Modeling And Simulation Of Rotor Side Fault Diagnosis Of Induction Motor By Using Fuzzy Based Controlled Identifier

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Abstract— Quality control is applied in manufacture process. The good condition of electrical machines can be obtained by using diagnostics. There are a lot of methods that can be used for diagnostics of electrical machines. In the literature, standard procedure are based on a study of electrical signals.

This work proposes, a novel automated practical implementation for non contiguous rotor side broken bars detection and diagnosis in induction motors. In this work process for detection and diagnosis of rotor side broken bars is there based on the spectral analysis via fast Fourier transform (FFT) and classification of the spectral response based on fuzzy controlled identifier. For the fault diagnosis objective, two features are choose from the spectrum of the stator current, one is the amplitude of the harmonics representing the broken bars defect 2sf (where s is the slip and f is the fundamental harmonics) and the second is the dc value. By using these obtained parameters a fuzzy identifier will there to identify the number of broken bars. For the designing of this fuzzy identifier these two parameters are used as inputs where the decision about the state of rotor will be made. once the successful implementation of the proposed system several tests have been performed for various motor and load conditions. The results of detection and diagnostic obtained from the developed system is found to be very prominent than the state of the art algorithms. The recognition and diagnosis efficiency of the proposed work is almost 100% in both the detection and diagnosis faces.

Keywords- Rotor side fault detection, Three Phase Induction Motor, Fast Fourier Transform, Fuzzy Controller.

1. Introduction

Induction motor for many years has been regarded as the workhorse in industrial applications. In the last few decades, the induction motor has evolved from being a constant speed motor to a variable speed, variable torque machine. Its evolution was challenged by the easiness of controlling a DC motor at low power applications. When applications required large amounts of power and torque, the induction motor became more efficient to use. The good condition of electrical machines can be obtained by using diagnostics. There are lots of methods that can be used for diagnostics of electrical machines. In the literature, popular methods are based on a study of electrical signals. The project work proposes new implementation of diagnostics of imminent failure conditions of induction motor especially due to rotor side fault.

In this work a method for detection and diagnosis of rotor side broken bars is proposed based on the spectral analysis via fast Fourier transform (FFT) and classification of the spectral response based on fuzzy controlled identifier. For the fault diagnosis objective, two features are selected from the spectrum of the stator current, first is the amplitude of the harmonics representing the broken bars defect 2sf (where s is the slip and f is the fundamental harmonics) and the second is the dc value. By using these obtained parameters a sugeno type fuzzy identifier is proposed to identify the number of broken bars. For the designing of the proposed sugeno type fuzzy identifier these two parameters will be used as inputs where the decision about the state of rotor will be made. After the implementation of the proposed work it is expected that the proposed technique will able to efficiently detect the number of broken bars at rotor side.

2. Proposed Methodology

In this work a technique for detection and diagnosis of rotor side broken bars is proposed based on the analysis of the stator current of the motor. theproposed work starts with the envelop detection of the stator current using hilbert transform. After detection of stator current envelop spectral analysis is proposed via fast Fourier transform (FFT). The last and important stage of the proposed work is the classification of the spectral response of stator current. For the efficient classification a sugeno type fuzzy controlled identifier is proposed. For the fault diagnosis objective, two features are selected from the spectrum of the stator current, first is the amplitude of the harmonics representing the broken bars defect 2sf (where s is the slip and f is the fundamental harmonics) and the second is the dc value. By using these obtained parameters proposed sugeno type fuzzy identifier is used to identify the number of broken bars. For the designing of the proposed sugeno type fuzzy identifier these two parameters will be used as inputs where the decision about the state of rotor will be made.

