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Induction Motor Electrical Fault Diagnosis by a Fundamental Frequency Amplitude using Fuzzy Inference System

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Abstract:

For reliability, availability, safety and cost efficiency in modern machinery, accurate fault diagnosis is becoming of paramount importance so that potential failures can be better managed. This paper presents an optimized induction motor fault identification system using fuzzy logic technique based on vibration signal analysis to investigate the type of AC induction motor failure using MATLAB Simulink. This is accomplished by getting a spectrum values, motor frequencies, and their amplitudes by making a code for each. These are linked to fuzzy inference system for five types of induction motor faults individually to recognize the fault. Fuzzy inference system contains input variables. This is represented by fault frequency features and sidebands in axial, vertical, and horizontal directions, membership function, rules of each fault, and the corresponding output variables. The system is tested by applying a fault simulation with one or more faults.

Keywords –*Fuzzy logic, fault diagnosis, vibration analysis, and induction motor faults.*

I. INTRODUCTION

All machines with moving parts give rise to sound and vibration. Each machine has a specific vibration signature related to its construction and its state. If the state of the machine is changed, the vibration signature will also change. Nowadays, the change in the vibration signature is used to detect incipient defects before they become critical. This is the basics of many condition monitoring methods. Condition monitoring can save money through increased maintenance efficiency as it reduces the risk of serious accidents due to breakdowns. Fuzzy logic-based fault diagnosis methods have the advantages of embedded linguistic knowledge and approximate reasoning capability. Zadeh (1973) proposed the fuzzy logic technique [1]; it performs well at qualitative description of knowledge. However, the design of such a system depends heavily on the intuitive experience acquired from practicing operators which results in identifying diagnosed faults. The fuzzy membership function and fuzzy rules cannot be guaranteed to be optimal in any case. Furthermore, fuzzy logic systems lack the ability of self-learning, which is compulsory in some highly demanding real-time fault diagnosis cases.Li, and Chow (1998) discussed motor bearing fault diagnosis based fuzzy decision system [2]. Zeraouliaet et. al. (2005) presented a method of using fuzzy logic to interpret current sensors signal of induction motor for its stator condition monitoring [3]. Liu, Ma and Mathew (2006) presented a feature level multi-parameter fuzzy integral data fusion method for machinery fault diagnosis [4]. El-Shafei et. al. (2007) investigated the application of neural networks and fuzzy logic to the diagnosis of faults in rotating machinery [5]. Iorgulescu and Beloiu (2008) evaluated the motor condition by performing a Fast Fourier Transform (FFT) of the induction motor vibration [6]. Kumar, Kumar and Ray (2009) discussed fault analysis on an induction motor using both experiments and simulation. They studied failure identification techniques applied for condition monitoring of the motor. They designed an On-line condition monitoring system with fuzzy logic controller using LabView [7]. Kumar, Kumar, and Praveena (2010) processed current signals and incorporated them within fuzzy decision system achieved high diagnosis accuracy [9]. Do and Chong (2011) presented signal model-based fault detection and diagnosis for induction motors using features of vibration signal in two- dimension domain [8]. Laala, Guedidi and Zouzou (2011) presented a novel approach for diagnosis and detection of broken bar in induction motor at low slip using fuzzy logic [10]. Bhardwaj and Agarawal (2012) performed fault analysis of three phase induction motor using MATLAB, and studied the failure identification techniques applied for condition monitoring of the motor. They designed an on-line condition monitoring system with fuzzy logic controller using current analysis [11]. Pandey and Choudhary (2013) discussed a method using fuzzy logic to interpret current signal of induction motor as a tool of monitoring stator condition [12]. S. Shukla, ManojJha and Qureshi (2014) presented implementation of broken rotor bar fault detection in an induction motor using motor current signal analysis (MCSA) and prognosis with interval type-2 fuzzy logic [13]. Nasiri and Hosseini proposed Wavelet Packet Transform as a proper method for detection of any fault occurs in three-phase induction motor such as mixed eccentricity using fuzzy logic [14].

II. FUNDAMENTAL MOTOR VIBRATION FEATURES

Vibrations of electrical machines such as motors, generators and alternators can be either mechanical or electrical in nature. Electrical problems also appear in the vibration spectrum and can provide information about the nature of the defects. Electrical problems occur due to unequal magnetic forces acting on the rotor or the stator. These unequal magnetic forces may be due to [15]:

- Stator Eccentricity, Shorted Laminations and Loose Iron
- Eccentric Rotor (Variable Air Gap)
- Rotor Problems (Broken or Cracked Rotor Bars or Shorting Rings, Shorted Rotor Laminations, Loose Rotor Bars, etc.)
- Electrical phasing problems due to loose or broken connectors

Understanding the nature of these vibrations can assist in identifying the exact defects in an electrical machine. The following are some terms that will be required to understand vibrations due to electrical problems [15]:

F_L = Electrical Line Frequency
(50 or 60 Hz, depending on electrical grid frequency)

$$N_S = (120\ F_L)/P \qquad (1)$$

Where:

N_s = Synchronous Speed with no Slip (RPM)
P = Number of Poles

$$F_S = (N_S \times N)/60 \qquad (2)$$

Where:
N = motor speed (RPM)
F_S = Slip Frequency (Hz)

$$F_P = \text{Poles No.} \times F_S \qquad (3)$$

Where:
F_P = Pole Pass Frequency (a key sideband frequency which will signal the presence of many electrical problems).

$$\text{RBPF} = \text{Bars No.} \times N \qquad (4)$$

Where:

RBPF = Rotor Bar Pass Frequency

A. Stator Problems

This generates a 2X Line frequency ($2F_L$) also known as *loose iron* (Fig. 1). Shorted stator laminations cause uneven and localized heating, which can significantly grow with time [15], [16].

