International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 8, Number 3 (2015), pp. 253-265

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Condition Monitoring of Induction Motors: Literature Review

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Abstract

In this paper, the literature on condition monitoring of electric machine is reviewed. This review covers some important topics such as condition monitoring, fault diagnosis, thermal monitoring, vibration monitoring, electric monitoring, noise monitoring, motor current signature analysis, Current park's vector approach, Wavelet transform, signal processing techniques, etc. In addition, this review also covers the major developments in this field.

1. Introduction

Electrical machines are extensively used and core of most engineering system. These machines have been used in all kinds of electric drives more often than any other electric motor. An induction machine is defined as an asynchronous machine that comprises a magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction. It is an electromechanical energy conversion device in which the energy converts from electric to mechanical form [1]. The energy conversion depends upon the existence in nature of phenomena interrelating magnetic and electric fields on the one hand and mechanical force and motion on the other. The rotor winding in induction motors can be squirrel-cage type or wound-rotor type. Thus, the induction motors are classified into two groups [2]:

- Squirrel-cage and
- Wound-rotor induction motors.

The squirrel cage induction motor consist of conducting bars embedded in slots in the rotor iron and short circuited at each end by conducting end rings. The rotor bars are usually made of copper, aluminum, magnesium or alloy placed in slots. Standard squirrel cage rotors have no insulation since bars carry large currents at low voltages.

Another type of rotor, called a form-wound rotor, carries a poly phase winding similar to three phase stator winding. The terminals of the rotor winding are connected to three insulated slip rings mounted on the rotor shaft. In a form-wound rotor, slip rings are connected to an external variable resistance which can limit starting current and associated rotor heating. During start-up, inserting external resistance in the wound-rotor circuit produces a higher starting torque with less starting current than squirrel-cage rotors [2]. This is desirable for motors which must be started often.

The squirrel-cage induction motor is simpler, more economical, and more rugged than the wound-rotor induction motor. A squirrel-cage induction motor is a constant speed motor when connected to a constant voltage and constant frequency power supply. If the load torque increases, the speed drops by a very small amount. It is therefore suitable for use in constant-speed drive systems [1,2]. On the other hand, many industrial applications require several speeds or a continuously adjustable range of speeds. DC motors are traditionally used in adjustable drive systems. However, since DC motors are expensive, and require frequent maintenance of commutators and brushes. Squirrel-cage induction motors are preferred because they are cheap, rugged, have no commutators, and are suitable for high-speed applications. In addition, the availability of solid state controllers has also made possible to use squirrel-cage induction motors in variable speed drive systems. The squirrel-cage induction motor is widely used in both low performance and high performance drive applications because of its roughness and versatility.

Electric machines are frequently exposed to non-ideal or even detrimental operating environments. These circumstances include overload, insufficient lubrication, frequent motor starts/stops, inadequate cooling, etc. Under these conditions, electric motors are subjected to undesirable stresses, which put the motors under risk of faults or failures [3]. There is need to improve the reliability of motors due to their significant positions in applications. According to IEEE Standard 493-1997 [4], the most common faults and their statistical occurrences are listed in Table 1. This table is based on a survey on various motors in industrial applications. According to the table, most faults happen to bearings and windings. A 1985 statistical study by the Electric Power Research Institute (EPRI) provides similar results, i.e., bearing (41%), stator (37%), rotor (10%) and other (12%) [5]. Several contributions deal with these faults.

