DEMODULATION OF INPUT CURRENT FOR THE ELECTRICAL FAULT DETECTION AND DIAGNOSIS OF A THREE PHASE INDUCTION MOTOR

Abstract

Owing to their sturdy structure and high power to weight ratio, induction motors are utilized extensively. These machines will also meet the requirements of many industries like low cost, minimal maintenance, and variable speed control etc. These motors frequently develop several defects because of their heavy use. Hence, fault diagnosis in induction machines become most demanded thing in industries to prevent unplanned downtime. A fault detection process that is efficient, stable, and worthwhile is required for prompt detection of faults in induction motors. Several studies have demonstrated in induction motors that faults introduce modulation of the stator currents in terms of their amplitude or frequency. Hence, Synchronous Demodulator is a sought-after method utilized in this paper to diagnose broken rotor bar and stator inter turn faults. Motor input current is acquired using LabVIEW software and the algorithm is executed in MATLAB environment. The experimental evaluation of proposed defect detection technique is carried out on 3-phase, 50 Hz, 415V and 2 HP squirrel cage motor.

Keywords: Induction motor, Synchronous demodulator, Stator Fault, Rotor Fault, Fault Detection.

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I. INTRODUCTION

Induction motors have become an integral part of industries, which helped to convert electrical energy to mechanical energy. These machines are used in industries for long period and hence are prone to failures [1]. To prevent a disastrous situation, it is essential to identify faults at its inceptive stage [2]. Thus, fault detection in induction motors is proving to be a herculean work for researchers. An IEEE survey on motors having horsepower greater than 200 has shown that, bearing faults account to 41%, stator faults to 37%, rotor faults to 10% and other faults to 12% out of total faults experienced [3-6]. The diagnosis of broken rotor bar and stator inter turn faults is carried out in this paper. The broken rotor bar makes up at least 8% of the total motor faults, [7-11]. The broken rotor fault usually damages the motor if it isn't detected in its incipient stage. On the other hand, the stator faults contribute at least 25% of the total motor faults [7-11]. A stator inter-turn fault produces circulating currents, which results in higher I^2R losses. This causes the winding isolation to deteriorate. Hence, different techniques to monitor these faults in an induction motor are available in literature. Vibration monitoring, torque, acoustic emission, flux, current, chemical and noise monitoring are the different types of methods that shows the state of the induction motor [12]. In the above-mentioned techniques, vibration and current monitoring are most preferred. The drawbacks of vibration monitoring are the presence of a noisy environment that contains shocks, external vibrations that can alter the results obtained from this type of monitoring [13]. They also require the presence of sensors at different positions on the machine. To overcome these drawbacks, one can use current monitoring. It is a cost-efficient, non-invasive, non-intrusive, provides easy access and requires less sensors. This kind of monitoring has become a popular method for researchers.

Motor current signature analysis is a condition monitoring technique that can discover and analyze problems present in induction machines [14-23][24]. This method was introduced for motors present in nuclear power plants and in hazardous areas, [25]. This test is performed online and does not disturb the normal operation of the motor under load. It can be used to find the fault at its incipient stage, prevent disastrous failures, extend the life of the motor and reduce power outages. The different fault detection techniques in MCSA include Fast Fourier transform, demodulation, wavelet transform and parks vector approach. Fast Fourier Transform is a popular method, but it has a resolution problem due to insufficient data, [26]. The wavelet transform originated to overcome the drawbacks of the short time Fourier transform (SFT) [28,29] and Wigner Ville distribution (WVD) [30,31]. This method was found to be only suitable for bearing related cyclic faults [12]. Demodulation on the other hand could be seen as an interesting method. This is because research shows that amplitude and frequency modulation of the motor current takes place due to electrical and mechanical faults, [27]. Load oscillation and eccentricity faults cause frequency modulation and amplitude modulation respectively. Whereas stator quantities of a motor are affected due to broken bars that induce modulation of amplitude in the rotor current, [27]. Based on this information, it proved to be better to use demodulation as the technique to detect the faults and its severity.

The different demodulation techniques are categorized with mono dimensional and multi-dimensional techniques, [27]. This paper deals with single-phase stator current. Hence, we proceed to choose a technique present in the mono dimensional techniques. Mono dimensional techniques include Hilbert transform, synchronous demodulator and Teager energy operator. Hilbert transform is a common method, which can efficiently compute the analytical signal if the Bedrosian conditions are satisfied. The only drawback of this method is the border effect. The Teager energy operator requires only three samples to find the fault indexing parameter but, this operator is sensitive to noise and assumes that the instantaneous frequency is slow. The synchronous demodulator is easier to implement than the other methods owing to its simplicity. The catch here is to assume the carrier frequency as known and its filtering stage tuning, [27]. Therefore, A synchronous demodulator is used in this paper to determine the fault severity with respect to stator inter turn and broken rotor bars.

