Fuzzy logic based Fault Diagnosis in Induction Motor

Greety Jose, P.G Scholar
Dept.of Electrical&Electronics
Amal Jyothi College of Engineering
Kottayam,India
greetyjose@ymail.com

Victor Jose, Assistant Professor
Dept. of Electrical&Electronics
Amal Jyothi College of Engineering
Kottayam,India
victorjose@amaljyothi.ac.in

Abstract— Induction motors are one of the commonly used electrical machines in industry because of many 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. Different fault monitoring techniques for induction motors can be broadly categorized as model based, signal processing based 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 give good analysis of a faulty system even if accurate models are unavailable. These techniques are easy to extend and modify and also give improved performance. Here the different soft computing techniques for fault diagnosis are discussed. A methodology based on Park’s Vector approach employing Fuzzy logic and Adaptive Neuro-Fuzzy Inference System (ANFIS) is used to diagnose electrical faults. Different kinds of simulations are carried out corresponding to faults like stator voltage unbalance; stator open phase and stator short-circuit.

Keywords- Induction Motor, Soft Computing, Signal Processing, Park’s Vector, Fuzzy Logic, Adaptive Neuro-Fuzzy Inference System (ANFIS)

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, broken rotor bars, unbalanced stator and rotor parameters, 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, temperature, efficiency and vibrations. Thus, considering safety and economic factors, 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 effective 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 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 [13,14,15,16], fuzzy logic [19,20], adaptive neural fuzzy inference system and genetic algorithm [22] 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. The use of above techniques increases the precision and accuracy of monitoring systems.

Figure 1. The on-line condition monitoring process
Recent developments in diagnosis systems have led to the consideration of radically different diagnosis strategies by making extensive use of ANNs. They have numerous advantages over conventional diagnosis techniques. Generally, after proper tuning, they can improve the diagnosis performance. It is easy to extend and modify them and they can be easily adapted by the incorporation of new data as they became available. Moreover, their design does not require a complete mathematical model of the induction motor.

II. 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, correct models of the faulty machines are necessary for achieving a good fault diagnosis. Sometimes it will be difficult to obtain accurate models of the faulty machines and also to make use of model based techniques. Soft computing techniques give good analysis of a faulty system even if accurate models are unavailable. Bazine et al.[8] proposed a diagnosis method for on-line inter-turns short-circuit windings and broken bars detection by parameters estimation.

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[7].

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 2(a) and 2(b) show the current spectrum of a healthy motor and a motor with damaged rotor respectively. Instead of traditional MCSA which uses the motor stator current, in [11], analysis using the Zero Crossing Time (ZCT) signal of the stator current is presented.

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. Thus, introduction of soft computing to this area can provide the unique features of flexibility, adaptation and embedded linguistic knowledge over conventional schemes [12].

III. SOFT COMPUTING METHODS

Soft computing techniques are employed to assist the diagnostic task to correctly interpret the fault data. To automate the diagnostic process, a number of soft computing diagnostic techniques such as artificial neural network, fuzzy logic, adaptive neural fuzzy inference system, genetic algorithm etc have been proposed.
A. Fuzzy Logic

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.

A 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[19]. A reliable method was presented for the detection of stator winding faults based on monitoring the line current amplitudes[20]. 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. It can be overcome by monitoring the voltage and introducing new rules in the inference system.

B. Artificial Neural Network (ANN)

Neural networks (NNs) are composed of simple elements which operate in parallel. These elements are inspired by the biological nervous systems. The network function is determined by the connections between elements. The NN can be trained to perform a particular function by adjusting the values of the weights between elements (Figure 3). 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[13-16].

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

Kolla and Varatharasa [13] 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. In [14], a PC based monitoring and fault identification scheme for a three-phase induction motor using ANNs was implemented and tested.

An automatic algorithm based on unsupervised neural network for an on-line diagnostics of three-phase induction motor stator fault is presented in [15]. This algorithm uses the alfa-beta stator currents as input variables. 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.

An neural approach was proposed in [16] to detect and locate automatically an inter turn short-circuit fault in the stator windings of the induction machine. The fault detection is achieved by a feed forward multilayer-perceptron neural network trained by back propagation algorithm. The location process is based on monitoring the three-phase shifts between the line current and the phase voltage of the machine.

C. Hybrid Approaches

Combination like Induction motor 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 [22], 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. GA is used to select the most important features from the whole feature database and optimize the ANN structure parameter. The 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.

Parameters of the induction motor modeled mathematically are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance</td>
<td>rs=6.03 Ω</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>rr=6.085 Ω</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>Ls=489.3 mH</td>
</tr>
<tr>
<td>Rotor inductance</td>
<td>Lr=489.3 mH</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>Lm=450.3 mH</td>
</tr>
<tr>
<td>Pole pair</td>
<td>P=2</td>
</tr>
<tr>
<td>Inertia</td>
<td>J=0.00488</td>
</tr>
<tr>
<td>Frequency</td>
<td>f=50 Hz</td>
</tr>
<tr>
<td>Phase peak voltage</td>
<td>V=220*sqrt(2/3)</td>
</tr>
</tbody>
</table>

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 4 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:

\[
\begin{align*}
    id &= \sqrt{3/2} \, ia - (1/\sqrt{6}) \, ib - (1/\sqrt{6}) \, ic \\
    iq &= (1/\sqrt{2}) \, ib - (1/\sqrt{2}) \, ic
\end{align*}
\]  

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 condition,

\[
\begin{align*}
    id &= (\sqrt{6}/2) \, I \sin \omega t \\
    iq &= (\sqrt{6}/2) \, I \sin (\omega t - \pi/2)
\end{align*}
\]

where,

- I = maximum value of the supply phase current;
- \(\omega_s\) = supply frequency;
- t = time variable.

