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An Assessment of Vibration Monitoring as an Effective Tool for Induction Motor Condition Monitoring and Fault Diagnosis: A Brief Review

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ABSTRACT

Research has advanced leaps and bounds in the area of fault detection of induction motors (IMs). Now-a-days, great emphasis is being laid on online and automated fault detection system of induction motors. In this regard, analysis of line current for fault detection and other signals such as vibration and power, axial leakage flux and partial discharge have been extensively explored. An effective condition monitoring algorithm with the choice of the right parameter to diagnose the various faults in IMs in incipient stages shall minimize unwanted downtime considerably and will help in achieving optimum levels of production. So keeping in mind the vast scope of this area of research, a review paper compiling the various literatures regarding the different fault monitoring machine parameters is presented. This study will reflect a broad perspective regarding the present status of the area of research at hand and will aid future researchers to comprehend the scope in this area at a glimpse.

Keywords: Induction motor, condition monitoring, vibration monitoring, current monitoring.

1. INTRODUCTION

Low cost and low maintenance makes induction motors (IMs) the mainstay of industries. Despite this, IMs are subjected to different undesirable faultswhich are broadly classified into [1]:

1. Bearing failure,
2. Rotor bar and winding faults,
3. Eccentric running, and
4. Stator winding faults.

Various parameters have been used in the past in the surge for an effective condition monitoring algorithm so as to diagnose the various faults of IMs in incipient stages thereby minimizing unwanted downtime and achieving optimum levels of production. In this regard the present study provides a detailed compilation of the various fault monitoring techniques used till date for effective condition monitoring and fault diagnosis.

This paper is organized in five sections. Section 2 enumerates the different mechanical faults that occur in the IMs. Section 3 presents the various electrical faults that IMs encounter. Furthermore, section 4 enlists the different parameters used for effective condition monitoring and fault diagnosis till date. The various advantages and disadvantages associated with the use of these parameters are also addressed in this section. Finally, section 5 concludes the work.

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2. MECHANICAL FAULTS IN INDUCTION MOTOR

2.1. Bearing Fault

Bearing fault is usually progressive but ultimately its effect upon motor is catastrophic. Irregular installation of bearings on the motor shaft is likely to damage which leads to premature failure [2]. Misalignment of the bearing is also a common result of defective bearing installation which varies the air-gap similar to a combination of rotational eccentricity in opposite directions. Bearing failure is accompanied by a rise in temperature. Moreover, any bearing failure produces a radial motion between the rotor and stator of the motor. An important effect of bearing corrosion for IMs is the eccentric running of the rotor that causes a degree of static and dynamic eccentricity, thereby causing unbalanced magnetic forces in neighbouring poles.

2.2. Eccentricity

Air-gap eccentricity, which is one of the major faults in an IM,results from a non- uniform air-gap between the rotor and stator. A high degree of eccentricity results in unbalanced radial forces which causes physical interaction between the stator and rotor. Furthermore, varying inductances due to eccentricity causes unbalanced magnetic flux in the air gap that creates fault frequencies in the line current. There are two types of eccentricity fault: static eccentricity, resulting from a persistent offset between the centreline of stator and rotor, and dynamic eccentricity, resulting from a mutable offset between the centreline of stator and rotor [3].

2.3. Broken Rotor Bar

A broken rotor bar produces an enriched field around the faulty region in the machine because of local demagnetising slip frequency and induced current in the faulty rotor slots. The flux density becomes progressively higher in magnitude close to the fault. The result shows that for an IM with 40 rotor bars, a damage of one broken bar causes a degradation of 2-4% in the steady state torque performance whereas, for three and five broken bars, it is between 10-15% [4].

3. ELECTRIC FAULTS IN THE INDUCTION MOTOR

3.1. Stator winding faults

There are two main classes of induction motor stator windings fault namely [5], [6]

a. Asymmetry in the stator winding such as open phase,

b. Short circuit of turns in a phase winding

Stator inter-turn short circuit leads to an open phase in the extremity.Consequently, the IM experiences a reduced torque operation. Stator winding insulation is affected by thermal, electrical, environmental and mechanical stresses [6].

3.2. Rotor winding faults

The principal stresses of concern on rotor windings, in case of a slip ring IM are thermal and mechanical. Fault in the rotor winding of IM is not easy to detect owing to the low-frequency currents induced in rotor windings.