In this work, application this technique in software simulation and then experimental work on the induction motor is executed. The faults that are analyzed in this work include the stator inter turn and broken rotor bars. The fault indexing parameters used to determine the fault severity are the RMS and standard deviation (SD) of a demodulated signal. The ratio of fault signal values to their healthy counterpart determines the fault severity. The respective results of the simulation and hardware are then analyzed and concluded.

II. SYNCHRONOUS DEMODULATION

A modulated signal is generated by nonlinear mixing of the message signal and the carrier signal. since the mixing is nonlinear, the output signal contains the sum and difference frequencies, which are known as sidebands. The two sideband frequencies are called upper and lower side band frequencies. The upper side band depicts the sum of the carrier and message signal whereas the lower side band depicts the difference of both the signals. A spectral display can show us the three frequencies i.e. carrier frequency, USB and LSB. In synchronous demodulation, an attempt to recover the information from the sidebands present in the modulated signal by translating it to baseband is made. The desired side band is maintained whereas the undesired sideband is removed using a filter that eliminates high frequencies. The output signal of the synchronous demodulator is called the demodulated signal.

The mathematical formula for synchronous demodulator is given below:

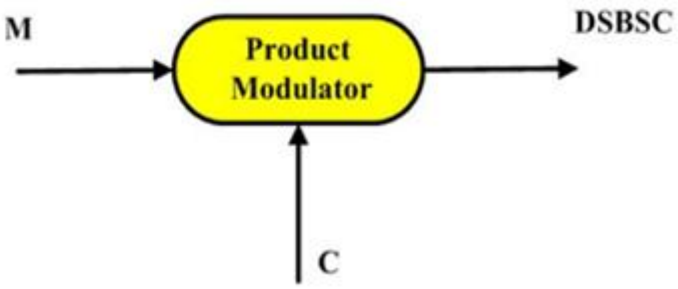


Figure 1: DSBSC signal generation

When the message signal is multiplied with the carrier signal using a multiplier or product modulator, the signal produced is DSBSC (Double side band suppressed carrier modulation).

$$S = M * C \tag{1}$$

$$S = A_m \cos(2\pi f_m t) * A_c \cos(2\pi f_c t) \tag{2}$$

$$S = \left(\frac{A_m A_c}{2}\right)\left(\cos(2\pi(f_c + f_m)t) + \cos(2\pi(f_c - f_m)t)\right) \tag{3}$$

Where S is DSBSC signal, M is motor signal, C is carrier signal, f_c carrier frequency, A_m is amplitude of motor signal, A_c is amplitude of carrier signal, and *fm* is the motor frequency.

The DSBSC signal is then multiplied with the carrier signal or local oscillator with the help of product modulator or multiplier, the produced signal is Vi. This signal is sent through the Butterworth low pass filter (LPF) to remove frequencies higher than cut off frequency of the filter. The output signal obtained is Vo, Demodulated DSBSC signal is further analysed to find the fault severity. Maintaining the Integrity of the Specifications.

$$v_i = S_{DSBSC} * C \tag{4}$$

$$v_i = A_m \cos(2\pi f_m t) * A_c \cos(2\pi f_c t) * A_c \cos(2\pi f_c t) \tag{5}$$

$$v_i = A_m \cos(2\pi f_m t) * A_C^2 \frac{(1+\cos(4\pi f_c t))}{2} \tag{6}$$

$$v_i = m(t)A_c^2 + m(t)\left(\frac{\cos(4\pi f_c t)}{2}\right) \tag{7}$$

The Butterworth filter eliminates higher frequencies i.e. greater than its cutoff frequency. Hence

$$v_i = m(t) * A_c^2 \tag{8}$$

III. MODELLING

The synchronous demodulation technique has been simulated in the MATLAB software by modelling the stator current and the carrier signal.

These are then subjected to synchronous demodulation to provide the demodulated signal. The demodulated signal contains information of the fault severity, which is analyzed by obtaining the value of RMS and SD from the demodulated signal.

1. Modelling of Stator Current:

$$I_0(t) = \sum_{K=1,3,5,7} \frac{I_m}{K} \sin(K\omega t) + W(t) \tag{9}$$

The above equation represents the healthy part of the stator current equation. Gaussian noise (WGN) is included to mimic the noisy conditions of a motor. This type of noise can be easily imposed on a sinusoidal signal and provide us accurate results. Where $I_0(t)$ is the stator current under normal situation, *K* is the harmonic order, *w* is the frequency of supply in rad/sec and *W(t)* is the WGN.

The fault part of the signal can be obtained by adding fault harmonics due to electrical faults to equation (9).

