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A BRIEF REVIEW OF MONITORING TECHNIQUES FOR ROTATING ELECTRICAL MACHINES

A. NEGOIȚĂ[1] Gh. SCUTARU[1] R.M. IONESCU[1]

Abstract: *The paper analyzes, in brief, various on-line condition monitoring techniques for rotating electrical machines. The different failure mechanisms of electrical machines and several monitoring techniques are analysed. The advantages, disadvantages and reliability of each technique are underlined. A few of the current state of the art techniques are reviewed by surveying the latest developments in mechanical and electrical condition monitoring and future research areas that could offer new opportunities for efficient condition monitoring are identified.*

Key words: *Monitoring, Electrical Machines, Failure mechanisms.*

1. Introduction

The paper takes a holistic view at the subject of electrical machinery condition monitoring which has received intense attention due to the benefits offered by preventive maintenance. Condition monitoring of electrical machines is essential because it helps avoiding heavy production losses in industry.

Nowadays, there are many monitoring techniques and tools that ensure a high reliability of a rotating electrical motor. However, many of these tools are expensive when used for low power motors.

New, cost-effective systems based on sensor arrays and smart software algorithms are needed.

There are a large number of survey papers that deal with the problem of condition monitoring techniques. In [14] techniques used for large machines are analyzed. In [9], [12] and [14], monitoring, diagnostics techniques and procedures for induction machines and drives are detailed.

2. Indicators of Induction Motor Faults

Because the diagnosis of a fault must always begin with the basic physical understanding of the problem, by studying the indicators of induction motor faults, one can choose the most suitable ones for condition monitoring. An important criterion for selection is the accessibility of such an indicator. For example, one of the most readily available fault indicators is the motor current.

Thus, the main objective of condition monitoring should be to find the ideal combination of the following factors: the relevance of the indicator, its accessibility

[1] Centre "Advanced Electrical Systems", *Transilvania* University of Braşov.

and the most appropriate technique for processing the fault indicator in order to provide a high reliability of the diagnostic system. This process is shown in Figure 1.

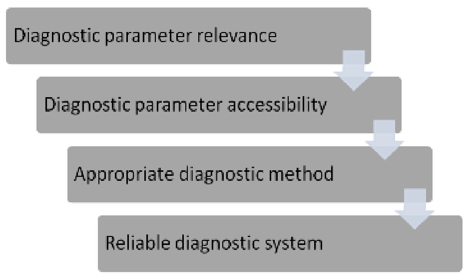

Fig. 1. *Steps needed for achieving a reliable diagnostic system*

3. Condition Monitoring Techniques

The root causes of electrical machines failures initiate the failure sequence and are detectable by condition monitoring if the degrading process is slow. Such root causes are [14]:

- defective design or manufacture,
- improper ambient conditions,
- overload,
- over-speed,
- fatigue,
- excessive vibration.

The failure modes accomplish the degrading process started by the root causes. Such failure modes are:

- core insulation failure,
- stator winding failure,
- bearing failure,
- rotor and stator mechanical integrity failure.

An effective condition monitoring strategy must concentrate on root causes and failure modes that show a slow failure sequence. For rotating electrical machines, the primary root causes for failures are bearing related, followed closely by winding and rotor related causes [15].

For small induction electrical machines, because of the low voltages used, the stator windings are rarely affected by faults. Also, thanks to the rugged design of the squirrel cage, there are few cage faults. The main factor that causes faults in this case is the improper bearings maintenance.

For large, high-voltage electrical machines, because of the dielectric stress and increased vibration, the percentage of stator windings faults is larger than in the case of small machines. Also, the bearings are large, which makes them more impervious to wear and tear. In order to identify possible machine faults a number of parameters that give a qualitative measure of the motor condition, can be monitored. Such parameters are (Figure 2): motor temperature, wear of components, mechanical vibrations levels, stator current harmonic components, rotor shaft flux or voltage and current, stator winding insulation condition.

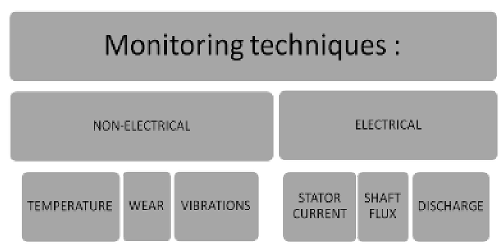

Fig. 2. *Monitoring techniques classification*

Temperature monitoring techniques aim to ensure that the temperature of the different components of the motor does not exceed the limits prescribed by the standards.

