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Review Article

GENERAL APPROACHES OF FAULT DIAGNOSIS AND CONDITION MONITORING OF SQUIRREL-CAGE INDUCTION MOTOR: A REVIEW

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A R T I C L E I N F O

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A B S T R A C T

The induction motor suffers from numerous faults and these faults consequence into lowering of overall industrial productivity and increased shutdown period. Thus, there is the need of prior detection of numerous faults while in operation. The condition monitoring and faults diagnosis mechanism are required to formulate a well-defined and skilled map in between motor signals as well as indications of the fault state of the induction motor. Hence, a number of advanced and optimum approaches have been identified, and employed for detecting various faults in a squirrel-cage induction motor. Faults in the motor pose their signature frequencies as harmonics in the motor current spectrum. In Motor Current Signature Analysis, various approaches like Park's vector scheme, Fast Fourier Transformation (FFT), Discrete Wavelet Transform (DWT) based digital signal processing techniques have been taken into consideration. Implementation with VLSI based diagnosis opens a broad door for its employment in numerous industrial and real-time application development.

INTRODUCTION

The electric motor is an electromechanical device that converts electrical energy into mechanical energy. Being a very prominent part of modern industry, the induction motors play a vital role in major applications like pumping systems, fans, elevating systems, electric-powered vehicles, crushers, cement plants and many more industrial segments.

These induction motors are mainly employed as a critical form of devices for major industrial activities and are in general, integrated with diverse commercially available apparatus and applications. All the equipments based on this motor drive, generally facilitate core competences, significant for making certain business success as well as operator safety. Numerous electrical components of the operational induction machines are highly prone to the system failure. For instance, the insulation breakdown in induction motor causes the stator winding fault, which is immensely influenced by factors like mechanical vibration, heat, functional duration or age of motor, damage occurred during installation. Similarly, in some cases, the contamination with oil material also causes faults in induction motors, that results in system failure. In case of a squirrel-cage rotor, its bars might be damaged by mechanical stresses that could arise in the machine. Meanwhile, the bearings in induction motor can be affected due to extreme wear and smash up, caused due to improper lubrication, unbalanced loading on motor, misalignment of bearing components with rotor, etc.

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Conventionally, the majority of manufacturers and users trust on very traditional approaches of induction motor protection like estimation of over-current or over-voltage to ensure the reliable system function. The high paced and immensely complicated applications of induction motor in modern industrial applications are alarming for an optimized system monitoring and supervision for induction machines. Even the reduction of the human-machine interface also demands for an on-line detection requirements, which can effectively diagnose the faults in induction motor without any hazards and process disruption.

Maintenance of induction motors is one of the serious problems faced by many industries and utilities. A number of researches have been done for the issues of automatic and on-line fault detection in induction motor. Few of the main research works and recommendations were like, Electric Power Research Institute motor reliability study [1], states that stator faults are responsible for 37% of the induction motor failures. According to Neale [2], the purchasing and installation costs of the equipments usually cost less than half of the total expenditure over the life of the machine for maintenance. According to Wowk [3], maintenance expenditure typically presents 15% to 40% of the total cost and it can be up to 80% of the total cost.

This is the matter of fact that the process of induction motor condition monitoring and its potential fault diagnosis is as old as the induction motor itself. Initially the fault detection in induction motor was based on the conventional approaches of estimation of over-current and over-voltage for ensuring the optimum operation. Regardless of the availability of these tools, numerous organizations are still facing problems due to unexpected failure of machineries with reduced motor life span [4]. Since, the works delivered by induction motors progressed more and more complicated, the enhancements for system was realized for condition monitoring and its fault diagnosis [5]. A number of enhanced diagnostic approaches were advocated and control mechanisms were devised for ensuring the fault resilient control devices.

A number of approaches and systems are there for monitoring the induction motor functions for ensuring the higher consistency. Few leading approaches are as follows [6]:

- EMF monitoring systems,
- Systems based on temperature estimation,
- Infrared recognition approach,
- Monitoring approach based on Radio frequency emissions analysis,
- Approaches based on the estimation of Noise and vibration in machines,
- Approaches considering the speed and torque of rotor,
- System based on chemical analysis,
- Acoustic noise measurement based techniques,
- Motor current signature analysis (MCSA) based systems,
- Artificial intelligence and neural network based fault diagnosis systems.

