • Not as easy to perform as DC High-pot |
| Surge test | Apply a short currents pulse a fast rise time to the winding resistance and measured voltage induced between the adjacent loop are measured | Detects deteriorations of the turn insulation | • Only test that measure the integrity of the turn insulation | • |
| Off-line partial discharge | | Detects deterioration of the phase and groundwall insulation | • Good practical results | • Non applicable to low-voltage machines<br>• Difficulty in interpretation of the data |
| Dissipation factor | | Detects deterioration of the phase and groundwall insulation | • Capable of determining the cause of deterioration | • Measurements on a regular basis have to be made in order to trend the obtained data over time |
| Inductive impedance | | It detects shorted turns | • | • Not as easy to perform as the winding resistance test<br>• No predictive value<br>• Undesired foreign influence on result |
| Temperature Monitoring | It measures temperature on stator frame and stator windings | It applies to failures in bearings, detect deterioration in groundwall and faults in turn-to-turn insulation | • Detects problems in insulation,<br>• Bearings at early stages | • Requires a lot of data and additional information such as ambient temperature,<br>• Is an invasive method (sensors are required) |
| Condition | It requires measurement of | It detects deterioration over | • Can be used as a | • Is invasive because it |

| | | | | |
|---|---|---|---|---|
| monitoring and tagging's compounds | temperature in the winding | the insulation groundwall and faults of the winding insulation | complement in detecting problems on insulation | requires equipment for detection of particles |
| Leakage currents | Current measurement is needed | It detects deterioration of the phase and groundwall insulation | • Is not invasive<br>• capable to determine causes of deterioration | • It cannot detect the turn-to-turn insulation deterioration |
| High frequency impedance/turn to turn capacitance | It requires current or voltage measurement on stator | It detects deterioration of turn-to-turn insulation | • Is the only technique capable to detect deterioration of turn-to-turn insulation condition | • It is invasive (search coil),<br>• It has not tested widely yet |
| Negative sequence current | It requires measurement current on the stator | It detects turn-to-turn faults on the stator winding | • It is a non-invasive method<br>• Compensates for potential non-idealities | • Several sources contribute to the negative sequence components |
| Zero sequence voltage | It requires measurement on stator phase voltages | It detects faults between turns in the stator winding | • It is non-invasive method<br>• Compensates for potential non-idealities | • The machine's neutral wire must be accessible |
| Sequence Impedance Matrix | Two stator currents and two stator voltages should be measured | It detects turn-to-turn faults on the stator winding | • It permits the detection of incipient fault,<br>• It is a non-invasive test<br>• Compensates for potential non-idealities | • It requires high precision in measurements |
| MCSA | It requires measurement of stator current | it detects broken bars in rotor, turn-to-turn faults on stator winding, air-gap eccentricity, and bearing failures | • It is a lower cost<br>• It is non-invasive method | • Subjective interpretation of results<br>• Fault signals vary from one machine to another<br>• Further research required to generalize results |
| CPV | Two stator currents are needed | It detects broken bars in the rotor, turn-to-turn faults in the stator winding, and air-gap eccentricity | • It is easily performed, is a non-invasive test | • Imbalances on power electric-supply are interpreted as failures |
| AF | Axial flux measurement is required | It detects broken bars in rotor, turn-to-turn stator winding faults, air-gap eccentricity | • It is a low cost test | • It is invasive because a coil is needed for measurements,<br>• The results depend strongly on the load |
| THA | It requires to measure two current sand two voltages on stator | It detects broken bars in the rotor and faults in turn-to-turn stator winding | • It detects mechanical failures,<br>• It is a non-invasive test | • It is not effective for short circuits detection |
| Vibration Signature Analysis | Vibration measurement needed | It detects broken bars in rotor, air-gap eccentricity, bearing failures, and turn-to-turn stator winding faults | • It is a well-documented traditional method | • It is invasive (accelerometers are required),<br>• It is necessary further research in order to generalize results |
| On-line PD | | It permits to detect the insulation system deterioration | • Good results in practice are obtained | • It is invasive<br>• It is not applicable to low-voltage machines,<br>• the interpretation of data is difficult |
| Ozone | Ozone measurement is required | It detects insulation system deterioration | • It is a PD by product | • It is invasive (gas analyzer or electronic instruments must be present) |
| ANN | Two currents and two stator voltages are necessary | It detects turn to turn stator winding faults | • It detects incipient faults,<br>• It is easy to be adapted to each machine,<br>• It is a non-invasive test | • It is constrained by the need if a training period,<br>• It is not effective for unforced seen states of the machine |

## 9. Conclusions

The main fault detection techniques for induction machines (IM) have been gathered and presented in this article. This was done by carefully reviewing the published work by different authors up to date. The comparison of these techniques indicates that the most suitable solution for any particular case is directly related to the importance of the machine in the process, by the specific type of failure and service that the machine carries on. On the other hand the amount of variables to be measured and the required monitoring systems are subject to economic considerations as a final making-decision criterion.

Faults such as shaft-misalignment generally appear after a prolonged periods of time while others like short-circuits in the winding of a machine may appear suddenly.

Many of the techniques described here require the machine to be working during monitoring to a specific load level. Therefore it is recommended to test and compare results periodically. For example, the spectrum frequency analysis of stator is justified when the harmonic levels are compared with those obtained with a non-failing machine.

Finally it is noticed that the non-invasive methods of failure detection have been developed rapidly in recent years and that practical applications will continue growing in this field.

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