Condition Monitoring and Fault Diagnosis in Induction Motor: Case Study

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ABSTRACT

Induction motors play a very important role in the industry and there is a strong demand for their reliable and safe operation. This paper presents a comprehensive idea of various faults, their causes, detection parameters techniques, and latest trends in the condition monitoring technology. This paper can also be used as a very simple clear guide to new researchers in the area of monitoring and diagnosing electrical machines. This paper surveys the current trends in on-line fault detection and diagnosis of induction motors. This paper has also provided the practical applications of the MCSA used for induction motors faults detection.

Keyword: Induction machine, MCSA, fault diagnosis, software.

INTRODUCTION

Electric motors especially induction motor play a very important role in the safe and efficient running of industrial plants and processes due to the low cost, strength and economical maintenance. Early detection of abnormalities in the motors will help to avoid expensive failures. The induction machine is the single most common electromechanical energy conversion device available. It is used to drive numerous important propulsion and medium transfer unit. The induction machine is considered inherently reliable due to its robust and relatively simple design. 75% of the electrical energy generated in India is utilized for running industrial and domestic motors. Condition monitoring of electric machinery can significantly reduce the cost of maintenance and the risk of unexpected failures by allowing the early detection of potentially catastrophic faults [11], [13]. On-line condition monitoring uses measurements taken while a machine is operating, to determine if fault exists. Faults which are in inductions motors have been categorized according to the main components of a machine – stator related faults, rotor related faults, bearing related faults and other faults.

MACHINE CONDITION MONITORING

The ultimate goal of machine condition monitoring [4], [7] and fault diagnostics is to get useful information on the condition of equipment to the people who need it in a timely manner. The people who need this information include operators, maintenance engineers and technicians, managers, vendors, and suppliers. These groups will need different information at different times. The task of the person or group in charge of condition monitoring and diagnostics must ensure that useful data is collected, that data is changed into information in a form required by and useful to others, and that the information is provided to the people who need it when they need it.

The following are the advantages of condition monitoring of the machines:

- Increased machine availability and reliability.
- Improved operating efficiency.
- Improved risk management (less downtime).
- Reduced maintenance costs (better planning).
- Reduced spare parts inventories.
- Improved safety.
- Improved knowledge of the machine condition (safe short-term overloading of machine possible).
- Extended operational life of the machine.
- Improved customer relations (less planned/unplanned downtime).
- Elimination of chronic failures (root cause analysis and redesign).

There are, of course, also some disadvantages that must be weighed in the decision to use machine condition monitoring and fault diagnostics. These disadvantages are listed below:

- Monitoring equipment costs (usually significant).
- Operational costs (running the program).
- Skilled personnel needed.
• Strong management commitment needed.
• A significant run-in time to collect machine histories and trends is usually needed.

The block diagram of condition monitoring of induction motor is as shown in Fig. 1.

Like all the rotating machines, the induction motors are exposed to many different adverse situations such as thermal and environmental stresses and mechanical damages, which demand maximum attention (Lambert-Torres et al., 2003). 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.

FAULTS IN INDUCTION MOTORS

Faults in induction motors [1], [3] have been categorized according to the main components of a machine—stator related faults, rotor related faults, bearing related faults and other faults. The largest of these surveys, carried out by the General Electric Company was reported in an EPRI (Electric Power Research Institute) publication and covered about 5000 motors, approximately 97% faults of which were three phase cage induction motors as given in Table 1.

<table>
<thead>
<tr>
<th>Bearing related (In %)</th>
<th>Stator faults (In %)</th>
<th>Rotor faults (In %)</th>
<th>Others (In %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>37</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

As the induction machine is highly symmetrical, the presence of any kind of fault in it affects its symmetry. This leads to a corresponding change in the interaction of flux between the stator and rotor, resulting in changes to the stator currents, voltages, magnetic field and machine vibration. Thus these signals can be used for on-line condition monitoring. According to Nandi and Toliat [2], the major faults arising in electrical machines may generally be classified as:

• Stator faults resulting in the opening or shorting of the winding.
• Turn to ground faults.
• Abnormal connection of the stator windings.
• Broken rotor bar or cracked rotor end-rings.
• Static and/or dynamic air-gap irregularities.
• Bent shaft which results in rub between the stator and rotor, causing serious damage to the stator core and windings.
• Shorted rotor field winding.
• Demagnetization of permanent magnets.
• Bearing and gearbox faults.

FAULT INDICATORS OF ELECTRICAL MACHINES

The history of fault diagnosis, condition monitoring, and protection is as old as technical devices themselves. Generally, on-line condition monitoring and diagnostics requires the sensing and analysis of such signals that contain specific information (symptoms) which is characteristic of the degradation process, problem, or fault to be detected. Various factors need to be considered when selecting the most appropriate monitoring technique for application in an industrial environment. The most important factors, according to Thomson (1999), are listed below:

- Sensor should be non-invasive.
- Sensor and instrumentation system must be reliable.
- Diagnosis must be reliable.
- Severity of the problem should be quantified.
- Ideally, an estimation of the remaining run-life should be given.
- Ideally, a prediction of the fundamental cause(s) of the fault should be provided via online information from sensors etc.