2.1 Rotor Side Fault Detection And Analysis

The surveys on induction motors have shown that the rotor failure (10%). Precisely, the cast aluminum bars of the squirrel-cage rotor may be subject to faults as a result of internal mechanical stresses. A single broken rotor bar may cause its neighbors to fail dues to increased currents in adjacent bars and consequently increased thermal and mechanical stresses. These faults cause considerable economic losses. However, to obtain a high level of reliability for an electric drive with induction motors, a diagnostic system is necessary [8]. Traditionally, the monitoring and diagnostic of rotor broken bars based on motor current signature analysis (MCSA) used as non-invasive method to detect sidebands harmonics around the fundamental supply frequency expressed by:

$$f_{rbb} = (1 \pm 2s)f \qquad ...(1)$$

Where*frbb*is the related broken bar frequency. However, at low slip these components $(1 \pm 2s)f$are relatively close to the fundamental component, which makes their detection much more difficult. To avoid this problem, the amplitude modulation (AM) of stator current induced by rotor asymmetry is exploited in aid of diagnostic. In fact, the rotor fault effect can be localized in the stator current envelope spectrum at frequency expressed by [9]:

$$f_0 = 2ksf \qquad ...(2)$$

As shown in figure (1, 5.2, and 5.3), the most important components amplitudes are localized in the low frequency bandwidth. In this range the important components amplitudes are related to the dc term and rotor broken bars (2sf). In this work, the Hilbert transform is used to extract the stator current envelope. Then this signal is processed via fast Fourier transform (FFT). To extract the fault frequency component (2*sf*) from the stator current envelope spectrum, the frequency bandwidth affected by broken bar can be easily limited at frequency [$f_m f_M$], where f_m et $f_M$are selected according to type of the machine. In our case, f_m,f_M are fixed respectively at 0.33 Hz and 6.2 Hz. However, the dependence of the component (2sf) amplitude, at the same time, to the load and to the defect severity, returns the detection of the broken bars number very difficult. For this reason, in order to make an efficient diagnosis at various loads, it is important to introduce a discernment criterion. This is presented by the dc component amplitude which reflects the slip image (Figure 5.4). These two previous amplitudes combined with fuzzy logic technique, as artificial intelligence diagnostic tool, can be defined as a new broken bar fault detection method [10-12].

2.1.1 Stator Phase Current Envelope:

Theoretically, in the case of rotor asymmetry created by broken bars, the stator current can be written as:

$$\mathbf{i_A}(\mathbf{t}) = I_f \cos(2\pi \mathbf{f}\mathbf{t} - \varphi) + \sum_k I^k_{\mathbf{RBB1}} \cos\left(2\pi(\mathbf{f} - 2\mathbf{ksf})\mathbf{t} - \varphi^k_{\mathbf{RBB1}}\right) + \sum_k I^k_{\mathbf{RBB2}} \cos\left(2\pi(f + 2ksf)\mathbf{t} - \varphi^k_{\mathbf{RBB2}}\right) \qquad ...(3)$$

Where, I_f The fundamental value of the phase stator current, φ The main phase shift angle of the phase stator current, I^k_{RBB1} The left magnitude for the harmonic component f_{Rbb}, I^k_{RBB2} The right magnitude for the harmonic component f_{Rbb}, φ^k_{RBB1} The left phase shift angle of component f_{Rbb}, φ^k_{RBB2} The right phase shift angle of component $f_{Rbb.}$

Above expression can be rewritten as:

$$i_A(t) = A(t)\cos(2\pi f t) + B(t)\sin(2\pi f t) \qquad ...(4)$$

And further can take the form:

$$i_A(t) = A_m(t)\sin(2\pi f t + \theta(t))$$

With:

$$A_m(t) = \sqrt{A(t)^2 + B(t)^2}\ , \quad \theta(t) = \arctan\left(\frac{B(t)}{A(t)}\right)$$

$$A(t) = I_f\cos(\varphi) + \sum_k \left((I^k_{RBB1}\cos\varphi^k_{\mathbf{RBB1}} + I^k_{RBB2}\cos\ \varphi^k_{\mathbf{RBB2}})\cos(2\pi(2ksf)t) + (I^k_{RBB2}\sin\varphi^k_{\mathbf{RBB2}} - I^k_{RBB1}\sin\varphi^k_{\mathbf{RBB1}})\sin(2\pi(2ksf)t)\right)$$

and

$$B(t) = I_f \sin(\varphi) + \sum_k ((I_{RBB1}^k \sin\varphi_{\mathbf{RBB1}}^k + I_{RBB2}^k \sin\ \varphi_{\mathbf{RBB2}}^k) \cos(2\pi(2ksf)t) + (I_{RBB1}^k \cos\varphi_{\mathbf{RBB1}}^k - I_{RBB2}^k \sin\varphi_{\mathbf{RBB2}}^k) \sin(2\pi(2ksf)t))$$

As shown in previous relation, the rotor faults in induction motor as rotor asymmetry, induced by the broken bar, modulate the amplitude of stator current at frequency 2ksf, by exploiting this fact; the stator current envelope can be used as a diagnostic signal.