2. **Modelling of Carrier Signal:** The carrier signal can be obtained by selecting suitable carrier frequency $f_{c.}$ The carrier signal with selected frequency can be derived using the following expression.

$$I_c(t) = \sin 2\pi f_c t \tag{10}$$

3. **Fault Harmonics:** The rotor and stator faults individually produce frequencies that can be observed using spectral analysis [32]. The fault frequencies developed by rotor faults are:

$$f_{brb} = |1 \pm 2Mf_m| \tag{11}$$

Where M=0, 1, 2, 3, ---, and f_{brb} is the fault harmonic due to broken rotor bar. The fault frequencies developed by stator faults are:

$$f_{sit} = f_m\left[\frac{m}{p}(1-s) \pm M\right] \tag{12}$$

Where P shows the pole pairs, m=1, 3, 5--- and s is the slip.

To diagnose the inter-turn faults, particular frequencies are used. The fault frequencies considered are of the broken rotor bars and inter turn fault. The fault frequency is obtained by using the formulas present in the above paragraph.

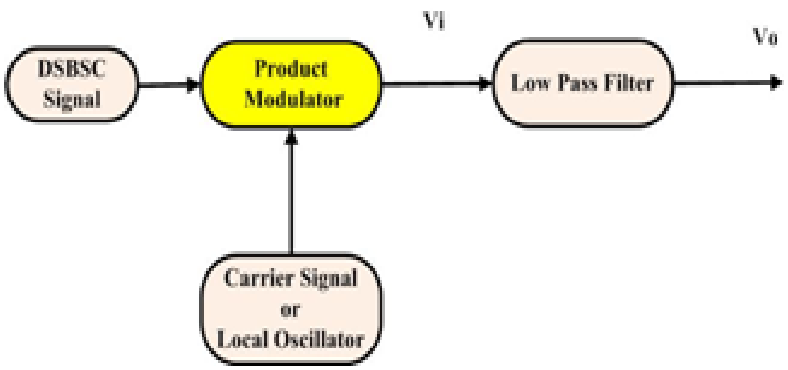


Figure 2: Synchronous demodulator

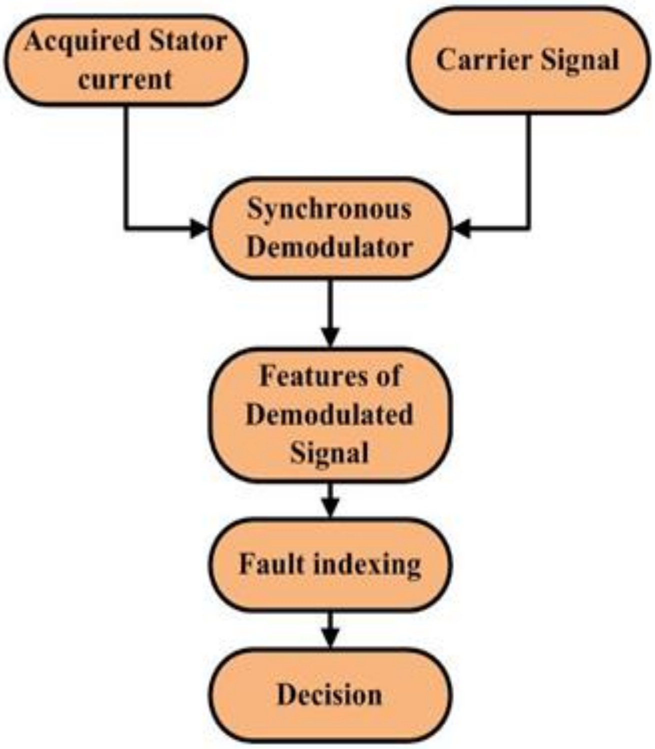


Figure 3: Proposed methodology

Once the fault frequencies and the fault magnitude are substituted in the program, the demodulated signal can be obtained.

Table 1:Fault Frequencies

Conditions	**Stator fault frequency (Hz)**		**Rotor fault frequency (Hz)**	
M = 1	74.6	-25.4	50.5	49.5
M = 2	174.6	-125.4	51	49

IV. PROPOSED METHODOLOGY

This paper deals with finding faults present in an induction motor using synchronous demodulator in MATLAB. This is done in five steps. The stator current from the machine and the carrier signal are sent to the synchronous demodulator. The demodulated signal is received from the synchronous demodulator are the fault features are obtained. The fault severity is calculated and analyzed. The processes are briefed in Figure 3.

