بسم الله الرحمن الرحيم

SUDAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF GRADUATE STUDIES

Induction Motor Faults Diagnosis Using Fuzzy Logic

تشخيص أعطال المحرك الحثي بإستخدام المنطق الغامض

A Thesis Submitted in Partial Fulfillment to the Requirement for the Degree of M.Sc. in Electrical Engineering

(Microprocessor and Control)

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July 2014

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DEDICATIONS

This thesis is lovingly dedicated to my parent, my brothers, my sisters and my friends whose has been constant source of inspiration for me. They have given me the drive and discipline to tackle any task with enthusiasm and determination. Without their love and support this project would not have been made possible

ACKNOWLEDGEMENT

*I wish to express my profound graduate to my supervisor **Dr.Awaddalla Taifour Ali,** for his valuable guidance, continuous encouragement, worthwhile suggestion and constructive ideas throughout this research. His support, pragmatic study a success and analysis and understanding made this knowledgeable experience for me.*

ABSTRACT

In this thesis, simulation model of three-phase induction motor is constructed using (MATLAB and SIMULINK) to represent the model case of normal operator and faults existing. The method proposed is a combination of analytical and fuzzy logic approach techniques which can deal effectively with nonlinear dynamics and uncertainties. The fault severity of the system is evaluated based on the membership functions and rule base developed by the fuzzy logic system. The main difficulty in this task is the lack of an accurate analytical model to describe a faulty motor having different types of faults like turn-turn short in one phase winding, break in stator winding and unbalance in input voltage .This thesis demonstrates the use of fuzzy logic as an extension to analytical system to enhance the overall performance of the system. In this method, fuzzy logic is used to make decisions about the motor condition. The fuzzy system is able to identify the motor stator condition with high accuracy.

مستخلص

يقدم هذا البحث محاكاة نموذج لمحرك حثي ثلاثي الأطوار باستخدام (MATLAB/SIMULINK) لتمثيل النموذج المعطى في حالة التشغيل الطبيعية وفي حالة العطل .

الطريقة المقترحة في هذه الدراسة الطريقة طريقة المنطق الغامض والتحليل والتي يمكنها التعامل بشكل كفء مع الحالات الديناميكية واللاخطية والحالات المحيرة. شدة الخطأ في النظام يقدر بواسطة العلاقات العضوية وأساس القانون الناشئ بواسطة المنطق الغامض. العائق الرئيسي لهذه المهمة نقص تحليلي في دقة الوصف الخاطئ لنموذج المحرك الحثي الذي يملك أنواع مختلفة من الأعطال مثل أعطال الملفات ،أعطال اللف في وجه واحد للملفات، فصل في الملفات وعطل عدم الإتزان في مصدر الجهد. هذه الدراسة تبرهن إستخدام المنطق الغامض بنفس المقدار لتحليل النظام ليعزز إنجازاته ، إستخدم المنطق الغامض لعمل قرار عن حال المحرك الحثي والمنطق الغامض له المقدرة علي التعرف علي حالة أعطال المحرك الحثي التي تحدث وبدقة عالية.

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LIST OF ABBERVIATIONS

AC	Alternative current
AL	Artificial Intelligent
DC	Direct Current
FIS	Fuzzy logic inference
HZ	Hertz
KW	Kilo Watt
MF	Membership Function
R	Resistance
VSD	Variable Speed Drive
VVVF	Variable Voltage Variable Frequency

LIST OF SYMBOLS

n_o	Synchronous rotational speed
f	Power supply frequency
p	Number of poles
n	Actual rotational
S	Sleep nipper unit
V	Voltage
R_S	Stator resistance
E_s	Stator induced voltage
X_S	Stator leakage reactance
E_r	Rotor induced voltage
X_r	Rotor leakage reactance
R_r	Rotor resistance
X_m	Magnetizing inductance
N_s	Stator turns
N_r	Rotor turns
I_s	Stator current
I_r	Rotor current
I_m	Magnetizing current
L_m	Mutual inductance
P	Active power
Q	Reactive power
0	O-axis
q	Quadratur axis
d	Direct axis
s	Stator variable
r	Rotor variable
I_{as} I_{bs} I_{cs}	Stator currents balance
I_{ar} I_{br} I_{cr}	Rotor currents balance
$\lambda_{as}\lambda_{bs}$ λ_{cs}	Stator flux in three phase balance
λ_{ar} λ_{br} λ_{cr}	Rotor flux in three phase balance
V_{as} V_{bs} V_{cs}	Stator voltage balance
V_{ar} V_{br} V_{cr}	Rotor voltage balance

V_{abcs}	Stator voltage balance
V_{abcr}	Rotor voltage balance
λ_{abcs}	Stator flux in three phase balance
λ_{abcr}	Rotor flux in three phase balance
L_{sr}	Stator leakage inductance
Ls	Stator self inductance
Lr	Rotor self inductance
I_{abcs}	Stator current balance
I_{abcr}	Rotor current balance
L_{lr}	Rotor leakage inductance
V_{qs} V_{ds}	q and d axis stator voltage
I_{qs} i_{ds}	q and d axis stator current
λ_{qs}	Stator flux on q-axis
λ_{ds}	Stator flux on d-axis
λ_{qr}	Rotor flux on q-axis
λ_{dr}	Rotor flux on q-axis
T_e	Electromagnetic torque
T_L	Load torque
J	Moment of inertia
V_{os}	Stator voltage on o-axis
V_{or}	Rotor voltage on o-axis
λ_{os}	Stator flux on o-axis
λ_{or}	Rotor flux on o-axis
i_{os}	Stator current on o-axis
i_{or}	Rotor current on o-axis

CHAPTER ONE
INTRODUCTION

1.1 General

Induction motors are complex electro-mechanical devices utilized in most industrial applications for the conversion of power from electrical to mechanical form. Induction motors are used worldwide as the workhorse in industrial applications. Such motors are robust machines used not only for general purposes, but also in hazardous locations and severe environments. General purpose applications of induction motors include pumps, conveyors, machine tools, centrifugal machines, presses, elevators, and packaging equipment. There are two types rotor in induction motor: squired-cage rotor and wound rotor. Both rotor types are contained in slots in laminated core which is mounted on the motor shaft. There are basically two general methods to control induction motor speed: Varying stator and rotor magnetic field speed and varying slip. Although induction motors are reliable electric machines, they are susceptible to many electrical and mechanical types of faults.

Because of costly machinery repair, extended process down time, and health and safety problems, a trend in modern industry is to focus attention on fault detection and predictive maintenance strategies for industrial plant [1, 2]. It is known that approximately 36% of induction motor failures are caused by failure of the stator winding, and it is believed that these faults begin as undetected turn-to-turn faults in a coil, which progress to catastrophic phase-to-phase or phase-to-ground short circuit faults. To achieve prior warning of failure, shorted turns within the stator winding coil must be detected or predicted in effect to avoid catastrophic failure.

Modeling of induction motors with shorted turns is the first step in the design of turn fault detection systems [3]. Simulation of transient and steady state behavior of motors with these models enable correct evaluation of the measured data by diagnostic techniques [4-7].

One of the most widely used techniques for obtaining information on the health state of induction motors is based on the processing of stator line current. Typically, in the motor fault diagnosis process, sensors are used to collect time domain current signals. The diagnostic expert uses both time domain and frequency domain signals to study the motor condition and determines the faults existed in the motor.

During the past years, researchers have proposed some diagnosis approaches. A major difficulty is the lack of a well processing of input data. This paper applies fuzzy logic, to the diagnosis of induction motor stator and phase conditions, based on the amplitude features of stator currents. In fact, fuzzy logic is reminiscent of human thinking process and natural language enabling decisions to be made based on vague information [8].

When conducting the fault diagnosis, there are several situations in which an object is not obviously “good” or “bad”, but may fall into some interior range. This method has been chosen because fuzzy logic has proven ability in mimicking human decisions, and the stator voltage and phase condition monitoring problem has typically been solved. The motor condition is described using linguistic variables. Fuzzy subsets and the corresponding membership functions describe the stator current amplitudes. A knowledge base, comprising rule and databases, is built to support the fuzzy inference. The induction motor condition is diagnosed using a compositional rule of fuzzy.

1.2 Problem Statement

Induction motors are reliable but often exposed to hostile environments during its operation which leads to early deterioration leading to the motors failure. Faults and failures of induction machines can lead to excessive downtimes and generate large losses in terms of maintenance and revenues.