2.1.2 Extraction of the Stator Phase Current Envelope

Typically, the stator current envelope can be extracted via different methods as Hilbert transform, filter demodulation and others. Hilbert transform (HT) is a well-known signal analysis method, used in different scientific fields such as faults diagnosis, and others. The HT of a real signal $i_A(t)$ is defined as[13]:

$$HT(i_A(t)) = y(t) = \frac{1}{\pi t} * i_A(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{i_A(\tau)}{(t-\tau)} d\tau \quad ...(5)$$

The combination of the real signal with its HT, the so called analytic signal i(t) is formed:

$$\tilde{\imath}(t) = i_A(t) + jy(t) = a(t)e^{j\theta(t)} \quad ...(6)$$

Where $a(t) = \sqrt{i_A(t)^2 + y(t)^2}$ $\quad \theta(t) = \arctan\left(\frac{y(t)}{i_A(t)}\right)$

a(t) is the instantaneous amplitude of i(t) known as envelope of $i_A(t)$ and θ(t) is the instantaneous phase of i(t). For the simulation model developed, a typical stator current waveform and its extracted envelop for 20% rated load for two broken bars condition are shown in figure (1) and figure (2) respectively.

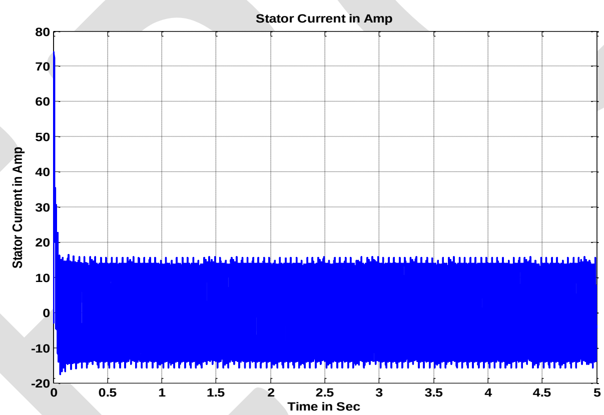

Figure (1) Stator current waveform for two broken bars at 20% of the rated load.

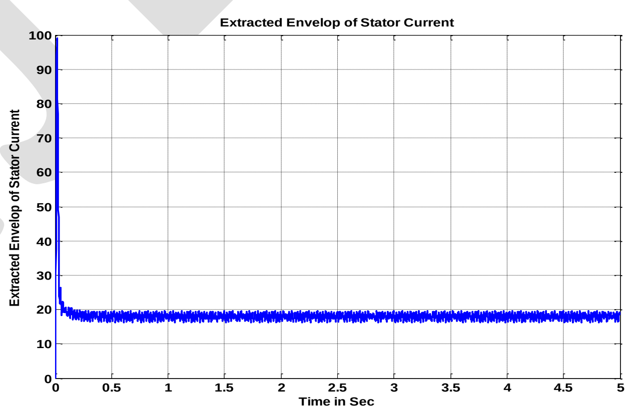

Figure (2) Extracted envelop of stator current for two broken bars at 20% of the rated load.

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2.1.3 Description of Developed Simulation Model

The developed model consists an induction motor of 3 HP, 220 volt and 1725 RPM, is fed by a current-controlled PWM inverter which is built using a Universal Bridge block available in Simulink library. Current and Voltage Measurement blocks provide signals for visualization purpose. Motor current, speed, and torque signals are available at the output of the Asynchronous Machine' block. The parameters used for the development of the simulation model are given in table-1.

Table-1 Important parameter used for Simulation.

Induction Motor Parameters	
Power Rating	3 HP
Voltage Rating	220 V
Speed Rating	1725 RPM
Stator Resistance	0.0435 Ohm
Stator Inductance	$4x10^{-3}$ H
Rotor Resistance	0.816 Ohm
Rotor Inductance	$2x10^{-3}$ H
Mutual Inductance	$69.31x\ 10^{-2}$
Inertia	0.089
Friction Factor	0
Pole Pairs	2

Finally figure (3), shows the simulation model for the project work with healthy motor condition.