1. **Extraction of Stator Current:** A transducer called hall effect transducer is used to extract the single-phase stator current form the induction motor. The data acquisition card is present between the stator current and the MATLAB software. The output terminals of the current sensor on which the supply lines of the motor are wrapped around is connected to the DAC. The DAC then captures the stator current signal which is then sent to the MATLAB to be analysed according to the respective sampling frequency. Hence, the single-phase stator current under different fault conditions can be extracted from the induction motor.

2. **Synchronous Demodulation:** Carrier signal is an alternating signal upon which information can be superimposed by using modulation techniques. By modulating this signal, one can transfer necessary information into the carrier signal. Modulation helps this signal to ‘carry’ the information of the message signal. The frequency of this signal is also called the centre frequency. Centre frequency is the frequency band’s centre occupied by the signal.

   “Maximally flat magnitude filter” is another name of the Butterworth filter. This is because in its frequency vs time plot, the filter produces a uniform output in its pass band and tends to null after its cut-off point. The order of the filter circuit is proportional to the concentration of reactive elements. This filter only consists of capacitors. So, more the capacitors, higher the order of the filter. A Butterworth low pass filter allows a signal with a frequency lesser than its cut-off frequency and limits the signals having a frequency that is more than the cut-off frequency.

3. **Fault Indexing Parameter:** In this paper, the features of the demodulated signal are analysed. The parameters used include the root mean square (RMS) and standard deviation (SD) of the output. The ratio of the faulty signal to healthy signal of the RMS and SD values are computed individually. The ratio shows the fault severity which is 1 for the healthy signal and increases as the faults are introduced.

V. EXPERIMENTAL SETUP

The setup arrangement shown in Fig 4, consists of a 1.5KW, 440 V, three-phase induction motor, meters, and a PC. A three-phase auto transformer supplies the motor with a voltage of 440V and the stator current is measured by a current sensor which contains the supply lines. A Data Acquisition Card made by the Nation instruments helps us to extract the stator current. The first test is done to acquire the healthy current from the machine depicted in Fig 5.

Figure 4: Experiment setup

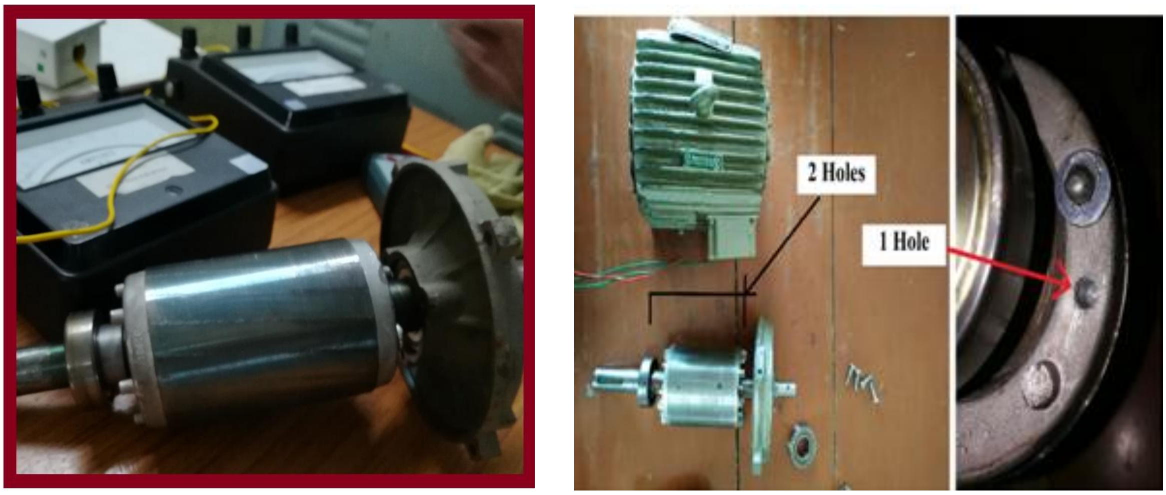


Figure 5: Healthy rotor

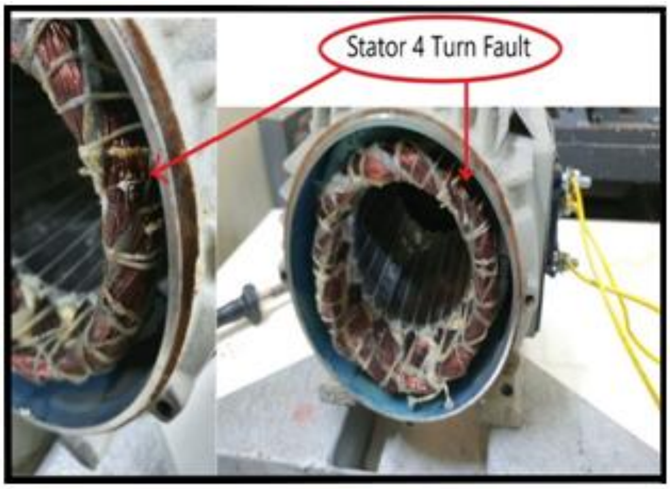


Figure 6: Stator 4 turn fault

Then the turns are shorted to create a stator fault as shown in Fig 6. The stator currents acquired are processed in MATLAB. A broken rotor fault is created by drilling hole on the rotor as shown in Fig. 7. A 5-mm diameter hole is created using the lathe machine. The stator current is extracted for a rotor fault of two holes and three holes.

