A FUZZY LOGIC APPROACH TO DIAGNOSE INDUCTION MOTOR FAULTS IN REMOTE SITE BY CELL PHONE

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Monitoring, fault detection, and diagnosis of electric induction motors are becoming increasingly important in the field of electrical machines as new data-processing techniques and methods for analyzing the motor stator current. Special attention has been devoted to noninvasive methods capable of detecting faults using measured data without requiring motor disassembly and its structural parts. Some enterprises such as Mining, Petroleum and Water and Sewage Treatment process uses induction motor of large power flow, what are installed at remote sites. The electrical and mechanical failures of such motors often disrupt productivity and require maintenance. Currently the containment of maintenance costs, these remote sites work without the presence of a service technician. A fuzzy logic approach may help to diagnose induction motor faults at these sites and to transmit the fault diagnosis (via 3G technology) to maintenance central or a cell phone programmed. The contribution of this paper is the use of fuzzy logic for the automated practical detection of broken bars in induction motors in remote locations without the presence of an experienced technician.

1. Introduction

Induction motors with squirrel-cage type rotors are rugged, reliable, and cheap. Therefore, they are widely used in industrial and manufacturing processes. However, the electrical and mechanical failures of such motors often disrupt productivity and require maintenance, thus presenting special challenges in production. In the literature, rotor and stator faults have been shown to account for a large proportion of industrial induction motor failures, occasionally being a major cause of failure in the field. Although an induction motor is highly symmetrical, it may still have a detectable signal component at the fault frequencies due to imperfect manufacture, improper motor installation and so an. Further, manufacture tolerance and working environment could also result in disturbing the motor fault diagnosis. Preventive measures should be periodically taken in order to protect motors and systems including motors. This is the most efficient way to keep motor operating continuously in healthy conditions [1-3].

2. Online Motor Condition Monitoring by MCSA Instrument

A crucial point about motor current signature analysis (MCSA) is that it is sensing an electrical signal that contains current components that are a direct by-product of unique rotating flux components caused by faults such as broken rotor bars, air gap eccentricity, and shorted turns in low voltage stator windings, etc. MCSA instrument can detect these problems at an early stage and thus avoid secondary damage and complete failure of the motor [2]. A typical online condition monitoring system by MCSA instrument is shown in Figure 1.

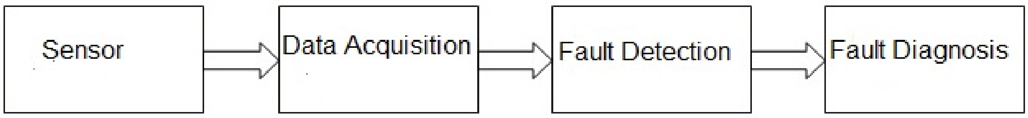

Figure 1. The online condition monitoring by MCSA instrument.

The sensor block measures physical quantities of the device and convert into an electrical response in the time domain. There are several kinds of sensors that are used in MCSA instruments. For example, current sensor, Hall Effect sensor, flux sensor, accelerometer, etc. The function of data acquisition block is sampling, amplification and converting in analogue to digital of the physical signal from sensors. The purpose of fault detection block is finding out the incipient fault appearing in the induction motor through processing the acquired data. This block utilizes a FFT algorithm to the representation of signal acquired in the frequency domain. The fault diagnosis block includes two different methods: (i) feature extraction; (ii); model-referenced.

3. Feature Extraction Methods

If there is only a forward rotating field at slip frequency relative to the rotor, the cage winding is symmetrical. Where rotor asymmetry occurs, then there will be a resultant backward rotating field at slip frequency relative to the forward rotating rotor. The result of this is that, relative to the stationary stator winding, this backward rotating field at slip frequency relative to the rotor induces a voltage and current in the stator winding at frequency given by Equation 1 [3]. This is referred to as a twice slip frequency sideband due to broken rotor bars. Where s is the motor slip and f_0 is the frequency of the power grid to which the motor is connected.