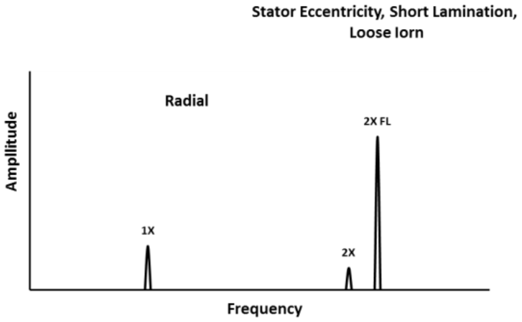


Fig.1Spectrum with a stator defect

B. Eccentric Rotor

An eccentric rotor most often produces a high vibration at twice line frequency $2F_L$ accompanied with sidebands spaced at pole pass frequencies as well as F_P sidebands around 1X rpm [15], [16],[17]. The pole-pass frequency F_P itself appears at a low frequency (Fig. 2).

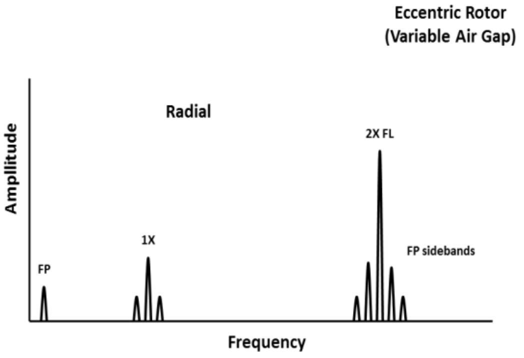


Fig.2 Eccentric rotor

C. Rotor problems

Broken or cracked rotor bars or short rings, bad joints between rotor bars and short rings, or shorted rotor laminations will produce high 1X running speed vibration with pole pass frequency sidebands (F_P) [15]. In addition, cracked rotor bars often will generate F_P sidebands around the third, fourth, and fifth running speed harmonics (Fig. 3). Loose rotor bars are indicated by 2X line frequency

($2F_L$) sidebands surrounding rotor bar pass frequency (RBPF) and/or its harmonics [16]. Often will causehigh levels at 2X RBPF, with only a small amplitude at 1X RBPF (Fig. 4).

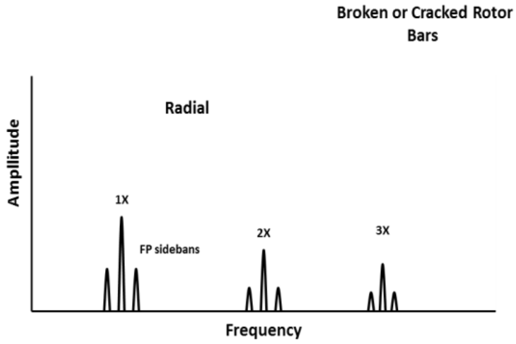


Fig.3 All harmonics with F_p sidebands

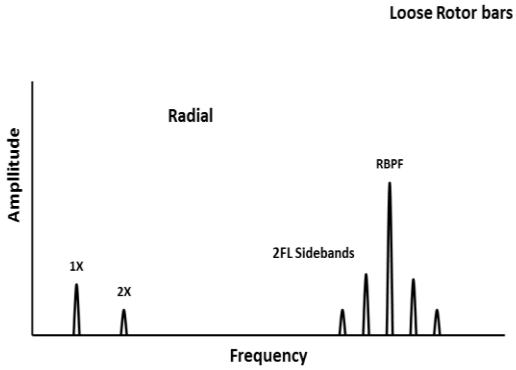


Fig.4 Rotor bar pass frequency.

D. *Electrical Phasing Problems (Loose Connectors)*

Phasing problems due to loose or broken connectors cause excessive vibration at $2F_L$, which has sidebands around it spaced at one third of the line frequency (⅓F_L) [16]. This is particularly a problem if the defective connector is only sporadically making contact (Fig. 5).

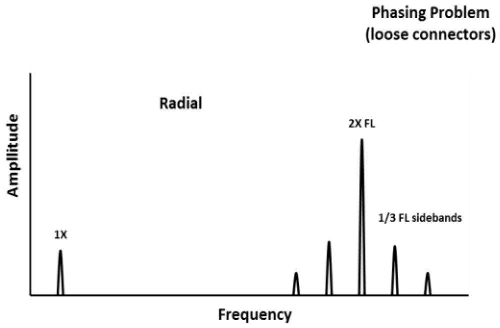


Fig.5 Phasing problem

III. FAULT DETECTION USING FUZZY LOGIC

Fuzzy expert is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox [18]. They are Mamdani-type and Sugeno-type. In the present study, Mamdani-type fuzzy inference system is used. Fig. 6 shows the internal structure of fuzzy logic controller.