Several approaches have been proposed for detecting and diagnosis faults in induction motor systems. One traditional method of induction motor fault diagnosis and detection is Motor Current Signature Analysis (MCSA) in which signals processing technique such as the Fast Fourier Transform (FFT) is used to obtain the frequency spectrum. Other signal spectrum methods based on wavelet transformation, time-frequency domain analysis, higher order spectra, etc., have also been proposed. Studied integrating the FFT and wavelets to classify fault modes in induction motors. Combated investigated an online model-based wavelet algorithm for time varying parameters. The authors defined a hierarchical fault tree to reach a correct fault diagnosis used the Hilbert transform to extract the envelope of the signal spectrum. The problems of these techniques are the: FFT is suffered from some serious drawbacks such as; it is applicable only in the constant load condition not for the variable load. The frequency-domain methods which are commonly used need accurate slip estimation for frequency components localization in any spectrum. It is also not suitable at the no-load or light load condition of the motor. At light load, it is difficult to distinguish between healthy and faulty rotors because the characteristic of broken rotor bar fault frequencies are very close to fundamental component and their amplitude are small in comparison. This method also suffered from the disadvantage that it shows the constant window for all the frequencies therefore, shows poor frequency resolution. The FFT in the stator current is quite difficult to apply with accuracy due to problems such as frequency resolution, magnitude accuracy at steady state, and more generally, due to data processing.

1.3 Objective

The main Objectives of this study are:

- To perform faults analysis of an induction motor using fuzzy logic controller and
- To present a useful and straight forward method to simulate inter turn-turn short circuits, break in any of stator phases and unbalance voltage in input voltage for diagnosis purpose.

1.4 Methodology

- Study of induction motor.

- Using mathematical method (differential equations) to build the system model.
- Using Matlab/Simulink software to simulate the model.
- Mamdani- style fuzzy logic process is performed in four steps:

  (i) Fuzzification of the input variable .

  (ii) Rule evaluation (inference).

  (iii) Aggregation of the rule outputs (composition).

  (iv) Defuzzification .

1.5 Layout

This thesis consists of five chapters: Chapter One represents an introduction to the principles of the work, the reasons and motivation and also discusses the objectives and outline methodologies of the study. Chapter two discuses a theoretical background of an induction motor, stator faults of an induction motor, fuzzy system. Chapter three presents the system model simulation of induction motor. Chapter four presents the simulation results. Finally, Chapter five provides the conclusions and recommendations.

CHAPTER TWO

GENERAL OVERVIEW AND THEOERTICAL BACKGROUND

2.1 Introduction

For industrial and mining applications, three phase AC induction motors are the prime movers for the vast majority of machines. These motors can be operated either directly from the mains or from adjustable frequency drives. In modern industrialized countries, more than half the total electrical energy used in those countries is converted to mechanical energy through AC induction motors. The applications for these motors cover almost every stage of manufacturing and processing. Applications also extend to commercial buildings and the domestic environment. They are used to drive pumps, fans, compressors, mixers, agitators, mills, conveyors, crushers, machine tools, cranes, etc. It is not surprising to find that this type of electric motor is so popular, when one considers its simplicity, reliability and low cost. In the last decade, it has become increasingly common practice to use three phase squirrel cage AC induction motors with Variable Voltage Variable Frequency (VVVF) converters for Variable Speed Drive (VSD) applications. To clearly understand how the (VSD) system works, it is necessary to understand the principles of operation of this type of motor. Although the basic design of induction motors has not changed very much in the last 50 years, modern insulation materials, computer based design optimization techniques and automated manufacturing methods have resulted in motors of smaller physical size and lower cost per kW. International standardization of physical dimensions and frame sizes means that motors from most manufacturers are physically interchangeable and they have similar performance characteristics. The reliability of squirrel cage AC induction motors, compared to DC motors, is high. The only parts of the squirrel cage motor that can wear are the bearings. Slip rings and brushes are not required for this type of construction. Improvements in modern prelubricated bearing design have extended the life of these motors. Although single-phase AC induction motors are quite popular and common for low power applications up to approx 2.2 kW, these are seldom used in industrial and mining applications. Single-phase motors are more often used for domestic applications .

2.1.1 Basic construction

The AC induction motor comprises two electromagnetic parts, Stationary part called the stator and Rotating part called the rotor, supported at each end on bearing.

- **The stator**

The stator is the outer stationary part of the motor, which consists of, the outer cylindrical frame of the motor, the magnetic path, and set of insulated electrical windings, which are placed inside the slots of the laminated magnetic path. The cross-sectional area of these windings must be large enough for the power rating of the motor. For a three phase motor, three sets of windings are required, one for each phase. Figure (2.1) shows the induction motor stator.

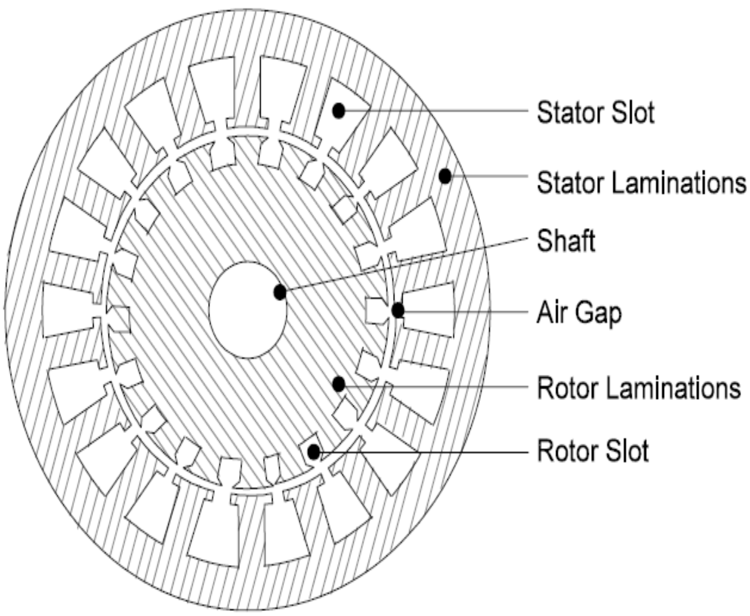

Figure (2.1): Stator and rotor lamination

- **The rotor**

This is the rotating part of the motor. As with the stator above, the rotor consists of a set of slotted steel laminations pressed together in the form of a cylindrical magnetic path and the electrical circuit. The electrical circuit of the rotor can be either wound rotor type or squirrel cage rotor type [9]

2.1.2 Principles of operation

When a three phase AC power supply is connected to the stator terminals of an induction motor, three-phase alternating currents flow in the stator windings. These currents set up a changing magnetic field (flux pattern), which rotates around the inside of the stator. The speed of rotation is in synchronism with the electric power frequency and is called the synchronous speed.

In the simplest type of three-phase induction motor, the rotating field is produced by three fixed stator windings, spaced 120° apart around the perimeter of the stator. When the three stator windings are connected to the three-phase power supply, the flux completes one rotation for every cycle of the supply voltage. Figure (2.2) shows the basic principle of two poles motor.

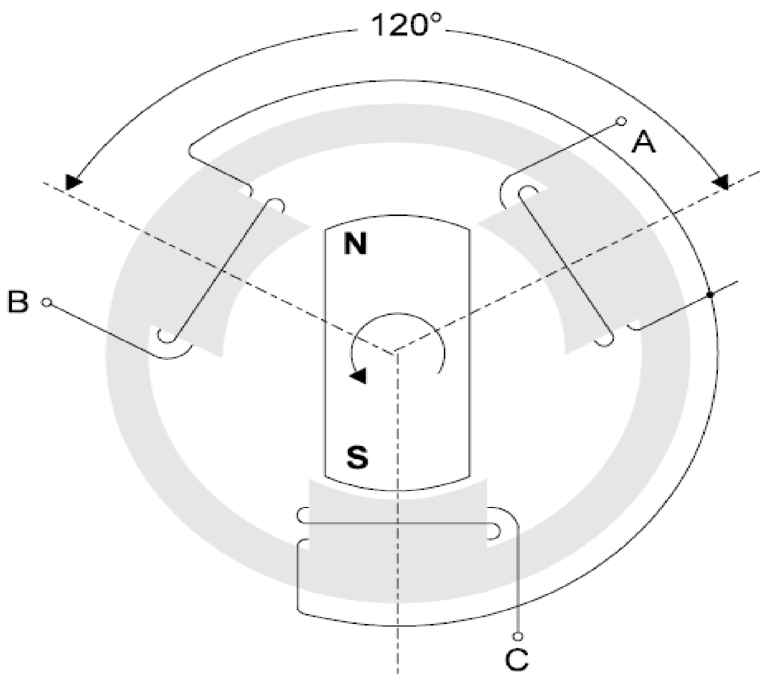

Figure (2.2) basic principle of a 2 pole motor

The speed at which the stator flux rotates is called the synchronous speed and is determined by:

$$n_0 = \frac{120f}{P} \text{ rev/min} \qquad (2.1)$$

Where :

no = Synchronous rotational speed in rev/min

f = Power supply frequency in H

p = Number of motor poles

To establish a current flow in the rotor, there must first be a voltage present across the rotor bars. This voltage is supplied by the magnetic field created by the stator current. The rotating stator magnetic flux, which rotates at synchronous speed, passes from the stator iron path, across the air-gap between the stator and rotor and penetrates the rotor iron path as shown in Figure (2.3). As the magnetic field rotates, the lines of flux cut across the rotor conductor