(1) $$f_{bb} = (1-2s)\,f_0\,\text{Hz.}$$

There is therefore a cyclic variation of current that causes a torque pulsation at twice slip frequency ($2sf_0$) and a corresponding speed oscillation that is also a function of the drive inertia. This speed oscillation can reduce the magnitude of the $(1-2s)\,f_0$ sideband, but an upper sideband current component at $(1+2s)\,f_0$ is induced in the stator winding due to the rotor oscillation [3]. This upper sideband is also enhanced by the third time harmonic flux. Broken rotor bars therefore result in current components being induced in the stator winding at frequencies given by Equation 2.

(2) $$f_{bb} = (1\pm 2s)\,f_0\,\text{Hz.}$$

3.1 Experimental Setup

To demonstrate the application of the feature extraction method, we performed an analysis of different signals collected from rotor broken bars, which were forced in the laboratory by opening the motor and drilling holes in different bars (Fig. 2a). For validating the feature extraction method that uses MCSA instrument, several tests were performed with a 4-pole, 3-phase, 60 Hz, 1.5 kW, 220/380 V (rated voltage), 1750 rpm (rated speed), and 28-rotor-bar induction motor. Figure 2b shows the experimental setup. The load was a 2 kW DC machine with a rated speed of 1800 rpm.

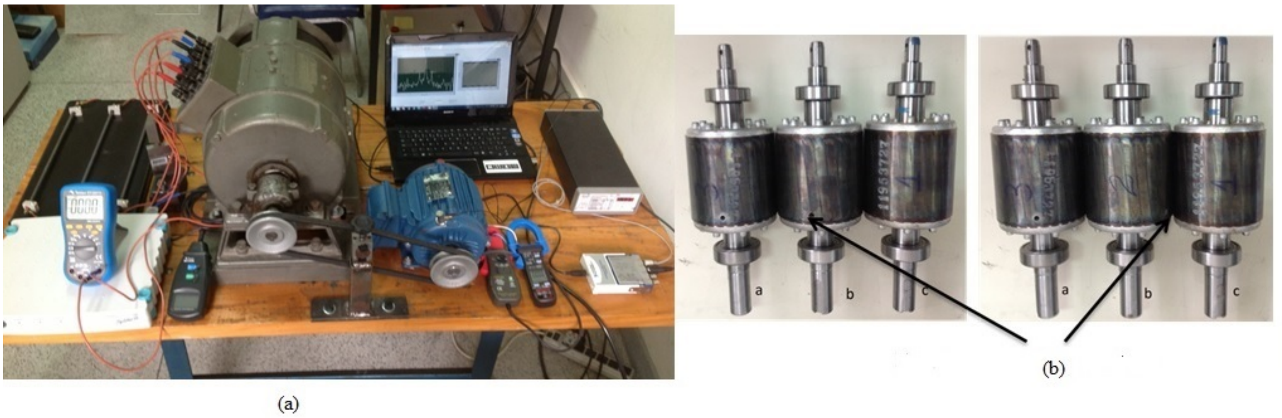

Figure 2. View of the experimental setup (a). Rotor broken bars forced (b).

3.2 Spectrum of Stator Current

To verify the efficiency of the feature extraction method, we carried out several tests under different loads for healthy rotors and faulty rotors with broken bars. In each case, the stator current was transformed to the frequency domain and analyzed by the MCSA instrument. Then, the amplitudes of the two fault frequency components Af_{bbl} (frequency broken bars left) and Af_{bbl} (frequency broken bars right) are analyzed and extracted. The results are summarized and shown. Fig. 3a shows spectrum of stator current for healthy motor at 95% of the rated load. The amplitude of Af_{bbl} is lower -55 dB relative the amplitude of the fundamental frequency (60 Hz).