There are three approaches to temperature monitoring, as shown in Figure 3. The first one refers to local point temperature measuring using sensors.

This method is very simple and cost-effective but has the disadvantage that local hot-spots can be missed and because the sensors are usually metallic devices, they cannot be placed where high temperatures occur.

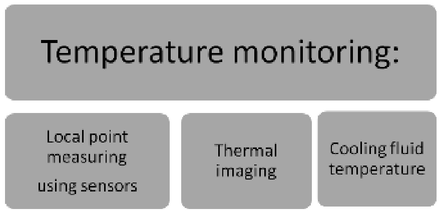

Fig. 3. *Temperature monitoring techniques classification*

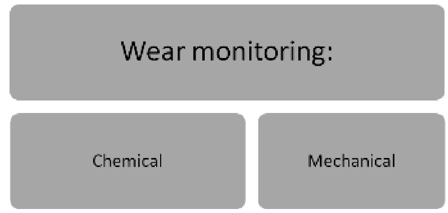

Fig. 4. *Wear monitoring techniques classification*

The second approach uses thermal imaging in order to determine the temperature of the moving parts where friction plays an important role. A detailed thermo-image of the motor, clearly showing the hot spots, can be obtained but with the use of highly specialised and costly measuring equipment. This approach is usually used for checking the bearing condition and for ensuring that they are properly lubricated.

The last approach offers a global view over the effectiveness of the machine cooling system, by measuring the temperature of the cooling fluid. The approach can also be used for determining the loading level of a motor. The main drawback is that it does not offer enough information for accurate diagnosis of an impending fault.

Wear monitoring techniques aim to ensure that the values of such parameters like the electric resistance of the isolation material of the stator winding or the dimensions of certain moving parts are situated within acceptable operating limits as stated by the operating standards. As shown in Figure 4, there are two types of wear monitoring techniques.

Thermal degradation and electrical action, leads in time, to the decomposition of insulation materials, a process which produces a number of pollutant products which can be corrosive or can have other detrimental effects on machine operation and the environment.

Insulation degradation can be monitored chemically by detecting the presence of gases or particulate matter in the coolant gas. The technique uses complex equipment and the output of the electrometer varies greatly with cooling gas temperature and pressure. Also the analysis method is non-specific so the materials being overheated can not be distinguished.

Mechanical wear monitoring techniques are mainly ferromagnetic techniques. Because bearing failure modes can produce debris of up to a millimetre in size, an AC bridge circuit can be used to measure the concentration of metal particles in the cooling gas. The advantages of this technique are its high precision and versatility but, the downsize is high cost when applied to a small or medium sized motor.

Mechanical vibrations levels monitoring techniques aim to ensure that the excitation of the support structure of the electrical machine, by the air gap electromagnetic field and torque spectrum, at natural and other frequencies, does not exceed the levels prescribed by the operating standards. There are two main approaches to mechanical vibration monitoring as shown in Figure 5.

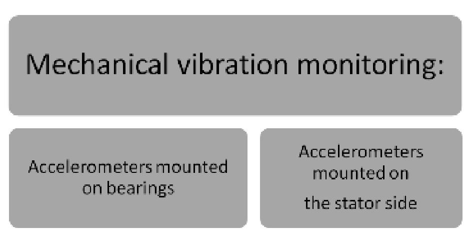

Fig. 5. *Mechanical vibration monitoring techniques classification*

The main excitation sources are:

- the electromagnetic forces that appear between the stator and the rotor;
- the dynamic behaviour of the rotor as it rotates;
- the response of the stator end-windings to the excitation caused by the electromagnetic forces on the structure.

Using numerical techniques the air-gap flux density distribution can be calculated [1], [2].

The sources of air-gap unbalanced magnetic pull and the corresponding effects were studied by [6], [8].

A straight forward method of calculating the flux wave form is by multiplying the magneto-motive force distribution by the air-gap permeance. This method was used in conjunction with a finite element approach in order to analyze the effects of winding faults and rotor eccentricity on the air-gap flux density distribution and the unbalanced magnetic pull.

The way in which mechanical and electrical faults influence the vibration level of the machine structure differs from case to case. A transversal motion in the machine frame is excited either by mechanical faults like shaft whirl and bearing wear or by static or dynamic eccentricity which is the main cause for the creation of the unbalanced magnetic pulls forces. These forces may cause mechanical faults like premature bearing wear. The transversal motion can be detected using vibration sensors mounted on the machine frame.

Accelerometers mounted on bearings (for detection of higher frequencies), or proximity sensors mounted adjacent to bearings (for detection of lower frequencies) can also be used, but the monitoring setup is hard to implement in industry.

