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A REVIEW ON 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 update about the most recent work and research in this field. The work is mainly oriented to engineering students interested in starting the research and study of electrical machines.

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

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UNA REVISIÓN SOBRE DETECCIÓN Y DIAGNÓSTICO DE FALLAS EN MÁQUINAS DE INDUCCIÓN

Resumen

El presente trabajo consiste en una revisión que describe los diferentes tipos de fallas, las formas características de las señales que generan y los métodos de diagnóstico en máquinas eléctricas. Además, se efectúa un comparativo de las ventajas de cada uno de los diferentes métodos de detección de fallas en función de la información que requieren para el diagnóstico, el número e importancia de las fallas que pueden detectar, la rapidez con la que son capaces de anticipar una falla y el grado de certeza en el diagnóstico final. En particular, esta revisión ayudará a proporcionar una visión rápida y clara acerca de los últimos trabajos y las nuevas investigaciones en el área. Esta enfocada principalmente hacia los estudiantes del área de ingeniería interesados en iniciarse en el campo de la investigación de máquinas eléctricas.

Palabras clave: Máquinas de inducción, tipos de fallas, características de las señales, métodos de detección de fallas y métodos de diagnóstico de fallas.

Introduction

Failures in electric machines are recognized to be developed gradually along the time instead of occurring 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 (Boukra & Lebaroud, 2010), (Bayindir, Sefa, Colak, & Bektas, 2008). The most applied techniques to identify failures are those involving vibration analysis, 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).

Electrical Machines Failure

Several surveys (Bayindir et al., 2008)-(Puche, Pons, Climente, & Pineda, 2004) have reported that percentage distribution of failures on IMs components is typically: Stator related: 38%, rotor related: 10%, bearing related: 40%, others: 12%.

Bearing failures

Most of electrical machines use ball bearings (or simply bearings) for rotating motion and this is 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 made 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 (Calero Pérez & Carta González, 1998). 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 (Puche, 2008). Although more than 40% of the electrical machines faults are related to ball bearings, this behavior can be erroneously attributed to rotor asymmetries (Calero Pérez & Carta González, 1998).

Failures in stator or armature

Almost 40% of all reported induction machine failures fall into this category (Siddique, Yadava, & Singh, 2005). 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 from happening, temperature sensors should be installed at strategic locations on stator. Standard procedures, such as IEEE 275 reveal that exceeding 10C the permitted limit temperature of insulation the useful life of machine is reduced to half (Kathir, Balakrishnan, & Bevila, 2011). The unbalanced magnetic field can also result in an excessive vibration that might cause premature bearing failure.

Failures related to the 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 unbalanced magnetic pull can cause mechanical vibration. All fault detection techniques require prior knowledge of the IMs behavior by measuring the appropriate data in order to distinguish normal operation conditions from failure conditions.

On-line monitoring

The online monitoring is generally preferred on applications having a continuous process, such as petrochemical, water treatment, management of materials, etc. The main advantage is that a machine will 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 online 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 (Boukra & Lebaroud, 2010), (Verucchi, Acosta, & Benger, 2009), (Tozzi, Cavallini, & Montanari, 2011), (Hidalgo, 2013), (Brown, David, & Essalihi, 2011). 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.

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 (Siddique et al., 2005), (Castelli & Andrade, 2008), (Hidalgo, 2013), (ANSI/NEMA, 2012)-(Grubic, Aller, Lu, & Habetler, 2008). 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 machines 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 (Gubric, Aller, Lu, & Habetler, 2012).

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 (Castelli & Andrade, 2008), (Gubric et al., 2012), (Grubic et al., 2008). 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.

Leakage currents

This is a non-invasive monitoring method based upon measurement of the differential leakage of currents through the ground conductor (Gubric et al., 2012). 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 to draw conclusions about the general condition of insulation system as well as its behavior through time. An increment or decrement 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.

High frequency impedance/Turn to turn capacitance

A non-invasive monitoring system using high-frequency response of the motor is presented by (Castelli & Andrade, 2008), (Gubric et al., 2012), (Hidalgo, 2013), (Brown et al., 2011), (Grubic et al., 2008). 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. To determine the status of insulation the impedance response is compared to a response recorded after 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.