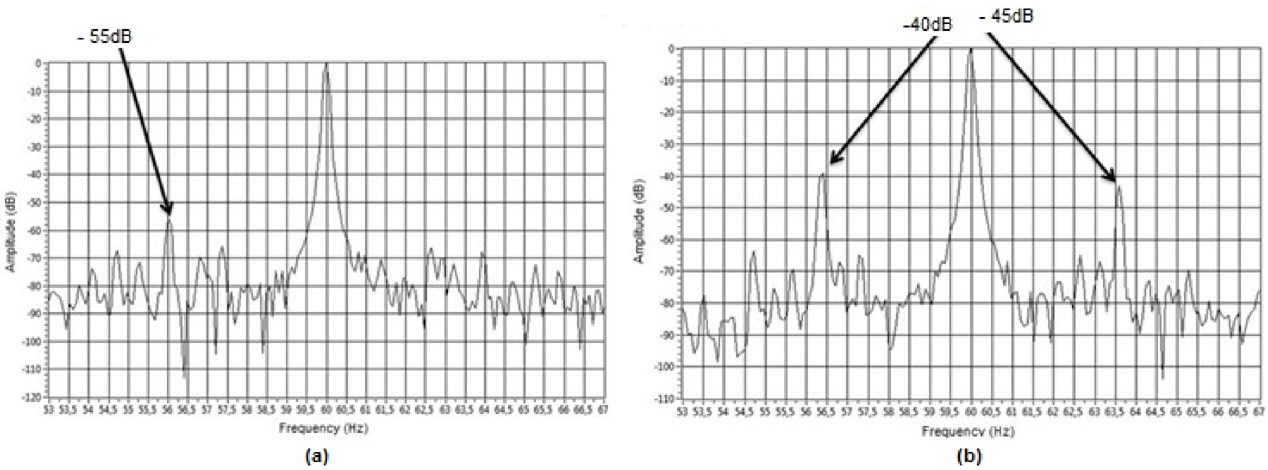

Figure 3. Current spectrum: loaded healthy motor (a). Loaded motor with one broken bar (b).

Fig. 3b shows spectrum of stator current for one broken bar at 95% of the rated load. The amplitude Af_{bbl} is lower – 40 dB relative the amplitude of the fundamental frequency and the amplitude Af_{bbr} is lower - 45 dB. A Fig. 4 shows spectrum of stator current for two broken bar at 95% of the rated load. The amplitude Af_{bbl} is lower -35 dB relative the amplitude of the fundamental frequency and the amplitude Af_{bbr} is lower - 40 dB.

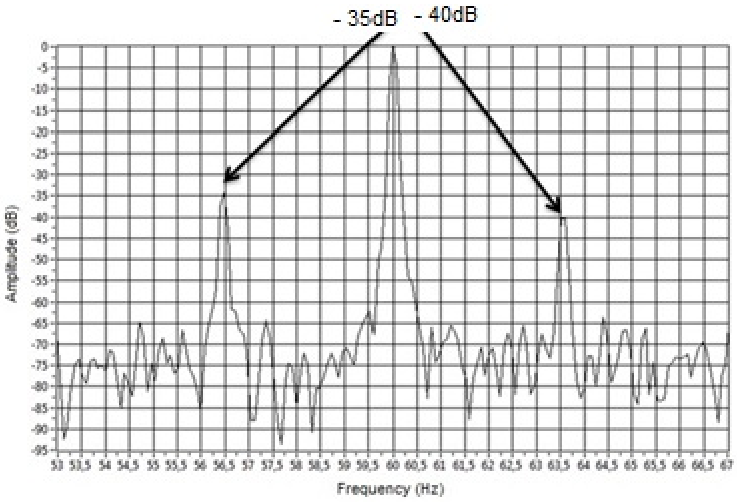

Figure 4. Current spectrum: loaded motor with two broken bar**.**

4. Fuzzy Controller Method for Diagnosis and Decision

The purpose of the fuzzy controller method is shown in Figure 5, through the block diagram of the system. The first step is acquiring data, i.e., collecting motor parameters that may be relevant in the search for information on the motor status. Herein, in particular, the stator current and the motor shaft speed will be collected from a current sensor and a motor shaft rotation sensor.