4. INDUCTION MOTOR CONDITION MONITORING

Initially conventional techniques such as overcurrent and overvoltage were used to ensure reliable operation of the IMs in industries [7-9].However, with the modernisation and mass production along with the advancement of automation and consequent reduction in machine accessibility owing to hazardous work environment, the need for automatic and online condition monitoring has increased to meet the need of continuous and uninterrupted mass production.Early detection of incipient fault results in short downtime for the motor drive system which consequently reduces financial losses thereby avoiding any catastrophic consequences. Moreover, a map between motor signals and fault indicator is a trivial necessity of an effective condition monitoring system.

An effective fault monitoring algorithmmust focus on root cause and failure mode of the fault at hand [10]. In a recent study [11], the distribution of major IM faults is listed as the bearing (69%), stator winding (21%), rotor fault (7%) and shaft/coupling (3%). The symptoms of faults are:

- Unbalanced Voltages and line currents,
- Vibration and noise,
- Torque Pulsation, and
- Excessive heating.

IM is a highly symmetrical electrical system and any kind of fault modifies their electrical symmetry. For the detection of fault related symptoms, there are several methods which include:

- Current Monitoring,
- Vibration Monitoring,
- Temperature Monitoring,
- Axial leakage flux monitoring, and
- Partial Discharge monitoring.

4.1. Current Monitoring

Motor Current Signature Analysis (MCSA) is non-invasive fault detection technique [12].Therefore, no extra hardware is required for it.The current spectrum of a healthy motor containsonlyfundamental slot harmonic.Faults in the IM will generate side bandsapart from theprincipal slot harmonics. The electrical signals associated with the induction motor can be measured by the voltage and current transducers present in the motor drive system. MCSA is one of the most extensive procedures to detect motor fault due to its ability to be monitored online and its non-invasive nature which makes it less computation intensive [13]. Initial efforts in MCSA were directed to provide non-invasive means for detecting the mechanical and electrical abnormalities in both motor and drive equipment [14]. The study done in [15] addresses the application of MCSA for the bearing damage detection in IMsby comparison of the vibration and current spectrum.In another study [16], a selective frequency filter is used to identify the characteristic fault frequencies of the IMsunder on-load conditions as input to neural network clustering algorithms. This combination maximises the spectrum change detection ability of the system[17].

4.2. Vibration Monitoring

Vibration monitoring is the most reliable method forevaluating IM condition [18]. Mechanical degradation resultsin dynamic or static electromagnetic unbalanced magnetic pull (UMP), thereby inducing characteristic frequency component in the vibration spectrum. It further utilizes fault indicators such as root mean square (RMS), crest factor, kurtosis etc.

Vibration can be detected by accelerometers and velocimetres, vibrometers and proximeters mounted on bearings.

4.2.1. Transverse Vibration Monitoring

In transverse vibration monitoring a bandwidth of 0.01–1 kHz or 0.01–10 kHz is analysed for the RMS value of vibration acceleration or velocity [7]. German Vibration Standard VDl 2056 and ISO 10816-1:1995 [19-20], illustrates the machine health at different vibration velocities for IMs,as shown in Table 1.

Table 1
German Vibration Standard VDI 2056[19]

Vibration Velocity, mm/s rms	*Vibration Velocity, dB, ref 10^{-6} mm/s*	*Small Plant*	*Medium Plant*	*Larger Noisier Plant*
45	153	Not tolerable	Not tolerable	Not tolerable
28	149		20dB(x10)	
18	145			Just tolerable
11.2	141		Just tolerable	
7.1	137	Just tolerable		Acceptable
4.5	133		Acceptable	
2.8	129			
1.8	125	Acceptable	Acceptable for IM between 15-75KW (or) < 300 kw on special foundations	Acceptable for IM with rigid and heavy foundations whose natural frequency > N
1.12	121			
0.71	117			
0.45	119	Acceptable		
0.28	109	for IM		
0.18	105	< 15 kw		

4.2.2. Spectral Transverse Vibration Monitoring (STVM)

STVMsplits the spectrum discrete bands, so that logarithmic frequency scaling results in narrow bands of equal width thus making it effective and computation easy (Fig.1). In SVTM, the trips are initiated at the operational envelope and the baseline is set at the expected maximum vibration. The application of vibration monitoring for fault diagnosis in large turbo-generators, as described in [1], applies computer analysis techniques off-line to thereal –time values [20], and the effect of the foundation response to machine excitation is given in [21]. Various recent signal processing techniques have been used on IM vibration analysis in [22-23].

