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MULTIPLE FAULT ANALYSIS USING A FUZZY LOGIC TECHNIQUE FOR AN INVERTER CONTROL DRIVE

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Key words: fuzzy logic, fault analysis, inverter switch fault, harmonics, torque ripple.

ABSTRACT

This study evaluates electrical faults on an inverter control drive using simulations in MATLAB Simulink and recommends a fuzzy logic technique for analyzing electrical faults of such drives. Fault analysis of a drive is based on voltage, speed, current, and torque. This article presents soft computing methods for voltage fluctuations and fault detection in an inverter switch to an inverter control drive with the support of a MATLAB Simulink model. Accordingly, failure analysis techniques based on fuzzy logic are explained. The fuzzy system allows altered voltage and open-switch fault detection. Soft computing techniques offer excellent analysis of a faulty structure, even if precise models are not available. This study presents a fuzzy logic–based fault diagnosis scheme for detecting and identifying faults. The simulation outcomes reveal excellent performance of the method, proving its applicability for fault detection in squirrel-cage induction motors. All simulated results, voltage fluctuations, torques, currents, ripples, and harmonics in healthy and defective situations are analyzed.

I. INTRODUCTION

Asynchronous motors are a category of alternating current motor that applies power to the rotor through mutual induction. Squirrel-cage induction motors, because of their trouble-free structure, high reliability, and low cost, have been favored for electromechanical force replacement in hydraulic systems, predominantly when the motors function as stylized, mechanized producer lines (Kalpana and Alok, 2012). Manufacturing unit automation has been a vital element of universal manufacturing development, and lines of manufacturing plants typically feature one or more changeable-speed motor drives.

Disturbances to industrial progression caused by mechanical or electrical problems create significant financial difficulties for a system. These interruptions can be caused by uneven voltage liability and open-switch faults (Belgacem et al., 2015). Asynchronous motors have captured the attention of modern trade because of their self-starting ability, powerful structure, persistence, low manufacturing costs, and consistency. Although these motors are reliable, they are prone to unexpected failures. Situational monitoring must be conducted to ensure their consistency, effectiveness, and safety. The fine roll of an induction motor results in line current as well as phase voltage and signal equal to the amplitude and shifted by 120 degrees. Alternatively, under a faulty condition, the amplitude and consequently the phase shifts are altered. A technique used worldwide for stator faults takes the root mean square of three-phase stator current signals and inserts it into a fuzzy inference system. In this inference scheme, three foremost sections must be considered: the first is related to the input of the scheme, which must be entered in fuzzy form; the second is the fuzzy inference base; and the final section requires realizing fuzzy output by using an appropriate defuzzifier (Lashkari et al., 2016). Squirrel-cage induction motors are preferred over other electrical motors typically because of their less sophisticated arrangement, greater reliability, less required maintenance, and greater task leniency. Nevertheless, it may be necessary to examine abnormalities of the squirrel-cage induction motor drive because of the harsh conditions arising from faults, which might occur outside or inside the motor, thereby impairing its steadiness. In industrialized applications, because squirrel-cage rotating induction motors are fed mostly by voltage source inverters (Tushar et al., 2017), dissimilar types of fault affect the front end of the rectifier, power inverter, and direct control subsystems; this leads to uneven supply to the motor through an excess of voltage in a few phases and the injection of harmonics in the applied input current. Numerous studies have been conducted on online situation monitoring and fault identification for squirrel-cage induction motor drives, and as a result, strategies have shifted from the conventional methods to artificial intelligence methods, integrating intellectual

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Table 1. Parameters of the rotating induction motor.

Motor Type	Power	Voltage	Frequency	Speed	Torque
Squirrel Cage Induction Motor	746 watts	440V	50Hz	1500Rpm	4.75

control with eminent performance drive control (Rajeshwaran et al., 2016). Recently, soft computing techniques such as expert schemes, neural networks, and fuzzy logic, have been employed to understand fault data through suitable analyses. Their improved performance is isolated from the lenience of reason and modification for assorted motors and fault scenarios makes them highly applicable for analytic schemes.