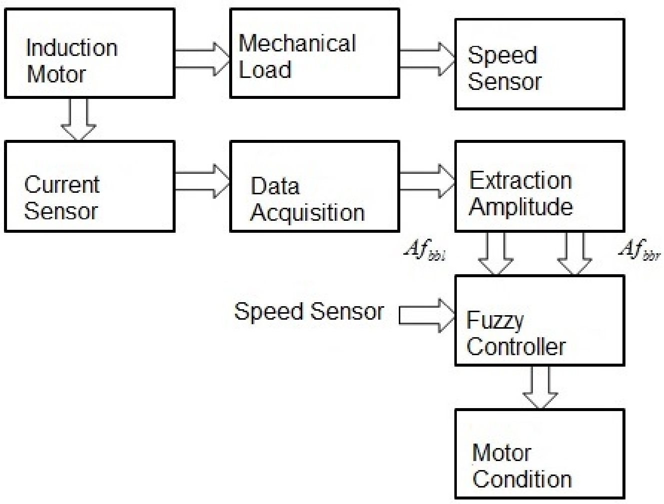

Figure 5. Block diagram of fuzzy controller method.

After collecting the data, the current signal is pre-processed, i.e., by means of the fast Fourier transform (FFT), the signal frequency spectrum is obtained to get frequencies of side failure of broken bars $(1 \pm 2s)\, f_0$. After obtaining the two side failure frequencies, their magnitudes will be extracted by means of an algorithm: Af_{bbl} (Magnitude of left broken bars frequency) and Af_{bbr} (Magnitude of broken bars right frequency).The third step, called fuzzy controller, refers to the use of Fuzzy logic techniques, which can automatically provide failure diagnosis without requiring a specialist technician.

4.1 Fuzzification (Membership Function)

Fuzzification is the mapping of the real numbers domain of (discrete in general) for the Fuzzy domain, defined by relevancy functions to the input variables [4, 5, 7, and 8]. It is a type of pre-processing of categories or classes of the input signals, thereby reducing the number of values to be processed. The input variables $Afbbl$ and $Afbbr$, in the domain of real numbers, have their values expressed in dB normalized from 0 to 1, 0 being equivalent to −100 dB and 1 being equivalent to 0 dB. This allows for these variables to be fuzzified from any motor. The *speed* variable in the real numbers domain has its values expressed in normalized rpm from 0 to 1, 0 being equivalent to 1740 rpm and 1 being equivalent to 1790 rpm. For each variable, three relevancy functions are stipulated, denominated *Small*, *Medium*, and *Big*. The *Medium* function refers to the nominal values of the input variables, where the values 0.50 (−50 dB) to 0.65 (−35 dB) indicate the motor relevancy value with one to two broken bars. The *Small* function outlines the values considered for a *healthy* motor, where values equal to or smaller than 0.45 (−55 dB) point to a maximum relevancy value. Similarly, the *Big* function depicts the motor values with defects of three or more broken bars, where values equal to or greater than 0.70 (−30 dB) point to a maximum relevancy value. The following characteristics are common to the three variables: Magnitude of the left side failure frequency (Af_{bbl}), Magnitude of the right side failure frequency (Af_{bbr}), and motor speed.

4.2 Base of Rules

An important part of a failure diagnosis system by Fuzzy logic is constructing the base of rules [4, 5, 7, and 8]. The knowledge acquisition begins with the transfer of knowledge of the motor rotor conditions for the rule base. Based on feature extraction method (experimental setup), a set of 10 rules was prepared, which composes the Fuzzy inference system. For the input variables, the letters S (Small), M (Medium), and B (Big) previously defined were used. As RCs (Rotor Condition), *Healthy*, *Severe Defect*, and *Defect* were used. As many rules are redundant, and moreover, it is sufficient for one of the lateral failures to be *Big* (B) or *Medium* (M) for the rotor condition to be *Severe Defect* or *Defect* respectively, the table may have the number of rules reduced to 10.

