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Fault Diagnosis of Induction Motor Using MCSA and FFT

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Abstract Both mechanical and electrical faults should be investigated carefully to get best operation of the induction motor. In this paper, a description of the diagnosis of the induction motor against unsymmetrical supply voltage and the broken rotor bar using the Motor Current Signature Analysis (MCSA) and Fast Fourier Transform (FFT) respectively has been explained. Investigations of the speed, torque, current and flux density have been done. The FTT investigation of the stator current to detect the broken rotor bar fault was performed. The control method used is the vector control.

Keywords Fault Diagnosis, Induction Motor, Unbalance Voltage, Broken Rotor Bar, MCSA, FFT, Vector Control

1. Introduction

Nowadays, there is a demand for high performance electric drives. These drives can be capable of achieving speed command accurately. This has necessarily lead to more sophisticated control methods to deal with such an issue. Special attention was directed induction motor because of known reason such as size, cost, efficiency[1]. Electric power is the most important discovery in the life, and it is the core of the foundation of industry and whole society[2] There are many research deals with the unsymmetrical supply voltage, load oscillation and many monitoring techniques to ensure a high degree of safety. Theory of induction motor was introduced in[3] where the MCSA used as a tool for fault diagnosis for the applications of the induction motor.

In spite of these monitoring techniques, the induction motors still face an unexpected failure that reduces the lifetime of the induction motors. Fig.1. shows the induction motor faults percentages. Squirrel cage motor are mostly important due to the fact that they can work under fault conditions without any visible fault seen until the fault becomes high[4].

The simplified faults in the induction motors can be shown in Figure2[5].

Once the fault detected, the (MCSA) can diagnose the faults, these techniques are widely used in the monitoring to diagnose many faults such as shorted turns in the low voltage stator winding, broken rotor bar, eccentricity and mechanical faults such as bearing, bear box and load oscillations[6].

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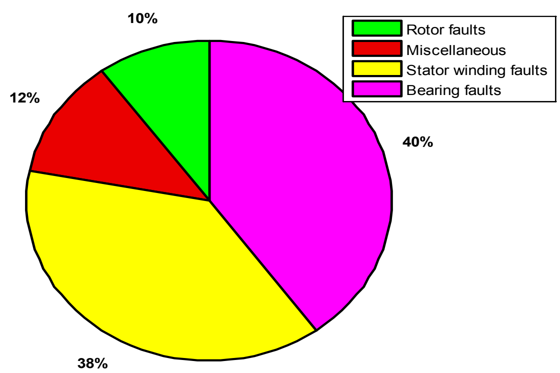

Figure 1. Induction motors faults percentages

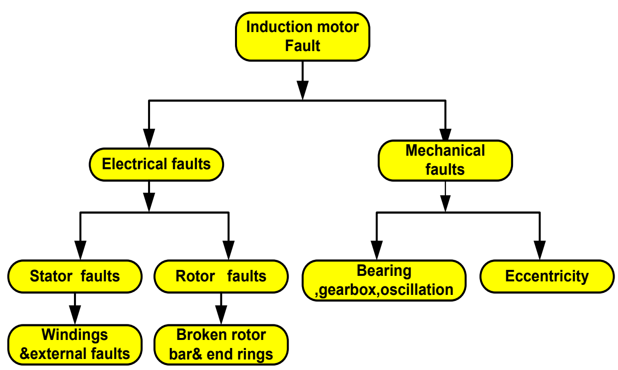

Figure 2. Simplified fault in the induction motors

Unbalance voltage is frequently occurred in many situations, and it is needed to be detected in the early stage to avoid the efficiency reduction, heating problem and consequently, the damage in the induction motor[7].The unbalance voltage is applied to the induction motor output in the unbalance three-phase circulating currents flowing in the stator winding A. The general rule of thumb is that for every 1% voltage imbalance, there is a 7% current imbalance is expected which is equivalent to the negative sequence voltage that causes negative braking torque. Rotating flux opposes the main flux unbalanced-voltage operation that will also create a pulsating torque which produces speed pulsation, mechanical vibration, and consequently, acoustic noise. The bearing maybe damaged because the component importance of the double system frequency is the stator that may cause a thermal problem[8]. To deal with this heating problem, the induction motor should be de-rating that means, another machine with large power should be founded as in Figure 3.

The vector control achieves robustness against model and parameter uncertainties over a wide speed range[9].

Design a vector control which is robust against rotor time constant a variation using the high gain observer has been investigated in[10].