The aforementioned methods have increased the accuracy and exactness of monitoring systems. Condition analysis of electrical motors and related drives is a large field, comprising dissimilar subjects related to signal processing and intellectual systems as well as monitoring methods and associated instrumentation. Fuzzy logic control, a strong control method, has the ability to adapt to discrepancies between parameters and does not rely on an accurate arithmetical form. Actually, the failure of stator phases differs with motor parameters, which can be dealt with consistently by ensuring the healthiness of the controller and absence of faults (Zhang et al., 2017).

Short-circuit faults that occur in motor coils and power converters must be detected immediately and normally handled by reconfiguring the power diagram (Zicheng et al., 2017). Three-phase induction motors are typically used in manufacturing applications because of their uncomplicated structure, consistency, and low cost. Detecting abnormalities early will help to avoid deterioration of the motor. Thus, situation monitoring of three-phase induction motors can moderate the continuance charge as well as enhance its motor performance (Ayaz et al., 2016). The performance of induction motors is hindered by three types of fault: electrical faults, mechanical faults, and environmental faults. Electrical faults include under-voltage faults, abnormal load faults, and earth faults. Mechanical faults include rotor coil faults, stator coil faults, and bearing faults (Jannati et al., 2016). In addition, outdoor humidity and contamination in ambient temperature affect the operation of induction motors; vibration faults along with faults caused by the aforementioned ambient disparities constitute environmental faults. Electrical faults of three-phase induction motors raise temperatures in both stator and rotor coils (Abadi et al., 2017). These electrical faults can reduce the lifetime of motor. The performance of induction motors with electrical faults, such as uneven supply voltage, overload, or earth faults, is explained in this paper. Furthermore, this paper presents fuzzy logic algorithm for the detection and analysis of electrical faults. An arithmetic model developed and replicated using MATLAB Simulink of three-phase squirrel-cage induction motors was used for fault investigation (Tian et al., 2017). In fuzzy logic, the fault situation of a motor is described using linguistic variables. Fuzzy subsets and corresponding membership functions clarify the amplitudes, negative sequence components, and speed of stator currents (Mini and Ushakumari, 2011). Fuzzy logic systems are used for fault analysis (Hamouda et al., 2017). This study developed a simple, supportive system for simulating electrical faults, such as uneven voltage and open-switch faults. A fuzzy logic algorithm was devised to identify and analyze these faults. Table 1 presents the specifications of the squirrel-cage rotary induction motor used in this study

II. MATHEMATICAL MODELING OF THE INDUCTION MOTOR

A rotary induction motor is illustrated using a model. It is represented as differential equations written in d–q rectangular coordinates. The modeling starts with a three-phase rotating induction motor, and an orthogonal two-phase form is introduced. This model is suitable under the following assumptions (Chakrabarti et al., 2017). Each stator phase of the motor has a similar number of coils and identical spatial displacement; magnetic saturation is not present. A popular rotating induction motor model is Krause's model, which was investigated in depth by (Eunsil and Kyo-Beum, 2016). According to this model, the flux linkage equations with proper subscripts are as follows:

$$\frac{dF_{qs}}{dt} = \omega_b \left[V_{qs} - \frac{\omega_e}{\omega_b} F_{ds} + \frac{R_s}{x_{ls}} \left(F_{mq} + F_{qs} \right) \right] \tag{1}$$

$$\frac{dF_{qs}}{dt} = \omega_b \left[V_{qs} - \frac{\omega_e}{\omega_b} F_{ds} + \frac{R_s}{x_{ls}} \left(F_{mq} + F_{qs} \right) \right] \tag{2}$$

$$\frac{dF_{qr}}{dt} = \omega_b \left[V_{qr} - \frac{(\omega_e - \omega_{r)}}{\omega_b} F_{dr} + \frac{R_r}{x_{lr}} \left(F_{mq} + F_{qr} \right) \right] \tag{3}$$

$$\frac{dF_{dr}}{dt} = \omega_b \left[V_{dr} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr} + \frac{R_r}{x_{lr}} \left(F_{md} + F_{dr} \right) \right] \tag{4}$$

Where F_{mq} and F_{md} are the q- and d-axis magnetizing flux linkage and are given by Eq. (5) and (6).

$$F_{mq} = x_{ml}^{*} [\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}] \tag{5}$$

$$F_{md} = x_{ml}^{*} [\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}] \tag{6}$$