Table 1: Statistics on motor fault/failure modes [4]

	Number of faults/failures				
	Induction motor	Synchronous motor	Wound rotor motors	DC Motors	All motors
Bearing	152	2	10	2	166
Winding	75	16	6	--	97
Rotors	8	1	4	-	13
Shaft	19	-	--	-	19
Brushes or slip rings	--	6	8	2	16
External device	40	7	1	-	18
Others	10	9	--	2	51

2. Need for Condition Monitoring

Condition monitoring is defined as the continuous evaluation of the health of the plant and equipment throughout its service life. It is important to be able to detect faults while they are still developing. This is called incipient failure detection [6]. The incipient detection of motor failures also provides a safe operating environment. It is becoming increasingly important to use comprehensive condition monitoring schemes for continuous assessment of the electrical condition of electrical machines. By using the condition monitoring, it is possible to provide adequate warning of imminent failure In addition, it is also possible to schedule future preventive maintenance and repair work. This can result in minimum down time and optimum maintenance schedules [7]. Condition monitoring and fault diagnosis scheme allows the machine operator to have the necessary spare parts before the machine is stripped down, thereby reducing outage times. Therefore, effective condition monitoring of electric machines is critical in improving the reliability, safety, and productivity.

3. Existing Condition Monitoring Techniques

This research is focused on the condition monitoring and fault diagnosis of electric machines. Fault diagnosis is a determination of a specific fault that has occurred to system. A typical condition monitoring and fault diagnosis process usually consists of four phases as shown in figure 2.1. Condition monitoring has great significance in the business environment due to following reasons [6,7]

- To reduce the cost of maintenance
- To predict the equipment failure
- To improve equipment and component reliability
- To optimize the equipment performance
- To improve the accuracy in failure prediction.

The condition monitoring of electrical and mechanical devices has been in practice for quite some time now. Several methods have evolved over time but the most prominent techniques are thermal monitoring, vibration monitoring, and electrical monitoring, noise monitoring, Torque monitoring and flux monitoring.

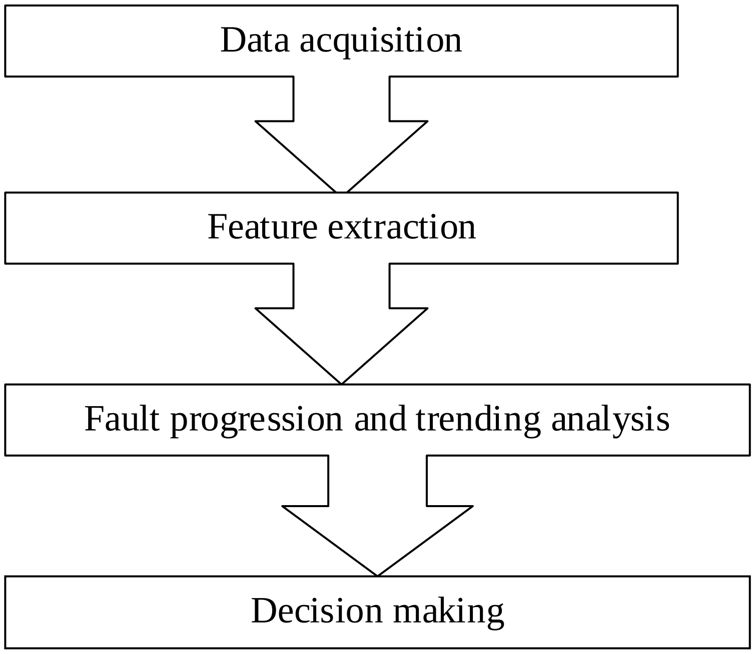

Figure 1: The process for fault diagnosis

3.1 Thermal Monitoring

The thermal monitoring of electrical machines is accomplished either by measuring the local or bulk temperatures of the motor, or by parameter estimation. A stator current fault generates excessive heat in the shorted turns, and the heat promulgates the severity of the fault until it reaches a destructive stage. Therefore, some researcher developed thermal model of electric motors. Generally, thermal models of electric machines are classified into two categories [8]:

- Finite element Analysis based model
- Lumped parameter thermal models

FEA based models are more accurate, but highly computational intensive. A lumped parameter thermal model is equivalent to thermal network that is composed of thermal resistances, capacitances, and corresponding power losses. The accuracy of model is generally dependent on the number of thermally homogenous bodies used in model [8-9]. The parameters of lumped parameter model are usually determined in the two ways. The first is by using comprehensive knowledge of the motors, physical dimensions and construction materials. The second is to identify the parameters from extensive temperature measurement at different locations in the motor. Even though an electric machine is made of various materials that have different characteristics, the machine can be assumed to consist of several thermally homogenous lumped bodies. Based on these assumption, simplified model of an induction model and a PMSM consisting of two lumped thermal bodies are proposed in [10], and [11]. Likewise, Milanfar and Lang [12] developed a thermal model of electric machine. This thermal model is used to estimate the temperature of the motor and identify faults. Thermal monitoring can, in general, be used as an indirect method to detect some stator faults (turn-to-turn faults) and bearing faults. In a turn-to-turn fault, the temperature rises in the region of the fault, but this might be too slow to detect the incipient fault before it progresses into a more severe phase-to-phase or phase-to-neutral fault. In the case of detecting bearing faults, the increased bearing wear increases the friction and the temperature in that region of the machine. This increase in temperature of motor can be a detected by thermal monitoring.

3.2 Torque Monitoring

All types of motor faults produce the sidebands at special frequencies in the air gap torque. However, it is not possible to measure the air gap torque directly. The difference between the estimated torques from the model gives anindication of the existence of broken bars. From the input terminals, the instantaneous power includes the charging and discharging energy in the windings. Therefore, the instantaneous power cannot represent the instantaneous torque. From the output terminals, the rotor, shaft, and mechanical load of a rotating machine constitute a torsional spring system that has its own natural frequency. The attenuations of the components of air gap torque transmitted through the torsional spring system are different for different harmonic orders of torque components [28].

3.3 Noise Monitoring

Noise monitoring is done by measuring and analyzing the acoustic noise spectrum. Acoustic noise from air gap eccentricity in induction motors can be used for fault detection. However, the application of noise measurements in a plant is not practical because of the noisy background from other machines operating in the vicinity. This noise reduces the accuracy of fault detection using this method. Ellison and Yang [13] were detected the air gap eccentricity using this method. They verified from a test carried out in an anechoic chamber that slot harmonics in the acoustic noise spectra from a small power induction motor were functions of static eccentricity.

3.4 Vibration Monitoring

All electric machines generate noise and vibration, and the analysis of the produced noise and vibration can be used to give information on the condition of the machine. Even very small amplitude of vibration of machine frame can produce high noise. Noise and vibration in electric machines are caused by forces which are of magnetic, mechanical and aerodynamic origin [14, 15]. The largest sources of vibration and noise in electric machines are the radial forces due to the air gap field. Since the air gap flux density distribution is product of the resultant m.m.f. wave and total permeance wave, and resultant m.m.f. also contains the effect of possible rotor or stator asymmetries, and permeanance wave depends on the variation of the air gap as well, the resulting magnetic forces and vibrations will also depends on these asymmetries. Thus by analyzing the vibration signal of an electric machine, it is possible to detect various types of faults and asymmetries [16]. Bearing faults, rotor eccentricities, gear faults and unbalanced rotors are the best candidates for vibration based diagnostics. The vibration monitoring of electric machines is accomplished through the use of broad-band, narrow-band, or spectral (signature) analysis of the measured vibration energy of the machine. Vibration-based diagnostics is the best method for fault diagnosis, but needs expensive accelerometers and associated wiring. This limits its use in several applications, especially in small machines where cost plays a major factor in deciding the condition monitoring method.