The experiment model is similar to the simulations done in MATLAB. First, the stator current signals are extracted and stored in an excel file. The file is then linked to the MATLAB program using the MATLAB code. The single-phase stator current can now be utilized in the MATLAB software. The extracted file contains the three-phase stator current for a motor having a rotor fault with 2 hole, a broken rotor bar with 3 holes, a stator 4 inter turn fault and one which is healthy. For each fault, the motor is loaded four times and is represented as load1, load2, load3 and load4. In this model, the same procedure as the simulation model is followed and fault severity is calculated. The graphs obtained in MATLAB are shown below for each fault and their respective loads. The different plots shown are current signal, carrier signal, DSBSC signal and the demodulated signal.

VI. RESULTS AND DISCUSSION

This section is divided into two. The first one provides us the results obtained from the simulation and the second one has results that are obtained from the experimental model.

1. **Simulation Results:** In this, the stator current is modelled at various situations of the machine and used for the evaluation of proposed methodology. The modelled current is under different situations are shown in Fig. 8. The sampling frequency is chosen as 10kHz and a total of 10000 samples are used to plot the current signals. The modelled signal in time domain has similar visualization and difficult to identify the fault frequency. Hence, the signals are processed using the proposed scheme of fault estimation. The synchronous demodulation of modelled signals is performed and plotted in Fig.9-10. Now the direct demodulation will show slight difference in healthy and faulty situations, but the fault magnitude and it’s nature is unpredictable especially at beginning stage of fault. To avoid this situation, feature based analysis is proposed in this work. The fault indexing parameters proposed in the above sections are used for fault estimation and are computed after demodulation of stator current at each state. The feature indexing parameters of simulated work are tabulated in Table-II & III. From the tables it is difficult to analyze the variation in feature values due to insufficient changes. Hence, the bar graphs are plotted for these values and shown in Fig. 11. From this, it is noticed that the fault indication is small and almost same as healthy condition. This leads to wrong diagnosis of the motor and hence the ratio of fault values to healthy values are computed and tabulated in Table IV. The Simulation results show us that synchronous demodulation can detect incipient faults having fault magnitude of 0.001. The fault severity of the stator and rotor faults in its premature state is shown to be high. Hence, the experimental verification is executed to support the simulation work and is discussed in the following.

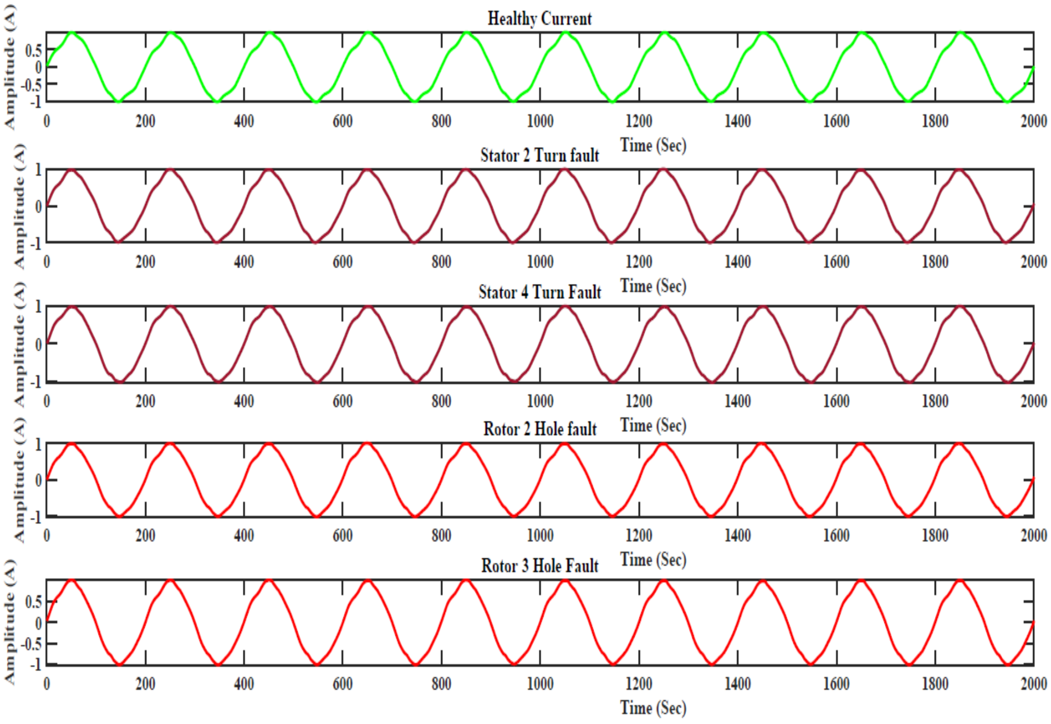


Figure 8: Modelled stator current under several situations of the induction motor