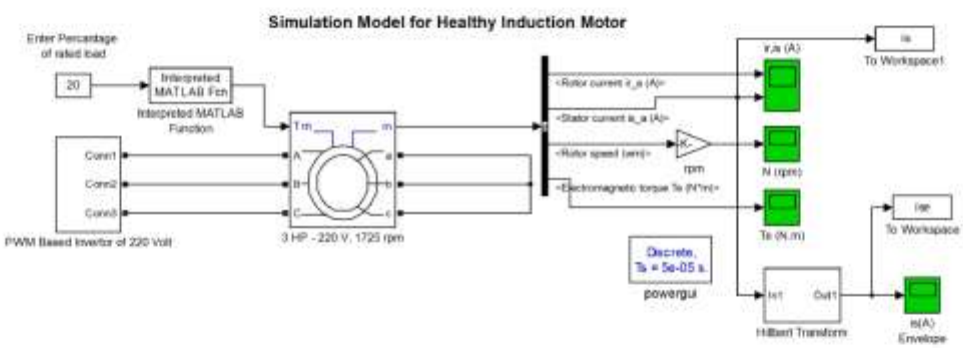

Figure (3) simulation model for the project work with healthy motor condition.

2.1.4 Simulation of Broken rotor bar

The key reasons for a broken rotor bar are [31]:

1. Direct on line starting which leads to excessive heating and mechanical problems.
2. Variable mechanical load.
3. Unsatisfactory rotor cage manufacturing.

Broken rotor bar faults can be simulated by connecting three resistances with the rotor resistance so that by increasing one of the rotor phase resistances, the broken rotor bar equivalent resistance can be computed as in (7).

$$R_{brk} \cong (0.33/4) R_r z_{nb} \Big/ N^2 s \quad \dots (7)$$

WhereR_r= Rotor resistance for healthy motor, z_{nb} = Total number of bars, N = number of broken bar, s = slip.

The external added resistances are changed in 0.0833 Ω steps, which represent the difference between the reference rotor resistance and the original rotor resistance for one broken rotor bar. Reference rotor resistance depends on the number of broken bars and the total number of rotor bars [32]. The resistance of induction motor rotor bar is assumed to be high.

On the basis of the above rotor bar broken technique two different simulation models have been developed for the simulation of one broken bar (1BRB) and two broken bar (2BRB).

2.1.5Spectrum of Stator Current Envelope

Several tests, under different loads, for healthy and faulty rotor were carried out by the researchers. In each case, after acquisition of one phase stator current and extraction of its envelope via Hilbert transform, the FFT is applied to obtain the envelope spectrum. Then, the dc and 2sf amplitude are extracted.

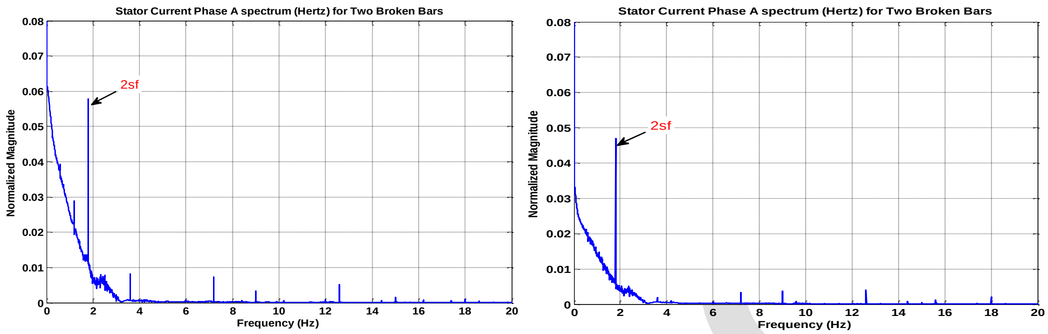

Figure (4) Spectrum of stator current envelope for two broken bars at 100% and 50 % of the rated load.