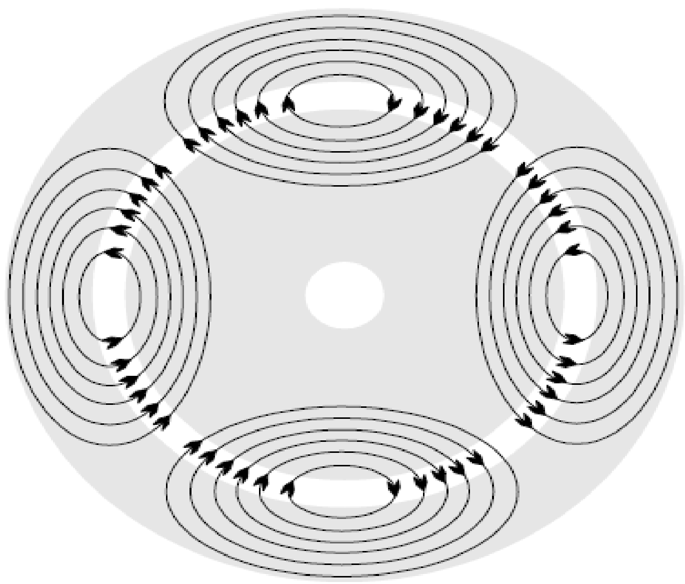

Figure (2.3) Flux distribution in a 4 pole machine at any one moment

Accordance to Faraday's Law, this induces a voltage in the rotor windings, which is dependent on the rate of change of flux. Since the rotor bars are short circuited by the end-rings, current flows in these bars will set up its own magnetic field. This field interacts with the rotating stator flux to produce the rotational force. In accordance with Lenz's Law, the direction of the force is that which tends to reduce the changes in flux field, which means that the rotor will accelerate to follow the direction of the rotating flux. At starting, while the rotor is stationary, the magnetic flux cuts the rotor at synchronous speed and induces the highest rotor voltage and, consequently, the highest rotor current. Once the rotor starts to accelerate in the direction of the rotating field, the rate at which the magnetic flux cuts the rotor windings reduces and the induced rotor voltage decreases proportionately. The frequency of the rotor voltage and current also reduces.

When the speed of the rotor approaches synchronous speed at no load, both the magnitude and frequency of the rotor voltage becomes small. If the rotor reached synchronous speed, the rotor windings would be moving at the same speed as the rotating flux, and the induced voltage and current in the rotor would be zero. Without rotor current, there would be no rotor field and consequently no rotor torque. To produce torque, the rotor must rotate at a speed slower (or faster) than the synchronous speed.

Consequently, the rotor settles at a speed slightly less than the rotating flux, which provides enough torque to overcome bearing friction and winding. The actual speed of the rotor is called the slip speed and the difference in speed is called the slip. Consequently, induction motors are often referred to as asynchronous motors because the rotor speed is not quite in synchronism with the rotating stator flux. The amount of slip is determined by the load torque, which is the torque required to turn the rotor shaft. For example, on a 4 pole motor, with the rotor running at 1490 r/min on no-load, the rotor frequency is 10/1500 of 50 Hz and the induced voltage is approximately 10/1500 of its value at starting. At no-load, the rotor torque associated with this voltage is required to overcome the frictional and winding losses of the motor. As shaft load torque increases, the slip increases and more flux lines cut the rotor windings, which in turn increases rotor current, which increases the rotor magnetic field and consequently the rotor torque. Typically, the slip varies between about 1% of synchronous speed at no-load to about 6% of synchronous speed at full-load and actual rotational speed is

$$n = \left(\frac{n_o}{1 - s}\right) \quad \text{rpm} \tag{2.2}$$

Where :-

n_0 = Synchronous rotational speed in rpm

n = Actual rotational speed in rev/min

s = Slip in per-unit

The direction of the rotating stator flux depends on the phase sequence of the power supply connected to the stator windings. The phase sequence is the sequence in which the voltage in the three-phases rises and reaches a peak. Usually the phase sequence is designated A-B-C, L1-L2-L3. If two supply connections are changed, the phase sequence A-C-B would result in a reversal of the direction of the rotating stator flux and the direction of the rotor.

2.1.3 The equivalent circuit

To understand the performance of an AC induction motor operating from a (VVVF) converter, it is useful to electrically represent the motor by an equivalent circuit. There are many different versions of the equivalent circuit, which depend on the level of detail and complexity. In Figure (2.4), the stator current I_s, which is drawn into the stator windings from the AC stator supply voltage *V*, can then be predicted using this model.

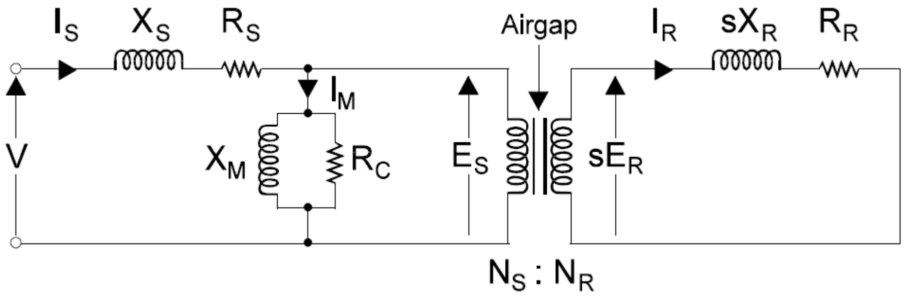

Figure (2.4): Induction motor equivalent circuit

Where :-

V = Stator supply voltage

R_s = Stator resistance

E_s = Stator induced voltage

X_s = Stator leakage reactance at 50 Hz

E_r = Rotor induced voltage

R_R = Rotor resistance

X_R = Rotor leakage reactance

X_M = Magnetizing inductance

N_s = Stator turns

N_r = Rotor turns

I_s = Stator current

I_r = Rotor current

I_M = Magnetizing current

R_C = Core losses, bearing friction, winding losses, etc

The main components of the motor electrical equivalent circuit are resistances represent the resistive losses in an induction motor and comprise of:

- Stator winding resistance losses (R_S)
- Rotor winding resistance losses (R_R)
- Iron losses, which depend on the grade and flux density of the core steel
- Friction and winding losses (R_C)

Inductances represent the leakage reactance. These are associated with the fact that not all the flux produced by the stator windings cross the air-gap to link with the rotor windings and not all of the rotor flux enters the air-gap to produce torque.

- Stator leakage reactance (X_S shown in Figure (2.5))
- Rotor leakage reactance (X_R shown in Figure (2.5))
- Magnetizing inductance (X_M which produces the magnetic field flux)

As shown in the equivalent circuit, the stator current therefore serves a double purpose, the first one is to carry the current (I_M) which provides the rotating magnetic field and the second is to carry the current (I_R) which is transferred to the rotor to provide shaft torque.

The stator voltage E_S is the theoretical stator voltage that differs from the supply voltage by the volt drop across X_S and R_S. X_M represents the magnetizing inductance of the core and R_C represents the energy lost in the core losses, bearing friction and winding losses. The rotor part of the equivalent circuit consists of the induced voltage $s.E_R$, which as discussed earlier is proportional to the slip and the rotor reactance $s.E_R$, which depends on frequency and is consequently also dependent on slip. This equivalent circuit is quite complex to analyze because the transformer, between the stator and rotor, has a ratio that changes when the slip changes. Fortunately, the circuit can be simplified by mathematically adjusting the rotor resistance and reactance values by the turns ratio $N^2 = (N_S/N_R)^2$, i.e. 'transferring' them to the stator side of the transformer. Once these components have been transferred, the transformer is no longer relevant and it can be removed from the circuit. This mathematical manipulation must also adjust for the variable rotor voltage, which depends on slip. The equivalent circuit can be re-arranged and simplified as shown in the Figure (2.5)

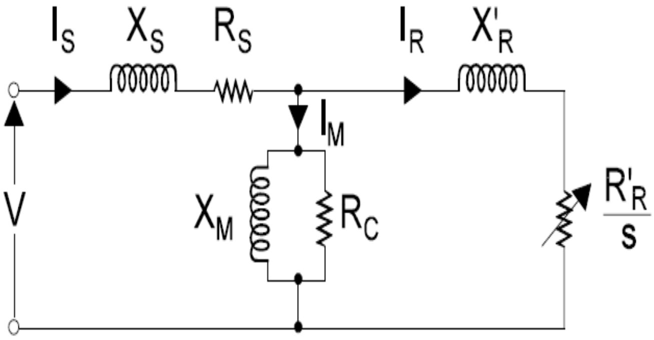

Figure (2.5) The simplified equivalent circuit of an AC induction motor

Where $X'_R = N^2 \times X_R$ (2.3)

$R'_R = N^2 \times R_R$ (2.4)

$N = N_S/N_R$, the stator/rotor turns ratio

In this modified equivalent circuit, the rotor resistance is represented by an element that is dependent on the slip s. This represents the fact that the induced rotor voltage and consequently current depends on the slip. Consequently, when the induction motor is supplied from a power source of constant voltage and frequency, the current I_S drawn by the motor depends primarily on the slip. The equivalent circuit can be simplified even further to represent only the most significant components, which are: Magnetizing inductance (X_M) and Variable rotor resistance (R'_R/s) all other components are assumed to be negligibly small and have been left out.

