A Proposed Fault Diagnostics Technique for Induction Motor Stator Winding

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Abstract: Online monitoring is widely used for induction motor fault diagnostics. This article presents a fault diagnostics technique for a 3-phase induction machine. The proposed technique was developed with fuzzy logic applied to a simplified induction motor model affected by the stator winding short turns. Based on the 3-phase time-domain model, the machine winding with different fault conditions has been simulated to check the resulting speed, torque, and stator current spectrum in each case. The results indicate that the developed fault diagnostics scheme is efficient to specify the fault type of the induction machines stator.

Key-words: fault diagnostics, Induction Motor, induction motor model, stator short winding, fuzzy logic, stator short winding model.

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1. Introduction

Because of their advantages such as low-cost maintenance and high reliability, induction motors are used in a variety of industrial applications including drive systems and electric vehicles. Although induction motor control is complicated, the field orientation technique simplifies it, elevating the induction motor to the status of the modern industry's beating heart. To optimize motor reliability, it is important to maintain induction motors operational via fault identification to avoid sudden motor damage, [1], [2], [3], [4], [5], [6], [7].

Due to the fact that motors are prone to failure, the problem of monitoring and preventing this unexpected failure is one of the most important challenges we face in the industry despite the high reliability of these machines. Researchers have always had to contend with the faults seen in induction motors, specifically those related to the stator winding, as well as faults related to the rotor electric side and eccentricity. Their thorough investigation has revealed that 30 to 40% of the total induction motor faults are linked to those seen in the winding of stator, [8]. To improve reliability, great attention is paid to the fault that occurs in induction motor drive system diagnostics. The drive system faults are classified into inverter faults, [9], [10] and motor faults, while induction motor faults are divided into two main faults categories mechanical faults and electrical faults. The induction motor's electrical faults are either broken bars or short circuit of the stator winding, [11]. Many methods used to detect the faults related to short circuit stator winding have been adopted, [12], [13], [14]. Motor current signature analysis (MCSA) related to the 50/60-Hz sidebands has become a standard test in the industry for monitoring the induction motor stator condition, [15], [16], [17], [18], [19], [20], [21], [22], [23].

Drive system fault diagnostics must include both the converter and the motor. Previous research [9], [10] presented a rule-based fuzzy Logic system for fault scenarios of inverter-fed induction machines, with a focus on the inverter's power switches. The created system is capable of determining the fault kind and location of the inverter.

The proposed technique has been validated by detecting various types of faults in stator winding with great accuracy. One of the most significant advantages of this method is the ability to diagnose faults online. The accuracy of motor defect identification and the feasibility of knowledge extraction are both confirmed by simulation results. The preliminary findings illustrate that the proposed fuzzy approach can be utilized to accurately diagnose stator faults.

2. Induction Motor Model in ABC Axes

In the ABC axis, the induction motor model is represented by the following equations. The induction motor's electrical and mechanical components are both included in this model.

Starting with the voltage equation

$$v = i.R + \frac{d\lambda}{dt} \tag{1}$$

Where $\lambda = L.i$

$$v = i.R + \frac{d(L.i)}{dt} \tag{2}$$

$$v = i.R + i.\frac{dL}{dt} + L\frac{di}{dt} \tag{3}$$

$$v = i.R + i.\frac{d\theta}{dt}\frac{dL}{d\theta} + L\frac{di}{dt} \tag{4}$$

Where $\frac{d\theta}{dt} = \omega$

$$v = (R + \omega\frac{dL}{d\theta})i + L\frac{di}{dt} \tag{5}$$

Leading to the electrical side equations in the form

$$\frac{di}{dt} = \frac{1}{L}(v - \left(R + \omega\frac{dL}{d\theta}\right)i) \tag{6}$$

While Mechanical Part can be driven from the torque equation

$$T_e = J\frac{d(\omega_m)}{dt} + B.\omega_m + T_L \tag{7}$$

Since $\frac{d\theta_m}{dt} = \omega_m$

$$Te = \frac{P}{4}.i'\frac{dL}{d\theta}i \tag{8}$$

Where

Resistance matrix [Ω]:

$$R = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{ra} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{rb} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{rc} \end{bmatrix}$$