Unbalanced currents in stator winding occur due to the non equal line voltage of induction motor. The variation of voltage should not exceed ±10% when the frequency is at the rated value and ±5% for frequency if the voltage is at the rated value[11].

There are many reasons for the unbalancing such as impedance of the electricity, generators terminal voltages, load currents, fault operations, power factor correction equipment and voltage regulators in the utility distribution lines[12].

According to National Electrical Manufacturers Association (NEMA) the unbalanced voltage percentage is given by Eq.1:

$$U_{unb} = \frac{\max imum\, voltage - rated\, voltage}{rated\, voltage} \quad (1)$$

For example, if the rated voltage for three-phase induction motor was 230 V and the phase voltages were (235,230,233), the rated voltage is:

$$(235+230+233)/3 = 232.67v$$

So the unbalance percentage is:

$$(235-232.67)/232.67 = 1.0014\%$$

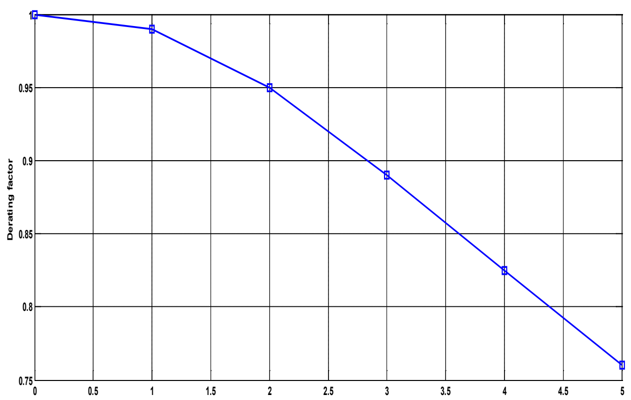

Figure 3. Percentage voltage unbalances

The unspecified harmonic numbers in the equations of abnormal harmonics induces ambiguous results from MCSA-based diagnosis methods[13]. A technique to distinguish the difference between the unbalance in voltage power supply and the intern fault based on the magnetic field pendulous oscillation was proposed in[14].

Unsymmetrical supply voltages and unbalance load in the voltage source rectifier which can be used by induction motor are investigated to get optimal control strategy[15]. The proposed work achieves good indication for any asymmetrical system in the voltage supply and the load oscillation as seen in the results. Induction machines fault diagnosis methods with respect its function and properties are listed in[16].

The effect of voltage variation on the motor characteristic can be summarized in Table1.

Table 1. Voltage variation effect[31]

Characteristic	Voltage 6%High	Volage 6%Low
Full load speed	Up to 0.5%	Down 5%
Starting torque	Up to 12 %	Down 11%
Starting current	Up to 6 %	Down 5%
Full load current	Down 4%	Up to 5 %
Temperature rise	Down 4%	Up to 6 %
Efficiency 0.5 load	Down 1.5%	Up to 5 %
Efficiency 75 load	Down 1.5%	Up to 2 %
Efficiency full load	No change	Down 1%
p.f 0.5 load	Down 4%	Up to 4 %
p.f 0.75 load	Down 3%	Up to 2 %
p.f full load	Down 2%	Up to 1 %

The losses in the induction motor can reduced when the current distortion is reduced. Increasing the switching frequency in the inverter will reduce current distortion, but this would result in increased switching losses in the inverter[17]. Also variable switching frequency, at very low speeds, is difficult to control torque and flux[18].

Space Vector Modulation method, which is a more mature control strategy was utilized to calculate the duty cycles of inverter to satisfy the input and output requirements[19].

This paper is organized as follows: section II describes the MCSA approach. Section III presents MC spectral components for unbalance voltage. Section IV describes the broken rotor bar fault. Section V. describes Field orient control, VI presents data specifications, VII presents the result and VIII concludes the main results of this paper.

2. MCSA Approach

The basic procedure of MCSA as follows:

1. Prepare the machine under test.

2. Check the performance specifications of this machine, using Eq.9, Eq.14, Eq.15, and Eq.16.

3. Analysis of these performance specifications and notice for any unusual operation (one stator current is needed).

4. Apply the fault diagnosis strategy[20].

MCSA is one of the good fault diagnosis methods. It has many advantages because it is non-intrusive, need just the stator winding, not affected by the load or asymmetries, simplicity of current sensors and the installation, but it has disadvantages, such as the stator current data should be sampled after motor speed arrives at the steady state.

The asymmetry of 4kw and broken rotor bar induction motor faults was detected according to the procedure shown in Figure 4.