1. If (Af_{bbr}) is Small) and (Af_{bbl}) is Small) and ($Speed$ is Small), then (Motor-Condition is Health);
2. If (Af_{bbr}) is Small) and (Af_{bbl}) is Small) and ($Speed$ is Medium), then (Motor-Condition is Health);
3. If (Af_{bbr}) is Medium) and ($Speed$ is Small), then (Motor-Condition is Defect);
4. If (Af_{bbr}) is Medium) and ($Speed$ is Medium), then (Motor-Condition is Defect);
5. If (Af_{bbr}) is Big) and ($Speed$ is Small), then (Motor-Condition is SevereDefect);
6. If (Af_{bbr}) is Big) and ($Speed$ is Medium), then (Motor-Condition is SevereDefect);
7. If (Af_{bbl}) is Medium) and ($Speed$ is Small), then (Motor-Condition is Defect);
8. If (Af_{bbl}) is Medium) and ($Speed$ is Medium), then (Motor-Condition is Defect);
9. If (Af_{bbl}) is Big) and ($Speed$ is Small), then (Motor-Condition is SevereDefect);
10. If (Af_{bbl}) is Big) and ($Speed$ is Medium), then (Motor-Condition is SevereDefect).

4.3 Desfuzzification

In desfuzzification, the value of the output linguistic variable inferred by the Fuzzy rules will be translated into a discrete value. The objective is to obtain a single discrete numerical value that best represents the inferred Fuzzy values of the output linguistic variable, i.e., the distribution possibilities [4]. Thus, desfuzzification is an inverse transformation that translates the output of the Fuzzy domain to the discrete domain. Figure 6a shows the functions assigned to the output variables and Fig. 6(b) presents the relevancy function graph common to the three input variables.

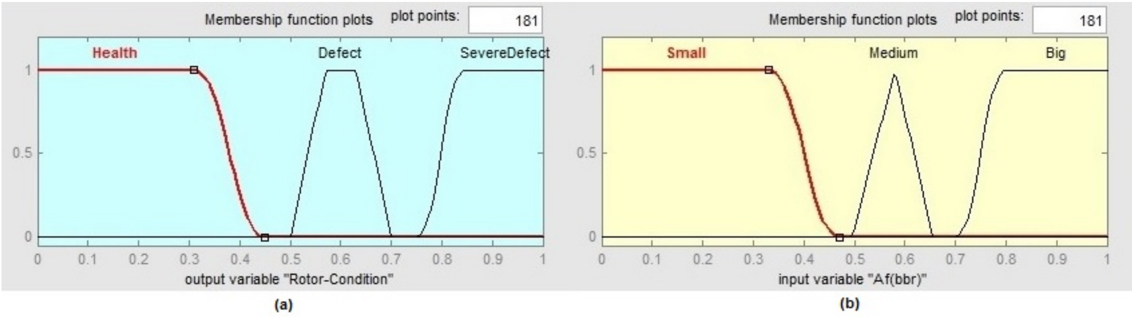

Figure 6.The Membership functions for outputs (a). The membership function for inputs (b)

There are three membership functions: Healthy, Defect, and Severe Defect. Table 1 describes the output range for these variables.

Table 1. Range of outputs variables.

Range	Rotor Condition	Nº of Broken Bars
$0 \leq output \leq 0.47$	Health (H)	0
$0.5 \leq output \leq 0.7$	Defect	1 - 2
$0.75 \leq output \leq 1$	Severe Defect	3 or more

5. Embedded System in Hardware FPGA

The hardware model of fuzzy controller was subsequently synthesized and implemented in a Field Programmable Gate Array (FPGA) chip [6, 7 and 8]. The embedded system used in the test bench is based on a controller, NI sbRIO 9602 from National Instruments. The controller architecture, includes a floating point processor running at 400 MHz, real-time operating system (RTOS), high-performance FPGA Xilinx, interface 10\100 Base T Ethernet. NI sbRIO 9602 is programmed using (i) PC LabVIEW; (ii) LabVIEW Real-Time; and (iii) LabVIEW FPGA. It runs applications (deterministically) developed with the LabVIEW Real-Time software and the FPGA executes simultaneously applications developed with the LabVIEW FPGA software. The development of the fuzzy controller diagnosis system warranted the development of three (VIs) programs. Two programs were developed in LabVIEW Real-Time and LabVIEW FPGA, running directly on CompactRIO. The other program was developed in LabVIEW PC, running on a personal computer (Host PC). The program (VI) in the host PC communicates with the LabVIEW Real-Time program through shared variables via the TCP/IP protocol. For data transfer between the LabVIEW FPGA and LabVIEW Real-Time programs, I/O Variables are used.