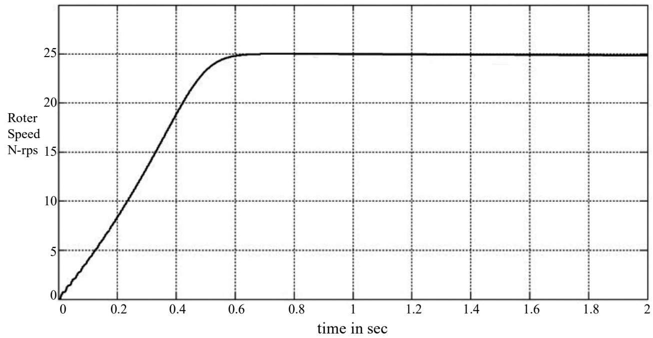

Fig. 1. Speed of the rotating induction motor (rps).

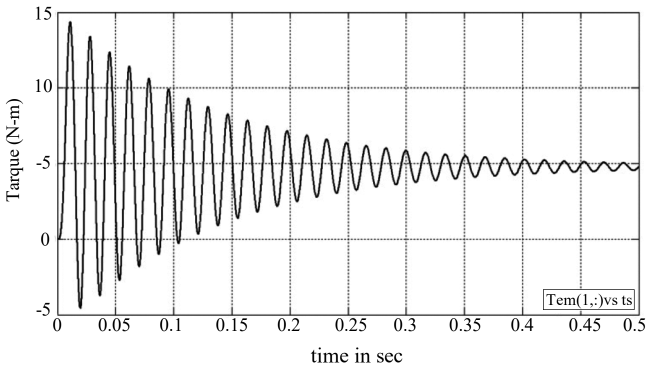

Fig. 2. Torque of the rotating induction motor ($T_e - N_m$).

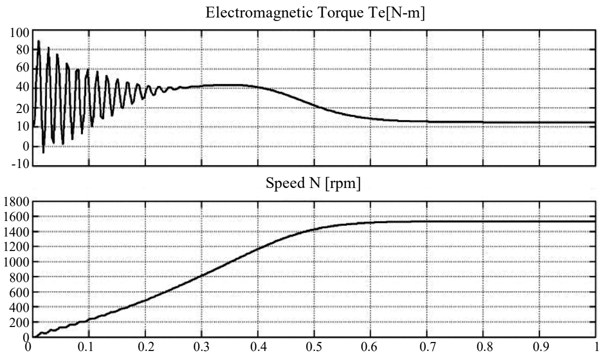

Fig. 3. Speed and torque characteristics of a healthy motor.

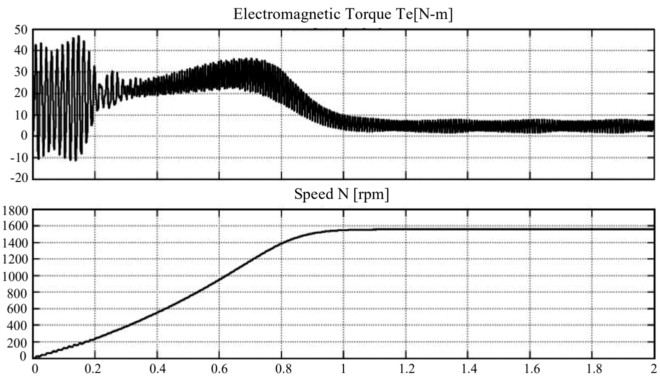

Fig. 4. Speed and torque characteristics of a faulty (uneven voltage) motor.

The stator currents can be found using Eq. (7)–(10).

$$i_{qs} = \frac{1}{x_{ls}}(F_{qs} - F_{mq}) \tag{7}$$

$$i_{ds} = \frac{1}{x_{ls}}(F_{ds} - F_{md}) \tag{8}$$

$$i_{qr} = \frac{1}{x_{lr}}(F_{qr} - F_{mq}) \tag{9}$$

$$i_{dr} = \frac{1}{x_{lr}}(F_{dr} - F_{md}) \tag{10}$$

Where T_e is the electromagnetic torque applied to the shaft of the mechanism and can be articulated as in Eq. (11).