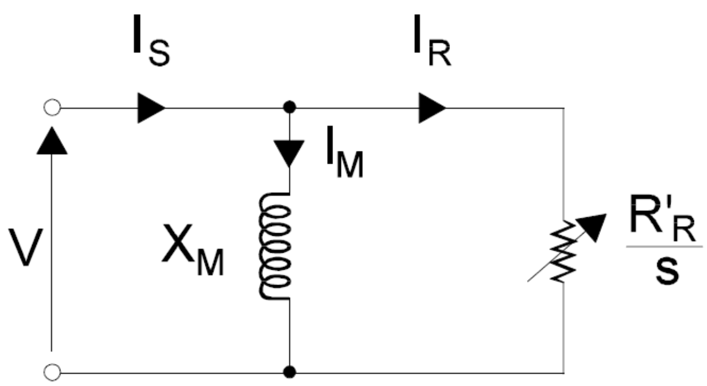

Figure (2.6) Very simplified equivalent circuit of an AC induction motor

As illustrated the total stator current I_S largely represents the vector sum of:

- The reactive magnetizing current *I*M, which is largely independent of load and generates the rotating magnetic field. This current lags the voltage by 90^O and its magnitude depends on the stator voltage and its frequency. To maintain a constant flux in the motor, the *V*/*f* ratio should be kept constant.

$$X_M = j\omega L_M = j(2\pi f)L_M \quad (2.5)$$

$$I_M = \frac{V}{j(2\pi f)L_M} \quad (2.6)$$

$$I_M = K\left(\frac{V}{f}\right) \quad (2.7)$$

where k = constant

• The active current I_R, which produces the rotor torque depends on the mechanical loading of the machine and is proportional to slip. At no-load, when the slip is small, this current is small. As load increases and slip increases, these current increases in proportion. This current is largely in phase with the stator voltage [9]. The Figure (2.7) shows the current vectors for low-load and high-load conditions.

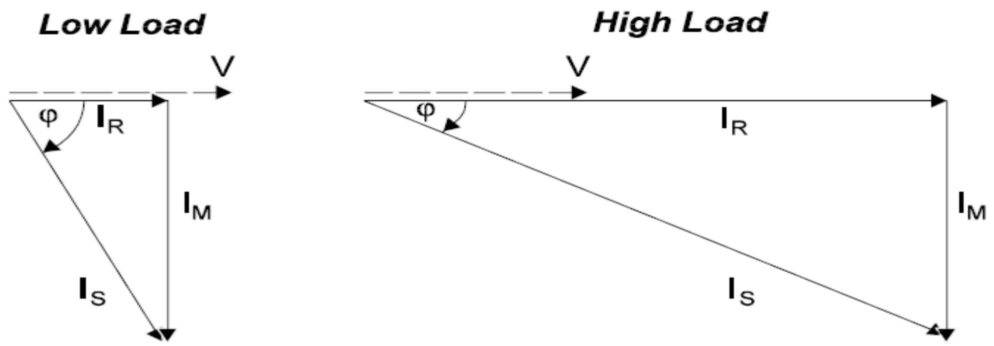

Figure (2.7) Stator current for low-load and high-load conditions

2.1.4 Electrical and mechanical performance

The angle between the two main stator components of voltage *V* and current I_S is known as the power factor angle represented by the angle φ and can be measured at the stator terminals. As shown, the stator current is the vector sum of the magnetizing current *I*M, which is in quadrature to the voltage, and the torque producing current I_R, which is in phase with the voltage. These two currents are not readily available for measurement. Consequently, the total apparent motor power *S* also comprises two components, which are in quadrature to one another

$$S = P + jQ \quad KVA \tag{2.8}$$

• Active power *P* can be calculated by

$$P = \sqrt{3} \times V \times I \quad KW \tag{2.9}$$

or

$$P = \sqrt{3} \times V \times I_S \times \cos \emptyset \quad KW \tag{2.10}$$

• Reactive power *Q*, can be calculated by

$$Q = \sqrt{3} \times V \times I_M \quad KVA_r \tag{2.11}$$

or

$$Q = \sqrt{3} \times V \times I_S \times \sin \emptyset \quad KVAr^3 \tag{2.12}$$

Where

S = Total apparent power of the motor in kVA

P = Active power of the motor in kW

Q = Reactive power of the motor in kVAr

V = Phase-phase voltage of the power supply in kV

I_S = Stator current of the motor in amps

φ = Phase angle between V and I_S (power factor = cos ∅)

Not all the electrical Input Power (*P*I) emerges as mechanical output power P_M. A small portion of this power is lost in the stator resistance ($3.I^2.R_S$) and the core losses ($3.I_M^2\ .R_C$) and the rest crosses the air gap to do work on the rotor. An additional small portion is lost in the rotor ($3I^2R'_R$). The balance is the mechanical output power P_M of the rotor. Another issue to note is that the magnetizing path of the equivalent circuit is mainly inductive. At no-load, when the slip is small (slip s ⇒ 0), the equivalent circuit shows that the effective rotor resistance R'_R/s ⇒ infinity. Therefore, the motor will draw only no-load magnetizing current. As the shaft becomes loaded and the slip increases, the magnitude of *R*'R/s decreases and the current rises sharply as the output torque and power increases.

This affects the phase relationship between the stator voltage and current and the power factor cos ∅. At no-load, the power factor is low, which reflects the high component of magnetizing current. As mechanical load grows and slip increases, the effective rotor resistance falls, active current increases and power factor improves.

When matching motors to mechanical loads, the two most important considerations are the torque and speed. The torque–speed curve, which is the basis of illustrating how the torque changes over a speed range, can be derived from the equivalent circuit and the equations above. By reference to any standard textbook on 3-phase AC induction motors, the output torque of the motor can be expressed in terms of the speed as follows:

$$T_M = \frac{3 \times s \times V^2 \times R'_R}{[(R_S + R'_S)^2 + s(X_S + X'_R)^2]n_o} \tag{2.13}$$

This equation and the curve in figure (2.9) show how the motor output torque *T*M varies when the motor runs from standstill to full speed under a constant supply voltage and frequency. The torque requirements of the mechanical load are shown as in Figure (2.8)

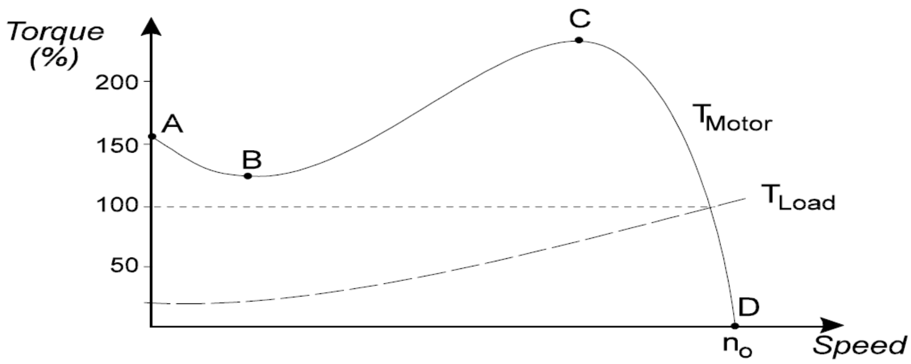

Figure (2.8) Torque-speed curve for a 3-phase AC induction motor

A: is called the breakaway starting torque

B: is called the pull-up torque

C: is called the pull-out torque (or breakdown torque or maximum torque)

D: is the synchronous speed (zero torque)

At starting, the motor will not pull away unless the starting torque exceeds the load breakaway torque. Thereafter, the motor accelerates if the motor torque always exceeds the load torque. As the speed increases, the motor torque will increase to a maximum T_{Max} at point C. On the torque–speed curve, the final drive speed (and slip) stabilizes at the point where the load torque exactly equals the motor output torque. If the load torque increases, the motor speed drops slightly, slip increases, stator current increases, and the motor torque increases to match the load requirements. The range CD on the torque–speed curve is the stable operating range for the motor. If the load torque increased to a point beyond T_{Max}, the motor would stall because, once the speed drops sufficiently back to the unstable portion ABC of the curve, any increase in load torque requirements T_L and any further reduction in drive speed, results in a lower motor output torque. The relationship between stator current I_S and speed in an induction motor, at its rated voltage and frequency, is shown in the Figure (2.9). When the induction motor is started. Direct-on-line from its rated voltage supply, the stator current at starting can be as high as 6 to 8 times the rated current of the motor. The motor approaches its rated speed, the current falls to a value determined by the mechanical load on the motor shaft.