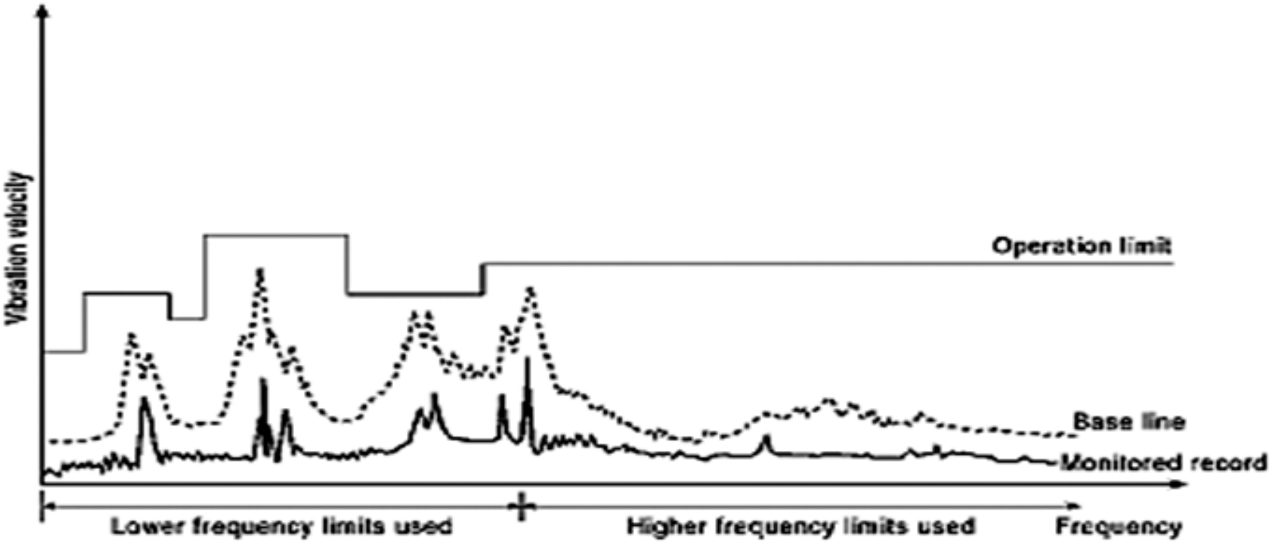

Figure 1: Operational envelope around vibration spectrum

4.2.3. Specific spectral transverse vibration monitoring

UMP,dynamic unbalance and coupling misalignment can excite stator side vibration components in orders of supply frequency due tointer-turn winding faults on the stator [24-27]. The transverse mechanical frequency λ_{sm}, measured on the stator frame, excited by radial forces [28]

$$\lambda_{sm} = \lambda_{se}\left[\left(hH_r \pm M_e\right)\frac{\left(1-s\right)}{z} \pm M\right] \tag{1}$$

It is suggested in [22, 24] that due to different plant noises the same integer slot harmonic may be indicative of various faults. Table 2 isaccumulated to filter the information to be found in these references.

Table 2
Frequency components based on explicit machine faults[7]

		Rotational angular frequency of the rotor, λ_{rm}, rad/s	*Transverse vibration angular frequency on the stator, λ_{sm}, rad/s*
Mechanical faults	Oil whirl and whip in sleeve bearings	–	$\lambda_{sm} = (0.43 \text{ to } 0.48)\ \lambda_m$
	Damage in rolling elements bearings	–	$\lambda_{sm} = \frac{h_b}{2}.\lambda_{rm}.\left(1-\frac{r_b}{R_b}\cos\theta\right)$ $\lambda_{sm} = \frac{h_b}{2}.\lambda_{rm}.\left(1+\frac{r_b}{R_b}\cos\theta\right)$ $\lambda_{sm} = \frac{R_b}{2r_b}.\lambda_{rm}\left(1-\left(\frac{r_b}{R_b}\right)^2\cos^2\theta\right)$ $\lambda_{sm} = \frac{1}{2}.\lambda_{rm}.\left(1-\frac{r_b}{R_b}\cos\theta\right)$
	Misalignment in the rotor shaft of a synchronous machine	$\lambda_{rm} = \frac{\lambda_{se}}{z}$	$\lambda_{sm} = 2z\lambda_{rm}$ $\lambda_{sm} = \lambda_{rm}$ $\lambda_{sm} = \lambda_{rm}$ $\lambda_{sm} = \lambda_{rm}, 2\lambda_{rm} \ldots$
	Static and dynamic eccentricity in an IM	$\lambda_{sm} = \frac{\left(1-s\right)h\lambda_{se}}{z}$	$\lambda_{sm} = \lambda_{rm}\left[\left(hH_r \pm M_e\right)\left(1-s\right) \pm zM\right]$
	Commutator faults in DC machine	–	$\lambda_{sm} = 2zM_e\lambda_{rm}$ *for lap wound* $\lambda_{sm} = 2M_e\lambda_{rm}$ *for wave wound*
	Broken rotor bar in an IM	$\lambda_{rm} \pm \frac{2hs\lambda_{se}}{z}$	$\lambda_{sm} = \left(\lambda_{rm} \pm \frac{2hs\lambda_{se}}{z}\right)$
Electrical faults	Stator winding faults	–	$\lambda_{sm} = z\lambda_{rm}, 2z\lambda_{rm}, 4z\lambda_{rm} \ldots$