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}\left(F_{ds}i_{qs} - F_{qs}i_{ds}\right) \tag{11}$$

$$T_e - T_L = J\left(\frac{2}{p}\right)\frac{d\omega_r}{dt} \tag{12}$$

The speed of the motor can be obtained from the torque equation shown in Eq. (13).

$$\omega_r(t) = \frac{P}{2J}\int (T_e - T_L)dt \tag{13}$$

Analytical Model

Logical modeling of the rotating induction motor was performed using MATLAB coding. Figs. 1 and 2 show the preferred speed of the motor and useful torque, respectively.

III. FAULT ANALYSIS OF ROTARY INDUCTION MOTOR

Asynchronous motors are popular in the manufacturing industry Thus, considering failures caused by multiple faults, such as open circuits, overloading, uneven voltage, short-circuits, and inverter leg faults, is crucial (Nguyen and Dong-Choon, 2017). In this section, we analyze the two major faults of rotary induction motors, namely uneven input voltage and open-switch faults. Fig. 3 presents the torque and speed performance characteristics of a healthy motor.

1. Uneven Input Voltage

This study simulated rotary induction motor with an uneven input voltage by changing the voltage magnitudes in only one

Table 2. FFT analysis of torque ripple.

Condition of Induction Motor	Total harmonic distortion (Torque ripple)
Healthy	9.47%
UnBalanced Condition	137.19%

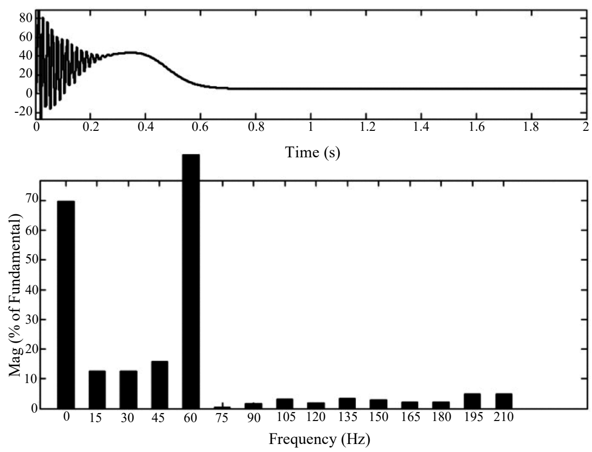

Fig. 5 FFT analysis of torque for a healthy motor, with total harmonic distortion.

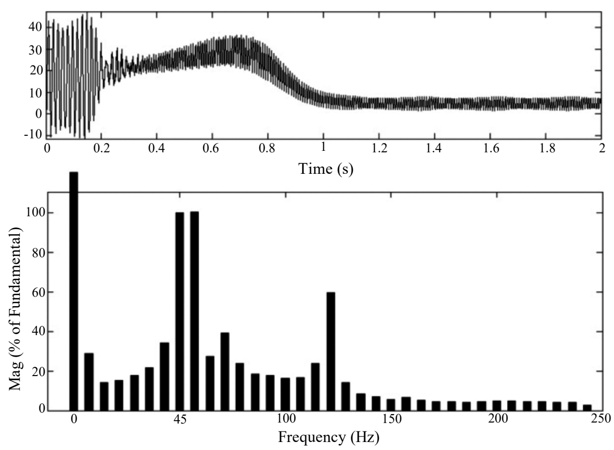

Fig. 6. FFT analysis of torque with ripples for a faulty motor.

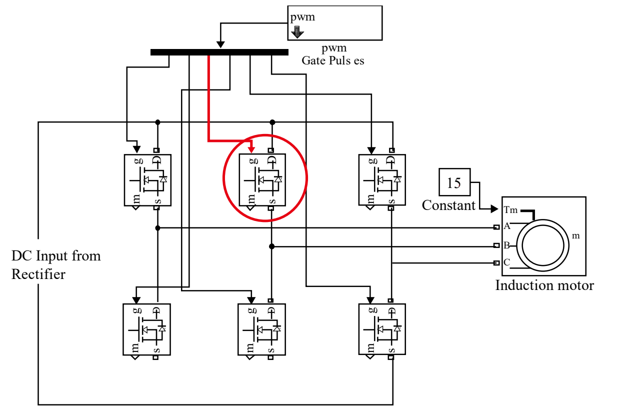

Fig.7. Block diagram of an inverter-fed rotary induction motor with a faulty switch.