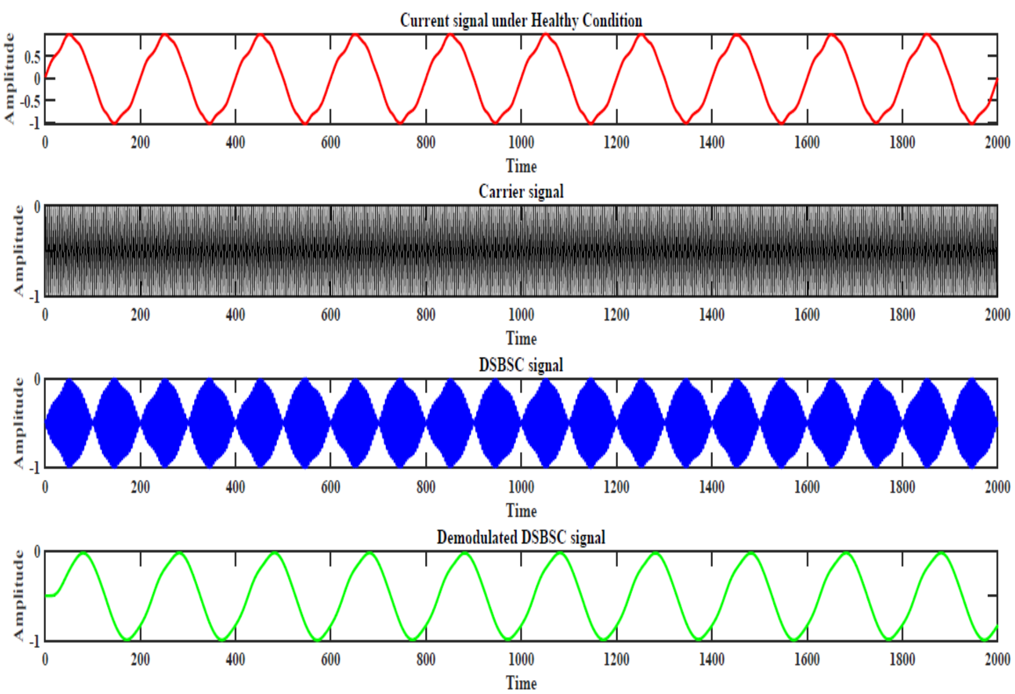


Figure 9: Demodulation of stator current with healthy situation

Table 2: RMS and SD values for K=1

Condition		Fm=0.001		Fm=0.01		Fm=0.1		Healthy value
		stator	rotor	stator	rotor	stator	rotor	
K=1	RMS	0.3472	0.3458	0.3481	0.3464	0.3518	0.3529	0.3399
	SD	0.3472	0.3458	0.3481	0.3464	0.3518	0.3529	0.3399