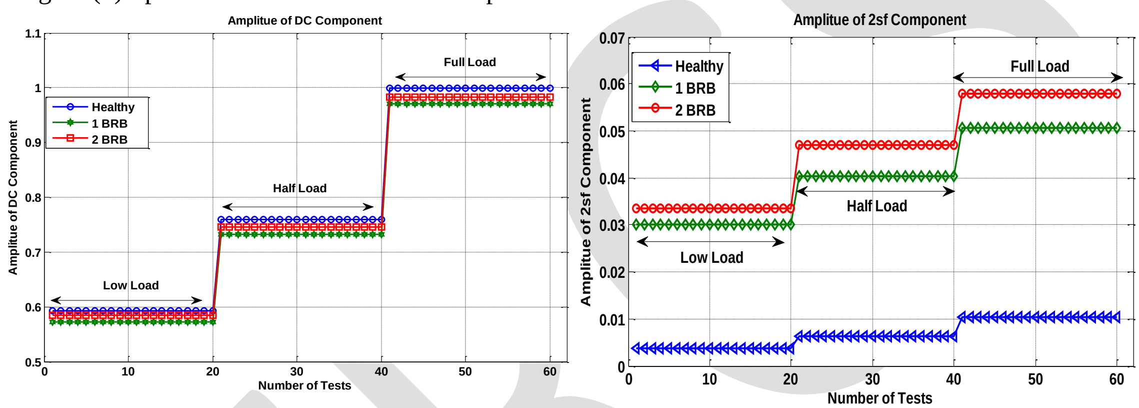

Figure (5) Amplitude of dc and 2sf components under different load and state (Healthy, 1 broken bar, 2broken bar.

Figure (4 and 5) shows the evolution of these amplitudes according to the defects severity and the load. It is obvious that the amplitude of a dc component is extremely sensitive to the load. On the other hand, the amplitude of the harmonic 2sf is sensitive at the same time to the defect severity (number of broken bars) and to the load variation. Thus, by the observation of this amplitude, the rotor state can be deduced.

2.2 Block Diagram Representation of Proposed Sugeno Type Fuzzy Logic Approach for Rotor Faults Diagnosis:

The aim of this work is to design an expert system for the detection and diagnosis of rotor broken bar broken with the as much as less input possible. In accordance to the simulation done, the selection of inputs is related at the harmonics amplitude 2sf, unfortunately this harmonics is sensitive to the load which leads to interference between data. For example, some amplitude extracted during functioning at, full load with one broken bar and the half load with two broken bars are interfered. For the distinction, another entry sensitive to the load proves to be indispensable. The amplitude of the dc component accomplished this task. Thus, the amplitudes of dc and 2sf components called respectively $\mathbf{A}_{dc}$ and $\mathbf{A}_{fbb}$, will be used as input for the proposed sugeno type fuzzy inference system figure (6). By fuzzy inference, using a knowledge base, compressing a rule and data base, the state of the rotor, is then obtained as output. The rotor condition is chosen as the output variable, which provides three levels of output.

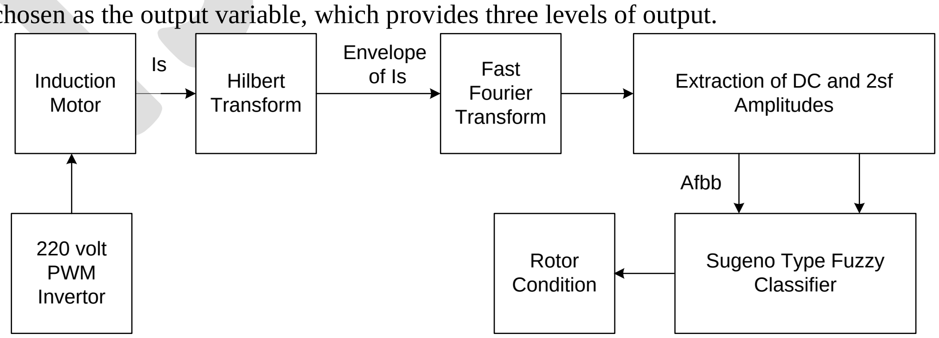

Figure (6) Proposed Motor fault diagnosis using Sugeno type fuzzy inference system.