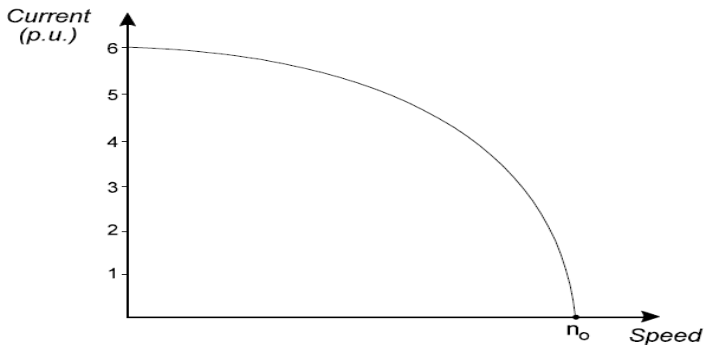

Figure (2.9) Current–speed characteristic of three phase AC induction motor

Some interesting observations about the AC induction motor that can be deduced from the above equations are:

• Motor output torque is proportional to the square of the voltage

$$T_M \propto V^2 \qquad (2.14)$$

Consequently, starting an induction motor with a reduced voltage starter, such as soft starters, star-delta starters, auto-transformer starters, etc, means that motor starting torque is reduced by the square of the reduced voltage.

• The efficiency of an induction motor is approximately proportional to $(1 - s)$

i.e. as speed drops and slip increases, efficiency drops

$$\text{Eff} \propto (1 - s) \tag{2.15}$$

The induction motor operates as a slipping clutch with the slip power being dissipated as heat from the rotor as ‘copper losses’. On speed control systems that rely on slip, such as wound-rotor motors with variable resistors, slip-recovery systems, etc, speed variation is obtained at the cost of motor efficiency.

Efficient use of an induction motor means that slip should be kept as small as possible. This implies that, from an efficiency point of view, the ideal way to control the speed of an induction motor is the step less control of frequency. 3-phase AC induction motors typically have slip values at full load of,

− 3% to 6% for small motors

− 2% to 4% for larger motors

This means that the speed droop from no-load to full load is small and therefore this type of motor has an almost constant speed characteristic. One of the most fundamental and useful formulae for rotating machines is the one that relates the mechanical output power *P*M of the motor to torque and speed

$$P_M = \frac{(T_M \times n)}{9550} \quad \text{kw} \tag{2.16}$$

Where:

P_M = Motor Output Power in kW

T_M = Motor Output torque in Nm

N = Actual Rotational speed in rev/min

2.2 Induction Motor Faults

Although induction motors are reliable electric machines, they are susceptible to many electrical and mechanical types of faults. Electrical faults include inter-turn short circuits in stator windings, open-circuits in stator windings, broken rotor bars, and broken end rings, while mechanical faults include bearing failures and rotor eccentricities Figure (2.10). The effects of such faults in induction motors include unbalanced stator voltages and currents, torque oscillations, efficiency reduction, overheating, excessive vibration, and torque reduction [10]. Moreover, these motor faults can increase the magnitude of certain harmonic components.

This thesis is focused on two types of electrically detectable induction motor faults, namely: inter-turn short circuits in stator windings and broken rotor bars. These two types of faults in induction motors are discussed in the next section.

2.2.1 Broken rotor bars

As shown in Figure (2.10) the squirrel cage of an induction motor consists of rotor bars and end rings. A broken bar can be partially or completely cracked. Such bars may break because of manufacturing defects, frequent starts at rated voltage, thermal stresses, and/or mechanical stress caused by bearing faults and metal fatigue [10].

A broken bar causes several effects in induction motors. A well-know effect of a broken bar is the appearance of the so-called sideband components [11]. These sidebands are found in the power spectrum of the stator current on the left and right sides of the fundamental frequency component. The lower side band component is caused by electrical and magnetic asymmetries in the rotor cage of an induction motor, while the right sideband component is due to consequent speed ripples caused by the resulting torque pulsations. The frequencies of this sideband are given by

$$f_b = (1 \pm 2s)f \tag{2.17}$$

Where s is the slip in per unit and f is the fundamental frequency of the stator current (power supply). The sideband components are extensively used for induction motor fault classification purposes [11]. Other electric effects of broken bars are used for motor fault classification purposes including speed oscillations, torque ripples, instantaneous stator power oscillations, and stator current envelopes. In this thesis, the fault monitoring method is based on torque ripples for broken bar detection, while the fault diagnostic method is based on the three-phase stator current envelope for classification of broken rotor bars and inter-turn short circuits. These induction motor features, stator current envelopes and air gap torque profiles

2.2.2 Inter-turn short circuits

Inter-turn short circuits in stator windings constitute a category of faults that is most common in induction motors. Typically, short circuits in stator windings occur between turns of one phase, or between turns of two phases, or between turns of all phases. Moreover, short circuits between winding conductors and the stator core also occur. The different types of winding faults are summarizes below as follows:

Inter-turn short circuits between turns of the same phase (Figure (2.10)a), winding short circuits (Figure (2.10) b), short circuits between winding and stator core at the end of the stator slot (Figure (2.10) c), Short circuits between winding and stator core in the middle of the stator slot (Figure (2.10) d), Short circuit at the leads (Figure (2.10 e). Short circuit between phases (Figure (2.10)f).

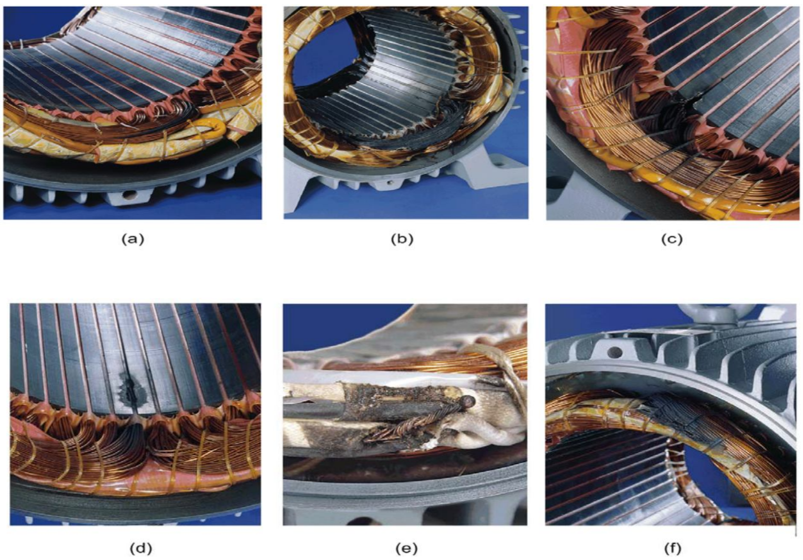

Figure (2.10) Images typical insulation damage leading to inter-turn short circuit of the stator windings in three-phase induction motors

- Burning of the winding insulation and consequent complete winding short circuits of all phase windings which are usually caused by motor overloads and blocked rotor, as well as stator energization by sub-rated voltage and over rated voltage power supplies. This type of fault can be caused by frequent starts and rotation reversals. These faults are shown in Figure (2.11) a and b. Inter-turn short circuits are also due to voltage transients as shown in Figure (2.11) c that can be caused by the successive reflection resulting from cable connection between motors and ac drives. Such ac drives produce extra voltage stress on the stator windings due to the inherent pulse width modulation of the voltage applied to the stator windings. Again, long cable connections between a motor and an ac drive can induce motor over voltages. This effect is caused by successive reflections of transient voltage.

-Complete short circuits of one or more phases can occur because of phase loss, which is cause by an open fuse, contactor or breaker failure, connection failure, or power supply failure. Such a fault is shown in Figure (2.11) d and e.