In spite of these above mentioned approaches and tools, a number of industries are there which suffer from unexpected failures of the systems that ultimately results into industrial lower productivity. Different issues like environment, functions and system installations might cause failure of the system in its combined form[7]. Therefore, any kind of system optimization and enhancements could be of significant interest for all.

The extensive utilization of the automation approaches and the reduction in the direct HMI opportunities in industries have ignited the demand for optimum condition monitoring and fault diagnosis. On the other hand, now a day the industries emphasize more on quality and reliable operation of systems throughout the life span of the machineries.

Fault Detection Approaches

The faults can be in various places like in the stator of the induction motor, its rotor, motor bearing parts, or the external peripheral systems associated with the induction motor [8]. Various fault detection approaches for Induction Motor are shown in Figure 1. The approaches are broadly classified into three categories viz. model based, signal processing based and artificial intelligence approaches [9].

Model based techniques make use of mathematical models of the system. Nevertheless, an accurate mathematical model of a physical system is hard to obtain. Usually, the parameters of the system may vary with time, and the features of the faults and noises cannot be modeled precisely. Hence, there is always a lack of congruence between the actual system (motor) and its mathematical model even under no-fault conditions. Such inconsistencies cause problems in fault detection and condition monitoring applications, and may act as sources of false alarms and missed alarms.

Many endeavors have been reported by researchers about the implementation of artificial intelligence (AI) in motor monitoring and fault diagnosis. Here, expert system has been widely used as a tool for the fault detection [10]. Several AI techniques have been developed and applied in the monitoring processes of faults, among them, the Artificial Neural Network (ANN), Fuzzy Logic (FL) and Support Vector Machines (SVM) [11]. Typically, expert systems are trained using a database that correlates measurement and corresponding fault. In practical applications, the severity levels of faults may vary and not exactly match the database used for training. This can lead to false diagnosis.

Thanks to the recent Digital Signal Processing technology developments, motor fault diagnosis can now be done in real-time, based on minimal signal procurements from the motor, e.g. stator line current or vibration signals. It facilitates precise and low-cost motor fault detection. While using DSP, the fault code is embedded into the algorithm that processes the instantly measured current data for both fundamental component and fault signature frequency.

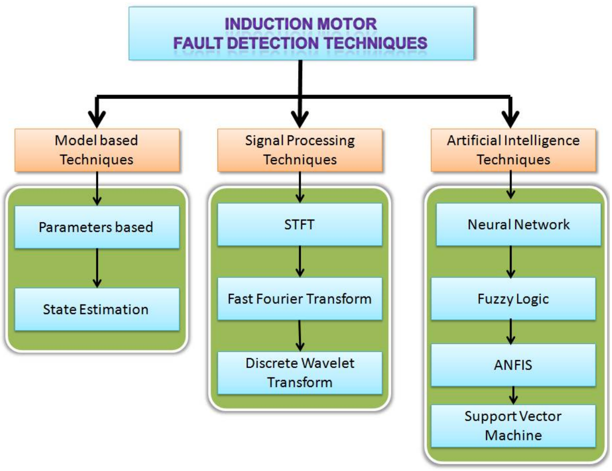

Figure 1 Various fault detection approaches for Induction Motor

The major faults in the induction motors can be classified as follows:

1. Windings or short circuit caused faults
2. Broken rotor bars faults
3. Eccentricity faults
4. Bearing and gearbox failures

These prominent faults in induction motor can cause single or even multiple effects, like,

1. Unstable voltages and line currents
2. Mechanical Vibration and noise
3. Pulsations in torques
4. Excessive heating of the machineries
5. Leakage of electromagnetic flux; etc

Fault Diagnosis Methods

A number of mechanisms and approaches have been developed for diagnosing the faults in induction motor. Numerous approaches have come out with impressive results. However, there persists a huge gap for further development and enhancement. Some important general approaches have been presented below.

Park's Vector Approach

One of the difficulties met in the investigation portrayal of the characteristics in majority of rotating electric machineries is that the inductance of the machine is the function of the relative position of the stator and rotor. In order to make the understanding of the electrical machines simpler, R.H. Park introduced a transformation approach that made their study straightforward by transforming equations of motor into an equivalent 2-phased orthogonal reference frame[12]. The transformation of the 3-phased system equation into the 2-phased orthogonal equation can be done by:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \left[P_{dq0}\right] . \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{1}$$

In the above equation, the variable f refers to the function to be transformed. The Park transformation matrix can be presented as follows:

$$\left|P_{dq0}\right| = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{2}$$

$\theta = \omega t$ refers to the angular displacement.