2.2.1 Development and Training of Sugeno Type Fuzzy Inference System for Rotor Faults Diagnosis:

For the efficient generation of sugeno type fuzzy inference system (SANFIS) for rotor side faults diagnosis 60 simulated parameter values for the three motor conditions (Healthy, 1BRB and 2BRB), obtained has been used as shown in table-2. Two parameters Afbb and Adc has been used as two inputs of SANFIS whereas surface Rotor condition is taken as the single output. Therefore the developed SANFIS is the two input and single output structure.

Table -2 Nine Experimental parameter values (Out of 60 observations) used for development and training of SANFIS.

S. No.	Motor Condition	Load Condition	Afbb	Adc	SANFIS Output (Rotor Condition)
1		full	0.0104	0.9994	1
2	Healthy	half	0.0063	0.759	1
3		low	0.0038	0.5932	1
4		full	0.0506	0.9711	2
5	1BRB	half	0.0403	0.732	2
6		low	0.03	0.5721	2
7		full	0.0578	0.9831	3
8	2BRB	half	0.047	0.7452	3
9		low	0.0335	0.5844	3

After the successful training of SANFIS the average testing error obtained is 5.3818×10^{-5}. Now the membeship functions of the developed SANFIS (VST_anfis.fis) after sucessful training and tecting are shown in figure (12).

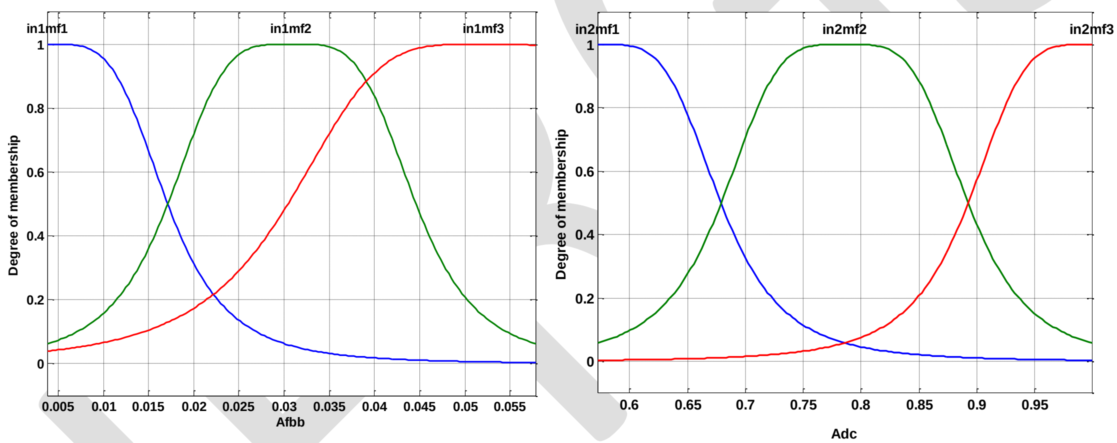

Figure (12)Input Afbb and Adc membership plots of developed SANFIS system.

the rules developed, which shows the characteristics of developed SANFIS are:

1. If (Afbb is in1mf1) and (Adc is in2mf1) then (RotorCondition is out1mf1) (1)
2. If (Afbb is in1mf1) and (Adc is in2mf2) then (RotorCondition is out1mf2) (1)
3. If (Afbb is in1mf1) and (Adc is in2mf3) then (RotorCondition is out1mf3) (1)
4. If (Afbb is in1mf2) and (Adc is in2mf1) then (RotorCondition is out1mf4) (1)
5. If (Afbb is in1mf2) and (Adc is in2mf2) then (RotorCondition is out1mf5) (1)
6. If (Afbb is in1mf2) and (Adc is in2mf3) then (RotorCondition is out1mf6) (1)
7. If (Afbb is in1mf3) and (Adc is in2mf1) then (RotorCondition is out1mf7) (1)
8. If (Afbb is in1mf3) and (Adc is in2mf2) then (RotorCondition is out1mf8) (1)
9. If (Afbb is in1mf3) and (Adc is in2mf3) then (RotorCondition is out1mf9) (1)

The training and testing process of developed ANFIS is shown in following figures.