Because of this, the preferred method is placing accelerometers on the stator side of the machine such that an overall transverse vibration monitoring is achieved over a bandwidth of 0.01 to 10 kHz. This method has the obvious advantage of simplicity but also a drawback in the fact that its sensitivity is low especially in an early stage of a fault.

Electrical flux, current and discharge monitoring techniques aim to predict possible faults by analyzing the frequency spectra of the supply system current and voltage. There are three main electrical monitoring techniques as shown in Figure 6.

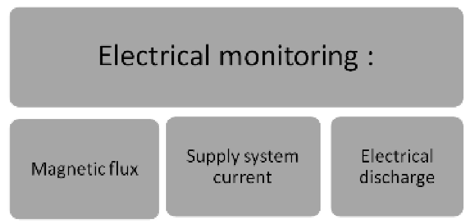

Fig. 6. *Electrical monitoring techniques classification*

Because of construction asymmetry or by the presence of such faults as winding short circuits, voltage unbalance or broken rotor bars, axial (shaft) leakage flux occurs in all electrical machines. This leakage flux causes homopolar fluxes to appear in the machine shaft which leads in turn, to the appearance of shaft voltages and currents. These currents can contribute to the overheating of the bearings, thus shortening the bearing lifespan.

The technique examines changes in the spectral components of the air-gap flux in the rotor frame given by [14]:

$$b_{n,2} = B_{n,2} \cos\left[\left(1 \pm (1-s)\frac{n}{p}\right)\omega t \pm n\varphi\right]. \quad (1)$$

The flux harmonics induce currents in the rotor circuit, which appear at specific frequencies [14]:

- For stator flux asymmetry, considering the fundamental harmonic of the stator winding magneto-motive force:

$$s \cdot \omega \quad \text{and} \quad (2-s)\cdot\omega ; \quad (2)$$

• For rotor flux asymmetry, considering the fundamental harmonic of the stator winding magneto-motive force:

$$s \cdot \omega \quad \text{and} \quad (2s-1)\cdot \omega, \tag{3}$$

where: s - the slip; ω - the angular frequency.

Faults, such as broken rotor bars, can be identified in the spectra of the signal taken from a search coil wound concentrically with the shaft of a machine. The method has the advantage that is non-invasive and a single sensor can be used for diagnosing a variety of fault types. However, the main drawback is that the method has not been fully tested.

A widely used electrical monitoring technique is the motor current spectral analysis. The monitored spectral components can result from a number of sources, including those related to normal operating condition. Thus, it is necessary to use some degree of expertise in order to distinguish a normal operating condition from a potential failure mode. Each motor fault has its own effect on the stator current.

The frequencies at which several faults occur are [3], [11]:

• For bearing faults:

$$f_{bearings} = \left| f_1 \pm m f_{i,0} \right|, \tag{4}$$

$$f_{i,0} = \frac{n_b}{2} \cdot f_r \cdot \left[1 \pm \frac{D_b}{D_p} \cdot \cos\alpha \right],$$

where: f_1 - supply frequency; m, k - integer numbers; $f_{i,0}$ - characteristic race frequencies; D_b - bearing diameter; D_p - bearing pitch diameter; α - contact angle of the ball on the races.

• For rotor faults:

$$f_{broken\_bars} = f_1 \cdot \left[k \cdot \frac{(1-s)}{p} \pm s \right], \tag{5}$$

where: p - number of pole pairs; s - slip.

• For eccentricity faults:

$$f_{ec} = f_1 \cdot \left[(kZ_2 \pm n_d) \cdot \frac{(1-s)}{p} \pm n_w \right], \tag{6}$$

where: Z_2 - number of rotor slots; n_d - rotating eccentricity order; n_w - stator magneto-motive force harmonic order.

For an ideal motor, the current spectra contain only the supply frequency.

In the case of a real motor, any type of fault generates sidebands around the supply frequency, with frequencies given by (4), (5) and (6). This can lead to a straight forward interpretation of the stator current spectra in order to determine possible faults.

However, as shown by [3], the distortions of the current waveform make very difficult the task of accurately distinguishing a fault mode from normal operation.

Electrical discharge monitoring techniques give a good indication on the state of the insulation system of an electrical machine by analyzing the influence of discharges on the supply voltage waveform. Discharges can be classified depending on their damage capability as follows [14]:

- Corona discharge - appears for high voltage windings (above 4 kV) on the surface of the insulation;
- Partial discharge - appears when voids are present inside the insulation system material;
- Spark discharge - appears when the electrical resistance of the insulation has dropped below a certain level;
- Arc discharge - appears when the degradation level of the insulation has reached a critical stage.

