Induction Motor Fault Diagnosis Methods: A Comparative Study

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***Abstract*— Induction motors are one of the commonly used electrical machines in industry because of various technical and economical reasons. They face various stresses during operating conditions leading to some modes of faults. Hence, condition monitoring becomes necessary in order to avoid catastrophic failures. Various fault monitoring techniques for induction motors can be broadly categorized as model based techniques, signal processing techniques, and soft computing techniques. It is difficult to obtain the accurate models of faulty machines and also to apply model based techniques. Soft computing techniques provide good analysis of a faulty system even if accurate models are unavailable. Besides giving improved performance, these techniques are easy to extend and modify. Here the major faults in induction motor and different fault detection techniques are discussed. An attempt is also made to review and compare the internal and external fault non-invasive detection methodologies considering recently utilized Artificial Intelligence based and signal processing based approaches. In addition, a non-invasive approach, based on the monitoring of stator current Park's Vector pattern, for detection of major faults is discussed.**

Keywords- Induction Motor, Soft Computing, Artificial Intelligence, Signal Processing, Park's Vector

I. INTRODUCTION

Induction motors are electro-mechanical devices used in most of the industrial applications. Although induction machines are considered relatively reliable and robust due to their simple design and well-developed manufacturing technologies, faults do occur and may severely disrupt industrial processes and even lead to disastrous accidents. If a fault is not detected or if it is allowed to develop further, it will lead to a failure. A variety of machine faults such as winding faults, unbalanced stator and rotor parameters, broken rotor bars, eccentricity and bearing faults may occur in an induction motor [1,2]. Several fault identification methods have been developed and been effectively applied to detect machine faults at different stages by using different machine variables, such as current, voltage, speed, efficiency, temperature and vibrations. Thus, for safety and economic considerations, it is essential to monitor the condition of motors of different sizes such as large and small.

Condition monitoring involves taking measurements on a machine in order to detect faults with the aim of reducing both unexpected failures and maintenance costs. An efficient condition-monitoring scheme is one that provides warning and predicts the faults at early stages. Monitoring system obtains information about the machine in the form of primary data and through the use of modern signal processing techniques; it is possible to give vital diagnostic information to equipment operator before it fails. The problem with this approach is that the results require constant human interpretation. The logical progression of the condition-monitoring technologies is the automation of the diagnostic process. To automate the diagnostic process, a number of soft computing diagnostic techniques such as artificial neural network [16,17,18,19], fuzzy logic [22,23], adaptive neural fuzzy inference system, genetic algorithm [25] etc have been proposed.

Soft computing techniques are employed to assist the diagnostic task to correctly interpret the fault data [3,4,5]. These techniques have gained popularity over other conventional techniques since they are easy to extend and modify besides their improved performance. The neural network can represent a non-linear model without knowledge of its actual structure and can give result in a short time. From the early stages of developing electrical machines, researchers have been engaged in developing a method for machine analysis, protection and maintenance. The use of above techniques increases the precision and accuracy of the monitoring systems. The area of condition monitoring and faults diagnostic of electrical drives is essentially related to a number of subjects, such as electrical machines, methods of monitoring, reliability and maintenance, instrumentation, signal processing and intelligent systems.

Current Park's vector approach [20] is an important electrical monitoring technique. Its basic idea is that, in three-phase induction motors, the connection to stator windings usually does not use a neutral. 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.

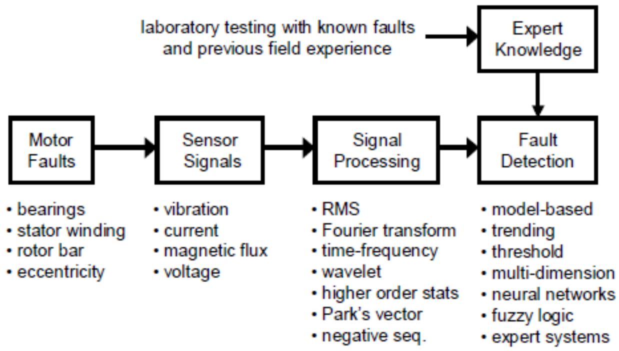


Figure 1. The on-line condition monitoring process

II. MAJOR FAULTS IN INDUCTION MOTOR

The distribution of induction motor major faults can be listed as: bearing (69%), stator winding (21%), rotor bar (7%), and shaft/coupling (3%) faults.

The Table 1 presents the surveys conducted by the Electric Power Research Institute (EPRI), which surveyed 6312 motors [1], and the survey conducted by the Motor Reliability Working Group of the IEEE-IAS, which surveyed 1141 motors [6],[7].