Sequence components

Several methods based on the sequence components for machines impedances, currents, or voltages have been developed for the online detection of turn-to-turn faults in the stator insulation system (Brown et al., 2011)-(Bakhri, Ertugrul, Soong, & Arkan, 2010), (Aguado, 2012). A disadvantage of the methods using sequence components is that only a failure but not the change of the overall condition and thus the deterioration of the insulation system, is monitored (Brown et al., 2011)-(Bakhri et al., 2010), (Aguado, 2012).

Negative sequence current

If there is an asymmetry caused by a turn to turn fault the negative sequence component will change and it can be used as an indicator of failure. The main problem with this method is that not only a turn to turn fault contributes to negative sequence components, but also the unbalanced voltages, the machine design load asymmetries and measurement errors have an effect on this value. The methods suggested in (Gubric et al., 2012), (Hidalgo, 2013), (Brown et al., 2011), (Grubic et al., 2008), (Filippetti, Bellini, & Capolino, 2013)-(Sin, Soong, & Ertugrul, 2012), represent those disadvantages through the use of the negative sequence voltage, impedance, and a databank.

Sequence Impedance Matrix

The calculation of the sequence impedance matrix at normal operating conditions is the basis of an approach presented in (Verucchi et al., 2009), (Gubric et al., 2012), (Brown et al., 2011), (Grubic et al., 2008). A databank of sequence impedance matrix as a function of motor speed for a machine under normal operating conditions is used during the monitoring process. The method is not sensitive to construction imperfections neither imbalances of power electric supply because they were taken into account during the development of the databank. Another robust method with high sensitivity that uses the impedance matrix sequence component is introduced in (Aguado, 2012). An external term from the diagonal of the matrix component sequence impedance is then used but not affected by unbalanced voltages, motor slip or measurement error.

Zero sequence voltage

A method that uses the zero-sequence voltage is proposed in (Aguado, 2012). The algebraic sum of the phase-to-neutral voltage is used as an indicator of failure. Ideally, the sum must be zero. The sensitivity of the method is improved by filtering the sum of voltages in order to eliminate higher-order harmonics. This method is not sensitive to power electric supply imbalances or load. The main disadvantage of this procedure is that the neutral wire of the machine must always be accessible (Gubric et al., 2012), (Grubic et al., 2008), (Aguado, 2012).

Signal forms analysis

Current signature analysis (MCSA):

Current spectral analysis constitutes a complement for diagnosis when using vibration methods because of their inherent limitations in detecting earlier electrical problems such as air-gap eccentricity, short circuits on stator windings turn to turn or rotor broken bars. 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 (Puche et al., 2004), (Siddique et al., 2005)-(Gubric et al., 2012), (Hidalgo, 2013), (ANSI/NEMA, 2012), (Grubic et al., 2008), (Nandi, Toliyat, & Li, 2005), (Sin et al., 2012), (Gnal & Nehiz, 2009), (Concari, Franceschini, & Tassoni, 2010)-(Mariun, Mehrjou, Marhaban, & Misron, 2011). 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.

Parks vector (CPV)

Park's transformation relates 3-phase 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. (Puche, 2008), (Puche et al., 2004), (Siddique et al., 2005), (Verucchi et al., 2009), (Sin et al., 2012), (Aguado, 2012), (Sánchez, Aguilar, & Jutinico, 2012). When a short circuit occurs on the windings of stator machines it behaves as an unbalanced load and the currents in stator will be no longer a balanced system. In figure 1 it is shown the current Park vector for an IM with an asymmetric stator. Parks vector is used by some authors for the detection of rotor eccentricity (Kathir et al., 2011), (Verucchi et al., 2009).

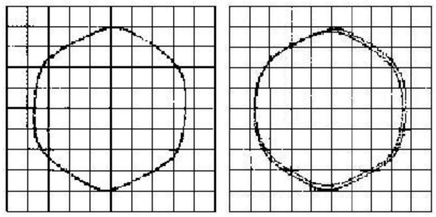

Figure 1: Parks vector for a healthy motor (left) and a motor with air-gap eccentricity (right)

Axial Magnetic Flux (AF)

A coil located at the end of a machine concentrically to its axis, allows to measure AF and from it, to diagnose faults (Puche, 2008), (Siddique et al., 2005), (Verucchi et al., 2009), (Gubric et al., 2012), (Grubic et al., 2008), (Nandi et al., 2005), (Sin et al., 2012), (Frosini, Borin, Girometta, & Venchi, 2011), (Spyropoulos, Gyftakis, Kappatou, & Mitronikas, 2012). Thus, analyzing the AFs frequency spectrum, short circuits on the stator windings, eccentricities and rotor broken bars can be detected. A major disadvantage of this method is its strong dependence on the load driven by the motor. The highest sensitivity can be obtained at full load conditions. Another disadvantage is that a tracker coil must be installed to detect axial flux.