5.1 GSM/GPRS Cellular Network

General Packet Radio Services (GPRS) is a packet -based wireless communication service that promises data rates from 56 up to 114 Kbps and continuous connection to the Internet for mobile phone and computer users. GPRS is based on Global System for Mobile (GSM) communication and complements existing services such circuit-switched cellular phone connections and the Short Message Service (SMS). GSM can be applied for tele-monitoring applications, where high mobility and low cost are necessary [9]. The Fuzzy controller via GSM \ GPRS cellular network consists of four elements: NIsbRIO card (Fuzzy Controller), application interface (communication software), communication base (Remote GSM provider) and GSM Modem. The Fuzzy controller monitors and makes the diagnosis of the induction motor conditions (healthy, defect, severe defect) on the remote site, and transmits the overall result, via communication network, to the central computer maintenance or a programmed cell phone.

6. Experimental Fuzzy Controller System Results

To verify the efficiency of the fuzzy controller system, several tests were performed via GSM network. These tests were performed under different loads and motor condition: healthy rotor, one broken bar and two broken bars. Table 2 presents the results of the diagnosis of a Healthy motor (value normalized and real) with low load, half load, and full load. The result with a single discrete numeric value normalized equal to 0.22, which indicates the rotor condition Healthy.

Table 2. Diagnostic results of Healthy.

Load	Af_{bbl}	Af_{bbr}	*Speed*	*Motor Condition*
Low	0.46 -55.54 dB	0.30 -70 dB	0.50 1769 rpm	0.22 Healthy
Half	0.46 -54.55 dB	0.30 -70 dB	0.50 1752 rpm	0.22 Healthy
Full	0.46 -54.11 dB	0.30 -58.91 dB	0.50 1769 rpm	0.22 Healthy

Table 3 shows the results of the diagnosis of a Defect motor (1 broken bar) with low load, half load, and full load. The result with a single discrete numeric value normalized equal to 0.6, which indicates the rotor condition Defect (1 broken bar).

Table 3. Diagnostic results of 1 broken bar.

Load	Af_{bbl}	Af_{bbr}	*Speed*	*Motor Condition*
Low	0.60 -40.37 dB	0.57 -43.50 dB	0.20 1745 rpm	0.6 Defect
Half	0.61 -40.50 dB	0.57 -43.64 dB	0.45 1760 rpm	0.6 Defect
Full	0.55 -44.73 dB	0.55 -45.29 dB	0.60 1774 rpm	0.6 Defect

Table 4 shows the results of the diagnosis of a Defect motor (2 broken bars) with low load, half load, and full load. The result with a single discrete numeric value normalized, equal to 0.6, which indicates the rotor condition Defect (2 broken bars).

Table 4. Diagnostic results of 2 broken bar.

Load	Af_{bbl}	Af_{bbr}	*Speed*	*Motor Condition*
Low	0.63 -37.34 dB	0.60 -40.45 dB	0.20 1746 rpm	0.6 Defect
Half	0.65 -35.50 dB	0.57 -42.84 dB	0.45 1760 rpm	0.6 Defect
Full	0.59 -41.30 dB	0.59 -41.25 dB	0.60 1776 rpm	0.6 Defect

7. Conclusion

In this paper, a real time condition monitoring device based on fuzzy controller was developed and tested. The target controller based on FPGA and GSM network is capable of measuring non-invasive sensor signals and is capable of analyzing them for extraction of rotor and stator problems in induction motors installed in remote sites. A diagnosis method using fuzzy logic to determine the state condition of induction motors was presented. In order to make an efficient diagnostic the amplitudes frequency (broken bars left and right) components of the spectrum stator current and speed motor are intended as input to the fuzzy controller system which converted to variables linguistic fuzzy subsets and their corresponding membership functions. The output of this system represents the motor conditions. The fuzzy controller system monitors and makes the diagnosis of the induction motors conditions on the remote-site and transmits de overall results, via GSM network, to the central computer of maintenance officer or a programmed cell phone. This results obtained with this system are good and is capable to detect the motor and stator problems in industrial induction motor installed in remote sites.

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