Inductance sub matrices [H]:

$$L_{ss} = \begin{bmatrix} L_s & -\frac{L_m}{2} & -\frac{L_m}{2} \\ -\frac{L_m}{2} & L_s & -\frac{L_m}{2} \\ -\frac{L_m}{2} & -\frac{L_m}{2} & L_s \end{bmatrix},$$

$$L_{rr} = \begin{bmatrix} L_r & -\frac{L_m}{2} & -\frac{L_m}{2} \\ -\frac{L_m}{2} & L_r & -\frac{L_m}{2} \\ -\frac{L_m}{2} & -\frac{L_m}{2} & L_r \end{bmatrix}$$

$$L_{sr} = L_m \cdot \begin{bmatrix} Cos(\theta) & Cos(\theta+\gamma) & Cos(\theta-\gamma) \\ Cos(\theta-\gamma) & Cos(\theta) & Cos(\theta+\gamma) \\ Cos(\theta+\gamma) & Cos(\theta-\gamma) & Cos(\theta) \end{bmatrix}$$

$$dL_{sr} = -L_m \cdot \begin{bmatrix} Sin(\theta) & Sin(\theta+\gamma) & Sin(\theta-\gamma) \\ Sin(\theta-\gamma) & Sin(\theta) & Sin(\theta+\gamma) \\ Sin(\theta+\gamma) & Sin(\theta-\gamma) & Sin(\theta) \end{bmatrix}$$

Where γ is the phase angle

$$L = \begin{bmatrix} dLss & dL_{sr} \\ dL_{sr}' & dLrr \end{bmatrix}$$

Matrix of inductance L:

$$\frac{dL_{sr}}{d\theta} = \begin{bmatrix} Zeros & dL_{sr} \\ dL_{sr}' & Zeros \end{bmatrix}$$

$$\frac{dL_{sr}}{d\theta} = -L_m \cdot \begin{bmatrix} 0 & 0 & 0 & Sin(\theta) & Sin(\theta+\gamma) & Sin(\theta-\gamma) \\ 0 & 0 & 0 & Sin(\theta-\gamma) & Sin(\theta) & Sin(\theta+\gamma) \\ 0 & 0 & 0 & Sin(\theta+\gamma) & Sin(\theta-\gamma) & Sin(\theta) \\ Sin(\theta) & Sin(\theta-\gamma) & Sin(\theta+\gamma) & 0 & 0 & 0 \\ Sin(\theta+\gamma) & Sin(\theta) & Sin(\theta-\gamma) & 0 & 0 & 0 \\ Sin(\theta-\gamma) & Sin(\theta+\gamma) & Sin(\theta) & 0 & 0 & 0 \end{bmatrix}$$

3. Induction Motor Model in d-q Axes

The mathematical model of the induction machine in the rotating reference frame will be supplied to derive the machine model in the α-β frame to be used in induction motor simulation in the d-q frame. This model can be deduced starting from basic equations (9, 10) refereeing to Fig. 1.

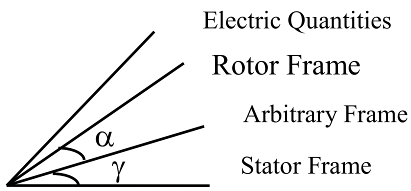

Fig. 1 Stator and rotor frame.