4.2.4. Shock Pulse Monitoring (SPM)

SPM is used solely for rolling bearings operating at the moving surfaces whereinterfacegenerates mechanical stress waves, or shock pulses, on the bearing surface which propagates into large fissures. LVDT detectsthese shock pulses usingShock pulse value (SPV) to assessesthe bearing condition as,

$$SPV = \frac{R}{N^2 F^2} \tag{2}$$

where N = shaft speed in rev/min, R = shock pulse meter reading, and F = bearing geometry factor

Low values of SPV indicate healthy bearings.

Moreover, bearing defects are categorized as outer race, inner race, ball defect and train defect [17] and the vibration frequencies to detect these faults are given as [18]

$$Inner\ race = \frac{H_b}{2}\left(1 + A\right) f_r \tag{3}$$

$$Outer\ race = \frac{H_b}{2}\left(1 - A\right) f_r \tag{4}$$

$$Train\ defect = \frac{D_d}{2C_d}\left(1 - A^2\right) f_r \tag{5}$$

$$Ball\ defect = \frac{1}{2}\left(1 - A\right) f_r \tag{6}$$

$$A = \frac{C_d}{D_d}\cos\theta \tag{7}$$

Nevertheless, in the absence of any of the parameters in (3)-(7) bearing fault characteristic frequencies can be estimated using (8)-(10).

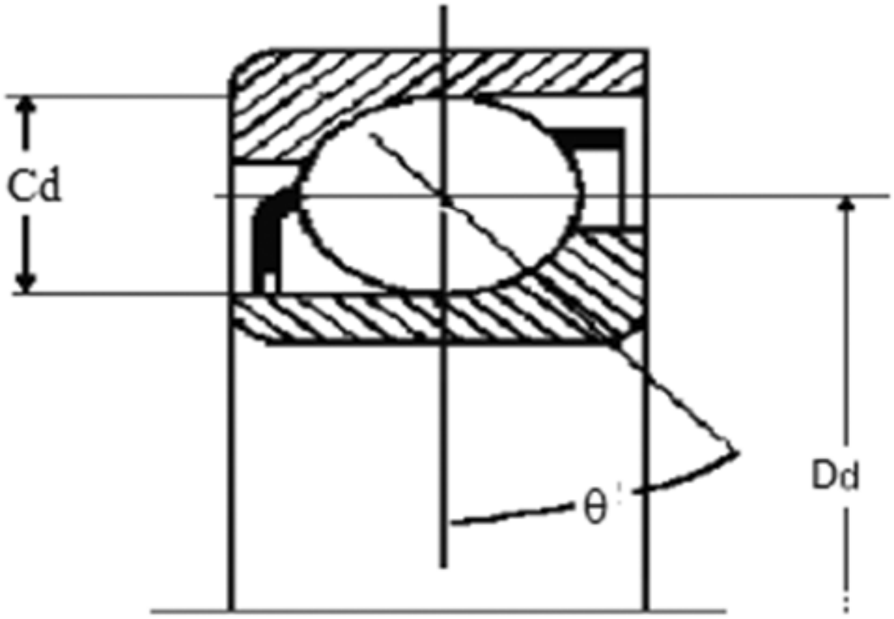

Figure 2: Bearing parameters to characteristic fault frequency

$$Inner\ race = 0.6H_b f_r \tag{8}$$

$$Outer\ race = 0.4H_b f_r \tag{9}$$

$$Train\ defect = \frac{0.35}{0.45 f_r} \tag{10}$$

The existence of asynchronous frequency components in the vibration spectrum is anindication of possible bearing failure. It is necessary to take into account that the previously mentioned formulasand equations (3-7) and (8-10) are subject to definiteextent of ambiguity, owing to the inability in predicting the results of axial loads and sliding effects. Outer race is seen to be more prone to the same fault as compared to inner race. This fact isconveniently understood if considered that the inner race is generally exiled from the load impact region, and therefore the amplitude of the impact is considerably lower than inner race failures, thereby producingcalamitous breakdowns earlier than any other type of faults.

4.3. Temperature Monitoring

An IM is a complex electromechanical system having materials with different thermal properties. High temperature is one of the major causes of stress on insulation system of IM [29]. The temperature limit to restrict deterioration is higher than the general working ambient temperature of the machine. Machine insulation suffers irreversible changes at high temperature. Thermal ageing is caused by the insulation degradation of the electrical and mechanical properties.