The quality of the insulation material as well as the mechanical and electrical conditions to which the isolation is exposed to, are important factors because the electrical discharge activity will increase as the insulation degrades in time. Because electrical discharges are transitory disturbances which radiate electromagnetic acoustic and thermal energy, several monitoring techniques have been developed.

The RF coupling method was developed in order to detect arcing in the stator windings of large turbo-generators, by measuring perturbation in the winding current. Because arcing produces broad-band electromagnetic energy that propagates into the neutral of a star connected winding, by wrapping the neutral with a radio frequency current transformer the activity could be detected using an interference field intensity meter. The main disadvantage of the method was that a signal increase of less than 50% was achieved when sparking occurred, making monitoring difficult [14].

Another RF monitoring method uses a Rogowski coil wrapped around the neutral cable. The Rogowski coil is an air-cored solenoidal search coil that is closed around a current-carrying conductor. The Rogowski coil has a good frequency response but a narrow bandwidth. It was calibrated in pico-coulombs and measured the average peak energy [14].

An important discharge monitoring technique is the capacitive coupling method. The winding connection is made through coupling capacitors at the machine line terminals and discharge pulses are interpreted by a specialised pulse height analyzer. The analysis of discharges is made at regular intervals throughout the life of the machine. A high frequency discharge monitoring technique is the broad-band RF method. The method is aimed at measuring corona and partial discharges that usually occur at frequencies of up to 350 MHz.

The advantage of the technique is that it allows the detection of high frequency (larger than 4 MHz) discharge components that radiate from the discharge site.

The potential of the broad-band RF techniques was investigated in [13], and it was found that, broad-band RF methods, despite their great potential for condition monitoring, have also some disadvantages, the most important of which are the need for large directional RF antennas for large hidrogenerators and that the method is invasive. Also, there is no way of relating the received signal to the discharge magnitudes in pico-coulombs as was the case for low frequency RF techniques. These facts make the use of this method impracticable in an industrial environment.

4. Research Areas

For **temperature monitoring** the research effort is concentrated for devising new methods for single temperatures to be obtained from devices embedded in the bulk of the machine. In order to obtain a high immunity of the collected signals to any kind of disturbance, the use of optical fibres has been suggested [5].

For **wear monitoring techniques, by using less sensitive techniques** the complexity level of the provided information is reduced. One of such technique makes use of the fact that many organic materials become florescent under ultra-violet light. The ultra-violet spectrum is less complex than a chromatogram. An alternative technique for wear monitoring implies the use of tagging components made up of special materials that decompose under high temperature, giving a clear chemical signature that can be quickly interpreted [7].

For **mechanical vibration levels monitoring,** the spectral vibration monitoring technique is widely used. The spectrum is split into discrete bands which allow the operator to trend machine condition more effectively. In order to obtain a more accurate digitally derived spectrum, more efficient signal processing techniques are needed.

For **electrical monitoring techniques** a fuzzy logic approach may contribute to a more comprehensive condition monitoring of the machine. Several closely linked electrical monitoring techniques e.g. stator current, shaft flux, electrical discharge activity and shat voltage and current can be combined into one measuring method. Because fuzzy logic can describe the characteristics of an industrial process by using linguistic terms [10] and the system can store certain information that could allow it to make decisions with a high degree of precision, this approach is well suited to fault diagnosis and monitoring. The knowledge needed for decision making comes from an analytical study of the motor and is expressed as rules and membership functions. However, this method needs correct input interpretation and properly defined membership functions, which are yet difficult to achieve as shown in [4].

5. Conclusions

This paper presents, in brief, the general techniques that are used for temperature, mechanical wear, vibration and electrical condition monitoring of electrical rotating machines. The root causes and failure mechanisms are also explained. Based on the current literature, several possible improvements and research areas are suggested for each category of techniques as follows:

- **Temperature monitoring**:

The application field and the reliability of the technique can be improved by using fibre-optics.

- **Mechanical wear monitoring**:

By using ultra violet light and fluorescent organic materials, the results interpretation process is greatly simplified.

- **Vibration monitoring**:

The widely used spectral vibration analysis technique can be improved by optimizing the signal processing methods that are used for creating the frequency spectrum.

A fuzzy logic approach may be the key solution for a complete fault monitoring system. Such a method may combine not only the electrical but all monitoring techniques into a complete solution.

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