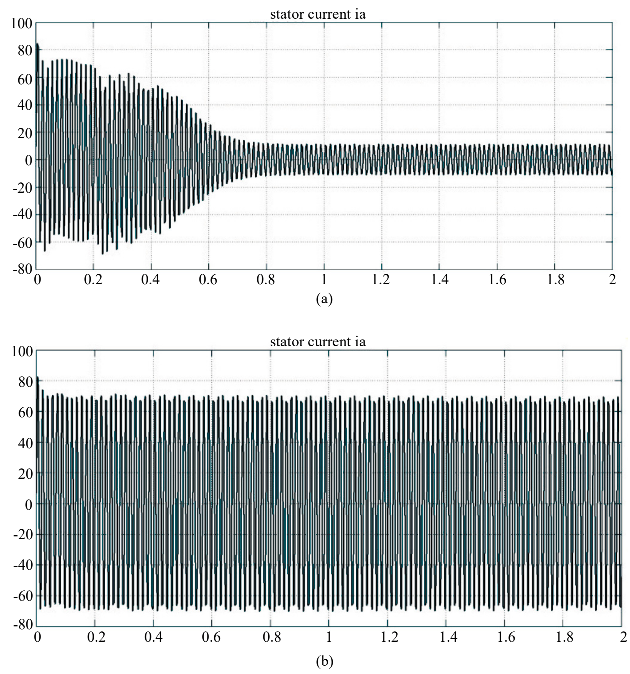

Fig. 8. (a)Stator current waveform under a normal condition and (b) with an inverter switch fault.

phase. Reducing one phase voltage causes inequality in the speed of the motor and produces torque ripple (Gomathy and Selvaperumal, 2016). Here, we add resistance value of 2Ωto the phase A input supply voltage. One of the phase-to-phase input voltage give minimum rate as compared with the supply voltage. The supply voltage of the motor is 400V; thus, each phase-to-phase voltage is also 400V. When we add resistance to one phase of the input, the phase-to-phase voltage drops to 350V. If these uneven voltage faults occur in motor, the output torque of the motor increases, more ripples occur, and the initial speed of the motor decreases, as shown in Fig. 4. Moreover, the uneven voltage affects the rotor and stator currents of the induction motors (Tsypkin and Mikhail, 2017). Field Fourier Transform (FFT) analysis of the usual torque and torque with ripples caused by faults was performed using MATLAB. The normal torque of a healthy motor has a(Total Harmonic Distortion) THD value of 9.47%, whereas the torque with ripples has a THD value of 137.19%, as shown in Figs.5 and 6. Table 2 presents the FFT results of torque ripple for uneven voltage and for a healthy motor.

2. Inverter Switch Fault in Motors

Fig.7. shows a block diagram of a voltage-fed inverter induction motor, which is susceptible to various faults because of the failure of semiconductor devices. Inverter semiconductor devices are usually controlled by isolated base drive

Table 3. Performance evaluation of motors in different situations.

Condition of Motor	Speed N-Rpm	Torque Te-Nm	Stator Current in Amps
Healthy	1500	4.75	10
Uneven Voltage	1500	4.75	20-30
Open switch fault	800	4	50-60

Table 4. Rule base table.

Condition of Motor \ Stator Current	Ia	Ib	Ic
Healthy Condition (HC)	A	A	A
	L	L	L
Faulty Condition (FC)	L	L	A
	L	A	A
	A	L	A
	L	A	L
	A	L	L
	A	A	L
Severely Faulty Condition (SFC)	Z	Z	Z
	H	H	H

Z: zero, L: low, A: average, H: high

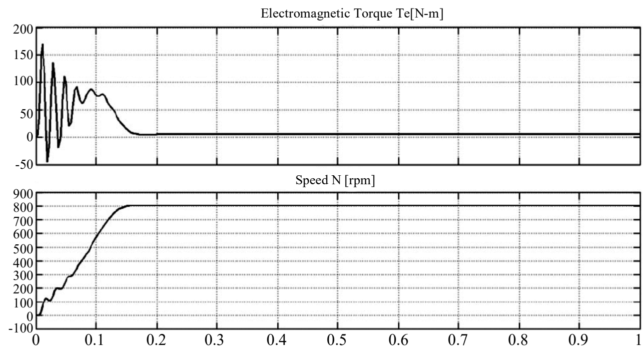

Fig. 9. Minimum torque is produced, and the speed of the motor is reduced from the rated speed because of a fault condition.