By implementing the above mentioned transformation approach, the orthogonal components of the Park's current vector can be estimated from the symmetrical 3-phased current system, encompassing the components i_a, i_b and i_c.

$$i_d = \sqrt{\frac{2}{3}} \left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \tag{3}$$

$$i_q = \sqrt{\frac{2}{3}} \left[i_a \sin + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \tag{4}$$

In case the reference is confined in the stator of the induction motor machine $(\theta = 0)$ the above-mentioned expression becomes,

$$i_d = i_a - \frac{i_b}{2} - \frac{i_c}{2} \tag{5}$$

$$i_q = \frac{\sqrt{3}}{2}(i_b - i_c) \tag{6}$$

In case the 3-phase stator current system of induction motor is completely symmetric, the stator currents can be written, as follows:

$$i_a = \sqrt{2}\ I \sin(\omega t) \tag{7}$$

$$i_b = \sqrt{2} \sin(\omega_s t + \frac{2\pi}{3}) \tag{8}$$

$$i_c = \sqrt{2}\, I \sin(\omega_s t + \frac{4\pi}{3}) \tag{9}$$

In above-mentioned expression, I refers to the maximum value of the input phase current, ωs refers to the input frequency and t refers to the time parameter. Now, substituting the equations, a final expression representing the two orthogonal components of Park's current vector for a healthy electrical machine are given below:

$$i_d = \frac{3}{2}\ I \sin(\omega t) \tag{10}$$

$$i_q = \frac{3}{2}\ I \cos(\omega t) \tag{11}$$

Considering the above mentioned expressions, it can be realized that in Park's representation the healthy motors exhibit faultless circle. Considering the retrieved matrices of induction motor the associated curve for faulty motor can be obtained. In case, there exists the rise in fault severity, then the graph would be getting distorted. In this implementation scheme, there is a major issue, as it suffers limitations for exhibiting isolation of varied faults in the squirrel-cage induction machine. This happens due to multiple faults and problems that might create similar deviation in the Park's vector results.

Fast Fourier Transformation

The Fourier transform converts the time domain into equivalent frequency domain or vice versa. FFT is the potential and highly efficient approach for performing aforementioned conversion by factorization of DFT matrix into a product of sparse factors [13]. This efficiency makes FFT applicable for various applications in science and engineering.

In practical application, the execution time can be reduced with higher degree and in such scenario, the enhancement is approximately in relation with N / log (N). Such huge enhancements cause strengthening of the estimation of DFT pragmatic and thus FFTs technique becomes more useful in a wide variety of applications, from digital signal processing to algorithms for quick multiplication of large integers.[7]

The expressions for various fault frequency components in the measured current signal of induction motor have been presented here.

Broken rotor bars

The mathematical expression for broken rotor bars can be presented as follows:

$$f_{br} = f_s(1 \pm 2s) \tag{12}$$

In the above mentioned expression, f_{br}= broken bars frequency, f_s= supply frequency,
s = slip.

Stator winding short circuits

In case of short circuit faults in induction motor the equation for frequency is given by the following expression:

$$f_{st} = f_s * \left\{\frac{n}{p}.(1 - s) \pm k\right\} \tag{13}$$

where, f_{st} = short circuit frequency, f_s= supply frequency, n = 1, 2, 3…
p = pole pairs, s = slip, k = 1, 3, 5…

Eccentricities

Eccentricity is also one of the major kinds of induction motor faults in which the frequency analysis is made based on following expression:

$$f_{ec} = f_s . \left[(r \pm n_d).\left(\frac{1-s}{p}\right) \pm n_{ws}\right] \tag{14}$$

Where, f_{ec} = eccentricity frequency, f_s= supply frequency, r = number of slots

$n_d = \pm 1$, p = pole pairs, s = slip frequency, n_{ws} = 1, 3, 5…

Bearing failures

One of the most frequent failures in industrial applications is caused due to bearing faults. The frequency analysis expression for bearing fault is given as follows,

$$f_{bb0} = 0.4 * n * f_{rm} \quad (15)$$

$$f_{bb1} = 0.6 * n * f_{rm} \quad (16)$$

Where, f_{bb0}= lower frequency, f_{bb1}= upper frequency, n = number of balls, f_{rm}= rotor mechanical frequency

With MCSA, taking into consideration of various parameters as well as the slip speed of induction motor, it is possible to estimate the frequencies for each failure.