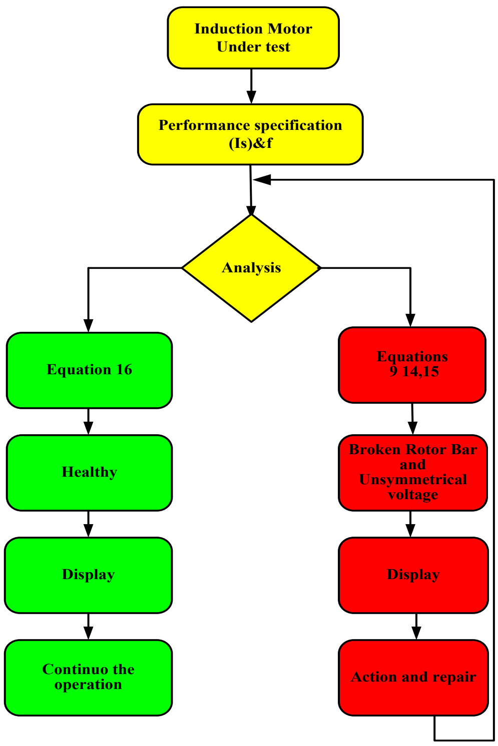

Figure 4. Flow chart of MCSA diagnosis procedure

3. MCSA Spectral Components for Unbalance Voltage

The stator current can be considered as the sum of the fundamental components and the influence of the oscillating load which can be written as:

The phase A stator current is:

$$I_a = I_1 \cos(2\pi f_1 t - \phi) + I_2 \cos(2\pi f_{sb} t - \phi) \quad (2)$$

The phase B stator current is:

$$I_b = I_1 \cos(2\pi f_1 t - 2\pi/3) + I_2 \cos(2\pi f_{sb} t - 2\pi/3) \quad (3)$$

The phase C stator current is:

$$I_c = I_1 \cos(2\pi f_1 t - 4\pi/3) + I_2 \cos(2\pi f_{sb} t - 4\pi/3) \quad (4)$$

The phasor quantity of the voltage:

$$\vec{v}_s = \frac{2}{3}(v_{ab} + \alpha v_{bc} \alpha^2 v_{ac} \quad (5)$$

Where

$$\alpha = \exp(j2\pi/3) \quad (6)$$

The power produced is

$$p = v_{ab} I_a + v_{bc} I_b + v_{ca} I_c \quad (7)$$

Or can be arranged as follows:

$$p = \frac{2}{3} v I_1 \cos(\phi) + \frac{2}{3} v I_{sb} \cos(2\pi(f_1 - f_{sb})t - \phi) \quad (8)$$

The frequency of unbalance voltage is:

$$f_{unbalance} = (1 + 2k) f_s \quad (9)$$

4. Broken Rotor Bar Fault

In rotor bar fault diagnosis, FFT phase difference will be utilized to estimate the fundamental frequency first .And the other fault frequency components should be calculated[21]. The broken rotor bar is one of the common faults in the induction motor. This fault happens due many reasons such as the anomalies of the rotor physical structure[22]. This leads to change the rotor resistance and the rotor inductance, which yields a modulated stator current carrying the characteristic frequencies of this fault as in Eq.13 and Eq.14. The characteristic frequency components of the induction motor stator current with broken rotor bar depend on the locations of sidebands frequencies around the supply frequency (50 Hz). FFT response in the steady state region is used as a tool to detect the broken rotor bar fault. The normal operation of the motor should have peaked at FFT response located at 50Hz without any sidebands, and if any fault happened, the sidebands will appear.

Using Matlab instruction, to implement FTT for vectors of length N as in following equations:

$$y = fft(x)$$

Where

$$X(k) = \sum_{j=1}^{N} x(j) \omega_N^{(j-1)(k-1)} \quad (10)$$

$$x(j) = (1/N) \sum_{j=1}^{N} X(K) \omega_N^{-(j-1)(k-1)} \quad (11)$$

$$\omega_N = e^{(-2\pi i)/N} \quad (12)$$

As can be shown in Figure5:

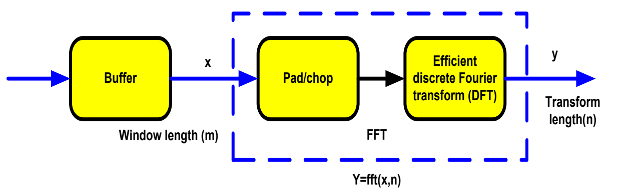

Figure 5. Fast Fourier transform algorithm

FFT is tested for 4% slip difference between the synchronous and rotor speed. In this case study, the number of broken rotor bar can be measured according to the Eq.13.

$$I_{BB} / I = 0.5 / N_b \quad (13)$$

The line spectrum of the negative sequence should appear at the location after 2sec.