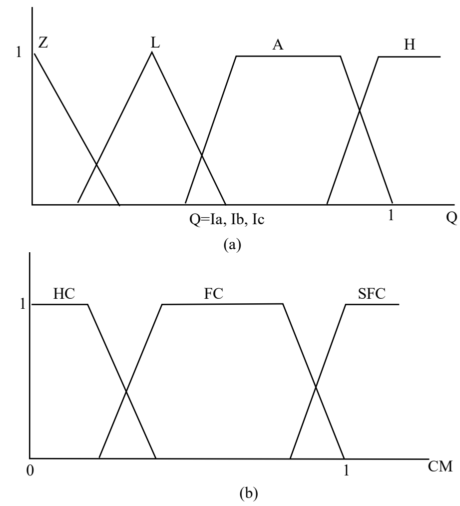

Fig. 10. Fuzzy membership functions for (a)stator currents and (b) stator condition of the motor.

amplifiers. Faults in one of these units can result in a missing base drive, leading to open-circuit faults in the inverter (Zheng et al., 2017). Short-circuit faults are caused by reverse breakdown of the device, or possibly because of insulation breakdown of the leg or circuit paralleling with the device is short (Ouni et al., 2017). This type of fault is severe and may result in faults other devices. Moreover, such faults occur frequently. For such a fault, the base drive of the healthy transistor in the same leg should be instantly suppressed to avoid a shoot during the fault. This paper discusses semiconductor open-circuit faults (Wang et al., 2016). In healthy conditions, the current in the stator of an induction motor is 10A. When a fault occurs in the inverter leg because gate pulses are not received or switches are damaged, the stator current of the motor increases from its desired value, as shown in Fig. 8. If an increase in current in the stator and rotor occurs, the torque values decrease, as does the speed of the motor from its rated speed, as shown in Fig.9.

Table 3 presents a comparison of the performance evaluations of induction motors healthy and faulty conditions and their values.

IV. FUZZY LOGIC IMPLEMENTAION

In motor fault diagnosis, time domain current signals are captured by sensors. Diagnostic experts then use both time and frequency domain signals to study the motor condition and determine faults are present (Rothenhagen and Fuchs, 2004). Knowledgeable engineers are often essential for inferring measurement data, which are regularly uncertain. A fuzzy logic method can facilitate diagnosing induction motor faults. Fuzzy logic is evocative of the progression of human ideas and natural language, enabling decisions made based on in certain information. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse. In this case, the stator current magnitudes Ia, Ib, and Ic are considered the input variables for the fuzzy scheme. The stator condition, CM, is selected as the output variable. All the system inputs and outputs are distinct using fuzzy set theory. Similarly, in Fig.10, the input variables Ia, Ib, and Ic are interpreted as linguistic variables, with t(Q) = {zero, low, average, high}. Here, Q= Ia, Ib, and Ic. Correspondingly, the term set t(CM) in Fig.11, which interprets stator condition (CM) as a linguistic variable, could be t(CM)= {healthy condition, faulty condition and severely faulty condition}. Here, each term of t(CM) is characterized by a fuzzy subset in a universe of discourse, CM.