One of the most significant concerns to be taken into consideration for the optimum failure diagnosis in induction motor is the process of signal interpretation in which the continuous input sinusoidal signal is composed of various frequencies.

These frequency constituents will be partially caused by different faults that may exist and the characteristics of the motor load. The stator current has to be sampled and the different frequency harmonics and their amplitudes should be obtained. Then, with these parameters, the failure (the frequency) and its intensity (amplitude) can be detected.

Discrete Wavelet Transform

In numerous applications, the wavelet transform has established itself as a robust tool for dealing with certain non-stationary signals such as vibration signal waveforms. The approach facilitates very precise and efficient interpretation for the signals of time domain as well as frequency domain simultaneously, with the goal to explore all the components such as local, transient or intermittent. In fact, the wavelet transform might be one of two kinds, discrete or continuous type [14].

The wavelet transform of continuous type reveals more significant information of a signal as compared to discrete wavelet transform but unfortunately, it posses higher computation time as compared to the discrete. On the other hand, for the majority of applications and especially in industrial applications the signal processing is needed with much higher efficiency and processing pace. Therefore, discrete wavelet transform becomes a potential player for such applications. The DWT takes into consideration of a dyadic grid and orthonormal wavelet basis functions that ultimately exhibit zero redundancy. DWT estimates the wavelet coefficients at certain definite discrete intervals of time components and scales. The estimated coefficients of DWT can be employed to construct a set of characteristics that explicitly represent different types of signals.

A function in DWT known as the dilation function can be expressed in terms of the tree of low and high pass filters where every individual step transforms the low pass filter into further lower and higher frequency signal components. The illustration of such transformation has been given in Figure 2. The process of signal decomposition takes place with the input original signal by successive decomposition into several signal components of lower resolution. In other words, the components with higher frequency are not processed for analysis in further steps. In DWT, the components with lower frequency of the signal are stated as approximations, while, on the other hand, the higher frequency components are referred as details.

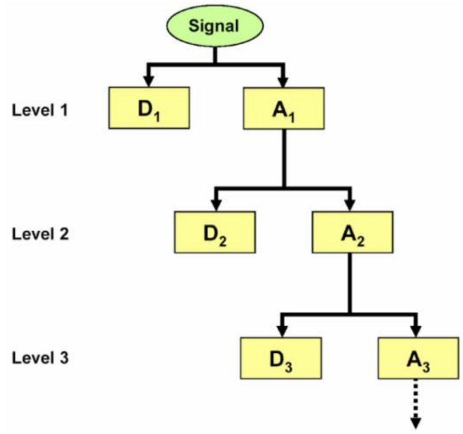

Figure 2 Filter bank representation of the DWT

The overall mechanism of signal decomposition in DWT has been illustrated in Figure 3.

In this process, the original signal $x[n]$ is initially processed with a half band high pass filter $g[n]$ and a filter for low pass, stated as $h[n]$. Once the filtering is accomplished, the samples generated are eliminated as per Nyquist's criteria. In general, eliminating other samples, it would further be decomposed into sub-samples of signal by two and then the signal would be divided into half of the number of points. Now, the scale of the signal is doubled. Here it must be noted that the filtering process makes the removal of a section of the frequency information, but the scale of components remains unchanged [15].

Majority of researchers have provided sophisticated expressions of fault frequency components; but they have not signified the most accurate diagnostic model, for stator current analysis. In numerous research works, machine models based on numerical calculations for fault detection are employed. Nevertheless, they do not facilitate the methodical stator current expressions, which are significant for the selection of appropriate signal analysis and fault detection approaches. The most extensively employed approach for stator current dealing out in this circumstance is the estimation of the spectrum. Generally, the power spectral density (PSD) for stator current is calculated by applying Fourier transform approaches. However, there is the need of highly robust and advanced approaches for analyzing the non-stationary signal[16].