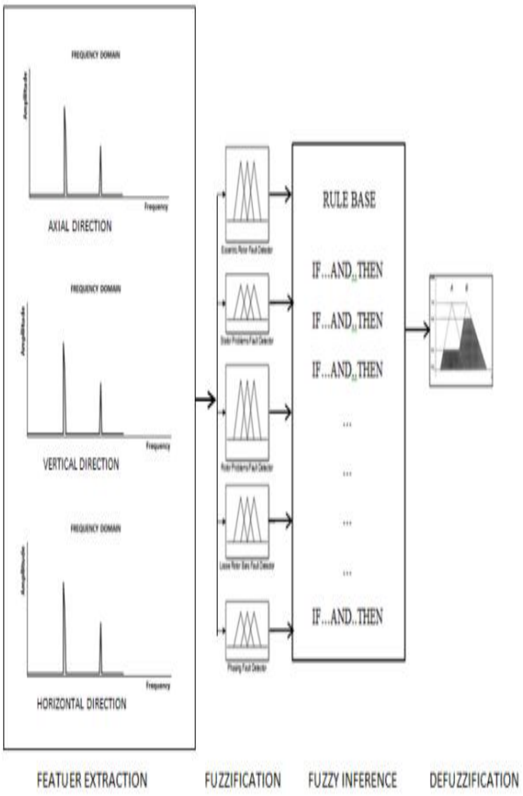
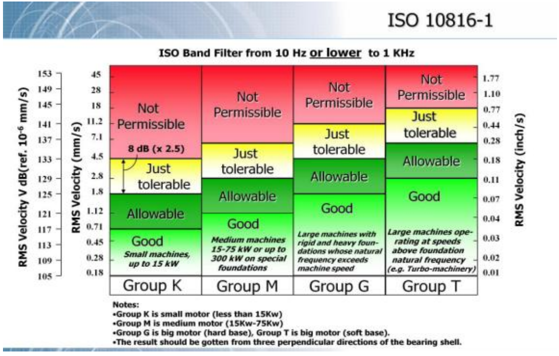


Fig.6 Internal structure of a fuzzy logic controller

A. *Input Membership Function*

The first step in fuzzy logic processing involves a domain transformation called fuzzification. Crisp inputs are transformed into fuzzy inputs. To transform crisp inputs into fuzzy inputs, membership functions must first be determined for each input. This is accomplished by using ISO 10816-1 severity chart (Group K partition) Table 1.

Table 1:Vibration ISO Standard10816-1 [19].


ISO 10816-1

ISO Band Filter from 10 Hz or lower to 1 KHz

Group K	Group M	Group G	Group T
Not Permissible	Not Permissible	Not Permissible	Not Permissible
Just tolerable	Just tolerable	Just tolerable	Just tolerable
Allowable	Allowable	Allowable	Allowable
Good *Small machines, up to 15 kW*	Good *Medium machines 15-75 kW or up to 300 kW on special foundations*	Good *Large machines with rigid and heavy foundations whose natural frequency exceeds machine speed*	Good *Large machines operating at speeds above foundation natural frequency (e.g. Turbo-machinery)*

Notes:
- Group K is small motor (less than 15Kw)
- Group M is medium motor (15Kw-75Kw)
- Group G is big motor (hard base), Group T is big motor (soft base).
- The result should be gotten from three perpendicular directions of the bearing shell.

The input variables used in induction motor fault diagnosis technique in the present work are amplitudes of stator and rotor frequencies and sidebands by vibration velocity unit (mm/s). The input membership function consists of four input variables. Line frequency and it's harmonics (F_L, $2F_L$, $1/3F_L$)**,** pole pass frequency (F_P), running speed frequency and it's harmonics (1X, 2X,…), rotor bar pass frequency (RBPF), pole pass frequency sidebands, line frequency sidebands, and one third line frequency sidebands in terms of vibration signal amplitudes in axial, vertical, and horizontal directions. Here trapezoidal membership function is used. The input variables are interpreted as linguistic variables, with Good (G), Allowable (AL), Tolerable (T) and Bad (B) as stated in vibration severity ISO chart label as shown in Table 2. The input membership function is shown in Fig. 7. The range of input membership function varies from 0 to 1.

Table 2: Input membership function

Member-ship function number	Member-ship function name	Left leg	peak	Right leg
1	Low	0	1	0.18
2	Good	0.18	1	0.71
3	Allowable	0.71	1	1.8
4	Tolerable	1.8	1	4.5
5	Bad	4.5	1	45

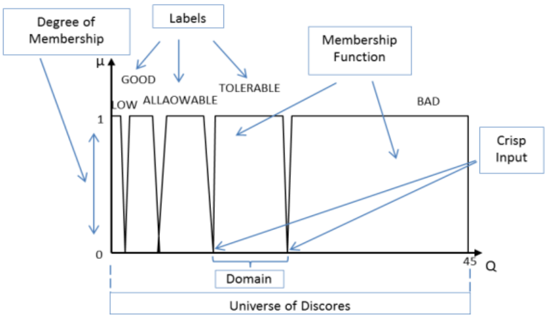


Fig.7 Input membership function plot

B. *Output Membership Function*

The Output membership consists of three variables. The variable is the condition of the motor. The output variables are interpreted as linguistic variable with Good, Alarm and Bad. Here also trapezoidal membership function is used. The output membership function is shown in Fig 8. The range of output membership function varies from 0 to 1. Output of Fuzzy Logic Controller:

1. No-Fault ----- 0 To 0.4
2. Alarm ----- 0.2 To 0.8
3. Fault ----- 0.6 To 1

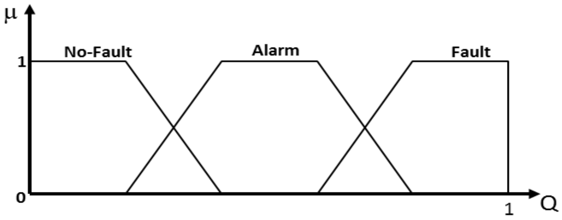


Fig.8 Output membership function

C. *Rule Evaluation*

In this step of fuzzy logic processing, the fuzzy processor uses linguistic rules to determine what control action should occur in response to a given set of input values. Rule evaluation, also referred to as fuzzy inference, applies the rules to the fuzzy input that were generated in the fuzzification process, then evaluates each rule with the inputs that were generated from the fuzzification process. The rule bases are then applied in order to diagnose the motor fault. The rule base is simply an (If) statement that assigns a value of the membership function of each input and relates them by a logical operator, either (AND) or (OR) operator. Tables 3,4,5,6, and 7 summarizes the rule bases built for eccentric rotor, loose rotor bars, broken rotor bars, phasing (loose connectors), and stator fault diagnosis process respectively.