The frequency of the broken rotor bar fault can be expressed in Eq.14 and Eq.15:

$$f_{brk} = f_s (1 \pm 2ks) \quad (14)$$

k/ p=1, 3, 5

$$f_{brk} = k/p((1 - s2) \pm s) f_s) \quad (15)$$

For the healthy case, the frequency of the stator is shown as in the Eq.16:

k=0, 1, 2, 3

$$f_{healthy} = [k \frac{R}{p}(1 - s) \pm \lambda] f_s \quad (16)$$

Consequently, there is a harmonic component will be induced in the stator current[10].

5. Vector Control

In order to obtain the desired performance, the control strategy of the AC machines often consists of making the electromechanical behavior similar to that of the DC machines.

This similarity is carried out by the application of the vector control.

The main objective is to decouple the electromagnetic torque from the direct components of stator flux and thus to control the torque, it is necessary to impose the components of the two stator currents and[23].

Position control of the vector control induction machine can be controlled by many methods like a sliding mode and field weakness of fixed gain. This is to make the position control robust to the parameter variation, which is studied by many research workers[24].

The vector control implies that the component of the stator current would be aligned with the rotor field, and the component would be perpendicular to the rotor torque[25].

This can be accomplished by choosing the speed of the rotor flux and locking for the phase of the reference frame system such that the rotor flux is aligned precisely with the d axis that yields the following two conditions:

$$\phi_{qr} = 0 \tag{17}$$

$$\phi_{dr} = const \tag{18}$$

The stator voltage can be expressed as shown in Eq.19:

$$V_s = R_s i_s + \frac{d\lambda_s}{dt} + j\omega_s M\lambda_s \tag{19}$$

The rotor voltage can be expressed in Eq.20:

$$V_r = R_r i_r + \frac{d\lambda_r}{dt} + (\omega_s - \omega_r) M\lambda_r \tag{20}$$

The induction motor torque as in Eq.21:

$$T_e = \frac{2pL_m}{3L_r}(i_{qs}\phi_{dr} - i_{ds}\phi_{qr}) \tag{21}$$

Where

$$\phi_{ds} = L_r i_{dr} + L_m i_{ds} \tag{22}$$

The vector control performs the following calculations [26] as can be expressed in Eq.23 and Eq.24:

$$\begin{bmatrix} i_{Qs} \\ i_{Ds} \end{bmatrix} = \begin{bmatrix} \cos\phi_s & \sin\phi_s \\ -\sin\phi_s & \cos\phi_s \end{bmatrix} \begin{bmatrix} I_q \\ I_d \end{bmatrix} \tag{23}$$

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -0.5 & -\sqrt{3}/2 \\ -0.5 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{24}$$

MCSA method is commonly used to diagnoses the induction motor faults. However, a basic solution that relies solely on FFT) current has only limited ability to make an accurate detection[27].

To satisfy this objective, the control using vector control for the model of the induction motor is necessary.

The main problem in identifying fault conditions, when the machine is controlled using this technique, is related to the action of the PI controller that, in some ways, acts to reduce the effects of the fault[28].

6. Motor Data Specifications

The fault detection is a very important issue before the complete motor failure. If the motor still working, this will lead to motor catastrophic failure causing downtime and large losses[29].

Unsymmetrical voltage and broken rotor bar failures are caused by a combination of various stresses that act on the induction motor such as thermal, residual environmental, mechanical, and electromagnetic stresses[30].

The characteristics of the 3-phase induction motor used in this paper are listed in the Table 2.

After the Simulink /MATLAB implementation of the proposed algorithm, the motor was tested for both healthy case (with 10% increasing in the phase A voltage) and three Hz oscillating load.

The simulation involved the collection of the three phase stator currents, using the proposed circuit as it can be shown in the Figure6.