- Short circuits in one phase are usually due to an unbalanced stator voltage, as shown in Fig.ure (2.11) f. An unbalanced voltage is caused by an unbalanced load in the power line, bad connection of the motor terminals, or bad connections in the power circuit. Moreover, an unbalanced voltage means Short circuits in one phase due to motor overload in Figure (2.11) a), Short circuits in one phase due to blocked rotor in Figure (2.11) b). Inter-turn short circuits are due to voltage transients in Figure (2.11) c). Short circuits in one phase due to a phase loss in a Y-connected motor in Figure (2.11) d). Short circuits in one phase due to a phase loss in a delta-connected motor in Figure (2.11) e). Short circuits in one phase due to an unbalanced stator voltage in Figure (2.11) f)

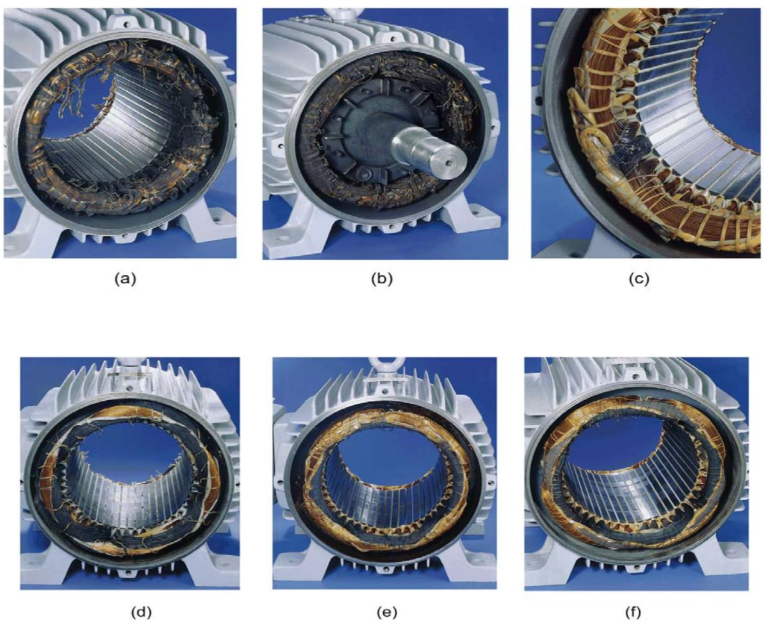

Figure (2.11) Images inter-turn short circuit of the stator winding in three-phase induction motors

The motor fault diagnostic method presented in this thesis is developed for inter-turn short circuits in one phase of the stator windings. This type of fault is referred to as inter-turn short circuit throughout the thesis. The two induction motor features, three-phase stator current envelope and air gap torque profile, which are used for broken bars and inter-turn short circuit.

2.3 Fuzzy Logic

One of the more popular new technologies is “intelligent control,” which is defined as a combination of control theory, operations research, and Artificial Intelligence (AI), by the billions of dollars worth of sales and thousands of patents issued worldwide, led by Japan since the announcement of the first fuzzy chips in 1987, fuzzy logic is still perhaps the most popular area in AI. To understand fuzzy logic, it is important to discuss fuzzy sets. In 1965, Zadeh wrote a seminal paper in which he introduced fuzzy sets, that is, sets with unship boundaries. These sets are generally in better agreement with the human mind and reasoning that works with shades of gray, rather than with just black or white. Fuzzy sets are typically able to represent linguistic terms, for example, warm, hot, high, low, close, far, etc.

Nearly 10 years later (in 1974), Mamdani succeeded in applying fuzzy logic for control in practice. Today, in Japan, United States, Europe, Asia, and many other parts of the world, fuzzy control is widely accepted and applied.

A new logic system based on the premises of fuzzy sets is known as fuzzy logic. The need and use of multilevel logic can be traced from the ancient works of Aristotle, who is quoted as saying “There will be a sea battle tomorrow.” Such a statement is not yet true or false, but is potentially either. Much later, around AD 1285–1340, William of Occam supported two-valued logic but speculated on what the truth value of “if p then q” might be if one of the two components, p or q, as neither true nor false. During the period of 1878–1956, Lukasiewicz proposed three-level logic as a “true” (1), a “false” (0), and a “neuter” (1/2), which represented half-true or half-false.

In subsequent times, logicians in China and other parts of the world continued on the notion of multilevel logic. Zadeh , in his seminal 1965 paper, finished the task by following through with the speculation of previous logicians and showing that what he called “fuzzy sets” was the foundation of any logic, regardless of the number of truth levels assumed. He chose the innocent word “fuzz” for the continuum of logical values between 0 (completely false) and 1 (completely true). The theory of fuzzy logic deals with two problems:

(1) The fuzzy set theory, which deals with the vagueness found in semantics, and

(2) The fuzzy measure theory, which deals with the ambiguous nature of judgments and evaluations.

The primary motivation and “banner” of fuzzy logic is the possibility of exploiting tolerance for some inexactness and imprecision. Precision is often very costly, so if a problem does not warrant great precision, one should not have to pay for it. The traditional example of parking a car is a noteworthy illustration. If the driver is not required to park the car within an exact distance from the curb, why spend any more time than necessary on the task as long as it is a legal parking operation? Fuzzy logic and classical logic differ in the sense that the former can handle both symbolic and numerical manipulation, whereas the latter can handle symbolic manipulation only.

In a broad sense, fuzzy logic is a union of fuzzy (fuzzified) crisp logics. To quote Zadeh, “Fuzzy logic’s primary aim is to provide a formal, computationally-oriented system of concepts and techniques for dealing with modes of reasoning which are approximate rather than exact.” Thus, in fuzzy logic, exact (crisp) reasoning is considered to be the limiting case of approximate reasoning. In fuzzy logic, one can see that everything is a matter of degrees [12].

2.3.1 Fuzzy sets and conventional sets

First proposed at 1965 and based on the concept of fuzzy sets, fuzzy set theory provides means for representing uncertainty. Probability theory is the primary tool for analyzing uncertainty and assumes uncertainty is not always random though and fuzzy set theory is used to model the kind of uncertainty associated with imprecision, and lack of information. Conventional set theory distinguishes between those elements that are members of a set and those are not, there being very, clear or crisp boundaries. Figure (2.12) shows the crisp set “medium temperature". Temperatures between 20 and 30 C lie within crisp set, and have a membership value of one.

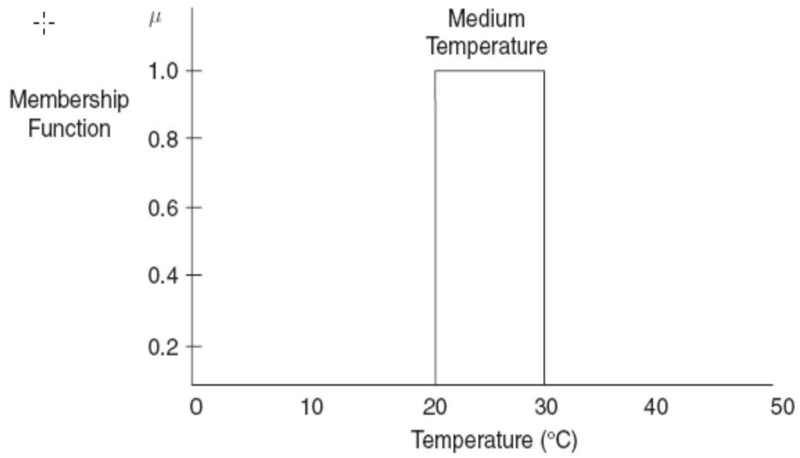

Figure (2.12): Crisp set

The central concept of fuzzy set theory is that the membership probability theory can have value of between 0 and 1. In Figure (2.13) the membership function μ has linear relationship with the x this produces a triangular shaped fuzzy set. Triangles are commonly used because they give good results and computation is simple. Other arrangement includes-non symmetrical triangles, trapezoids, and Gaussian.

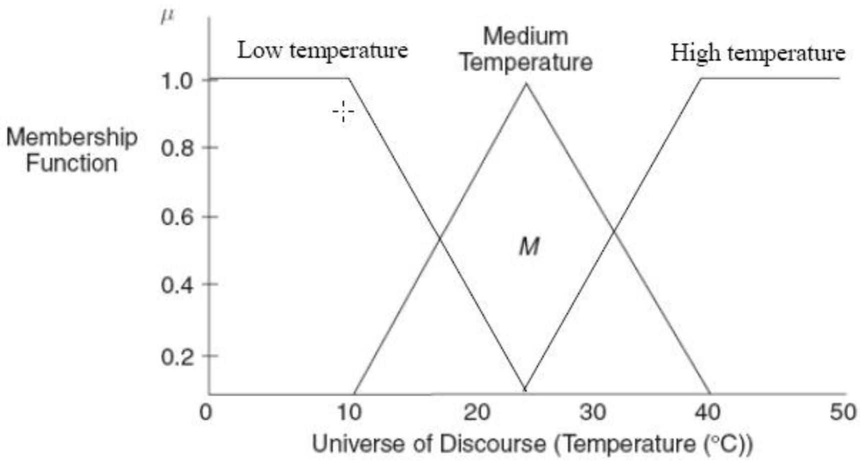

Figure (2.13): Fuzzy set.