The stator voltage can be written in the following vector form:

Where

$$\frac{d}{dt}(\gamma+\alpha)=\omega_r,\quad \frac{d}{dt}\gamma=\omega_a,\qquad \frac{d}{dt}\alpha=\omega_a-\omega_r$$

Referred to arbitrary reference frame quantities, the stator voltage equation can be written as the following

$$v_s^s e^{j(\gamma+\alpha)}=R_s i_s^s e^{j(\gamma+\alpha)}+\tfrac{d}{dt}[L_m i_r^s e^{j(\gamma+\alpha)}+L_s i_s^s e^{j(\gamma+\alpha)}] \tag{9}$$

$$v_s=R_s i_s+j\omega_s[L_m i_r+L_s i_s]+[L_m \tfrac{d}{dt}i_r+L_s\tfrac{d}{dt}i_s] \tag{10}$$

The above equation can be represented in the following form:

$$v_s=R_s i_s+j\omega_a\lambda_s+\tfrac{d}{dt}\lambda_s \tag{11}$$

Where the flux components are

$$\lambda_{ds}=L_s i_{ds}+L_m i_{dr}$$

$$\lambda_{qs}=L_s i_{qs}+L_m i_{qr}$$

Decomposing the stator voltage into two components labelled as d,q

$$v_{sd}=R_s i_{sd}-\omega_a\lambda_{sq}+\tfrac{d}{dt}\lambda_{sd} \tag{12}$$

$$v_{sq}=R_s i_{sq}+\omega_a\lambda_{sd}+\tfrac{d}{dt}\lambda_{sq} \tag{13}$$

The rotor voltage can be written in the following vector form:

$$\bar{v}_r=R_r\bar{i}_r+\frac{d}{dt}\bar{\lambda}_r$$

Referred to the arbitrary reference frame

$$v_r^r e^{J(\alpha)}=R_r i_r^r e^{j(\alpha)}+\tfrac{d}{dt}[L_m i_s^r e^{j(\alpha)}+L_r i_r^r e^{j(\alpha)}] \tag{14}$$

$$v_r^s=R_r i_r^s+j(\omega_a-\omega_r)[L_m i_s^s+L_r i_r^s]+[L_m\tfrac{d}{dt}i_s^s+L_r\tfrac{d}{dt}i_r^s] \tag{15}$$

The above equation can be written in the following form:

$$\lambda_{dr}=L_r i_{dr}+L_m i_{ds} \tag{16}$$

$$\lambda_{qdr}=L_r i_{qr}+L_m i_{qs}$$

Decomposing the rotor voltage into two components labelled as d,q

$$v_{rd}=R_r i_{rd}-(\omega_a-\omega_r)\lambda_{rq}+\tfrac{d}{dt}\lambda_{rd} \tag{17}$$

$$v_{rq}=R_r i_{rq}+(\omega_a-\omega_r)\lambda_{rd}+\tfrac{d}{dt}\lambda_{rq} \tag{18}$$

The motor in the d-q axis can be expressed using the following matrix form equations

$$\begin{bmatrix} v_{sd}\\ v_{sq}\\ v_{rd}\\ v_{rq}\end{bmatrix}=\begin{bmatrix} R_s+pL_s & -\omega_a L_s & pL_m & -\omega_a L_m\\ \omega_a L_s & R_s+pL_s & \omega_a L_m & pL_m\\ pL_m & -(\omega_a-\omega_r)L_m & R_{rd}+pL_r & -(\omega_a-\omega_r)L_r\\ (\omega_a-\omega_r)L_m & pL_m & (\omega_a-\omega_r)L_r & R_{rq}+pL_r\end{bmatrix}\cdot\begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix} \tag{19}$$

Simplifying the above equation leads to obtaining the motor model in the arbitrary rotating reference frame

$$p.\begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix}=\frac{1}{L_sL_r-L^2{}_m}.A\cdot\begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix}+\frac{1}{L_sL_r-L^2{}_m}.\begin{bmatrix} L_r & 0 & -L_m & 0\\ 0 & L_r & 0 & -L_m\\ -L_m & 0 & L_s & 0\\ 0 & -L_m & 0 & L_s\end{bmatrix}\begin{bmatrix} v_{sd}\\ v_{sq}\\ 0\\ 0\end{bmatrix} \tag{20}$$