Transducer Selection

A transducer is a device which is generally used to senses a physical quantity and converts it into an electrical output signal, which is proportional to the measured variable [11]. As such, the transducer is playing an important role in the measurement chain. Accurate analysis results depend on an accurate electrical reproduction of the measured parameters. If information is missed or distorted during measurement, it cannot be recovered later. Hence, the selection, placement, and proper use of the correct transducer are important steps in the implementation of a condition monitoring and fault diagnostics program. The transducer must have the following features:

- Correct for the task.
- It should be properly mounted.
- In good working order (properly calibrated).
- Fully understood in terms of operational characteristics.
Transducers usually require amplification and conversion electronics to produce a useful output signal.

Traditional vibration sensors fall into three main classes:

- No contact displacement transducers (also known as proximity probes or eddy current probes).
- Velocity transducers (electro-mechanical, piezoelectric)
- Accelerometers (piezoelectric)

Force and frequency considerations dictate the type of measurements and applications that are best suited for each transducer. Recently, laser-based no contact velocity/displacement transducers have become more commonplace. These are still relatively expensive because of their extreme sensitivity.

Fig. 2: Shows the relationship between the different transducer types in terms of response amplitude and frequency.

![Fig. 2 (frequency versus amplitude)](image)

For constant velocity vibration amplitude across all frequencies, a displacement transducer is more sensitive in the lower frequency range, while an accelerometer is more sensitive at higher frequencies.

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**Visual Monitoring**
This method ranges from a simple visual inspection by the unaided eye, through to the use of borescopes for better access, microscopes to increase magnification, and closed circuit television cameras.

**Vibration Monitoring**
Vibration monitoring is one of the oldest condition monitoring techniques and is widely used to detect mechanical faults such as bearing failures or mechanical imbalance. A piezo-electric transducer providing a voltage signal proportional to acceleration is often used to sense the acceleration of a moving part.

This acceleration signal can be integrated to give the velocity or position. Most vibration monitoring systems can be divided into three distinct parts: data acquisition, feature extraction and condition classification. Data is acquired using transducers [3]. This is normally recorded in either analog or digital form on magnetic tape or computer disk. In simple systems it may however be possible to perform the analysis in real-time, removing the storage requirement and providing continuous monitoring.

**Electrical Current Monitoring**
In electrical machines, some faults can be detected by measuring the currents or voltages in the machine windings. The magnetic field created near electrical machines changes when faults occur and therefore using induction loops to measure flux can also aid in condition monitoring. The stator current is usually measured using a clip-on Hall-effect current probe. It contains frequency components which can be related to a variety of faults.

**Flux Monitoring**
Magnetic leakage flux of an induction machine is readily measured using a circular search coil which is placed on the non-drive (rear) end of the machine, concentric with the shaft. The search coil produces an output voltage which is proportional to the rate of change of the axial leakage flux. This signal contains many of the same frequency components which are present in the stator current. It is particularly useful for estimating the speed as it contains a strong component at the slip frequency.

**Voltage Monitoring**
Stator voltage can be safely measured using a high frequency differential voltage probe or isolation amplifier. It has been used to calculate the instantaneous power, instantaneous torque and negative sequence impedance.

**Other Techniques**
Temperature sensors monitoring the bearings and stator windings have been traditionally used for condition monitoring. They provide a useful indication of machine overheating but offer limited fault diagnostic capability. Partial discharge analysis is used for detecting stator insulation faults in higher voltage motors. It consists of detecting the low amplitude, ultrafast pulses (nS) produced by electric discharges in small voids in the insulation. Partial discharges occur even in healthy machines; however an increase in the amount of partial discharge activity can be associated with insulation degradation.

**Fault Detection Techniques**

**Complex Park Vector**
This approach is used to detect the fault in the machines. In normal condition, when motor without fault works through a three phase balanced supply system. The Park vector form a circle centered in the origin of the D-Q plane with constant radius. In case of any fault, the motor behave as an unbalanced load and...
the stator current stop being a balanced system. Such unbalance cause an oscillation in the radius of park vector and turned in to elliptical shapes.

Some authors propose the use of the park vector approach to detect eccentricities in the rotor. In this case what is obtained is a double circle with the center displaced as it shows in the Fig. 3.

Motor Current Signature Analysis (MCSA) Method

MCSA is techniques which are used to determine the operating condition of Alternating current motors like induction motor without interrupting production. MCSA uses electric motor (induction motor) as a transducer, allowing the user to evaluate the electrical and mechanical condition from the motor control centre. The most important advantage of these methods is that their implementation is relatively simple, given that they need only simple measurement instruments. MCSA can diagnose many problems like broken rotor bars, abnormal air gap eccentricity, shorted turns in stator winding. The motor current signature analysis method can detect these problems at an early stage and thus avoid secondary damage and complete failure of the machine and also improve the efficiency and reliability of the system [9], [10].