D. *Defuzzification*

Defuzzification is defined as the conversion of fuzzy output to crisp output. There are many types of defuzzification methods available. Here we used Center of Area (COA) method for defuzzification. Despite its complexity it is more popularly used because, if the areas of two or more contributing rules overlap, the overlapping area is counted only once [18].

Table 3: Eccentric rotor rule basis

Logical Operator		2X F_L_A	2X F_L_SIDE_A	F_P_A	X_SIDE_A	2X F_L_H	2X F_L_SIDE_H	F_P_H	X_SIDE_H	2X F_L_V	2X F_L_SIDE_V	F_P_V	X_SIDE_V		
AND	IF	--	--	--	--	B	NOT L	NOT L	NOT L	--	--	--	--	THEN	FAULT
AND	IF	--	--	--	--	T	NOT L	NOT L	NOT L	--	--	--	--	THEN	FAULT
AND	IF	--	--	--	--	AL	L	L	L	--	--	--	--	THEN	ALARM
AND	IF	--	--	--	--	G	L	L	L	--	--	--	--	THEN	NO FAULT
AND	IF	--	-	--	--	L	L	L	L	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	--	--	NOT L	L	L	L	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	--	--	B	NOT L	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	--	--	--	T	NOT L	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	B	NOT L	NOT L	NOT L	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	T	NOT L	NOT L	NOT L	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	AL	L	L	L	THEN	ALARM
AND	IF	--	--	--	--	--	--	--	--	G	L	L	L	THEN	NO FAULT
AND	IF	--	--	--	--	--	--	--	--	L	L	L	L	THEN	NO FAULT
AND	IF	--	--	--	--	--	--	--	--	NOT L	L	L	L	THEN	NO FAULT
AND	IF	--	--	--	--	--	--	--	--	B	NOT L	--	--	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	T	NOT L	--	--	THEN	FAULT

Table 4: Loose rotor bars rule basis

Logical Operator		1X F_{RPB}_A	1X F_{RPB}_H	1X F_{RPB}_V	1X F_{RPB}_SIDE_A	1X F_{RPB}_SIDE_H	1X F_{RPB}_SIDE_V	2X F_{RPB}_A	2X F_{RPB}_H	2X F_{RPB}_V	2X F_{RPB}_SIDE_A	2X F_{RPB}_SIDE_H	2X F_{RPB}_SIDE_V		
AND	IF	--	B	--	--	NOT L	--	--	B	--	--	NOT L	--	THEN	FAULT
AND	IF	--	B	--	--	NOT L	--	--	T	--	--	NOT L	--	THEN	FAULT
AND	IF	--	T	--	--	NOT L	--	--	T	--	--	NOT L	--	THEN	FAULT
AND	IF	--	T	--	--	NOT L	--	--	B	--	--	NOT L	--	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	B	--	--	NOT L	--	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	T	--	--	NOT L	--	THEN	FAULT
AND	IF	--	AL	--	--	--	--	--	AL	--	--	--	--	THEN	ALARM
AND	IF	--	AL	--	--	--	--	--	G	--	--	--	--	THEN	ALARM
AND	IF	--	G	--	--	--	--	--	AL	--	--	--	--	THEN	ALARM
AND	IF	--	G	--	--	--	--	--	G	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	B	--	--	NOT L	--	--	B	--	--	NOT L	THEN	FAULT
AND	IF	--	--	B	--	--	NOT L	--	--	T	--	--	NOT L	THEN	FAULT
AND	IF	--	--	T	--	--	NOT L	--	--	T	--	--	NOT L	THEN	FAULT
AND	IF	--	--	T	--	--	NOT L	--	--	B	--	--	NOT L	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	B	--	--	NOT L	THEN	FAULT
AND	IF	--	--	--	--	--	--	--	--	T	--	--	NOT L	THEN	FAULT
AND	IF	--	--	AL	--	--	--	--	AL	--	--	--	--	THEN	ALARM
AND	IF	--	--	AL	--	--	--	--	G	--	--	--	--	THEN	ALARM
AND	IF	--	--	G	--	--	--	--	AL	--	--	--	--	THEN	ALARM
AND	IF	--	--	G	--	--	--	--	G	--	--	--	--	THEN	NO FAULT
AND	IF	--	L	--	--	--	--	--	L	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	L	--	--	--	--	--	L	--	--	--	THEN	NO FAULT