$$A=\begin{bmatrix} -R_sL_r & \omega_aL_sL_r-(\omega_a-\omega_r)L^2{}_m & R_rL_m & \omega_aL_mL_r-(\omega_a-\omega_r)L_mL_r\\ -\omega_aL_sL_r+(\omega_a-\omega_r)L^2{}_m & -R_sL_r & -\omega_aL_mL_r+(\omega_a-\omega_r)L_mL_r & R_rL_m\\ R_sL_m & -\omega_aL_mL_s+(\omega_a-\omega_r)L_mL_s & -R_rL_s & -\omega_aL^2{}_m+(\omega_a-\omega_r)L^2{}_r\\ \omega_aL_mL_s-(\omega_a-\omega_r)L_mL_s & R_sL_m & \omega_aL^2{}_m-(\omega_a-\omega_r)L^2{}_r & -R_rL_s\end{bmatrix}$$

$$T_e = \frac{3P}{2} L_m (i_{rd}.i_{sq} - i_{rq}.i_{sd}) \quad (21)$$

$$T_e = J\frac{d(\omega_m)}{dt} + B.\omega_m + T_L \quad (22)$$

The machine model can be referred to rotor reference frame by putting $\omega_a = \omega_r$

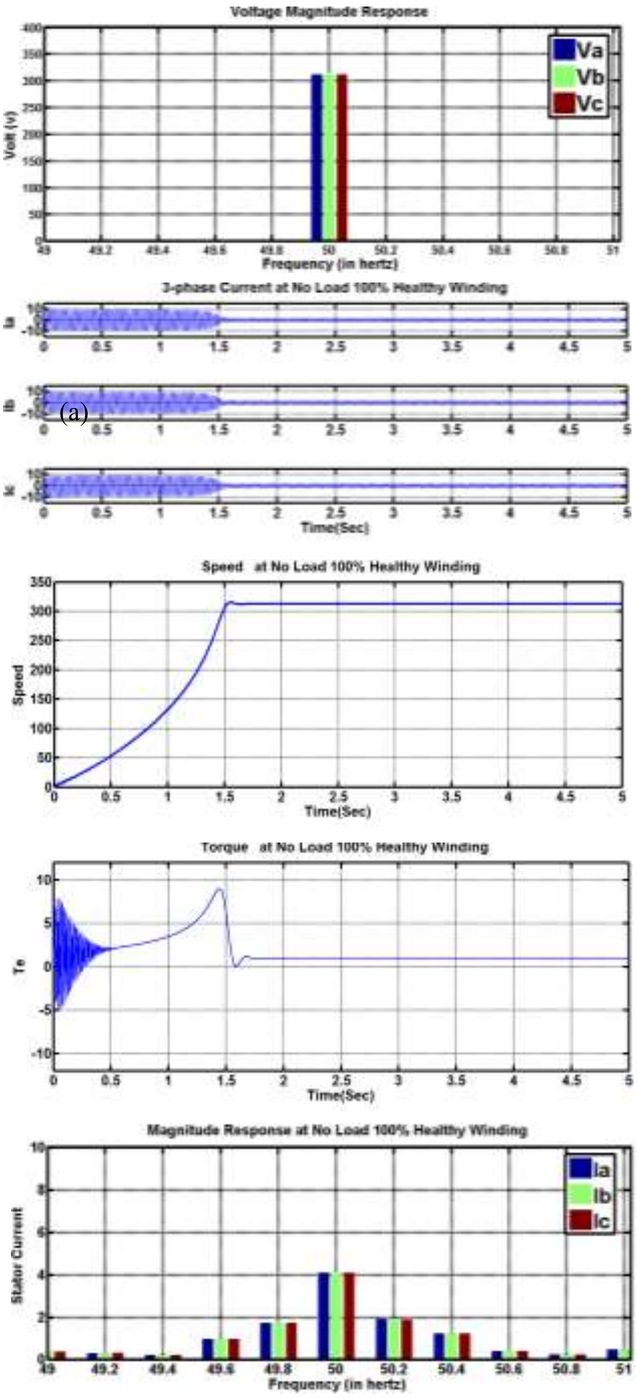

Fig. 2 Healthy motor input output quantities (a) the motor supply voltage, (b) motor stator current, (c) motor speed, (d) motor torque, and (e) three phase stator current spectrum

The ABC model has been investigated on a healthy case with the parameters listed in section VII and the simulation has been carried out at a frequency of 50 Hz. The current, speed, and torque of the motor under investigation are illustrated in Fig. 2.