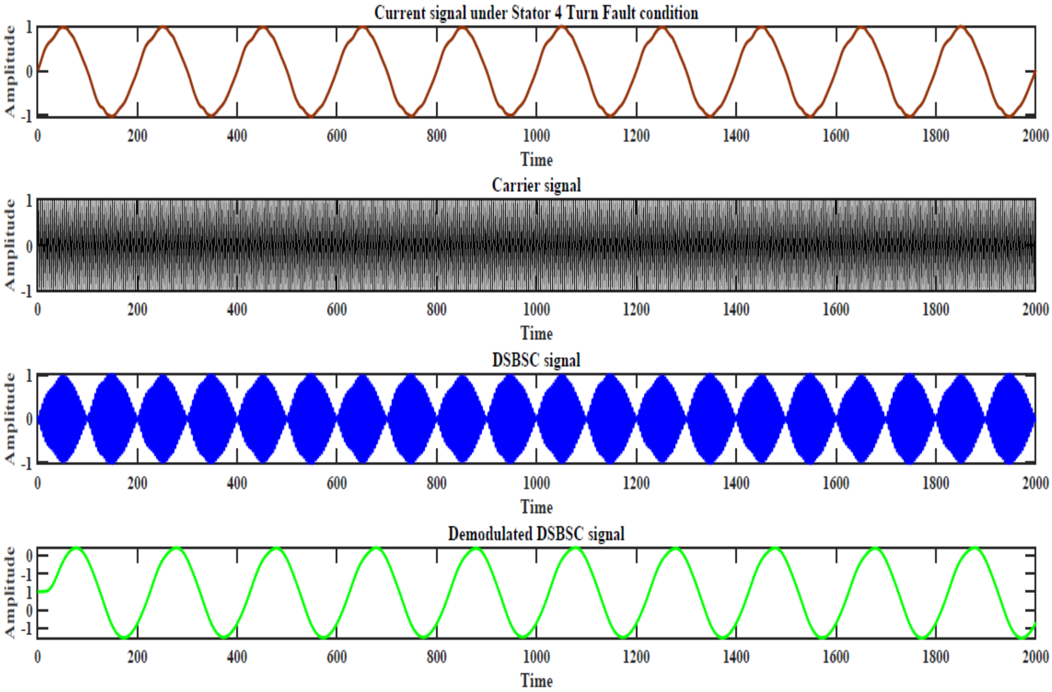


Figure 10: Demodulation of stator current with stator fault situation with 4 turns short.

Table 3: RMS and SD values for K=2

Condition		Fm=0.001		Fm=0.01		Fm=0.1	
		stator	rotor	stator	rotor	Stator	rotor
K=2	RMS	0.3469	0.3466	0.3484	0.3482	0.351	0.3517
	SD	0.347	0.3466	0.3484	0.3482	0.351	0.3517

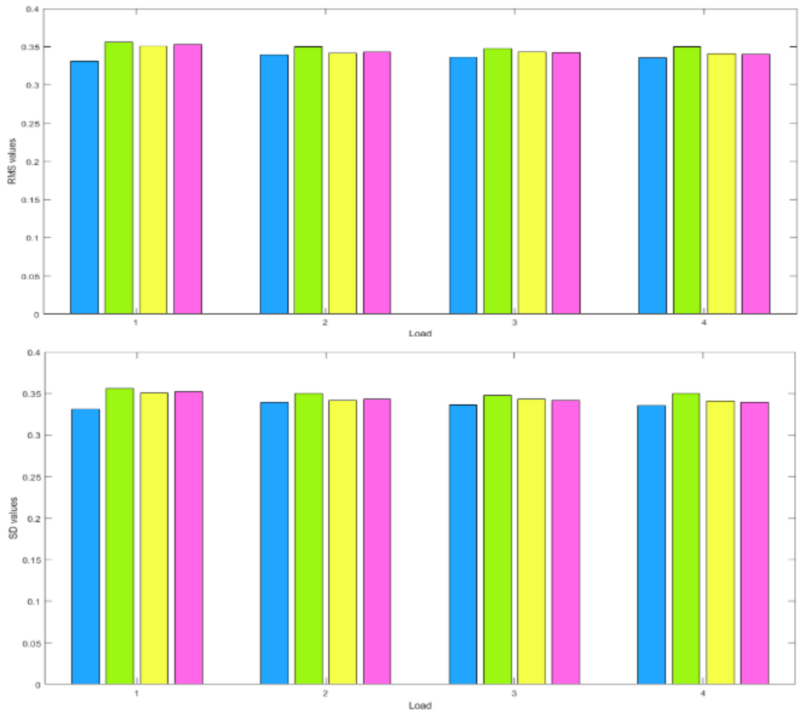


Figure 11: RMS and SD values of healthy current, stator and rotor faults for different loads

Table 4: Fault Severity

Fault severity		Fm=0.001		Fm=0.01		Fm=0.1	
		Stator	Rotor	Stator	Rotor	Stator	Rotor
K=1	RMS	1.0214	1.0173	1.0241	1.0191	1.035	1.0382
	SD	1.0214	1.0173	1.0241	1.0191	1.035	1.0382
K=2	RMS	1.0205	1.0197	1.025	1.0244	1.032	1.0347
	SD	1.0208	1.0197	1.025	1.0244	1.032	1.0347

2. **Experimental Results:** In the experimental verification of proposed fault detection scheme, various electrical faults are created manually as mentioned in the above section. The stator current under normal and abnormal conditions is acquired using data acquisition card with same sampling frequency used for simulation work. Further, the acquired signals are demodulated using synchronous demodulation and the signal analysis is carried out like simulation work. The RMS and SD values from the experiment model have been obtained and displayed in tables V and VI given below. From these tables, it is noticed that the feature parameters have shown great change in healthy and fault signals. Further, the fault severity is estimated using above mentioned indexing parameter and is tabulated in VII-VIII. The corresponding bar graphs are plotted in Fig. 12. Finally, it can be concluded that the experimental results have confirmed the perfectness in fault detection using synchronous demodulation. Loads 1 and 4 have good variation for faults whereas, the loads 2 and 3 have less variation in fault index. This requires further concentration in improving fault indexing especially at variable loads.