Table 1: Percentage of failure by component

Failed Component	**IEEE-IAS**	**EPRI**
Bearings Related	44	41
Windings Related	26	36
Rotor Related	8	9
Others	22	14

A. Bearing Failure

Bearing failure is usually progressive but ultimately its effect upon the motor is catastrophic. Installation problems are often caused by improperly forcing the bearing onto the shaft or in the housing. This produces physical damage which leads to premature failure. The mechanical displacement resulting from damaged bearing causes variation in the motor air gap.

B. Eccentricity

Eccentricity is defined as unbalanced air gap between the rotor and stator of an induction motor. It may be caused by incorrect position of the stator or rotor. Some reasons for eccentricity are elliptical stator inner cross-section and relative misalignment of rotor and stator in the fixing and commissioning stage.

C. Broken Rotor Bar

Broken rotor bar can be caused by thermal stresses due to thermal overload and unbalance, magnetic stress caused by electromagnetic forces, electromagnetic noise, and vibration, residual stresses due to manufacturing problems, dynamic stress arising from shaft torques and environmental stresses caused by contamination and abrasion of rotor material due to chemicals or moisture.

D. Stator Winding related Faults

Majority of motor stator winding failure happens due to the destruction of the turn insulation caused by the short circuit in stator windings. The shorts could be inter-turn shorts of same phase, short between coils of same phase, short between two phases and short between phase to earth.

According to an IEEE and EPRI motor reliability study[38], stator faults are mostly responsible for 37% of the failures in an induction motor. Figure 2 shows the schematic diagram of the different types of stator winding problems.

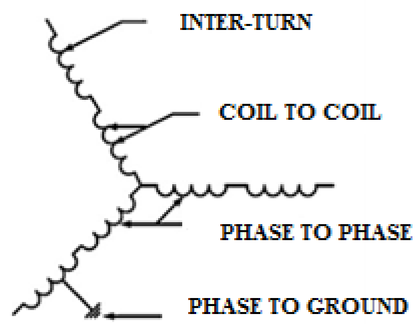


Figure 2: Schematic diagram of the different types of stator winding problems

E. Stator Core Related Faults

Stator core problems are rare and are not usually a major concern for small machines. However, the repair or rebuild process is more costly in the case of the stator core failure, since it usually requires the entire core to be replaced. Therefore, there has been interest in identifying the causes of core problems and finding ways of monitoring the core in order to detect and prevent stator core failure.

F. Rotor Winding Faults

Short circuit turns in induction machine rotor windings cause operational problems such as high vibration levels; therefore early detection is essential. Faults on the rotor windings of induction motor have not been easy to detect because there is not necessarily an electrical connection to the winding and it is difficult to measure the low-frequency currents induced in the rotor winding.

III. DIFFERENT FAULT DIAGNOSIS METHODS

Various fault monitoring techniques for induction motors can be broadly categorized as model-based technique, signal processing technique and soft computing technique.

A. Model Based Techniques

In case of model based techniques, accurate models of the faulty machine are essentially required for achieving a good fault diagnosis. Sometimes it becomes difficult to obtain accurate models of the faulty machines and also to apply model based techniques. Soft computing techniques provide good analysis of a faulty system even if accurate models are unavailable.

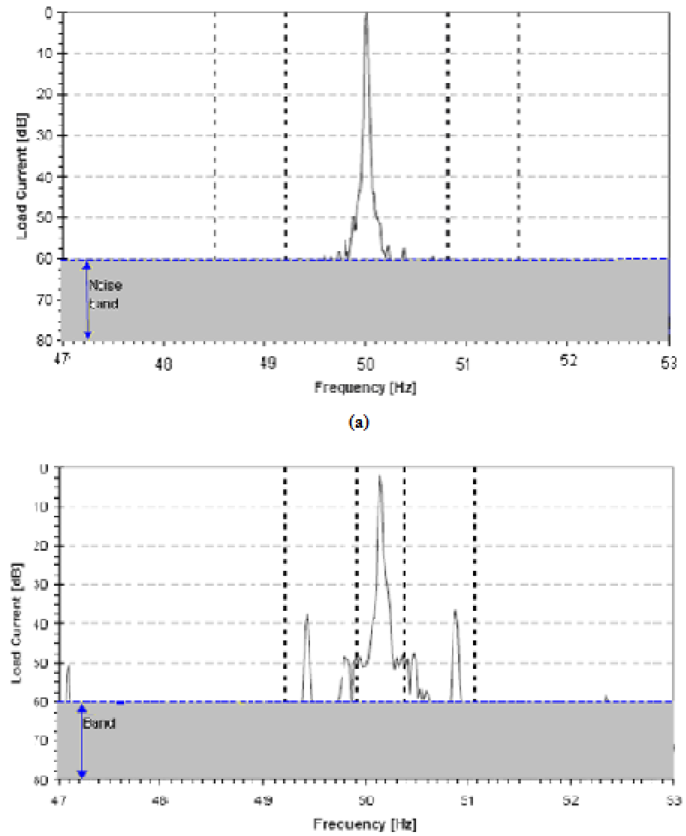
Bazine et al.[11] proposed a diagnosis method for on-line inter-turns short-circuit windings and broken bars detection by parameters estimation. Experimental rig is used to validate the on-line identification of stator fault. An on-line technique has been proposed to detect rotor broken bars. This technique was validated by using finite element software (Flux2D). Estimation results show a good agreement and demonstrate the possibility of online stator and rotor faults detection.