Let the fuzzy set "medium temperature" be called fuzzy set M. If an element u of the universe of discourse U lies within fuzzy set M, it will have a value of between 0 and 1

1. This is expressed as

$$\mu_M \in [0,1] \quad (2.18)$$

When the universe of discourse is discrete and finite, fuzzy set M may be expressed as

$$M = \sum_{i=1}^{N} \frac{\mu_M(u_i)}{u_i} \quad (2.19)$$

2.3.2 Operations on fuzzy set

Let A and B be two fuzzy sets within a universe of discourse U with membership function $\mu_A \in$ l[0,1] and $\mu_B \in [0,1]$ respectively. The following fuzzy set operations can be defined

- **Equality**

Two fuzzy sets A and B are equal if they have the same membership function within a universe of discourse *U*

$$\mu_A(u) = \mu_B(u), \forall u \in U \quad (2.20)$$

- **Union**

The union of two fuzzy sets A and B corresponds to Boolean OR function and is given by:

$$\mu_{A\cup B}(u) = \max[\mu_A(u), \mu_B(u)], \forall u \in U \quad (2.21)$$

- **Intersection**

The intersection of two fuzzy sets A and B corresponds to the Boolean AND function and is given by:

$$\mu_{A\cup B}(u) = \min[\mu_A(u), \mu_B(u)], \forall u \in U \quad (2.22)$$

- **Complement**

The complement of fuzzy set A corresponds to the Boolean NOT function and is given by [13]:

$$\mu_{1-A}(u) = 1 - \mu_A(u), \forall u \in U \quad (2.23)$$

2.3.3 Fuzzy relations

Many application problem descriptions include fuzzy relations. For example, to describe a plant or a control system one determines, how an output(s) depends on inputs, or the relationship between outputs and inputs. If one constructs a database and an information system, one determines the relations between different attributes.

To model a fuzzy system one uses rules like if speed is slow then pressure should be high. If the speed is denoted as variable A and pressure as variable B then one will have in a general case the rule: if A then B [14].

2.3.4 Linguistic variables

To specify rules for the rule-base, the expert will use a "linguistic description"; hence, linguistic expressions are needed for the inputs and outputs and the characteristics of the inputs and outputs. "linguistic variables" is used (constant symbolic descriptions of what are in general time-varying quantities) to describe fuzzy system inputs and outputs. For our fuzzy system, linguistic variables denoted by $\tilde{u}i$ are used to describe the inputs ui. Similarly, linguistic variables denoted by $\tilde{y}i$ are used to describe outputs yi. For instance, an input to the fuzzy system may be described as $\tilde{u}1$="position error" or $\tilde{u}2$ ="velocity error," and an output from the fuzzy system may be $\tilde{y}1$ ="voltage in."[15].

2.3.5 Fuzzy control system design

Fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system. In this section we seek to provide a philosophy of how to approach the design of fuzzy controllers.

The fuzzy controller block diagram is given in Figure (2.14), where we show a fuzzy controller embedded in a closed-loop control system. The plant outputs are denoted by y(t), its inputs are denoted by u(t), and the reference input to the fuzzy controller is denoted by r(t).

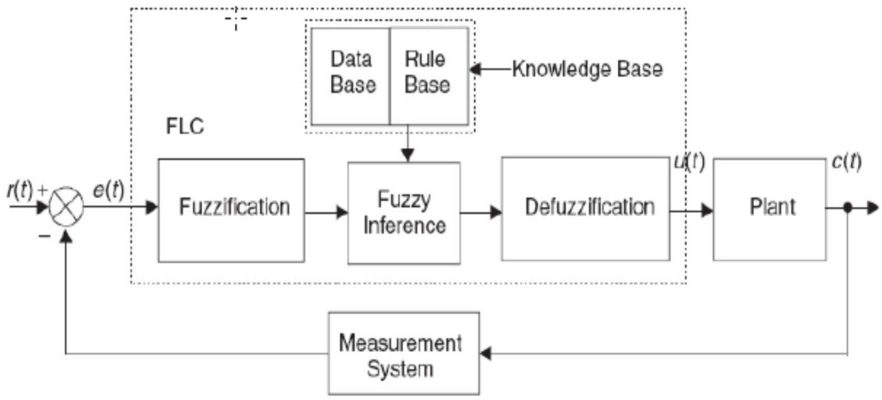

Figure (2.14): Fuzzy controller architecture

The fuzzy controller has four main components:

(i) The “rule-base” holds the knowledge, in the form of a set of rules, of how best to control the system.

(ii) The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.

(iii) The fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base.

(iv) The defuzzification interface converts the conclusions reached by the inference mechanism into the inputs to the plant.

Basically, you should view the fuzzy controller as an artificial decision maker that operates in a closed-loop system in real time. It gathers plant output data y (t), compares it to the reference input $r(t)$, and then decides what the plant input $u(t)$ should be to ensure that the performance objectives will be met.

To design the fuzzy controller, the control engineer must gather information on how the artificial decision maker should act in the closed-loop system. Sometimes this information can come from a human decision maker who performs the control task, while at other times the control engineer can come to understand the plant dynamics and write down a set of rules about how to control the system without outside help.

These “rules” basically say, “If the plant output and reference input are behaving in a certain manner, then the plant input should be some value”.

A whole set of such “If-Then” rules is loaded into the rule-base, and an inference strategy is chosen, then the system is ready to be tested to see if the closed-loop specifications are met [16].

CHAPTER THREE

MODEL OF A THREE-PHASE INDUCTION MOTOR

3.1 Introduction

The induction machine is used in wide variety of applications as a means of converting electric power to mechanical power. Pump steel mill, hoist drives, household applications are few applications of induction machines. Induction motors are most commonly used as they offer better performance than other ac motors.

In this chapter, the development of the model of a three-phase induction motor is examined starting with how the induction motor operates. The derivation of the dynamic equations, describing the motor is explained. The transformation theory, which simplifies the analysis of the induction motor, is discussed. The steady state equations for the induction motor are obtained. The basic principles of the operation of a three phase inverter are explained, following which the operation of a three phase inverter feeding a induction machine is explained with some simulation results.

3.2. Principle of Operation

The operating principle of the induction motor can be briefly explained as, when balanced three phase voltages displaced in time from each other by angular intervals of 120 is applied to a stator having three phase windings displaced in space by 120 electrical, a rotating magnetic field is produced. This rotating magnetic field has a uniform strength and rotates at the supply frequency, the rotor that was assumed to be standstill until then, has electromagnetic forces induced in it. As the rotor windings are short circuited, currents start circulating in them, producing a reaction. As known from Lenz's law, the reaction is to counter the source of the rotor currents. These currents would become zero when the rotor starts rotating in the same direction as that of the rotating magnetic field, and with the same strength. Thus the rotor starts rotating trying to catch up with the rotating magnetic field. When the differentia l speeds between these two become zero then the rotor currents will be zero, there will be no emf resulting in zero torque production [17]. Depending on the shaft load the rotor will always settle at a speed ω_r, which is less than the supply frequency ω_e. This differential speed is called the slip speed ω_{so}. The relation between ω_e and ω_{so} is given as equations (3.1) (3.2)

$$\omega_{so} = \omega_e - \omega_r \tag{3.1}$$

$$\omega_r = \frac{p}{2}\omega_m \tag{3.2}$$

3.3 Derivation of Machine Equations

The winding arrangement of a two-pole, three-phase wyes-connected induction machine is shown in Figure (3.1)

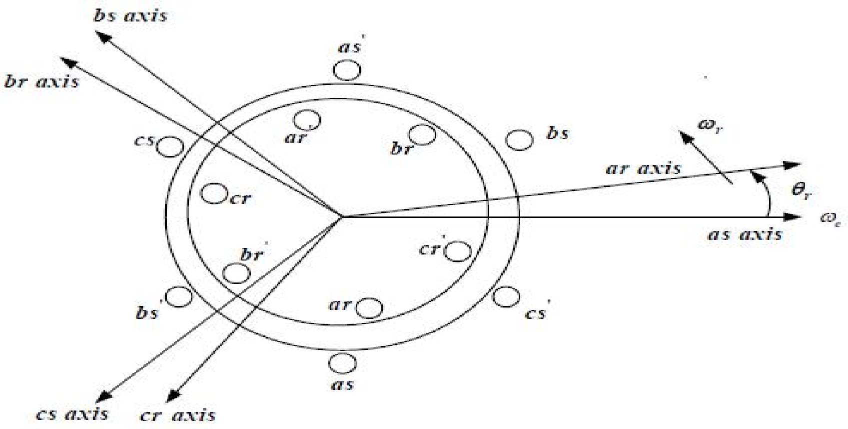

Figure (3.1).Two-pole three-phase symmetrical induction machine

The stator windings of which are identical, sinusoidal distributed in space with a phase displacement of 120^0, with N_S equivalent turns and the rotor is assumed to symmetrical with three phase windings displaced in space by an angle of 120, with N_r effective turns and a resistance of. The voltage equations for the stator and the rotor are as given in Equations (3.3) to (3.8).