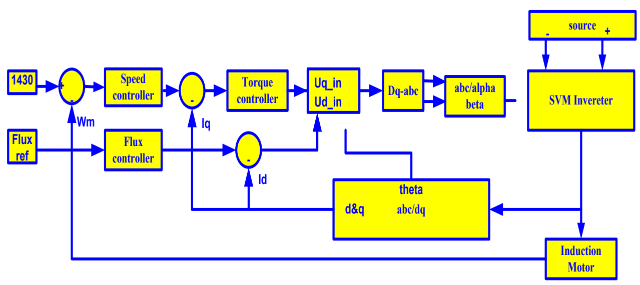

Figure 6. The proposed circuit

Table 2. Induction Motor specifications

Motor specifications	Unit	Value
Power	Kw	4
Current	Amp	15
Voltage	Volt	400
Rated speed	RPM	1430
No.poles		4
Moment of inertia	Kgm2	0.013

7. Simulation Results

As described in section I, the MCSA depends on the stator currents, the following results are obtained:

Figure 3 shows de-rating graph for induction motors based on the percent of voltage unbalance (from National Electrical Manufacturers Association MG-1-1993).

Figure7 shows the stator current of induction motor without any fault.

Figure 8 shows the currents of the stator of faulty case (unsymmetrical voltage supply); in this Figure one can notice distortion of stator current due to unsymmetrical voltage, (6.5-8) disconnection.

Figure9 shows the waveform of the stator currents when one phase is disconnected between (6.5-8). This is thicker than the normal one of the Figure10.

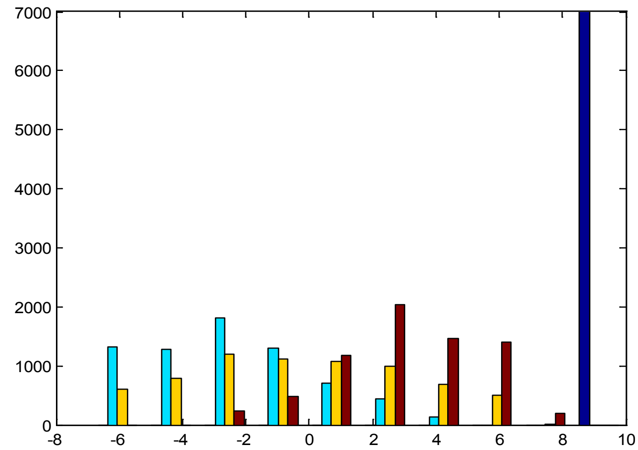

Figure 7. Stator currents I_{abc} of healthy case

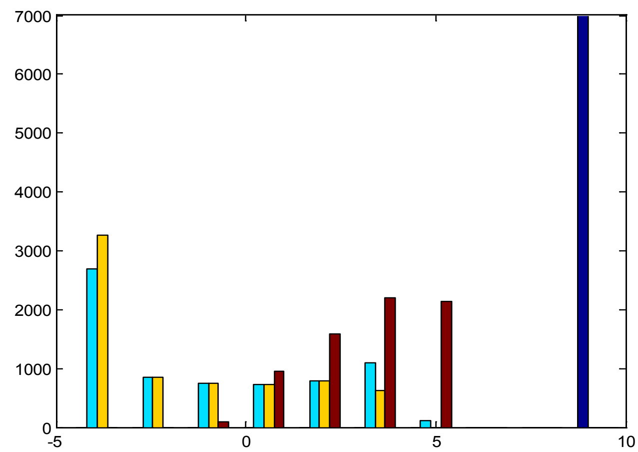

Figure 8. Stator Currents I_{abc} of the faulty case

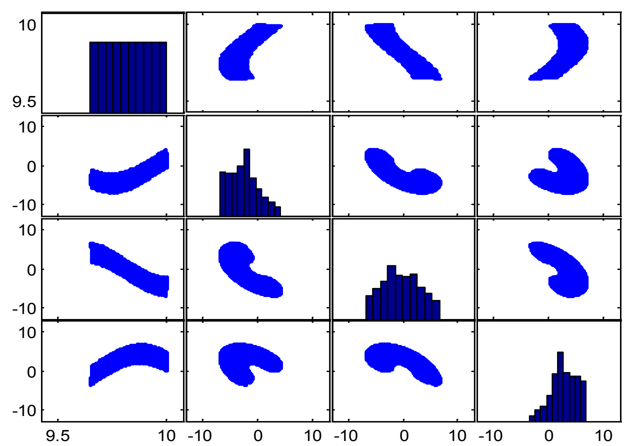

Figure 9. I_{abc} Waveform for the faulty case

The responses of both torque and speed in the two cases were as follows: Figure11. Shows the torque response in healthy case, this response was constant and stable (9.518) but with oscillation in the transient region.

Figure12 shows the torque response in the faulty case, this response was the oscillated torque between (9.7 -10).

Figure13 shows the constant speed response in the steady state region and became oscillated between (9.7 -10) as in Figure 14.