Table 5: Electrical phasing rule basis

Logical Operator		2X F_L_A	2X F_L_H	2X F_L_V	1/3X F_L_SIDE_A	1/3X F_L_SIDE_H	1/3X F_L_SIDE_V		
AND	IF	--	B	--	--	NOT L	--	THEN	FAULT
AND	IF	--	T	--	--	NOT L	--	THEN	FAULT
AND	IF	--	AL	--	--	NOT L	--	THEN	ALARM
AND	IF	--	G	--	--	NOT L	--	THEN	NO FAULT
AND	IF	--	--	B	--	--	NOT L	THEN	FAULT
AND	IF	--	--	T	--	--	NOT L	THEN	FAULT
AND	IF	--	--	AL	--	--	NOT L	THEN	ALARM
AND	IF	--	--	G	--	--	NOT L	THEN	NO FAULT
AND	IF	--	NOT L	--	--	L	--	THEN	NO FAULT
AND	IF	--	--	NOT L	--	--	L	THEN	NO FAULT
AND	IF	--	L	--	--	L	--	THEN	NO FAULT
AND	IF	--	--	L	--	--	L	THEN	NO FAULT

Table 6: Cracked or broken rotor bars rule basis

Logical Operator		1X_A	1X_H	1X_V	1X_SIDE_A	1X_SIDE_H	1X_SIDE_V	2X_SIDE_A	2X_SIDE_H	2X_SIDE_V	3X_SIDE_A	3X_SIDE_H	3X_SIDE_V		
AND	IF	--	B	--	--	NOT L	--	--	NOT L	--	--	NOT L	--	THEN	FAULT
AND	IF	--	T	--	--	NOT L	--	--	NOT L	--	--	NOT L	--	THEN	FAULT
AND	IF	--	B	--	--	NOT L	--	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	T	--	--	NOT L	--	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	AL	--	--	NOT L	--	--	--	--	--	--	--	THEN	ALARM
AND	IF	--	G	--	--	--	--	--	--	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	B	--	--	NOT L	--	--	NOT L	--	--	NOT L	THEN	FAULT
AND	IF	--	--	T	--	--	NOT L	--	--	NOT L	--	--	NOT L	THEN	FAULT
AND	IF	--	--	B	--	--	NOT L	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	--	T	--	--	NOT L	--	--	--	--	--	--	THEN	FAULT
AND	IF	--	--	AL	--	--	NOT L	--	--	--	--	--	--	THEN	ALARM
AND	IF	--	--	G	--	--	--	--	--	--	--	--	--	THEN	NO FAULT
AND	IF	--	L	--	--	--	--	--	--	--	--	--	--	THEN	NO FAULT
AND	IF	--	--	L	--	--	--	--	--	--	--	--	--	THEN	NO FAULT

Table 7: Stator defect rule basis

Logical Operator		$2X\,F_L$_A	$2X\,F_L$_H	$2X\,F_L$_V		
AND	IF	--	B	--	THEN	FAULT
AND	IF	--	T	--	THEN	FAULT
AND	IF	--	AL	--	THEN	ALARM
AND	IF	--	G	--	THEN	NO FAULT
AND	IF	--	--	B	THEN	FAULT
AND	IF	--	--	T	THEN	FAULT
AND	IF	--	--	AL	THEN	ALARM
AND	IF	--	--	G	THEN	NO FAULT

IV. SIMULATION OF INDUCTION MOTOR FUNDAMENTAL FREQUENCIES FOR FAULT DETECTION USING MATLAB/SIMULINK

Procedure of induction motor fault detection system (Fig. 9) consists of five main processes to achieve vibration cause. First of all is entering all the system requirements like motor specification and importing frequency spectrum data as digits in axial, horizontal, and vertical directions, then starting frequency spectrum analysis using MATLAB/SIMULINK as follows, Fig. 10:

1- Getting Curve Value:
This code reads frequency in Hz and amplitude in mm/s data from the frequency spectrum

2- Getting Motor Frequency:
The function of this code is to employ induction motor specifications (synchronous speed, speed, line frequency, and number of rotor bars) as input values to calculate pole pass frequency (F_P), and rotor bar pass frequency (RBPF)

3- Identify Frequency Amplitudes:
The function of this code is to identify the amplitudes of the input values which are represented by frequencies of induction motor with 14 output parameters as follows:

-amp_2fl
-side_2fl
-amp_fp
-amp_frbp
-side_frbp
-amp_2frbp
-side_2frbp
-amp_1x
-side_1x
-amp_2x
-side_2x
-amp_3x
-side_3x
-side_dFl

All parameters are introduced in axial, vertical, and horizontal directions. Then we have a feature extraction process to choose the appropriate frequency and amplitude for every fuzzy inference fault system to identify type of fault using numeric display block of input value to display the center of gravity (COG) as a result of fuzzy process (Fig. 9).

