CONDITION MONITORING OF LARGE ELECTRICAL MACHINES

Abstract: Large electrical machines, both synchronous and asynchronous, are the mainstay in critical installations both to generate electricity and to provide motive power for essential services in power stations, water supply, manufacturing plant, food industries and sewerage treatment. Although “out of sight, out of mind” for the majority in today’s society, their role is undeniably critical to the reliable provision of vital services. Faults are costly, if not fatal. This paper discusses issues related to condition monitoring of industrial motors, focusing on types of fault possible and associated symptoms. It solicits the bases for devising an effective condition monitoring scheme.

1. Introduction

Electrical machines are inseparably integrated in modern life in a gamut of applications ranging from power windows in automobiles to hard disk drives in computers. Although not widely appreciated, large electrical machines hold special importance since their reliable operation is critically important to the smooth functioning of society; without them, it would be impossible to provide essential services such as electricity, water supply and sewerage. Therefore, it is strategically important to ensure their reliable functioning. Yet, despite their innate robustness, they are subject to faults. This is where condition monitoring becomes crucially important since it enables developing faults to be detected early before they assume threatening proportions. Condition monitoring of electrical machines does not appear to have received the same attention as the condition monitoring of mechanical machinery. This may be due to the misguided impression that not much can go wrong with electrical machines. Yet, electrical machines can also suffer from a range of operational faults. These include faults of both mechanical and electrical nature such as bearing defects, shaft fractures, fan blade damage, winding short circuits, unbalanced magnetic pull, insulation degradation and conductor fractures.

Figure 1. Conceptual condition monitoring scheme
A very large proportion of the total electricity generated is consumed by electrical motors, unit sizes of which have been growing steadily. Synchronous generators and squirrel cage induction motors with ratings in the order of 1GW and 40MW respectively are becoming increasingly common in power generation and utilisation. There have been sustained efforts toward getting the best performance in terms of power-to-weight ratio, efficiency and cost employing mathematical techniques of multi-criterion optimisation. This emphasis on optimality has invariably raised the stakes in terms of electrical, magnetic, thermal and mechanical stresses beyond levels considered permissible previously, because they aim at reducing the amount of active materials used so as to satisfy the overall optimisation criteria. Ultimately this may lead to high stress levels, creating problems of their own.

Growth in unit sizes of machines has been accompanied by a rise in rated voltages causing insulation problems uncommon in low voltage machines.

Large electrical machines are generally employed in critical installations including power stations, essential services such as water supply and sewerage, petrochemical plant and mining operations. In all these cases continuity of service is critically important since breakdowns are not only costly in terms of production loss and repairs, but also perilous in terms of cessation of vital services.

The current economic climate makes it imperative to extend the life span of electrical machines currently in operation beyond their projected design life. Thus considerable effort is expended to extend the operational life of these costly machines, irrespective whether they are motors or generators [1]. Condition monitoring becomes indispensable for this. Consequently, reliable condition monitoring of electrical machines has emerged as being of paramount importance.

A range of techniques has been developed and used with varying success. These include vibration analysis, wear debris analysis of lubricants and a variety of techniques based on the processing of electromagnetic information obtained during machine operation. Some of these techniques are well established, as in the case of vibration analysis; others are still under development, such as the use of electromagnetic signals, recently often transmitted wirelessly using advanced knowledge-based paradigms [2] [3]. Each technique has its own strengths in being able to detect and diagnose a specific range of faults [4] [5]. No single technique appears to have the capability of comprehensibly detecting and diagnosing operational faults.

An integrated condition monitoring approach for comprehensive fault detection and diagnosis would have the advantages of (1) covering a wide range of faults, (2) enhancing certainty in fault detection and diagnosis, and (3) aiding in the development of prognostic techniques.

3. Objectives of condition monitoring

The main objectives of a condition monitoring scheme are (1) to detect change, (2) to identify the cause of change (diagnosis), and (3) to predict what the state of the machine will be in the foreseeable future (prognosis).

Of these three objectives, prognosis is the most challenging one. A condition-monitoring scheme achieving all three objectives is what designers strive for, although in most cases only the first two objectives are achieved. Schemes, which only partially seek to establish cause-effect relationships are inadequate in terms of effective condition monitoring.

4. Fundamentals of condition monitoring

Condition monitoring is based on the notion of change, and that change takes time. Reasonably, this assumes that change may indicate deterioration in condition, hence raising the likelihood of a fault developing. The challenging task then is to identify the cause of change and determine whether it constitutes a threat to the continued reliable operation of the machine. If the change is caused by a developing fault, it is also highly desirable to predict how long it will be before the fault reaches critical proportions, possibly leading to a catastrophic failure. This latter task is the most challenging in the realm of condition monitoring.

Obviously, the earlier a developing fault is detected, the more effective the operational intervention can become, averting a possible catastrophic failure. Benefits of early detection are manifold, ranging from avoiding costly repairs and loss of production caused by a major breakdown to being able to sustain critically important services without interruption.