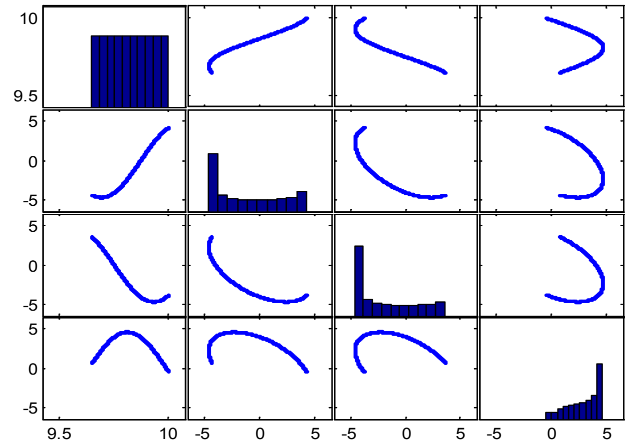

Figure 10. I_{abc} Wave form in the healthy case

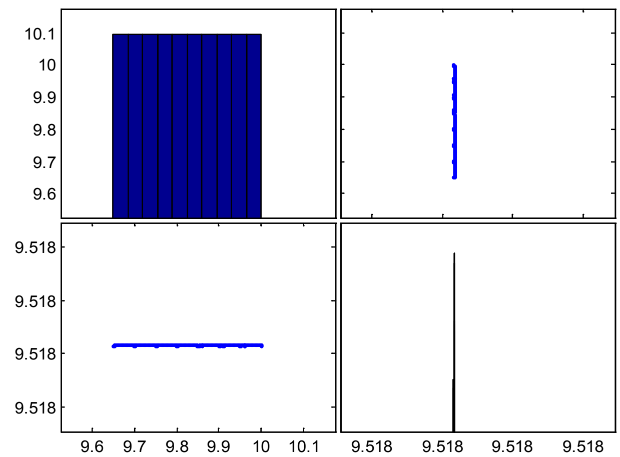

Figure 11. T_e (Torque) response in the healthy case

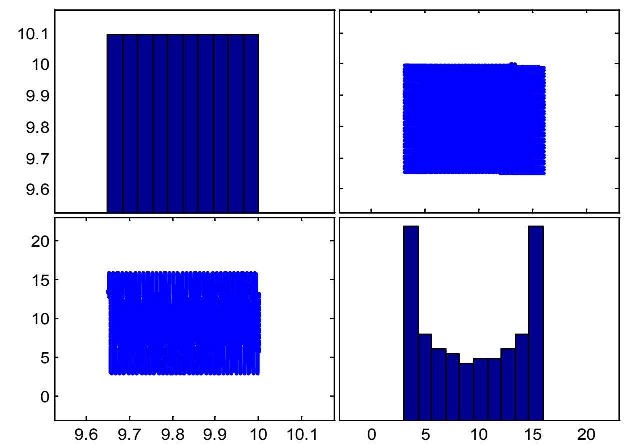

Figure 12. T_e (Torque) response in the faulty case

Figure15 shows the space vector representation of the flux sinusoidal distribution as the vector points to the maximum positive field (along the horizontal axis) where from the proportional length to the maximum field strength is around the (4.25) circle for healthy I.M.