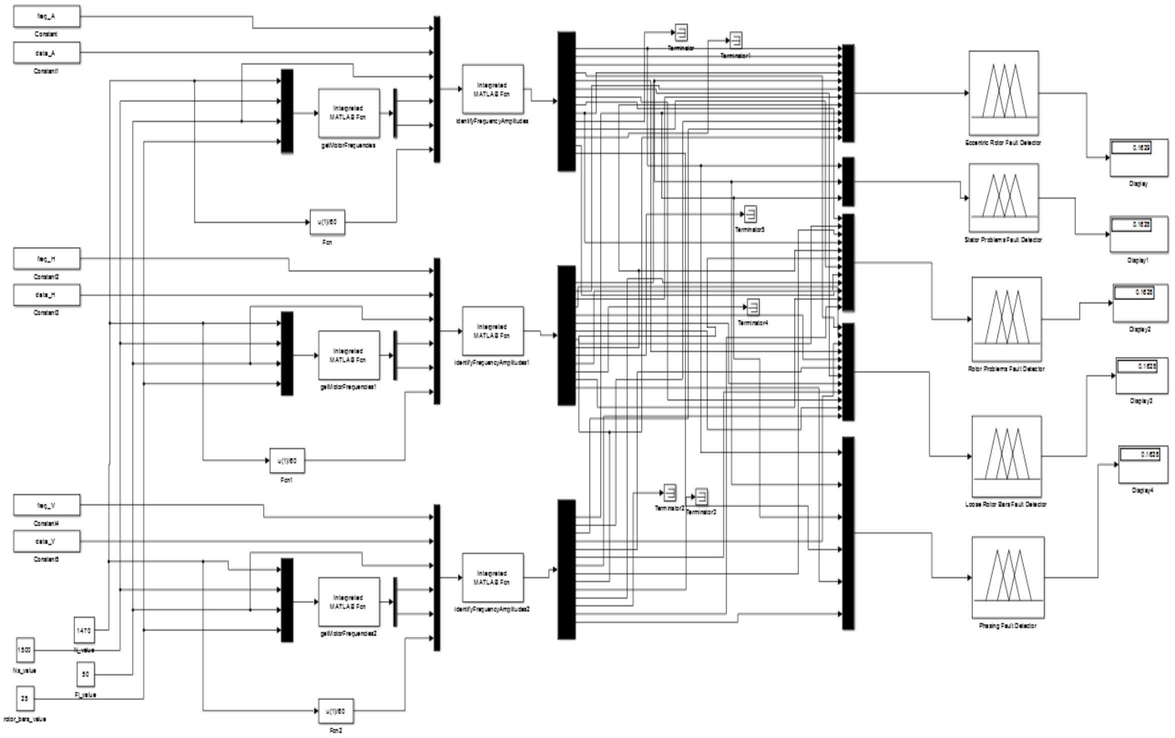


Fig.9 MATLAB/SIMULINK code

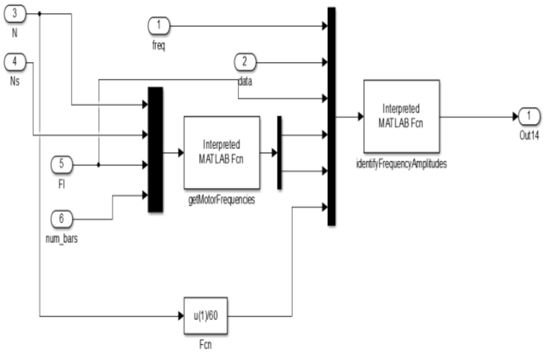


Fig.10 Spectrum analyzer

V. FAULT DIAGNOSTIC RESULTS

Testing a fault diagnosis system (Fig. 10) accomplished by feeding induction motor cases. The relationship between the displacement of the mass and time is expressed in the form of a sinusoidal equation. By using the harmonic function (5) for the oscillation of a simple pendulum, a MATLAB code built using a harmonic motion (Fig. 11) to simulate time waveform and FFT spectrum for a certain fault and then applied to the system.

$$x = X_0 \sin(wt) \qquad (5)$$

x = displacement at any given instant t; X_0 = vibration peak amplitude.

$\omega = 2\,\pi\,f$ *wheref* is the vibration frequency (Hz) and t is the time (s).

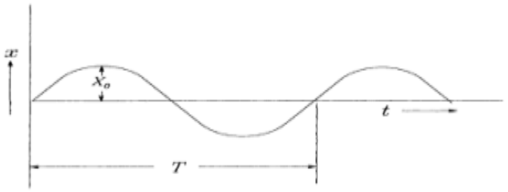


Fig.11 Simple harmonic waveform

Motor specifications are assumed as follows:
Power = 10 kW
Synchronous speed = 1500 rev/min
Speed = 1470 rev/min
Number of rotor bars = 25
Line frequency = 50 Hz

These specifications are used to identify motor frequencies F_L, F_S, and F_P (Fig. 9) which are used in the fault identification process. Two trials are applied to fault diagnosis system:

A. *No-fault condition*

Observed that frequencies of FFT spectrum in axial, vertical, and horizontal directions (Fig. 12) are in the good condition zone of vibration ISO chart severity (Table 1).

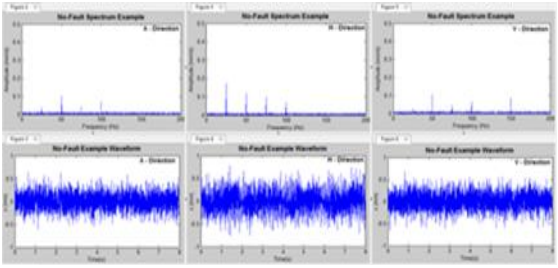


Fig.12 No-Fault time waveform and spectrum

B. *Stator fault*

Stator problems generate high vibration at 2X line frequency ($2F_L$). Stator eccentricity produces uneven stationary air gap between rotor and stator which produces very directional vibration (Fig. 13). Using code to generate stator fault FFT spectrum model, then fault diagnosis process applied for fault identification which represented by center of gravity number (Table 8).