B. Signal Processing Techniques

Signal processing techniques are applied to the measured sensor signals in order to generate features or parameters (e.g. amplitudes of frequency components associated with faults) which are sensitive to the presence or absence of specific faults. Calculation of simple statistical parameters such as the overall RMS value of a signal can give useful information[10].

Motor Current Signature Analysis (MCSA) is the on-line analysis of current to detect problems in a three-phase induction motor drive while it is still operational and in service. MCSA is considered the most popular fault detection method at present because it can easily detect the common machine fault such as turn to turn short circuit, cracked or broken rotor bars, bearing deterioration etc. Figure 3(a) and 3(b) show the current spectrum of a healthy motor and a motor with damaged rotor respectively.

A work on detection of stator short circuit faults in three-phase induction motors using motor current zero crossing instants presented a MCSA based diagnostics of the stator winding short circuit fault. This type of fault happens due to the destruction of the turn insulation, and can be very detrimental causing motor shutdown. Instead of traditional MCSA using the motor stator current, in [13], analysis using the Zero Crossing Time (ZCT) signal of the stator current is presented.



(b)

Figure 3: Motor current spectrum of (a) healthy motor (b) motor with damaged rotor

C. Soft Computing Techniques

Soft computing is considered as an emerging approach to intelligent computing, which parallels the remarkable ability of the human mind to reason and learn in circumstances with uncertainty and imprecision. Qualitative information from practicing operators may play an important role in accurate and robust diagnosis of motor faults at early stages. Therefore, introduction of soft computing to this area can provide the unique features of adaptation, flexibility, and embedded linguistic knowledge over conventional schemes [15].

Kolla and Varatharasa [16] presented an Artificial Neural Network (ANN) based technique to identify faults in a three-phase induction motor. Three phase currents and voltages from the induction motor are used in the proposed approach. A feed forward layered neural network structure is used. The network is trained using the back propagation algorithm. On-line testing results on a 3 HP induction motor model show that the proposed ANN based method is effective in identifying various types of faults.

A neural approach was proposed in [19] to detect and locate automatically an inter turn short-circuit fault in the stator windings of the induction machine. The fault detection and location are achieved by a feed forward multilayer-perceptron neural network trained by back propagation. The location process is based on monitoring the three-phase shifts between the line current and the phase voltage of the machine.

Fuzzy logic is reminiscent of human thinking process and natural language enabling decisions to be made based on the vague information. In fuzzy logic, the fault condition of the motor are described using linguistic variables. Fuzzy subsets and corresponding membership functions describe the stator current amplitudes, negative sequence components of stator currents and the speed. A knowledge base comprising rules and data- base is built to support the fuzzy inference. The induction motor conditions are diagnosed using a compositional rule of fuzzy inference.

A useful and straight forward method was presented to simulate electrical faults such as under voltage fault, over load fault, unbalanced fault and earth faults. A method of using fuzzy logic to interpret stator current signal, speed and leakage current signals of induction motor for its electrical fault condition monitoring was also proposed[22]. A reliable method was presented for the detection of stator winding faults based on monitoring the line/terminal current amplitudes[43]. In this method, fuzzy logic is used to make decisions about the stator motor condition.

A possible drawback of the method is associated with the fact that a current unbalance originating from the supply source may be identified as a fault condition of the motor. But even this shortcoming can be overcome by monitoring the voltage and introducing new rules in the inference system.

Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between elements (Figure 4). ANN have been proposed and have demonstrated the capability of solving the motor monitoring and fault detection problem using an inexpensive, reliable, and noninvasive procedure[16-19].

The design of the neural networks based fault diagnosis comprises of the following four steps:

1. Preparation of a suitable training data set for the NNs
2. Selection of a suitable NNs Structure
3. Training of the NNs
4. Evaluation of the test pattern

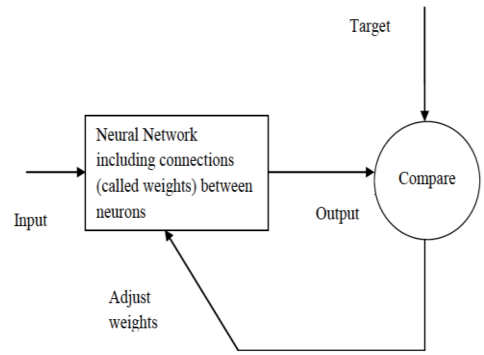


Figure 4: Functional block diagram of ANN

A PC based monitoring and fault identification scheme for a three-phase induction motor using ANNs was implemented and tested recently[17]. To accomplish the task, a hardware system was designed and built to acquire three phase voltages and currents from a 1/3 HP squirrel-cage, three-phase induction motor. JavaNNS software was used and the trained network was placed in a LabVIEWTM based program formula node that monitors the voltages and currents online and displays the fault conditions and turns the motor off.

An automatic algorithm based on unsupervised neural network for an on-line diagnostics of three-phase induction motor stator fault is presented in [18]. This algorithm uses the alfa-beta stator currents as input variables. Then, a fully automatic unsupervised method is applied in which a Hebbian-based unsupervised neural network is used to extract the principal components of the stator current data. These main directions are used to decide where the fault occurs and a relationship between the current components is calculated to verify the severity of the fault.

Combination like I.M Model and any signal processing method, model and soft computing method etc; are considered as hybrid approaches for the fault detection of induction motor. Most of the recent diagnostic techniques are based on this approach. The combination of advanced techniques reduces the learning time and increases the diagnosis accuracy.

The main problems facing the use of ANN are the selection of the best inputs and how to choose the ANN parameters making the structure compact, and creating highly accurate networks. Many input features require significant computational effort to calculate, and may result in a low success rate. To make operation faster, and also to increase the accuracy of the classification, a feature selection process using Genetic Algorithm(GA) is used to isolate those features providing the most significant features for the neural network, whilst cutting down the number of features required for the network.

In [25], an online fault diagnosis system is proposed for induction motors through the combination of discrete wavelet transform (DWT), feature extraction, GA, and ANN techniques. The DWT improves the signal-to-noise ratio during the pre-processing stage. Features are extracted from motor stator current, while reducing data transfers and making online application available. GA is used to select the most significant features from the whole feature database and optimize the ANN structure parameter. Optimized ANN is trained and tested by the selected features of the measurement data of stator current.

Each intelligent technique has its strengths and limitations. Efforts have been made to develop motor condition monitoring and fault diagnosis schemes based on combinations of intelligent techniques. Previous research results show that combining multiple approaches can result in better performance for many applications.

IV. SIMULATION OF FAULTS BY PARK'S VECTOR APPROACH

The simulations were conducted using MATLAB and simulink tool box. The dynamic modeling of an induction motor based on dynamic equations was done and several fault conditions in induction motor, such as one phase open condition, dip in supply voltage, and stator fault were simulated. At first, a healthy motor condition was simulated and later, the above mentioned faults were introduced and the corresponding waveforms and current park's vector patterns were obtained. Figure 5 shows the simulink model of a healthy motor.

The current Park's vector components (id; iq), as a function of mains phase variables (ia; ib; ic) are:

$$id = \sqrt{(2/3)}\, ia - (1/\sqrt{6})\, ib - (1/\sqrt{6})\, ic$$
$$iq = (1/\sqrt{2})\, ib - (1/\sqrt{(2)}\, ic$$

Under ideal conditions, balanced three phase currents lead to a park's vector that is a circular pattern centered at the origin of coordinates. In that case,

$$id = (\sqrt{6}/2)\, I \sin \omega t$$
$$iq = (\sqrt{6}/2)\, I \sin (\omega t - \pi/2)$$

where,
I = maximum value of the supply phase current;
ω_s = supply frequency;
t = time variable.

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.