Thus, by monitoring the deviation of current Park's Vector, it is possible to predict the motor condition and the presence of a fault can be detected.

![Figure 4: Model of a healthy motor](image)

![Figure 5: Current Park’s Vector patterns for (a) healthy (b) one open phase (c) voltage dip (d) stator fault conditions](image)
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 5(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 5(b), 5(c) and 5(d).

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.

V. FUZZY LOGIC BASED FAULT DIAGNOSIS

In the proposed method using fuzzy logic, the stator current Park’s Vector patterns of healthy machine and faulty machine under different operating conditions are utilized. The errors of stator current Park’s Vector patterns are taken as input variables. The inputs e1 and e2 are defined as:

\[ e_1(k) = P_h(k) - P_f(k) \]  \hspace{1cm} (5)

\[ e_2(k) = e_1(k) - e_1(k-1) \]  \hspace{1cm} (6)

where,

\( P_h(k) \) = Park’s Vector pattern of healthy machine

\( P_f(k) \) = Park’s Vector pattern of faulty machine

The input membership function values are Negative(N), Zero(Z) and Positive(P). According to fuzzy if-then rules, the possible output states are Low(L), Medium(M) and High(H) representing the fault severity. Simulation results obtained were satisfactory and are tabulated as follows:

<table>
<thead>
<tr>
<th>Input1(e1)</th>
<th>Input2(e2)</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
<td>M</td>
</tr>
<tr>
<td>Z</td>
<td>N</td>
<td>L</td>
</tr>
<tr>
<td>P</td>
<td>N</td>
<td>M</td>
</tr>
<tr>
<td>N</td>
<td>Z</td>
<td>H</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>Z</td>
<td>M</td>
</tr>
<tr>
<td>N</td>
<td>P</td>
<td>H</td>
</tr>
<tr>
<td>Z</td>
<td>P</td>
<td>L</td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>H</td>
</tr>
</tbody>
</table>

Table 1: The Fuzzy if-then Rules

Figure 6 shows the simulink model of fuzzy logic based fault diagnosis scheme for induction motor. Figures 7 and 8 represent the membership function values of input and output variables respectively. The fuzzy if-then rules are formulated as shown in Table 1.

Figure 6: Simulink model of Fuzzy Logic based Fault Detection Scheme

Figure 7: The membership function of input variables

Figure 8: The membership function of output variable

The input membership function values are Negative(N), Zero(Z) and Positive(P). According to fuzzy if-then rules, the possible output states are Low(L), Medium(M) and High(H) representing the fault severity. Simulation results obtained were satisfactory and are tabulated as follows:
The Table 2 indicates that fault severity is more for one phase open condition and least for stator fault condition. Fuzzy logic-based motor fault diagnosis methods have the advantages of embedded linguistic knowledge and approximate reasoning capability. However, the design of such a system heavily depends on the intuitive experience acquired from practicing operators.

The fuzzy membership functions and fuzzy rules cannot be guaranteed to be optimal in any sense. Furthermore, fuzzy logic systems lack the ability of self-learning, which is compulsory in some highly demanding real-time fault diagnosis cases. The above drawbacks can be partly overcome by the fusion of neural networks and fuzzy logic–neural-fuzzy technique. Thus, an Adaptive Neuro-Fuzzy (ANFIS) based fault diagnosis scheme was developed.

In ANFIS, fuzzy membership functions and fuzzy rules are obtained automatically from the training data instead of by trial and error. It also speeds up the initial design procedure. After obtaining the training data from fuzzy based system, an ANFIS based diagnosis scheme is developed using ANFIS editor toolbox in Simulink. The comparison of obtained results are tabulated in Table 3:

Table 2: Simulation Results using Fuzzy Logic

<table>
<thead>
<tr>
<th>Condition</th>
<th>Input1(e1)</th>
<th>Input2(e2)</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
<td>0</td>
<td>0</td>
<td>0.08018</td>
</tr>
<tr>
<td>Voltage Dip</td>
<td>-0.1467</td>
<td>0.2942</td>
<td>0.4038</td>
</tr>
<tr>
<td>One Phase Open</td>
<td>-0.2666</td>
<td>0.2686</td>
<td>0.4758</td>
</tr>
<tr>
<td>Stator fault</td>
<td>-0.005283</td>
<td>-0.04442</td>
<td>0.1199</td>
</tr>
</tbody>
</table>

The above results prove that fault severity is more for stator fault and least for voltage dip. Comparing the outputs corresponding to fuzzy and ANFIS based system, it can be seen that the results are approximately equal in all the operating conditions considered.

VI. REFERENCES


VI. 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 Artificial Intelligence (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 field, 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 employing Fuzzy logic and Adaptive Neuro-Fuzzy Inference System by which electrical faults in induction motor can be diagnosed. Simulation results obtained are satisfactory and show the effectiveness of proposed methods. As a future scope, hybrid approaches can be employed to obtain better performance.


**Greety Jose.** Received B Tech in Electrical and Electronics Engineering from Rajagiri School of Engineering and Technology, Kochi in 2011 and pursuing M Tech in Power Electronics and Power System from Amal Jyothi College of Engineering Kanjirapally, Kerala. Her research interests include Electric Drives and Control, Soft Computing Techniques and Power System.

**Victor Jose.** Received B Tech in Electrical and Electronics Engineering from Mar Athanasius College of Engineering, Kerala in 2005 and M Tech in Energy Systems from Indian Institute of Technology, Bombay. He is now working as Assistant Professor in Electrical and Electronics Engineering Department of Amal Jyothi College of Engineering, Kanjirapally His research interests include Renewable Energy Resources, Electric Motors and Energy Conservation and Management.