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 IMs. (Puche, 2008), (Siddique et al., 2005), (Gubric et al., 2012), (Kia, Henao, & Capolino, 2010), (Spyropoulos et al., 2012) 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 electric torque provided by the motor can be estimated from magnetic flux linkage and stator current:

$$T_{est}(t) = \frac{p}{3}[\lambda_{ds}(t)i_{qs}(t) - \lambda_{qs}(t)i_{ds}(t)] \quad (1)$$

where: T_{est} is the estimated electric torque, p is the number of poles and λ_{ds}, λ_{qs}, i_{ds}, and i_{qs} are magnetic flux and current on dq axis, respectively. 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. Short circuits in stator can be detected both in power and torque from components at twice the central frequency of the power electric supply.

Vibration Signal Analysis

Vibrations on machines are periodical oscillations caused by imperfections associated with the design, manufacture and operation of the machine. Diagnostic and detection of failures can be done by measuring vibration. The vibrational 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 vibrational 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 stresses to which the machine is subjected vary, and thus also varies its vibrational response. That is why it has been one of the first methods used for detection of faults. Typically the transducers mostly used are 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, (Calero Pérez & Carta González, 1998)-(Castelli & Andrade, 2008), (Gubric et al., 2012), (ANSI/NEMA, 2012), (Nandi et al., 2005)-(Aguado, 2012), (Rangel, Romero, Osornio, Cabal, & Contreras, 2009), (Kia et al., 2010), (Kreitzer, Obermeyer, & Mistry, 2008)-(Boesing & Doncker, 2012).

Acoustic Noise

Under normal operating conditions IMs might fail because of wearing down associated with their operation. When a failure begins to occur on a machine, vibration and levels of acoustic noise increase (Puche, 2008), (Siddique et al., 2005), (ASA, 2010), (ASA, 2009), (ANSI/NEMA, 2012), (Baldizzone, Novak, & Kar, 2012), (Boesing & Doncker, 2012). The failure frequencies re related to the construction of the machines themselves in such a matter that an increment of motor speed produces electromagnetic noise (Siddique et al., 2005), (Baldizzone et al., 2012), (Boesing & Doncker, 2012). The IMs 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.

Partial discharge (PD)

A popular and reliable method for medium and high voltage machines is the method of partial discharges (PD) (Siddique et al., 2005), (Tozzi et al., 2011), (Hidalgo, 2013), (Grubic et al., 2008), (Nandi et al., 2005) 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 imperfections on 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 (Siddique et al., 2005), (Tozzi et al., 2011).

A damaged winding will produce 30 times or even more PDs than a winding in good conditions (Gubric et al., 2012). As a complement to partial discharge test it can be used the ozone detection test which was developed when high voltage peaks appear as a consequence of a breakdown of motor 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 (Verucchi et al., 2009), (Brown et al., 2011).

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.

Artificial Neural Networks (ANN)

The ANNs have 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 ANNs to detect faults in IM have been studied by several authors (Verucchi et al., 2009), (Grubic et al., 2008), (Nandi et al., 2005), (Sin et al., 2012), (Guedidi, Zouzou, Laala, Sahraoui, & Yahia, 2011). 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.

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 to combine information from different signals in getting a more accurate judgment about the condition of the motor (Gubric et al., 2012), (Nandi et al., 2005), (Sin et al., 2012).

Expert Systems

Based on different techniques for detection and diagnosis, expert systems can be developed, based on the analysis of the acquired variables from the motor, conclusions based on rules developed from empirical knowledge can be obtained. (Sin et al., 2012). The advantage of this is that the expert systems can be applied to online monitoring and diagnosis.