Li et al. [17] carried out vibration monitoring for rolling bearing fault diagnoses. The final diagnoses are made with an artificial NN. The research was conducted with simulated vibration and real measurements. In both cases, the results indicate that a neural network can be an effective tool in the diagnosis of various motor bearing faults through the measurement and interpretation of bearing vibration signatures. In this study, the vibration features are obtained from the frequency domain using the FFT technique. Five vibration signatures are constructed. They are created from the power spectrum of the vibration signal and consist of the corresponding basic frequencies, with varying amplitudes based on the defect present. Time domain information, such as the maximum and mean value of the amplitude vibration waveform and the Kurtosis factor of the vibration waveform, are also considered. Thus, the complete neural network has six input measurements. Researchers showed how the neural network can be used effectively in the diagnosis of various motor bearing faults through appropriate measurement and interpretation of motor bearing vibration signals. In Jack & Nandi [18], there is an approach that brings better results. In this, the artificial neural network is helped by a genetic algorithm. In this study, statistical estimates of the vibration signal are considered as input features. The paper examines the use of a genetic algorithm to select the most significant input features in the machine condition monitoring contexts. By doing this, a subset of six input features from a large set of possible features is selected, giving a very high classification accuracy of 99.8 %. Li et al. [17] and Jack & Nandi [18] are devoted to detecting mechanical faults; a similar approach could be extended to analyse the vibration pattern when an electrical machine is working with an electrical fault.

The major disadvantage of vibration monitoring is cost. For example, a regular vibration sensor costs several hundred dollars. A high product cost can be incurred just by employing the necessary vibration sensors for a large number of electric machines. Another disadvantage of vibration monitoring is that it requires access to the machine. For accurate measurements, sensors should be mounted tightly on the electric machines, and expertise is required in the mounting [19-21] In addition, sensors themselves may fail. This could be a problem given that the typical lifetime of a bearing is several years.

3.5 Wavelet Analysis

The wavelet based detection method show good sensitivity, short detection time, and can be easily applied for on line fault detection. This method works on principle that all signals can be reconstructed from the sets of local signals of varying scale and amplitude, but constant shape. LeventErenand Michael J. Devaney[19] analyzed the stator current via wavelet packet decomposition to detect bearing defects. The proposed method has several advantages over Fourier analysis tools used in motor

current signature analysis. Due to the non-stationary nature of the stator current, the wavelet packet transform provides better analysis under varying load conditions. The wavelet packet transform also permits the tailoring of the frequency bands to cover the range of bearing-defect induced frequencies resulting from rotor speed variations.
SzabóLorándet. al. [20] applied the Wavelet Transform to diagnose the rotor faults of wound rotor induction motor. The motor was tested when it was considered healthy and with provoked rotor fault. The difference signal at the 11^{th} level of the one-dimensional discrete wavelet analysis wavelet decomposition tree was used for the rotor fault detection of motor. RMS of the 11^{th} d_{11} wavelet coefficient and of the line current was observed in order to compare it with a machine considered healthy, Finally, it was concluded that wavelet analysis can be successfully used for rotor fault detection.
Jose A. Antonino-Daviuet. al. [22] proposed a method for the diagnosis of rotor bar failures in induction machines, based on the analysis of the stator current during the startup using the discrete wavelet transform (DWT). In the case of bar breakage, the higher level components of the DWT of the startup stator current follow a characteristic pattern, which is described in detail and physically assessed. Several experiments are developed under different machine conditions (healthy machine and machine with different levels of failure) and operating conditions (no load, full load, pulsating load, and fluctuating voltage). In each case, the results are compared with those obtained using the classical approach, based on the analysis of the steady-state current using the Fourier transform. Finally, the results are discussed, and some considerations about the influence of the DWT parameters (type of mother wavelet, order of the mother wavelet, sampling rate, or number of levels of the decomposition) over the diagnosis are done. The tests show that if the startup transient is not very short, the reliability of the proposed method for the diagnosis of bar breakages is similar to that of the classical approach, based on the Fourier transform, in the case of loaded motors, but, in addition, the method can detect faults in an unloaded condition, and it allows a correct diagnosis of a healthy machine in some particular cases where Fourier analysis leads to an incorrect fault diagnosis.
Cusidoet. al. [23] proposes a different signal processing method, by combination of Wavelet and Power Spectral Density techniques. It presents good theoretical and experimental results. They concluded that MCSA is a good method for analyze motor faults over constant load torque, but in case of do not constant load torque an improvement is needed: Wavelets Decomposition is the right technique for non stationary signals and Power Spectral Density would be the right solution for introduce it on Industrial applications.