In the case of HV industrial motors – mainly squirrel-cage induction motors (SCIM) – the following performance parameters may be used.
either singularly or in combination with one another, for detecting change. Information content of these parameters varies widely, ranging from the richest to the minimal in the order of input power, line current, stray flux, noise, vibration and shaft speed. Changing of the operating condition due to a fault will be reflected in one or more of these performance parameters, which can thus be used to monitor the health of the motor.

Various several criteria apply in the selection of monitoring signals. They must be easy to access, simple to measure and must contain information, which can reveal the nature of a particular fault discriminately. Input power, line current, axial stray field, acoustic noise, vibration and speed are all potential candidates. Yet, not all of these signals are affected to the same extent by the presence of a certain fault. That is why a comprehensive condition monitoring system, making combined use of information gained from a multiple range of signals, may be far more effective in detecting and diagnosing condition changes.

5. Level of sophistication

The extent and the level of sophistication in devising a condition-monitoring scheme will be guided by factors such as the size and cost of the machines in the plant, the likely faults to occur and the critical nature of the plant. In a number of cases it is a course of wisdom to devise a monitoring system which can discriminate between faults by virtue of monitoring multiple parameters such as current, flux, vibration and noise simultaneously.

Processing the information gathered can be done at various different levels depending on the stage of the fault development: a simple level monitoring may allow the detection of a changed condition, which may be followed by processing the signal in time, frequency and quefrency domains, depending on the nature of the fault and diagnostic accuracy needed. For instance, current ‘orbits’ – which are nothing but Lissajous figures, which depict the variation of current versus voltage – may provide a simple, yet effective means of detecting a condition change. The current ‘spectrum’ may reveal the nature of the fault, since various different types of fault are identifiable by means of corresponding spectral elements. An example is that of characteristic frequencies associated with ball bearing defects. Similarly, rotor asymmetries are indicated by the presence of characteristic sideband harmonics around the fundamental, whereas any discharge activity is revealed by high frequency components in electromagnetic spectra [5] [6].

6. An example

The following example of a HV squirrel cage induction motor is presented to emphasise the importance of condition monitoring in plant operation. The motor under focus is used for pumping water through a dual pipeline to supply water to an arid region in South Australia. It is fed from a 3.3 kV feeder line and is started direct-on-line. The deep-bar cage is made of copper, with the end-rings at both ends of the rotor being supported by the protruding rotor bars only. This type of topology is sometimes referred to as “floating end-ring design”. It is generally recognised as being a design which is prone to fatigue fracturing. Table 1 below gives the name plate details.

<table>
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<th>Table 1. Motor data</th>
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<td>Voltage</td>
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<tr>
<td>Power Rating</td>
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<td>Connection</td>
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<td>Insulation Class</td>
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Direct-on-line starting is widely practiced in industry applications with squirrel cage induction motors. Unfortunately, floating end-ring design spells trouble when the machine is started direct-on-line. During start-up the machine is subject to excessive currents; both in the stator and the rotor. But, the situation is far worse in the rotor due to thermal and centrifugal effects. Cage temperature rises rapidly, which causes a rapid expansion of the cage structure, possibly accompanied by annealing effects if the temperature exceeds limits. The portions of rotor bars, embedded in the rotor core, are restricted in movement: their expansion within the slots increases the mechanical stresses on them without moving. But the bar sections outside the rotor core joining onto the rings are free to move! So they move both axially and radially as dictated by thermal excesses and centrifugal effects, leading to a substantially deformed ending region topology as depicted in Fig. 2. Deformation leads to excessive stresses, particu-
larly at stress raiser points with sharp transitions in geometry, which are more than likely to initiate fatigue fracturing at the interface between rotor bars and end rings (as at point A in Fig. 2). The repetitive practice of direct-on-line starting invariably leads to fracture initiation. Once the fracture is initiated, it progresses with each start-up, until complete fracturing occurs due to material fatigue. Unfortunately the process is insidious. To the uninitiated and unsuspecting observer the machine appears to be operating normally. The tell-tale signs are subtle and can be easily overlooked.

Fig. 4 shows a close-up view of the damaged end-ring region at the drive-end. Fig. 5 shows the extent of the damage with several severe fractures. This outcome would have more than justified the use of a sophisticated condition monitoring scheme as solicited previously in the paper. Presence of the fault, however, could have been detected by much simpler indicators such as current orbits as in Fig. 6. The spikes in orbit (b) arise from arcing across fractures.

![Figure 2. Deformation of end-ring region during start-up](image1)

In the case discussed, the post mortem examination revealed that about a quarter of the bar joints were fractured as depicted in the fracture map of Fig. 3.

![Figure 3. End-ring fracture map](image2)

- ×: fracture at drive-end
- o: fracture at non-drive end

![Figure 4. Close-up view of damage region](image3)

![Figure 5. Cage-end fractures](image4)
7. Conclusion

Condition monitoring of large electrical machines is critically important to the reliable delivery of essential services in today’s complex technological society. The health of machines must be monitored, and appropriate measures taken, if functions, critically vital to the welfare of the society, are to be maintained.

8. References


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