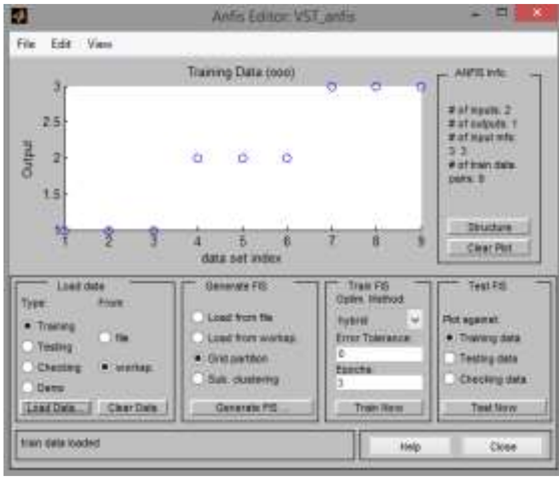

Figure (13)Plot of Training data

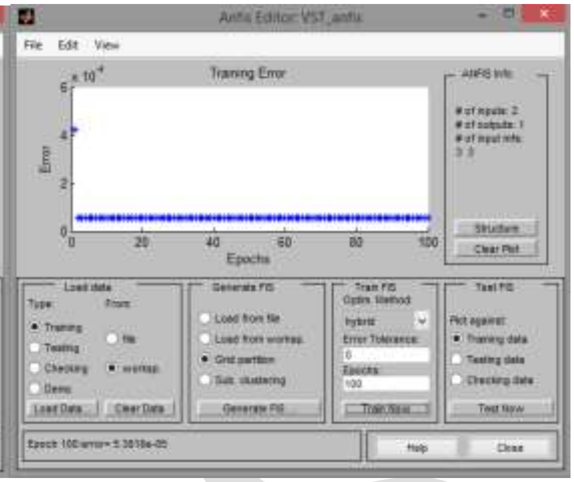

Figure (14)Plot of Training error

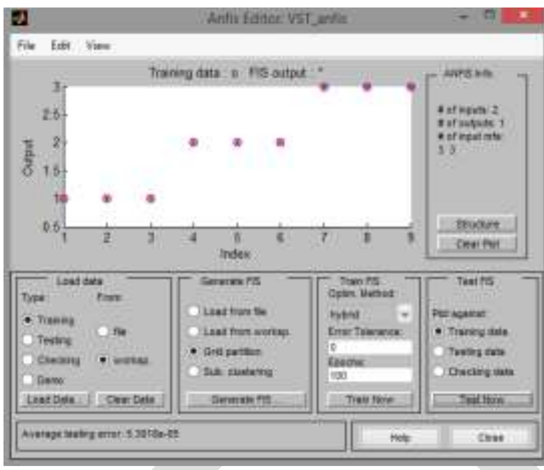

Figure (15)Plot of Testing error

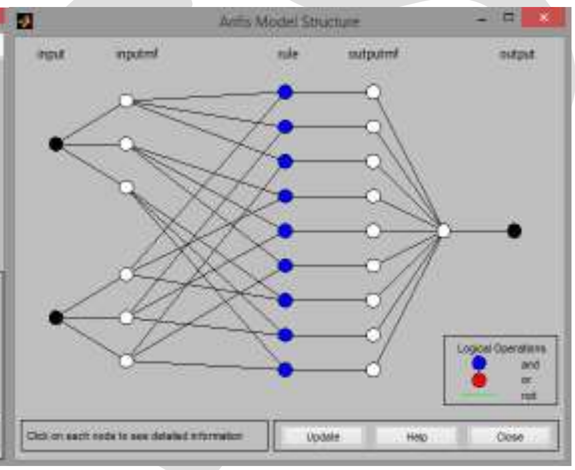

Figure (16)Structure of the developed SANFIS

Now after the successful development of the proposed technique table 5.3 describes the three conditions of the SANFIS output variable rotor condition.

Table-3the three conditions of the SANFIS output variable rotor condition.

S. No.	Rotor Condition	SANFIS Output (Rotor Condition)
1	Healthy	1
2	1BRB	2
3	2BRB	3

3. Results and Discussions

In this work a novel method for detection and diagnosis of rotor side broken bars has been developed based on the spectral analysis via fast Fourier transform (FFT) and classification of the spectral response based on sugeno type fuzzy controlled identifier. For the fault diagnosis objective, two features are selected from the spectrum of the stator current, first is the amplitude of the harmonics representing the broken bars defect 2sf (denoted as Afbb) (where s is the slip and f is the fundamental harmonics) and the second is the dc value (denoted as Adc). By using these obtained parameters a sugeno type fuzzy identifier is developed to identify the number of broken bars. This section describes the results obtained for rotor bar broken diagnosis.