3.6 Current park vector

Another important electrical monitoring technique is CurrentPark’’s vector. The basic idea of current Park’s vector is that in three-phase induction motors, the connection to stator windings usually does not use a neutral. For a Y-connection induction motor, the stator current has no zero-sequence component. A two-dimensional representation of the three-phase currents, referred to as current Park’s vector, can then be regarded as a description of motor conditions. Under ideal conditions, balanced three phase currents lead to a Park's vector that is a circular pattern centered at the origin of coordinates [64]. Therefore, by monitoring the deviation of current Park's vector, the motor condition can be predicted and the presence of a fault can be detected.

J. Marques Cardoso,and E. S. Saraiva [24] discussed the subject of on-line detection of airgap eccentricity in three-phase induction motors. Experimental results show that it is possible to detect thepresence of airgap static eccentricity in operating three-phaseinduction motors, by computer-aided monitoring of the statorcurrent Park's Vector. Qualitative information about theseverity of the fault can be easily obtained by observing thesplitting of the current Park's Vector pattern.

Mendes and Cardoso [26] detected faults in voltage-sourced inverters using the current Park's vector. Nejjari and Benbouzid [27] analyzed the deviation in the pattern of current Park's vector to diagnosis the supply voltage unbalance of induction motors. However, this method ignores the non-idealities of electrical machines and inherent unbalance of supply voltages. In addition, it is difficult to isolate different faults using this method alone, since different faults may cause a similar deviation in the current Park's vector.

Douglaset. al. [28] proposed a new technique "Extended park's Vector Approach" (EPVA), which was successfully applied in the steady diagnosis of rotor faults, inter-turn stator faults and unbalanced supply voltage, and mechanical load misalignment. This technique was based on the park's vector approach; however, it provides greater insight into the severity of the faults.

IzzetyOnelet. al. [29] investigated the application of induction motor stator current signature analysis (MCSA) using Park's transform for the detection of rolling element bearing damages in three-phase induction motor. This study presents bearing faults and Park's transform and then gives a brief overview of the radial basis function (RBF) neural networks algorithm. Data acquisition and Park's transform algorithm were achieved by using Labview and the neural network algorithm is achieved by using MATLAB programming language. The diagnosis process was tested on a 0.75kW, squirrel-caged induction motor. Experimental results showed that it is possible to detect bearing damage in induction motors using an ANN algorithm. ANN was trained, giving 100% correct prediction for training data. When ANN was presented a set of Park's vector pattern, the diagnosis system was found to provide very good performance.

The research carried out by SzabóLorándet. al. [30] show that how the Park's vector approach based method can be used for detecting the rotor faults of the squirrel cage induction machine. The squirrel cage induction machine was tested with two rotors, a healthy one, and one having broken rotor bars. The line currents of the motor were visualized on an oscilloscope using a special electronic circuit which was able to synthesize the two orthogonal components of the current, voltage and flux phasors. Beside this the line currents were acquired by a DAQ board from a PC. Using advanced virtual instruments (VIs) built up in LabVIEW environment. Several characteristics of the motor under study were plotted. Due to the broken rotor bars, there was significant fluctuation in the torque of the machine, and the amplitude of the line current at the end of the starting period was quite high. The shape of the current's phasor of faulty motor was not of perfect circular shape, which was the clear indication a fault in the squirrel cage induction machine.

Izzetonel and Benbouzid [31] diagnosed the problem of bearing failure in induction motors by using park vector approach. They also compared two fault detection and diagnosis techniques, namely the Park transform approach and the Concordia transform. Experimental tests were carried out on a 0.75 kW two-pole induction motor with artificial bearing damage. These results seem to indicate that the Park transform approach has better diagnosis capabilities than the Concordia transform.