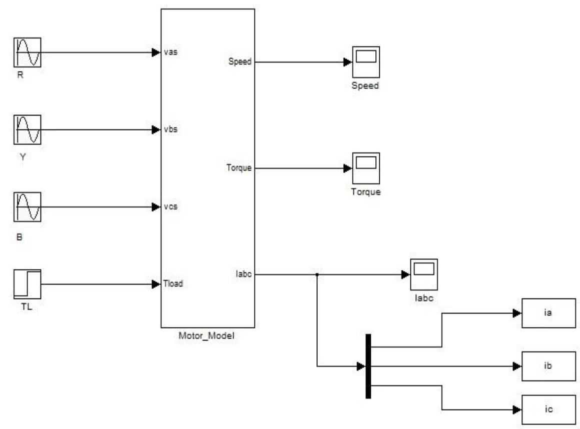


Figure 5: Model of a healthy motor

A. SIMULATION RESULTS

The induction motor model has been initially simulated, in the absence of faults, in order to determine the reference current park's vector pattern corresponding to the supposed healthy motor, as shown in Figure 6(a). This pattern differs slightly from the expected circular one, because the supply voltage is not exactly sinusoidal.

Afterward, three kinds of fault conditions were simulated, as mentioned in previous section. The current park's vector patterns corresponding to these faulty conditions are, respectively, shown by Figures 6(b), 6(c) and 6(d).

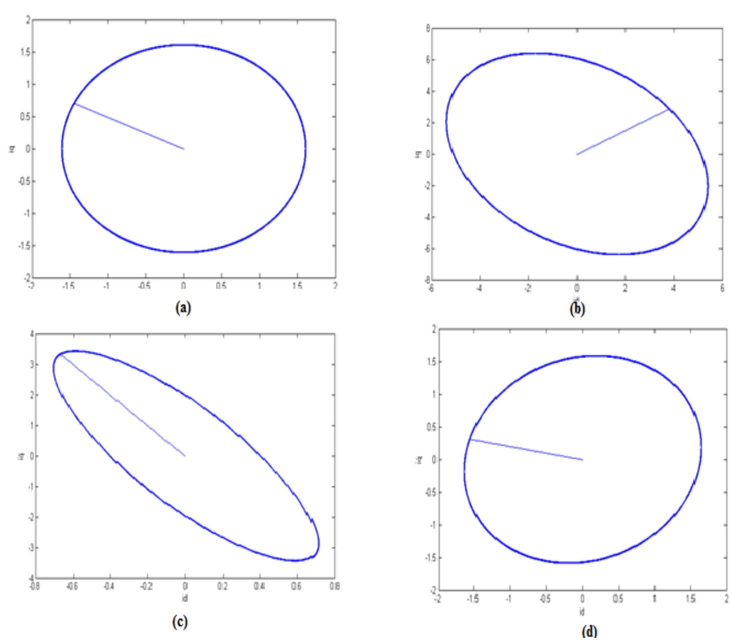


Figure 6: Current Park's Vector patterns for (a) healthy (b) one open phase (c) voltage dip (d) stator fault conditions

The occurrence of a voltage dip or an open phase manifests itself in the deformation of the current park's vector pattern corresponding to a healthy condition. This deformation leads to an elliptic pattern whose major axis orientation is associated to the faulty phase.

V. CONCLUSION

An efficient motor condition monitoring and fault diagnosis scheme is capable of providing warning and predicting the motor faults at early stages. Condition monitoring of the induction motor has attracted researchers in the past few years because of its influence on the safe operation of motor drive system in industrial processes. It is used for increasing motor availability and performance, reducing consequential damage, increasing motor life, reducing spare parts inventories, and reducing breakdown maintenance.

An ideal motor fault diagnosis system should take the minimum measurements necessary from a motor, and can give a clear indication of incipient fault modes in a minimum time. In recent years, the monitoring and fault diagnosis of motors have moved from traditional techniques to AI techniques. The main problem of traditional methods is that they need constant human interpretation. In order to automate the diagnostic process, AI techniques are used. However, the development of AI for induction motor fault diagnosis is still in its infancy and despite the considerable work that has been done in this area, much more is required to bring such techniques into the mainstream of fault diagnosis.

This work discusses the major faults in induction motor and different fault detection techniques. An attempt is made to review internal and external fault non-invasive detection methodologies considering recently utilized AI based, signal processing based and hybrid approaches. This also presents a methodology based on Park's vector approach by which induction motor's electrical faults can be diagnosed. As a future scope, the current park’s vector patterns obtained can be used to train artificial neural network for automatic fault diagnostic purposes.

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