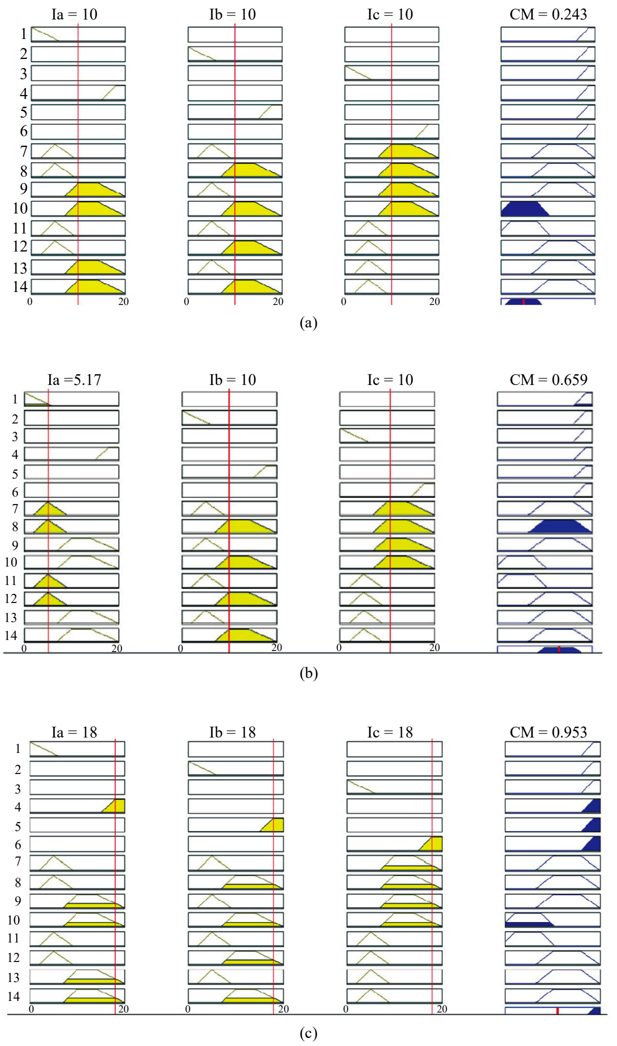

Fig. 11. The fuzzy inference of a healthy condition(a),faulty condition (b) and severely faulty condition (c)

Fuzzy Rules

We obtained the following 14if/then rules:
Rule (1): If Ia is Z,then CM is SFC.
Rule (2): If Ib is Z,then CM is SFC.
Rule (3): If Ic is Z,then CM is SFC.
Rule (4): If Ia is H,then CM is SFC.
Rule (5): If Ib is H,then CM is SFC.
Rule (6): If Ic is H,then CM is SFC.
Rule (7): If Ia is L and Ib is Land Ic is A, then CM is FC.
Rule (8): If Ia is L and Ib is A and Ic is A, then CM is FC.
Rule (9): If Ia is A and Ib is L and Ic is A, then CM is FC.
Rule (10): If Ia is A and Ib is A and Ic is A, then CM is HC.
Rule (11): If Ia is L and Ib is L and Ic is L, then CM is HC.
Rule (12): If Ia is Land Ib is A and Ic is L, then CM is FC.
Rule (13): If Ia is A and Ib is L and Ic is L, then CM is FC.
Rule (14): If Ia is A and Ib is A and Ic is L, then CM is FC.

A fuzzy logic technique was developed to interpret the current signal of an induction motor for monitoring its stator condition. Properly detecting these current signals and inputting them into a fuzzy decision method achieves high diagnostic accuracy. As expected, room remains for perfecting the technique using an intelligent means of optimization. In Fig. 11(a), Rule (10) is used, and in fact Ia = Ib = Ic = 10A is low (L). The motor is in this case supposed as healthy (CM = 0.243). In Fig. 11(b), Rule (8) is used, and in fact Ia =5.17A is low (L), whereas Ib= Ic = 10A is average (A). The motor in this case is faulty (CM = 0.659). Finally, for in Fig.11(c), Rules (4), (5), and (6) are used, and Ia = Ib=Ic= 18 A, which is a high (H) current value. The motor in this case is severely faulty (CM =0.953).

V. CONCLUSION

A competent motor fault analysis system is capable of providing warnings and predicting motor faults in abnormal situations. In recent years, the monitoring and fault analysis of rotary induction motors have stimulated advances over conventional soft computing technique. This study discusses multiple faults, such as uneven voltage and open-switch inverter faults, and their detection techniques for rotary induction motors. An approach is proposed based on MATLAB and fuzzy logic, through which various electrical faults in induction motors can be analyzed. Additional merits of the approach are flexible creation and achievement lenience. The importance of this work comes from identifying switches that are not severely damaged and thus can be replaced as well as those that are critically damaged condition and hazardous for people to operate. As a future research direction, a hardware system could be developed for the online monitoring of induction motor conditions and implemented in various industries to reduce the downtime of drives thereby reducing related losses and maintenance costs.

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