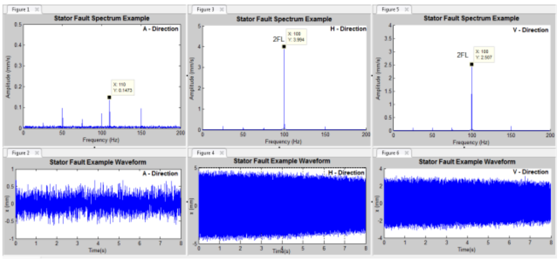


Fig. 13Stator fault time waveform and spectrum

Rule Viewer

The rules can also be seen from the rule viewer using the fuzzy logic toolbox in MATLAB software, The Rule Viewer allows to interpret the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. Since it plots every part of every rule, fig. 14 shows rules that characterized induction motor fault and severities of each fault by ranging output membership function from 0 to 1.

Experiment Results

Fault diagnosis procedure applied on air-heater wash pump with 65 hp which classified as group (M) in vibration ISO standard (Table 1) for matching motor power (48.49 kW), then converted into input membership function. Motor specifications are illustrated at Table 9 which are used as input variables to spectrum analyzer (Fig. 9) with vibration measurements in axial, vertical, and horizontal directions.

Table 8: Processed testing data

Fault Example	Eccentric Rotor Fault COG	Stator Problem Fault COG	Rotor Problem Fault COG	Loose Rotor Bars Fault COG	Phasing Fault COG
No-Fault	0.1629	0.1629	0.1629	0.1629	0.1629
Stator Fault	0.1629	0.8596	0.1629	0.1629	0.1629

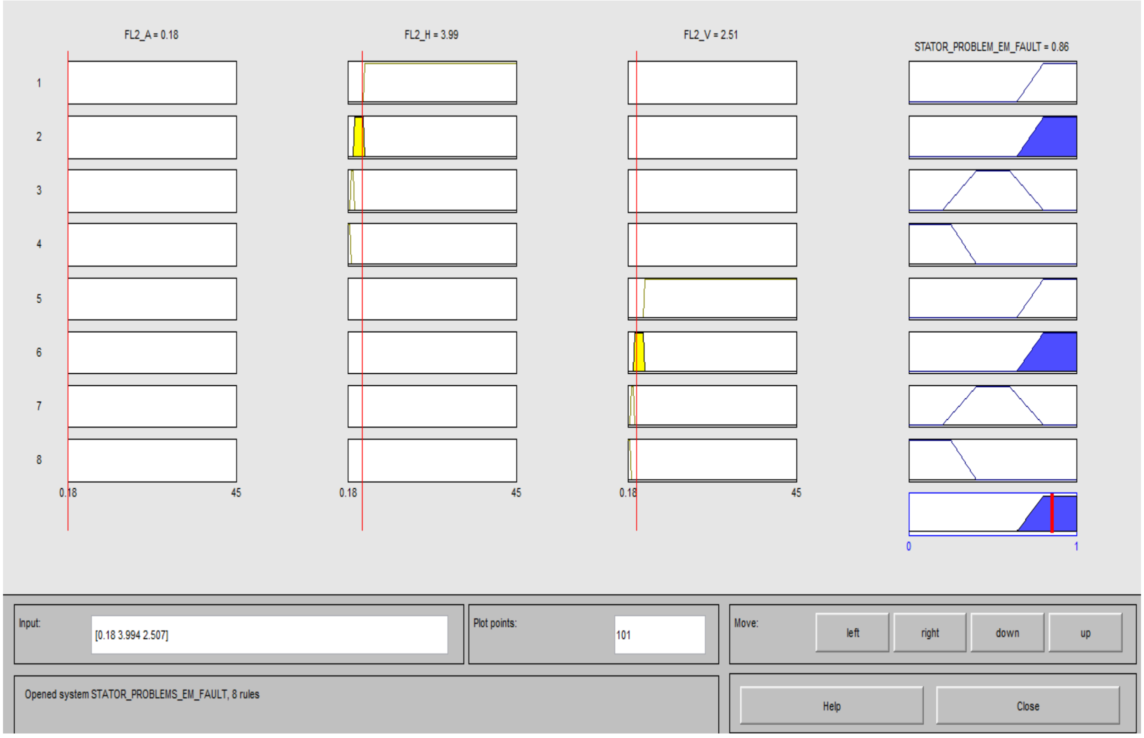
Table 9: Motor specifications

Motor Specification (input variables)	Air-heater Wash Pump
Synchronous Speed (RPM)	3000
Speed (RPM)	2970
Line Frequency (Hz)	50
Number of Rotor Bars	67

Fuzzy inferences technique applied on FFT spectrum to monitor motor condition which is represented as a balance point of COG (Table10). For air-heater wash pump Motor Non-Drive End (MNDE)vibration measurement in axial, horizontal, and vertical directions are shown in Fig. 16, 17, and 18 respectively. High radial vibration observed at twice line frequency ($2F_L$) which indicated stator fault. High running speed frequency (1X) with pole pass frequency sidebands (F_P) indicated eccentric rotor defect. These two faults correspond with fuzzy system results (Table 10), the nearer the balance point of the center of gravity is to number 1, the higher the possibility of failure and severity, here the motor condition is at a critical stage.