4. Proposed Stator Fault detection Technique

Figure 3 depicts the effect of decreasing the stator resistance from R1 (rated value) to R1 –dr, as seen on the current amplitude. It is obvious that expanding the short circuit winding reduces the stator resistance, causing the stator current to rise. If knowing this, the stator re[illegible]e reduces as the number of series windings that make up the stator resistance per phase decreases. As a result, the stator defective phase resistance is r[illegible]d, and the stator current is increased depend[illegible] the ratio of the SC winding. In other words, the amplitude of the stator current is proportional to the stator short turns. The variation of the resistance detected from the current amplitude of the stator faulty phase and hence the percentage of the short circuit stator winding can be determined. By eliminating the shorted winding resistance, the faulted phase stator resistance is calculated as follows.

$$R_s = R_s(1-n) \quad (23)$$

Where

R_s: total resistance of the stator winding

n : The SC percentage winding

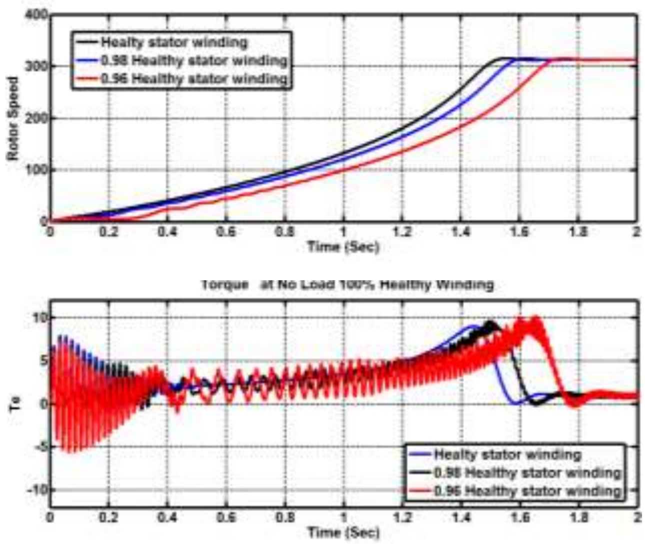

Fig.3 Induction motor torque and speed under stator resistance variation

5. Simulation Results

Figure 2 illustrates the simulation results for the healthy induction motor powered by a pure sinusoidal supply. The three phase stator voltage spectrum, three phase stator current, motor speed, motor toque, and three phase stator current spectrum are illustrated in Fig. 2. Figure 4 gives the current waveform and spectrum of the motor with a 0.05 short circuit stator winding. In terms of settling time and current amplitude, the distinction between a healthy and a malfunctioning motor is obvious in the faulty phase current.