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:

a. **Temperature monitoring.** It measures temperature on case and stator windings. It applies to failures in bearings and insulation turn to turn failure; advantage: it detects problems in insulation and bearings at early stages; disadvantage: it requires a lot of data and additional information such as temperature; it is an invasive method.

b. **Condition monitoring and taggings compounds.** It requires measurement of temperature in the winding; it detects deterioration over the insulation wall and faults of the winding insulation system; advantage: it can be used as a complement in detecting problems on insulation; disadvantage: it is invasive because it requires equipment for detection of particles.

c. Leakage currents. Current measurement is needed; It detects deterioration of the phase-to-ground and phase-to-phase insulation; advantage: is not invasive and is capable to determine causes of deterioration; disadvantage: it cannot detect the turn to turns insulation deterioration.

d. High frequency impedance/turn to turn capacitance. It requires current or voltage measurement on stator; it detects deterioration of turn to turns insulation; advantage: is the only technique capable to detect deterioration of turn to turns insulation; disadvantage: it is invasive (search coil) and it has not been used widely.

f. Zero sequence voltage. It requires measurement on stator phase voltages; it detects faults between turns in the stator winding; advantage: it is non-invasive method and compensates for potential non-idealities; disadvantage: the machines neutral wire must be accessible.

g. Sequence Impedance Matrix. Two stator currents and two stator voltages should be measured; it detects turn to turn faults on the stator winding; advantage: it permits the detection of incipient fault, it is a non-invasive test and compensates for potential non-idealities; disadvantage: it requires high precision in measurements.

h. (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; advantage: it is a lower cost, non-invasive method; disadvantage: subjective interpretation of results, fault signals vary from one machine to another.

i. (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; advantage: it is easily performed, is a non-invasive test; disadvantage: imbalances on power electric-supply are interpreted as failures.

j. (AF). Axial flux measurement is required; it detects broken bars in rotor, turn to turn stator winding faults, air-gap eccentricity; advantage: it is a low cost test; disadvantage: it is invasive because a coil is needed for measurements, the results depend strongly on load.

k. (THA). It requires to measure two currents and two voltages on stator; it detects broken bars in the rotor and faults in turn to turn stator winding; advantage: it detects mechanical failures, it is a non-invasive test; disadvantage: it is not effective for short circuits detection.

l. Vibration Signature Analysis. Vibration measurement needed; it detects broken bars in rotor, air-gap eccentricity, bearing failures, and turn to turn stator winding faults; advantage: It is a well documented traditional method; disadvantage: it is invasive (accelerometers are required) and it is necessary further research in order to generalize results.

m. (PD). It permits to detect the insulation system deterioration; advantage: good results in practice are obtained; disadvantage: it is invasive, it is not applicable to low-voltage machines, the interpretation of data is difficult.

n. Ozone. Ozone measurement is required, it detects insulation system deterioration; advantage: it is a PD byproduct, disadvantage: it is invasive (gas analyzer or electronic instruments must be present).

o. ANN. Two currents and two stator voltages are necessary; it detects turn to turn stator winding faults; advantage: it detects incipient faults, it is easy to be adapted to each machine, it is a non-invasive test; disadvantage: it is constrained by the need if a training period, it is not effective for unforeseen states of the machine.

Conclusions

The main fault detection techniques for induction machines (IM) have been gathered and presented in this article. This was done through a 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.

Recommendations for future research

A thorough study of induction machines must be able to: correlate different types of data to depict a reliable image of a machine when analyzed, detect undesirable changes and the cause of failures. Therefore, an analysis combining several of these methods is a recommended step to detect incipient failures in IM with the additional advantage that they can be implemented by means of online inspection without disconnecting the machine. For instance it is well known that if a machine fails it will show variation on the vibration characteristics and changes its acoustic emission characteristics. Detection of failures in areas considered critical there must always be a way to check the former diagnosis.

Despite the progress made in the field of IMs monitoring there is not an online method capable to oversee the vibration patterns noninvasively yet. Because of this and based on the results of the study, the authors suggest that it could be developed a non-invasive online detection method capable to classify and diagnose faults by means of vibro-acoustic signals and to extend this method to all rotating machines particularly synchronous machines (SM). The justification for this is because the vibration frequency spectrum has unique properties for each type of failure that can be readily assessed. The importance of these machines is due to their wide use for generating electricity and recognized as the most important component in a power system.

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