Table 10: Motor condition

Motor Name	Eccentric Rotor Fault COG	Stator Fault COG	Rotor Problem Fault COG	Loose Rotor Bars Fault COG	Phasing Problem Fault COG
Air-heater Wash Motor	0.3512	0.3512	0.1628	0.1628	0.1628

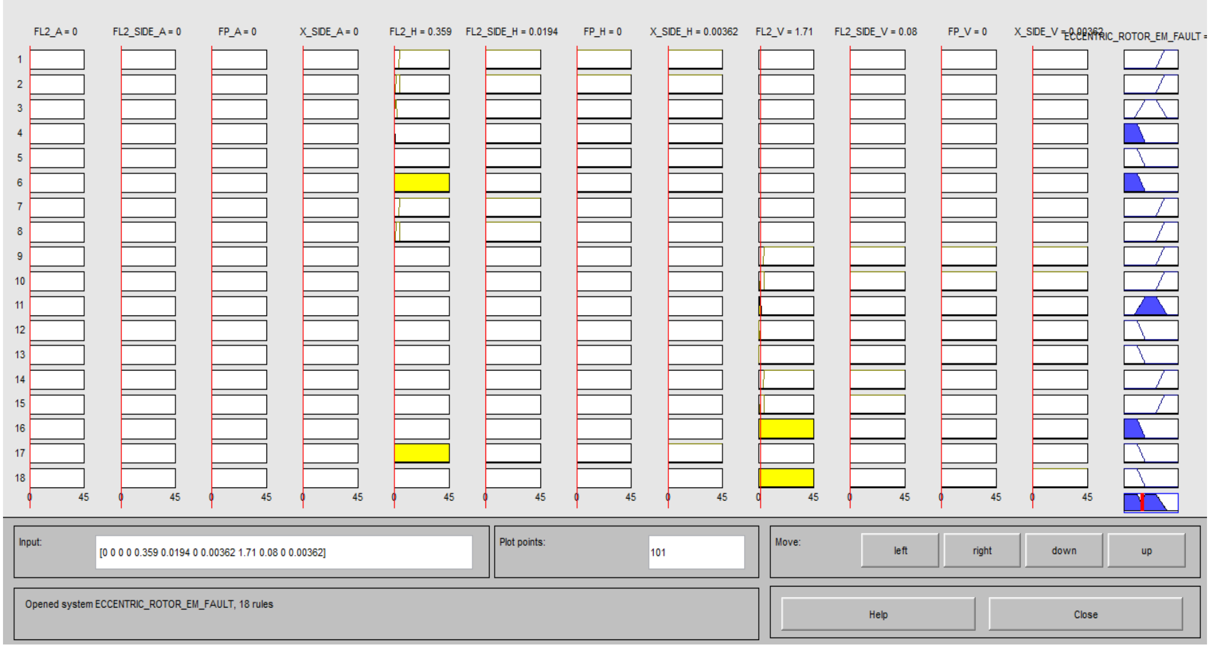


Input: [0.18 3.994 2.507]

Plot points: 101

Opened system STATOR_PROBLEMS_EM_FAULT, 8 rules

Fig. 14 Fuzzy inference rules diagram for motor stator fault



Input: [0 0 0 0 0.359 0.0194 0 0.00362 1.71 0.08 0 0.00362]

Plot points: 101

Move:

Opened system ECCENTRIC_ROTOR_EM_FAULT, 18 rules

Fig. 15Fuzzy inference rules diagram for air-heater wash pump

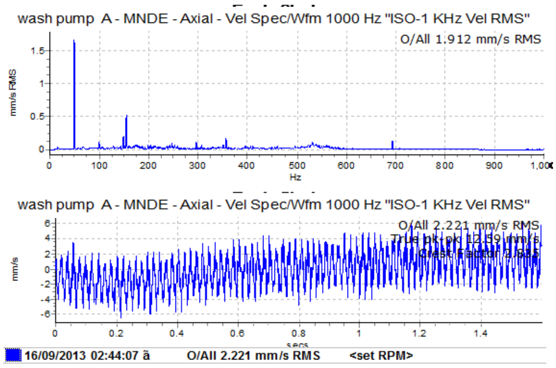


Fig. 16 Motor non-drive end time waveform and FFT spectrum in axial direction

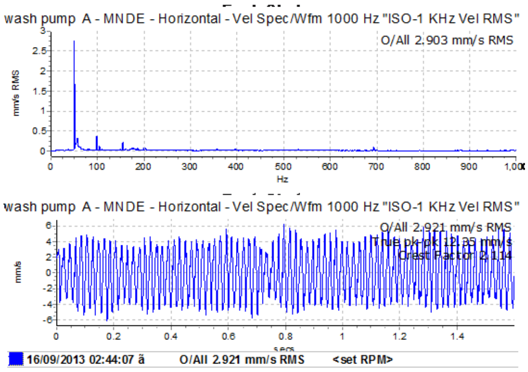


Fig. 17 Motor non-drive end time waveform and FFT spectrum in horizontal direction

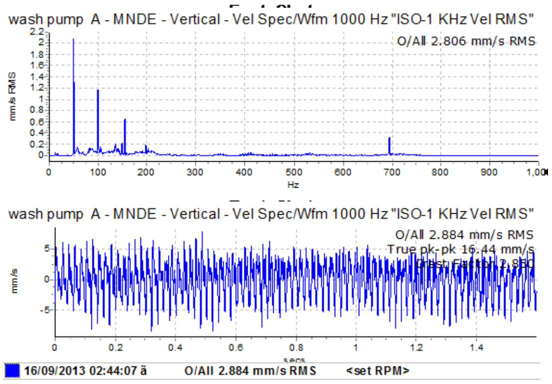


Fig. 18 Motor non-drive end time waveform and FFT spectrum in vertical direction

VI. CONCLUSION

This paper presented an induction motor electrical fault detection using fuzzy logic technique based on fundamental frequency amplitude. Motor frequency spectrum simulation applied to identify type of failure and its severity using fuzzy inference system for process validation. The electrical motor experimental results showed that the proposed method performed very well identifying both the motor electrical and mechanical faults.

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