Table 5: RMS values

RMS	Healthy	Stator 4 turn	Rotor 2 hole	Rotor 3 hole
Load 1	0.3307	0.3561	0.3505	0.3525
Load 2	0.3394	0.35	0.3414	0.343
Load 3	0.3361	0.3474	0.3428	0.3419
Load 4	0.3356	0.3496	0.3407	0.3397

Table 6: SD Values

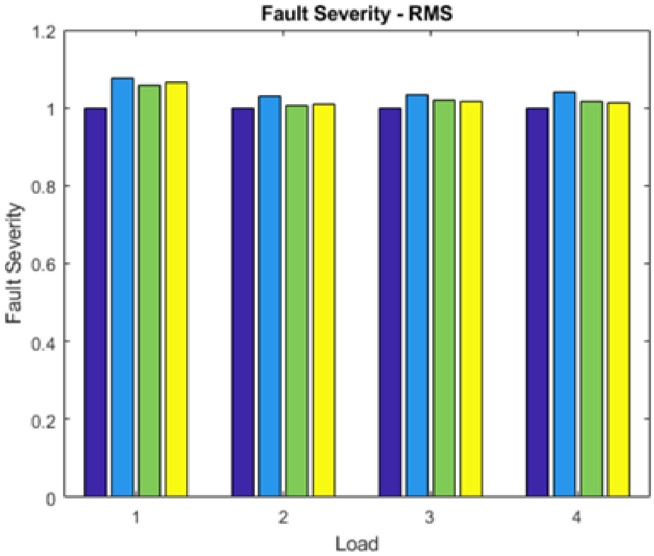
SD	Healthy	Stator 4 turn	Rotor 2 hole	Rotor 3 hole
Load 1	0.3306	0.3559	0.3504	0.3524
Load 2	0.3393	0.3498	0.3413	0.3429
Load 3	0.3361	0.3472	0.3427	0.3418
Load 4	0.3356	0.3495	0.3407	0.3396

Table 7: Fault severity with respect to RMS

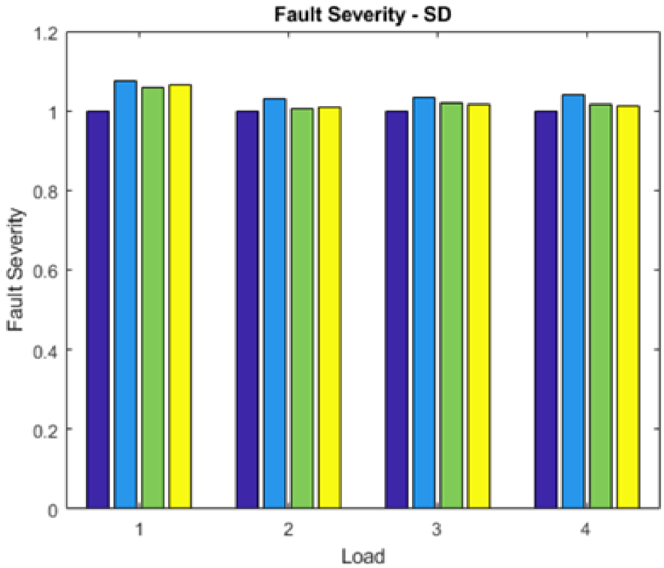
Fault severity RMS	Healthy	Stator 4 turn	Rotor 2 hole	Rotor 3 hole
Load 1	1	1.0768	1.0598	1.0659
Load 2	1	1.0312	1.0058	1.0106
Load 3	1	1.0336	1.0199	1.0172
Load 4	1	1.0417	1.0151	1.0122

Table 8: Fault severity with respect to SD

Fault severity SD	Healthy	Stator 4 turn	Rotor 2 hole	Rotor 3 hole
Load 1	1	1.0765	1.0598	1.0659
Load 2	1	1.0309	1.0058	1.0106
Load 3	1	1.033	1.0196	1.0169
Load 4	1	1.0414	1.0151	1.0119



(a)



(b)

Figure 12: Bar graphs of fault indexing parameters at different load conditions

VII. CONCLUSIONS

Fault diagnosis of induction motor is done in this work using synchronous demodulation of stator current. Various faults related to stator winding and rotor are proposed. Both simulation and experimental tests have done under various load condition which has helped in estimating the fault severity. Two fault estimation parameters have proposed for fault severity calculation namely RMS value and Standard Deviation (SD) after demodulation and both parameters have shown good indication. Further, the proposed work can be extended to all categories of faults like bearing related, eccentricity etc.

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