4. Software Used for Fault Diagnosis

The main software programs that can be used with fault diagnosis techniques either with classical methods or the artificial methods to give high facilitate.here we manifests the most important among them: Matlab program, Tiberius program, Ansys program, Lab view program, Knoware program, ABAQUS program, SAMCEF program, OOFELIE program CalculiX program, OOFEM program, ALGOR program, Sundance program, JMAG program, PERMAS program, STRANDS7 program, PAM program, solid work program, Neural net. Program, Jaffa neural program, Free Master program, Maxwell pc program, Motor monitor program, Neuro solution program, DLI watchman program COSMOS WORK program, Maple Sim program, Fault tolerant software, Sim20 software, pscad software, Free Master, etc.

5. Important observations

Literature review indicates that thermal monitoring, vibration monitoring, and electrical monitoring, noise monitoring, torque monitoring and flux monitoring are the some important techniques of condition monitoring and fault diagnosis of electric machines.

Wavelet Transform can be used for fault diagnosis of induction motor. It works on principle that all signals can be reconstructed from sets of local signals of varying scale and amplitude, but constant shape. It is an easy and fast to implement data processing technique. It analyses the signal at different frequency bands with different resolution by decomposing the signal into coarse approximation and detail information.

Current park vector is most frequent used method in literature review applied to diagnose the common faults of induction motor. The analysis of the three-phase induction motor can be simplified using the Park transformation. The method is based on the visualization of the motor current Park’s vector representation. If this is a perfect circle the machine can be considered as healthy. If an elliptical pattern is observed for this representation, the machine is faulty. From the characteristics of the ellipse the fault's type can be established. The ellipticity increases with the severity of the fault. From literature cited, the following observations can be made:

a. Condition monitoring has great significance in the business environment because there is need to improve reliability of machine and to reduce the cost of maintenance.
b. The major disadvantage of vibration monitoring is cost. A regular vibration sensor costs several hundred dollars. A high product cost can be incurred just

by employing the necessary vibration sensors for a large number of electric machines. Another disadvantage of vibration monitoring is that it requires access to the machine. For accurate measurements, sensors should be mounted tightly on the electric machines, and expertise is required in the mounting. On other hand, there is no physical contact between the current sensor and motor-driven equipment in electric monitoring therefore electric monitoring is particularly attractive to applications where safety is of major concern.

c. In current based fault detection, various types of faults may cause broadband changes in power spectra of stator current. Therefore, researchers choose the signal processing as the tool for stator current based fault detection.

d. Investigations reveal that the fault frequencies occur in motor current spectra are unique for different motor faults.

e. It has been a broadly accepted requirement that a diagnostic scheme should be non-invasive and capable of detecting faults accurately at low cost. Therefore, Motor Current Signature Analysis {MCSA) has become a widely used method because its monitoring parameter is a motor terminal quantity that is easily accessible.

f. Numerous applications of using electric monitoring in motor health monitoring have been published among the nuclear-generation, industrial, defense industries. In published work, researchers used the variety of motors of different rating to diagnose the faults. But very little work has been done to diagnose the all possible common fault of induction motor by using the motor of same rating and same signal processing technique. So, there is need to use the same type of motor and same signal processing technique to diagnose common faults of induction motor so that effectiveness of all signal processing techniques can be studied.

g. In addition, very few experimental studies have been published which diagnosed the faults of induction motors with variety of signal processing techniques. Therefore, an experimental study must be conducted to diagnose the single fault with different signal processing techniques so that limitation of each signal processing technique can be studied.

h. The effectiveness of signal processing techniques for non-stationary signals has not been addressed appropriately in the literature. Therefore, more experiments need to be carried out with different signal processing techniques so that it may be examined which technique is best suited for non-stationary signals.

6. Conclusion

This paper presented a review of existing induction motor condition monitoring methods. This literature review covered a variety of topics, techniques, methods, and approaches. The literature was basically categorized into two major themes: types of faults of induction motor, and practical use of various condition monitoring methods for fault diagnosis of electric machines. The review presented in this paper indicates that previously proposed methods of fault diagnosis for electric machines still remains an unexplored area. The usage of electric motors is rapidly increasing in a wide variety of industrial and transit applications. Therefore, the demand for reliable fault detection methods for electric machines is increasing.

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