However, for precise detection and identification of the fault, a good frequency resolution and precise knowledge of the motor slip is required. Moreover, this technique requires the motor operation at steady state. To overcome this limitation, wavelet based analysis can be used. The motor current signature analysis method is used by many authors in literature for fault detection of induction motor. This methodology can also be used to detect multiple fault diagnosis in induction motor.

A basic MCSA instrumentation system will consist of the following:

- A current transformer (CT) which is used for sensing the signal.
- A resistive shunt which are connected across the output of the CT.
- An instrument or spectrum analyzer to produce the current spectrum or signature.

An idealized current spectrum is shown in the Fig. 4.

In this illustration the twice slip frequency sidebands due to broken rotor bars near the main harmonic can be clearly observed. Generally a decibel (db) versus frequency spectrum is used in order to give wide dynamic range and to detect the unique current signature patterns that are the characteristics of different faults. Then with reference to IEEE survey [2] is shown in Table 2, the condition of the rotor is identified.

<table>
<thead>
<tr>
<th>AMPLITUDE DIFFERENCE dB</th>
<th>Rotor condition (with at least 75% of rated load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;60</td>
<td>Excellent</td>
</tr>
<tr>
<td>54-60</td>
<td>Good</td>
</tr>
<tr>
<td>48-54</td>
<td>Moderate</td>
</tr>
<tr>
<td>42-48</td>
<td>Bar crack may be developing or high resistance joints</td>
</tr>
<tr>
<td>36-42</td>
<td>Two bars may be cracked or high resistance joints likely</td>
</tr>
<tr>
<td>30-36</td>
<td>Multiple cracked or open bars or end ring probable</td>
</tr>
<tr>
<td>&lt;30</td>
<td>Multiple broken bars and/or end rings very likely</td>
</tr>
</tbody>
</table>

With Broken Rotor Bars

With broken rotor bars there is an additional magnetic field produced, which produce a backward rotating field at slip speed (-ve direction).

What does the stationary stator winding observe?

Let \( N_b \) = backward rotating field produced by the rotor due to broken bar

\[ N_b = N_1 (1-2s) \]

Expressed in terms of frequency, speed of rotating magnetic field, and number of pole pairs this gives:

\[ f_b = f_1(1-2s) \]
This means that a rotating magnetic field at that frequency cuts the stator winding and induces a current at that frequency (1b).
Speed and torque oscillation occur at 2sf1, and this induces an upper sideband at 2sf1 above f1. Classical twice slip frequency band occur at ±2sf1 around the supply frequency.

Case Study - 1
Table 3 shows the rotor bar health condition of typical induction motor. In this case the value of pole pass frequency is 0.710 Hz.

<table>
<thead>
<tr>
<th>Summary of Rotor Bar Health</th>
<th>Power line dB diff.</th>
<th>Rotor bar Health index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pass frequency</td>
<td>Upper SB</td>
<td>Lower SB</td>
</tr>
<tr>
<td>0.710</td>
<td>-74.7</td>
<td>-73.1</td>
</tr>
<tr>
<td>Rotor Condition Assessment</td>
<td>Excellent</td>
<td></td>
</tr>
</tbody>
</table>

Current signature of such motor is as shown in Figure 5.

The above figure shows typical current spectrum of induction motor under full load condition. The amplitude difference between fundamental and the left sideband is more than 70 dB which shows the excellent condition of the rotor.

Case Study - 2
Table 4 shows the rotor bar health condition of another induction motor. In this case the value of pole pass frequency is 0.459 Hz.

<table>
<thead>
<tr>
<th>Summary of Rotor Bar Health</th>
<th>Power line dB diff.</th>
<th>Rotor bar Health index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pass frequency</td>
<td>Upper SB</td>
<td>Lower SB</td>
</tr>
<tr>
<td>0.459</td>
<td>-47.4</td>
<td>-48.5</td>
</tr>
<tr>
<td>Rotor Condition Assessment</td>
<td>- Rotor bar crack may be developing or problems with high resistance joints</td>
<td></td>
</tr>
</tbody>
</table>

Current spectrum of this motor is shown in Fig. 6.

In this case presence of broken rotor bars is indicated by the difference in amplitude between the fundamental and the left sideband. A difference less than 50dB are an indication of broken rotor bars. This condition shows that the rotor bar condition is moderate.

Fuzzy Logic
This involves making decisions based on classifying signals into a series of bands (fuzzy values) rather than simply as healthy or faulty based on a single threshold. For instance, based on the broken bar sideband amplitude, a motor could be classified as healthy, marginal, or faulty. Fuzzy logic allows combining fuzzy information from different signals together to make more accurate judgments regarding the health of the motor.

Expert Systems
Expert systems seek to represent the knowledge of a human expert by defining a series of rules from which conclusions can be drawn [7], [8]. An example of a rule could be: if the broken bar sidebands are greater than -45dB and the Park’s current vector is circular then it is likely that a broken bar fault is present.

CONCLUSION
Condition monitoring can improve the reliability and reduce the maintenance costs of induction motors. A brief review of the most prominent electrical faults in case of induction motors has been presented here giving the state-of-art trends in the detection and diagnosis of these faults. It is hoped that this analysis will be of help to those who are interested in understanding the powerful capability of MCSA.

REFERENCES