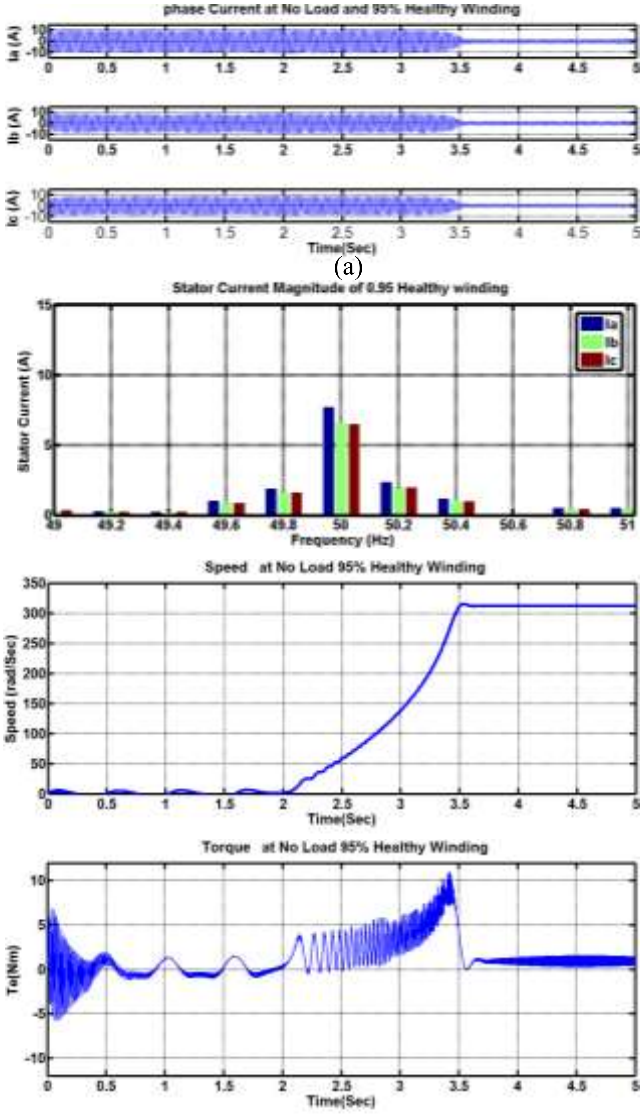

Fig. 4 Faulty motor input output quantities (a) motor stator current, (b) three phase stator current spectrum (c) motor speed, and (d) motor torque

Figure 5 illustrates the faulty phase current waveform and current spectrum for the Motor with different short circuit winding. It is clear the difference between different cases in settling time and current amplitude. A high number of turns of shorted winding results in a big rise time accomplished with a high current amplitude. These results mean that the quantity of rise time and current amplitude can be used to determine the amount of stator short winding in a faulty induction motor.

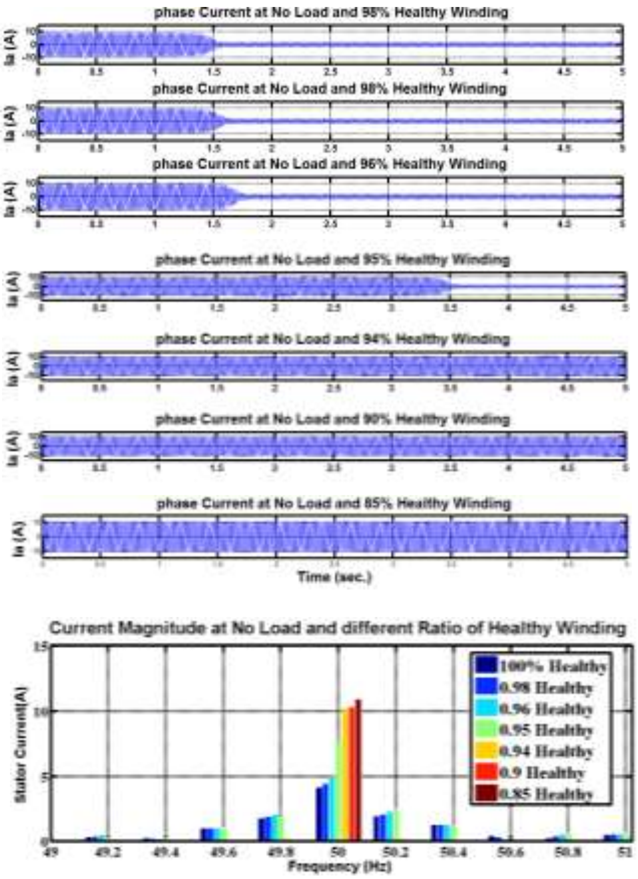

Fig. 5 Motor current and its spectrum associated with different percentages of the faulty stator winding

6. Detecting the Faulty Motor

The proposed technique consists of three steps: first, measurement of the induction motor stator current waveform; second, the Amplitude of the stator current is computed; and third, a rated speed raise time is determined, then the computed variables are subjected to a fuzzy algorithm. This technique allows a simplified algorithm to carry out by a simple low-cost controller to be used to classify the stator fault. A mathematical model of fault analysis has been implemented using fuzzy based on the previous rule base table as illustrated in Table 1.