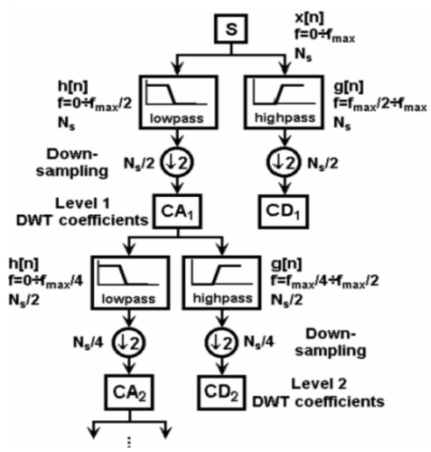

Figure 3 The DWT decomposition of a signal

One of the potential analysis approaches of WT is multiresolution analysis (MRA). This scheme provides an efficient way to exhibit analysis of the characteristics of a signal at varied frequency bands. The WT acts as a 'mathematical microscope', through which different parts of the signal are examined by adjusting the focus. Such features become significant in the process of pattern recognition. Therefore, MRA scheme is employed with the applications for on-line detection and classification of faults in induction motors.

The discrete wavelet transformation accomplishes better time-frequency representation of data signal. In recent times, the DWT approach is a preferred technique for diagnosing squirrel-cage induction motor and its condition monitoring. The scheme is based on the process of recognition or diagnosis of various features. The retrieved patterns are used to analyze and identify the faulty components in motor. The DWT MRA is an approach that can be considered as a potential candidate to deal with fault identification requirement, as this scheme is highly robust for performing analysis of the faults in the induction motors.

Fault Signature Analysis through Vibrations and currents

One of the important approaches for supervising mechanical faults or system failure is vibration-monitoring technique. Because of the characteristics of the mechanical faults, the vibration emerges with the allied components of machineries. As the mechanical vibration causes the generation of acoustic noise, thus it facilitates the possibility of noise monitoring. Then, while, none of these approaches are economical as the cost of transducers being used is higher and therefore, these approaches could be implemented only with the large machines or highly critical industrial applications.

In such scenario, a cost effective approach could be the implementation of the stator current based monitoring approaches, because the measurement of current is relatively simple. Furthermore, current measurement approaches are by now accessible in numerous control drives for machinery or application protection intentions[17]. However, the influences caused due to mechanical faults or system failures on the current variables of the stator of motor become very complicated to estimate. Consequently, the monitoring process based on the stator current analysis is undoubtedly more complicated as compared to the monitoring process based on mechanical vibrations.

One of the prime advantages of current based fault monitoring approach, as compared to vibration based schemes is that this system does not need additional or many sensory transducer interfaces. The consideration of numerous sensor based systems makes the overall system highly complicated and thus the overall overheads get increased.

In order to get a complete monitoring system, a huge number of transducers dedicated for vibration measurement are required to be placed on different system apparatus, that are probable to fail like, bearings, gearbox machines, stator frame, load components. Then, a severe mechanical defect in any component affects the electric machinery throughout the load torque and the speed of the shaft. This demonstrates that the machineries or motor might be considered as an intermediate transducer component where a collection of fault effects congregates collectively [18].

VLSI Platform for Fault Diagnosis

The approach of digital signal processing offers robust techniques for diagnosing numerous faults in induction motor. On the other hand, the use of Field Programmable Gate Array can play a vital role in overall system optimization and efficiency enrichment. Considering the vital factors viz. time, speed, memory and thus resulting performance, the FPGA implementation in the fault diagnosis applications could be a better step to optimize fault diagnosis in induction motor [19].

The important issues in existing approaches are the higher complexity and lower performance. On the other hand, majority of new systems cannot be implemented with conventional techniques. Therefore, a highly optimum and effective system is desired, which can perform on a VLSI platform and can be effective with real-time embedded system implementation. In spite of these facts, it is also required that the system must be functional for multiple faults as the detection and diagnosis with individual faults cannot be a better or optimum solution [20].

CONCLUSIONS

Considering all these factors and constraints, a number of approaches have been explored for fault detection and diagnosis in induction motor. The diagnosis system setups have been developed with faults like stator faults, inter-turn faults, bearing faults, rotor bar faults and many more with different approaches. Approaches such as FFT, Park's vector, DWT enabled MCSA system and FPGA based systems have been explored for fault identification.

By using signal processing based approaches, like discrete wavelet transforms, one can identify the particular phase of the induction motor, where the fault occurs, using multiresolution analysis. Subsequently, a quantitative analysis technique could be exploited for not only the detection of broken rotor bars fault, but also, to know the severity of such faults in the motor.

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