To verify the efficiency of the developed sugeno type fuzzy logic based controlled identifier several simulation has been performed. These simulations were made on various load conditions, for the healthy and faulty motor. In each case the extracted envelope of stator current is transformed to frequency domain using fast Fourier transform (FFT). After the extraction of Afbb and Adc components from frequency domain, they are transferred to corresponding universe of discourse as input variables. The developed sugeno type fuzzy logic inference system SANFIS evaluates the inputs and diagnosis the rotor condition by providing the corresponding output. The recognition results obtained are shown in table-4, table-5 and table-6 for healthy motor, motor with one broken bar (1BRB) and motor with two broken bar (2BRB) respectively.

Table-4 Diagnostic Result for Healthy Motor.

S. No.	Motor Condition	Load Condition	Afbb	Adc	SANFIS Output (Rotor Condition)
1	Healthy	full	0.0104	0.9994	1
2			0.0104	0.9994	1
3			0.0104	0.9994	1
4		half	0.0063	0.759	1
5			0.0063	0.759	1
6			0.0063	0.759	1
7		low	0.0038	0.5932	1
8			0.0038	0.5932	1
9			0.0038	0.5932	1

Table-5 Diagnostic Result for Motor with one Broken Bar.

S. No.	Motor Condition	Load Condition	Afbb	Adc	SANFIS Output (Rotor Condition)
1	1BRB	full	0.0506	0.9711	2
2			0.0506	0.9711	2
3			0.0506	0.9711	2
4		half	0.0403	0.732	2
5			0.0403	0.732	2
6			0.0403	0.732	2
7		low	0.03	0.5721	2
8			0.03	0.5721	2
9			0.03	0.5721	2

Table 0-4 Diagnostic Result for Motor with Two Broken Bar.

S. No.	Motor Condition	Load Condition	Afbb	Adc	SANFIS Output (Rotor Condition)
1	2BRB	full	0.0578	0.9831	3
2			0.0578	0.9831	3
3			0.0578	0.9831	3
4		half	0.047	0.7452	3
5			0.047	0.7452	3
6			0.047	0.7452	3
7		low	0.0335	0.5844	3
8			0.0335	0.5844	3
9			0.0335	0.5844	3

It is clearly observable form the tables 4, 5 and 6, that the developed rotor bar broken diagnosis system is highly efficient to detect and diagnose the rotor broken bars for the test system developed. As far as the recognition and diagnosis efficiencies are concern, the developed system provides almost 100% efficiency in both the detection and diagnosis faces.

4. Conclusions and Future Scope

In this paper a diagnosis method using sugeno type fuzzy logic controlled identifier has been successfully developed to determine the state condition of the induction motor. The developed system is based on the spectral analysis via fast Fourier transform (FFT) and classification of the spectral response based on sugeno type fuzzy controlled identifier. For the fault diagnosis objective, two features are selected from the spectrum of the stator current, first is the amplitude of the harmonics representing the broken bars defect 2sf (denoted as Afbb) (where s is the slip and f is the fundamental harmonics) and the second is the dc value (denoted as Adc). For the efficient generation of sugeno type fuzzy inference system (SANFIS) for rotor side faults diagnosis 60 simulated parameter values for the three motor conditions (Healthy, 1BRB and 2BRB), obtained has been used. Two parameters Afbb and Adc has been used as two inputs of SANFIS whereas surface Rotor condition is taken as the single output. By using these obtained parameters a sugeno type fuzzy identifier is developed to identify the number of broken bars.

After the successful implementation of the developed system several tests have been performed for various motor and load conditions. The results detection and diagnostic results obtained from the developed system is found to be very prominent than the state of the art algorithms.

It is clearly observable form the resultant tables 4, 5 and 6, that the developed rotor bar broken diagnosis system is highly efficient to detect and diagnose the rotor broken bars for the test system developed. As far as the recognition and diagnosis efficiencies are concern, the developed system provides almost 100% efficiency in both the detection and diagnosis faces.

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