The measurement of temperature is widely used in condition monitoring of induction motor [30]. It can be done using thermocouples, embedded temperature sensors, or resistance temperature detector. Temperature signals are usually used to monitor specific areas of the stator core and bearing etc. The temperature signal analysis of IM can contribute substantially to a better understanding of the overall performance and prevention of faults. Temperature measurement together with vibration signal provides the standard approach to the assessment of the condition of the components of the motor drive system.

4.4. Axial Leakage Flux monitoring

Axial flux *aka* shaft flux is present in almost all the machines due to construction asymmetry, hence one can expect to measure axial flux, even in machines that are in ‘perfect health’. Nevertheless, any gross change in the air gap due to eccentricity will lead to axial leakage flux. The winding short circuit faults, broken rotor bars and voltage imbalances disintegrate the internal asymmetry of the machine, results in the production of axial leakage flux.With the help of axial flux monitoring, it is possible to detect the loss of supply[31]. The demarcation between various faults can be done by analysing the axial flux signals [32]. The purpose of axial flux monitoring is therefore to decodethe nature of the axial leakage flux into an warning of fault condition. Axial leakage flux in Squirrel cage IM was studied by Jordan*et al.* [33,34] with particular stress on the fluctuations occurring due to static eccentricity. Erlicki *et al.* [35] exhibitedthe detection ofsingle-phasing through axial flux monitoring.

The axial flux monitoring technique is still embryonic but essentially it requires the collection of an axial flux signal, using a search coil wound around the shaft of IM [36]. This signal is then spectrally analysed and on the basis of the appearance of certain harmonic groups a decision is made as to the condition of the machine. The attraction of the method is its non-invasiveness. It is, however, a complicated technique requiring specialised equipment, and is relatively untested [37].

4.5. Partial Discharge Monitoring (PD)

PD is a native electrical discharge that partially disrupts the insulation of the supply line and the machine.It is indicative of the local stress in the insulation of the system, so its monitoring gives the quick check on the health of the insulation of the motor. The implementation of the PD monitoring gives the idea of the early detection of the insulation failure. Due to the presence of different levels of insulation and voltage in the small IMs,the PD does not take place. PDs may occur in the air filled gaps between the adjacentstator turns, hence causinginter-turn insulation breakdown.The transient over-voltages reaching the threshold of breakdown of air voids between the glazed wires causePDs, inter-turn insulation degradation and shorted turns in stator coils.Presence of voids in the body of the insulation system will also exhibit when the local electric field strength exceeds the Paschen curve level [38] for the gas in the void at that temperature. Neither that surface or body activity is necessarily damaged unless the activity is sufficiently powerful to degrade the insulation system. This effect can gradually worsen depending on the class of insulation and field strength. Certain parts of high-voltage winding insulation system like stator slot wall, the slot emergence and end-winding surfaces are particularly vulnerable to discharge activity [7].

There are several methods for early detection of the discharge in IMs which include:

- RF coupling method,
- earth loop transient method,
- capacitive coupling method,
- widerband RF method, and
- insulation remanent life.

The fundamental problem for all PD detection systems owes to variations in ambient conditions, small changes in the insulation regularity and noise conditions. Therefore one cannot generalisethe background discharge activity for a winding and therefore this activity will vary naturally with time.

5. CONCLUSION

The present work describes a brief study of the various parameters used for effective condition monitoring of IMs working in hazardous industrial scenario. In this regard, a detailed review of the working IM parameters employed for the efficientmachine health monitoring and fault analysis used till date are presented. A detailed literature survey reveals that vibration monitoring is at the nub of all the available monitoring techniques. The survey also illustrates the fact that mechanical faults that occur in an IM (comprising of about 80% of the total faults to occur in an IM) are more effectively diagnosed using machine vibration as a viable parameter. Vibration monitoring is non-intrusive technique but it requires specialised sensors whose location should be selected precisely. This monitoring has wide application in the rotating electrical machines as it is very reliable as compared to partial discharge technique and axial flux leakage monitoring. It is capable in discriminating between mechanical and electromagnetic exciting forces which is quite desirable in detecting the root cause of the faults in the electrical machines. The availability of superior and digitally sampled mechanical vibration data ventures the possibility of better and efficient online monitoring of the IMs.

The present work is illustrated with the relevant mathematical equations, results and basic concepts related to different fault detection parameters, taken from the various publications of different authors. It will give future researchers a bird's eye view of the present topic of research and shall aid to comprehend the area of research at a glance.

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