The membership of the stator current and rise time, which comprises three fuzzy sets, is shown in Fig. 6. In addition, Fig. 6 depicts the stator winding state, which shows whether the winding of the stator is healthy, small faulty winding, medium faulty winding, high faulty winding, or seriously bad winding. All memberships are set up to work on a per-unit basis. The rule base table used as an inference rule basis table is given in Table 1.

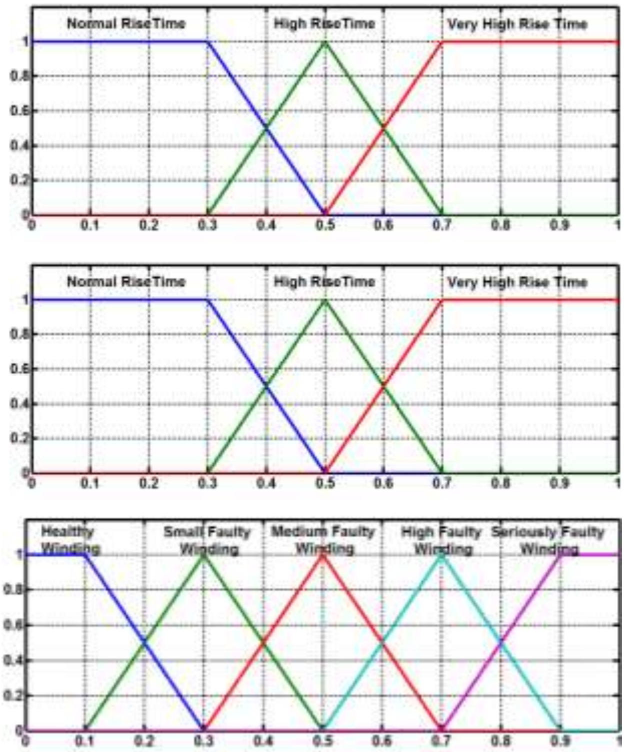

Fig. 6 Current membership, rise time membership, and stator winding membership

Settling Time / Current Amp.	Normal	High	Very High
Normal	Healthy Winding	Small Short Winding	medium Short Winding
High	medium Short Winding	High Short Winding	High Short Winding
Very High	High Short Winding	High Short Winding	Seriously Short Winding

Table 1 Rule base table

The fuzzy prediction program is carried out for five different cases illustrated in Table 2 which includes logged data and a database for fault diagnostic technique. The results indicate that the percentage error in predicting healthy turns of the stator winding is about 0.24% which verifies the robustness of the prediction technique.

	Actual Healthy Turns	I(A)	I%	Tr	Tr%	Predicted Healthy Turns
1	1	4.0711	0.333	1.5	0.333	1
2	0.98	4.3689	0.358	1.65	0.367	0.9791
3	0.96	4.7833	0.392	1.75	0.389	0.9623
4	0.95	7.7006	0.630	3.5	0.778	0.9500
5	0.94	10.1809	0.834	5.78	1.284	0.9400

Table 2 Data and results of the fuzzy prediction program

7. Conclusion

A three phase induction machine fault diagnosis technique has been proposed and development for the diagnostic technique is presented. The mathematical model of an induction motor has been created and tested under various fault circumstances using a time domain simulation model. The existing spectrum enables fault diagnostic of shorted stator windings of induction by utilization of the motor model. The proposed fault diagnostics system has produced logged data that indicates the problem condition based on the database status. The created technique can determine how much of a stator winding is short. The technique is suitable for usage in an induction motor on-line fault diagnostics system. The proposed work can be extended to include the other electrical faults and mechanical faults to be a complete faults diagnostics algorithm

8. Machine Parameters

$R_{sa}=R_{sb}=R_{sc}=3.85$ Ohm
$R_{ra}=R_{rb}=R_{rc}=2.50$ Ohm
$L_{ls}=0.0576$ H $L_{lr}=0.0576$ H
$L_m=0.28779$ H P=4
J =0.03 kg.m^2 B=0.003 kg.m^{2}Sec
Number of rotor bars=28

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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