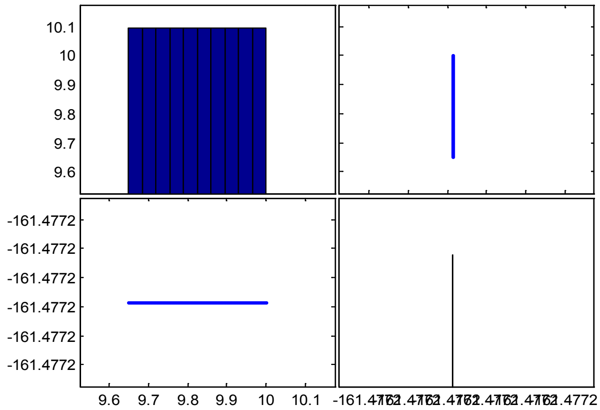

Figure 13. w_m (Speed) response of in the healthy case

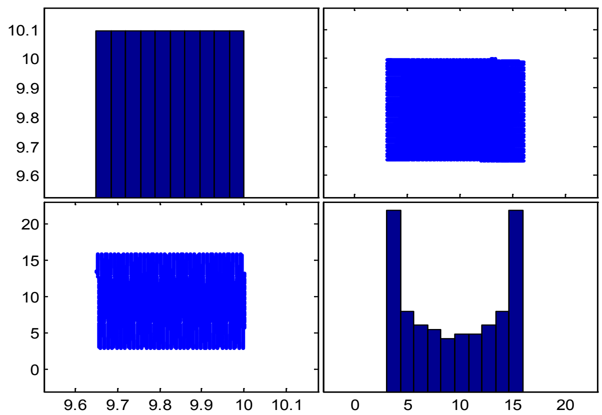

Figure 14. w_m (Speed) response in the faulty case

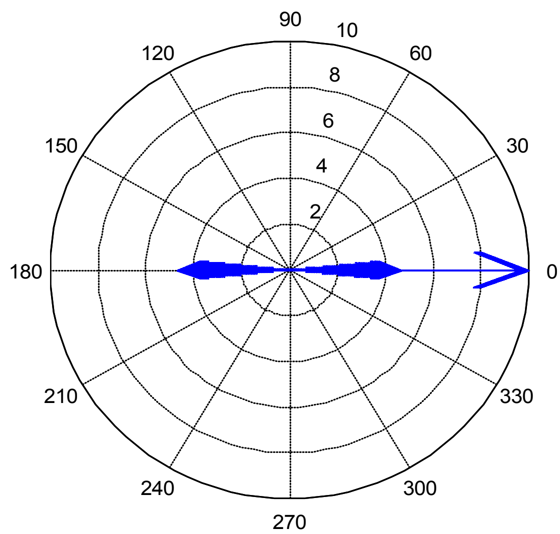

Figure 15. Phasor diagram of the healthy case

Figure16 shows space vector representation of flux sinusoidal distribution of the faulty case which is around the (6.8) circle.

One can notice some abnormality in the flux distribution of the healthy case that may result from the amplitude modulation between the fundamental component of the supply voltages due to electrical reason(asymmetry from one half of the cycle of to the other) and the mechanical cause where there is inherent asymmetry in the motor.

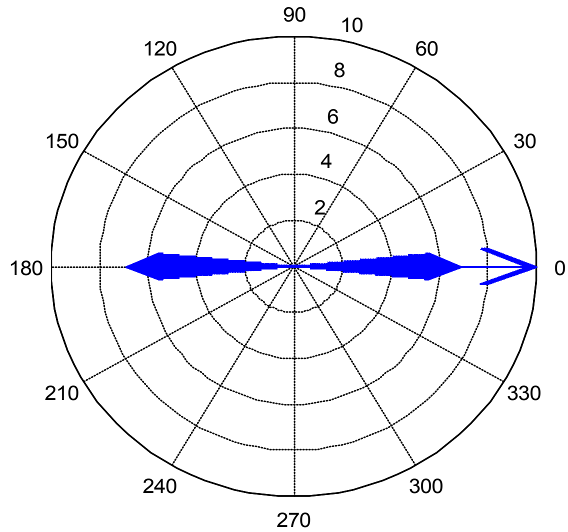

Figure 16. Phasor diagram of the faulty case

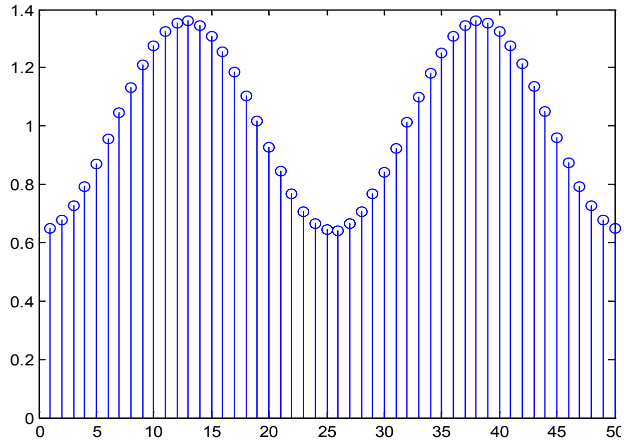

Figure 17. Flux distribution in faulty case

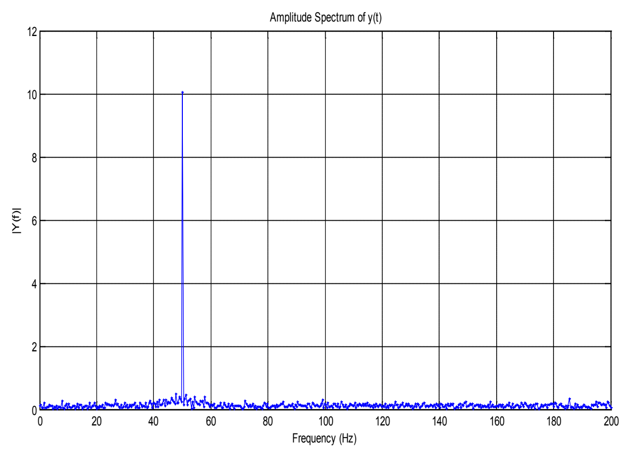

Figure 18. FFT of the healthy induction motor

The stator flux distribution oscillation of the faulty case is shown in Figure17.The healthy motor flux is always settled on 0.6 Wb.

Figure18 shows the Fast Fourier transform of the healthy induction motor. In this Figure, the peak response was at 50 Hz and there are no sideband frequencies.

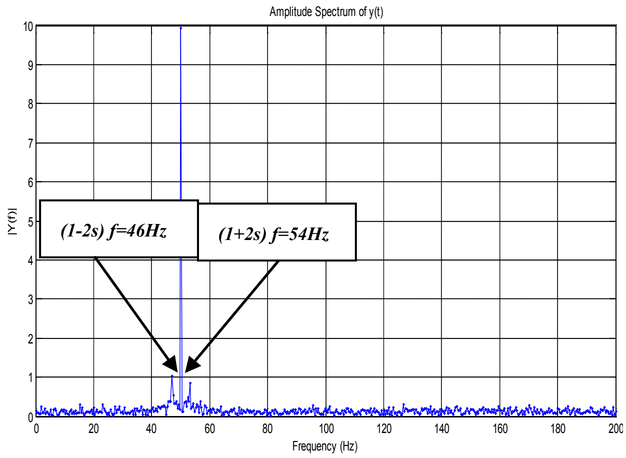

Figure 19. FFT of the rotor broken bar induction motor

Figure19 shows the Fast Fourier transform of the broken rotor bar. It is very clear to notice the location of sideband frequencies (54, 46) Hz around the fundamental frequency (50) Hz.

When Eq. 13 is applied; the number of broken bars of the faulty induction motor will be 5 bars. Table3 shows power spectral densities estimated of the motor in both cases. Table4 shows the amplitude and location of the flux sinusoidal distribution of the unsymmetrical voltage supply fault and healthy induction motor.

In Table5, the harmonics of the induction motor stator current, for healthy, unsymmetrical and broken rotor bar are listed

Table 3. Power spectral density estimated

normalized frequency	Healthy (db)	Faulty(db)
0.01	18	12
0.1	-25	0
0.2	-42	-44
0.4	-42	-52
0.8	-42	-54
1	-42	-75
2	-42	10

Table 4. Amplitude and location of the flux sinusoidal distribution in the unsymmetrical and healthy I.M

Location	Healthy motor	Faulty motor
+ve minimum	$0\angle 0$	$0\angle 0$
+ve maximum	$4.1\angle 0$	$8.2\angle 0$
-ve minimum	$0\angle 180$	$0\angle 180$
-ve maximum	$0\angle 180$	$8.8\angle 180$

Table 5. Harmonics of induction motor stator curren

Frequency	Healthy	broken rotor bar	unbalance v
$(1-4s)f_S$	0.001	0.001	0.001
$(1-4s)f_S$	0.001	0.001	0.001
$(1+2s)f_S$	0.001	54	150
$(1+2s)f_S$	0.001	46	0

8. Discussion

This paper discussed the fault diagnosis of induction motor using both motor current signature analysis and fast at different conditions .to evaluates the algorithm two faults are considered with non stationary signal which detected by MCSA and with stationary signal detected by FFT.

Normally the induction motor works on rated torque and speed. Due to the load increasing, the speed drops and draws much current. The induction motor can take up to 3 times the torque with around 24% decreasing in the speed and flux distortion. Since the torque is directly proportional to current and its magnetic field, the stator voltage is directly proportional to the product of stator flux (Weber) and angular velocity (rad/sec).the early fault detection and diagnosis will prevent the system from damage and increasing the operation live.

9. Conclusions

Through the investigation of the induction motor, MCSA used to diagnose unbalance motor supply voltage and broken rotor bar. The unsymmetrical supply and broken bar faults have a significant effect on the induction motor working operation. There are many methods to overcome the damage consequences of unbalance, but the easiest method is to install overload production and it may be protected by control circuits. MCSA is a simple and an accurate method because it needs only one stator current. Vector control is implemented on the induction motor drive to solve slow response, unsuitable performance, torque ripple and impossibility of the operation at all points of the speed and torque curve of the scalar control.

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