For the stator:

$$V_{as} = r_s I_{as} + p\lambda_{as} \tag{3.3}$$

$$V_{bs} = r_s I_{bs} + p\lambda_{bs} \tag{3.4}$$

$$V_{cs} = r_s I_{cs} + p\lambda_{cs} \tag{3.5}$$

Where V_{as}, V_{bs} , and V_{cs} are the three phase balanced voltages which rotate at the supply frequency. For the rotor the flux linkages rotate at the speed of the rotor, which is ω_r:

$$V_{ar} = r_r I_{ar} + p\lambda_{ar} \tag{3.6}$$

$$V_{br} = r_r I_{\mathrm{br}} + p\lambda_{br} \tag{3.7}$$

$$V_{cr} = r_s I_{cr} + p\lambda_{cr} \tag{3.8}$$

The above equations can be written in short as :

$$V_{abcs} = r_s I_{abcs} + p\lambda_{abcs} \tag{3.9}$$

$$V_{abcr} = r_r I_{abcr} + p\lambda_{abcr} \tag{3.10}$$

Where

$$(V_{abcs})^{\mathrm{T}} = [\mathrm{V_{as}} \quad \mathrm{V_{bs}} \quad \mathrm{V_{cs}}] \tag{3.11}$$

$$(V_{abcr})^{\mathrm{T}} = [\mathrm{V_{ar}} \quad \mathrm{V_{br}} \quad \mathrm{V_{cr}}] \tag{3.12}$$

In the above two equations‘s’ subscript denoted variables and parameters associated with the stator circuits and the subscript ‘r’denotes variables and parameters associated with the rotor circuits. Both r_s and r_r are diagonal matrices each with equal nonzero elements. For a magnetically linear system, the flux linkages may be expressed

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \tag{3.13}$$

The winding inductances can be derived and in particular

$$L_s = \begin{bmatrix} L_{ls} + L_m & -\frac{1}{2}L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & L_{ls} + L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & -\frac{1}{2}L_m & L_{ls} + L_m \end{bmatrix} \tag{3.14}$$

$$L_r = \begin{bmatrix} L_{lr} + L_m & -\frac{1}{2}L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & L_{lr} + L_m & -\frac{1}{2}L_m \\ -\frac{1}{2}L_m & -\frac{1}{2}L_m & L_{lr} + L_m \end{bmatrix} \tag{3.15}$$

$$L_{sr} = \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\theta_r \end{bmatrix} \quad (3.16)$$

In the above inductance equations, L_{ls} and L_m are the leakage and magnetizing inductances of the stator windings; L_{lr} and L_m are for the rotor windings. The inductance L_{sr} is the amplitude of the mutual inductances between stator and rotor windings.

From the above inductance equations, it can be observed that the machine inductances are functions of the rotor speed, whereupon the coefficients of the differential equations which describe the behavior of these machines are time varying except when the rotor is at standstill. A change of variables is often used to reduce the complexity of these differential equations, which gives rise to the reference frame theory. For the induction machine under balanced operating conditions the synchronous reference frame of transformation is employed in which the reference frame rotates with the same frequency as that of the supply frequency ω_e. The transformation matrix used for the synchronous reference frame transformation is

$$K_s(\theta_s) = \frac{2}{3}\begin{bmatrix} \cos\theta_s & \cos\left(\theta_s - \frac{2\pi}{3}\right) & \cos\left(\theta_s + \frac{2\pi}{3}\right) \\ \sin\theta_s & \sin\left(\theta_s - \frac{2\pi}{3}\right) & \sin\left(\theta_s + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3.17)$$

Where $\theta_s = \int \omega_s t + \theta_{so}$, θ_{so} being the initial angle of the reference frame. The inverse transformation for the above transformation is given as

$$(K_s(\theta_s))^{-1} = \begin{bmatrix} \cos\theta_s & \sin\theta_s & 1 \\ \sin\left(\theta_s - \frac{2\pi}{3}\right) & \cos\left(\theta_s - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_s + \frac{2\pi}{3}\right) & \sin\left(\theta_s + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \quad (3.18)$$

The new variables after the transformation are related to the original variables as:

$$f_{qdo} = \left(k_s(\theta_s)\right) f_{abc} \tag{3.19}$$

Where can be voltage current flux or anything? For the equations in (3.9) and (3.10) after transforming them in to the synchronous reference frame these equations become:

$$V_{qs} = r_s i_{qs} + p\lambda_{qs} + \omega_e \lambda_{ds} \tag{3.20}$$

$$V_{ds} = r_s i_{ds} + p\lambda_{ds} - \omega_e \lambda_{qs} \tag{3.21}$$

$$V_{os} = r_s i_{os} + p\lambda_{os} \tag{3.22}$$

$$V_{qr} = r_r i_{qr} + p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr} \tag{3.23}$$

$$V_{dr} = r_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} \tag{3.24}$$

$$V_{or} = r_s + p\lambda_{or} \tag{3.25}$$

Where V_{qs}, I_{qs}, λ_{qs} are the q-axis components, V_{ds}, I_{ds}, λ_{ds} are the d-axis components, and V_{os}, I_{os}, λ_{os} belong to the 0- axis and usually represent the unbalances in the system. In case of balanced voltages the zero-axis currents, voltages and flux are zero under normal operating conditions. The flux linkage equations expressed in abc variables given in Equation (3.13) yields the flux linkage equations for a magnetically linear system

$$\begin{bmatrix} \lambda_{qd0s} \\ \lambda_{qd0r} \end{bmatrix} = \begin{bmatrix} k_s L_s\left(k_s^{-1}\right) & k_s L_{sr}\left(k_s^{-1}\right) \\ k_s L_{sr}\left(k_s^{-1}\right) & k_s L_r\left(k_s^{-1}\right) \end{bmatrix} \begin{bmatrix} i_{qd0s} \\ i_{qd0r} \end{bmatrix} \tag{2.26}$$

Where L_s , L_r are as defined in Equations (3.14) to (3.16). Evaluating each term in the matrix of Equation (3.26) we get

$$k_s L_s\left(k_s^{-1}\right) = \begin{bmatrix} L_{ls} + L_m & 0 & 0 \\ 0 & L_{ls} + L_m & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} \tag{2.27}$$

$$k_s L_r\left(k_s^{-1}\right) = \begin{bmatrix} L_{lr} + L_m & 0 & 0 \\ 0 & L_{ls} + L_m & 0 \\ 0 & 0 & L_{lr} \end{bmatrix} \tag{2.28}$$

From above the flux linkages the expressions are modified as

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{3.29}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{3.30}$$

$$\lambda_{os} = L_{ls} i_{os} \tag{3.31}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.32}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.33}$$

$$\lambda_{or} = L_{lr} i_{or} \tag{3.34}$$

The expression for the electromagnetic torque in terms of the reference frame variables can be expressed as

$$T_e = \left(\frac{p}{2}\right)\left[(K_s)^{-1} i_{qdos}\right]T \frac{\partial}{\partial\theta_r}[L_{sr}](K_s)^{-1} i_{qdor} \tag{3.35}$$

The torque expression in Equation (3.35) can be expressed in terms of currents as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right) L_m\left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{3.36}$$

Where T_e is positive for motor action. Alternative expressions for the torque can be expressed in terms of flux linkages are given in Equations (3.37) and (3.38)

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}\right) \tag{3.37}$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{3.38}$$

The expression for the rotor speed is expressed in terms of torque as

$$p_{\omega_r} = \frac{p}{2J}(T_e - T_L) \tag{3.39}$$

Where T_e ,T_L the electromagnetic and the load torque are, respectively, depending on the load torque the motor settles at a speed, which is always less than the angular frequency with which it gets excited [18]. The load torque should be positive for motoring operation of the induction machine

3.3.1 Equivalent circuit of the induction machine

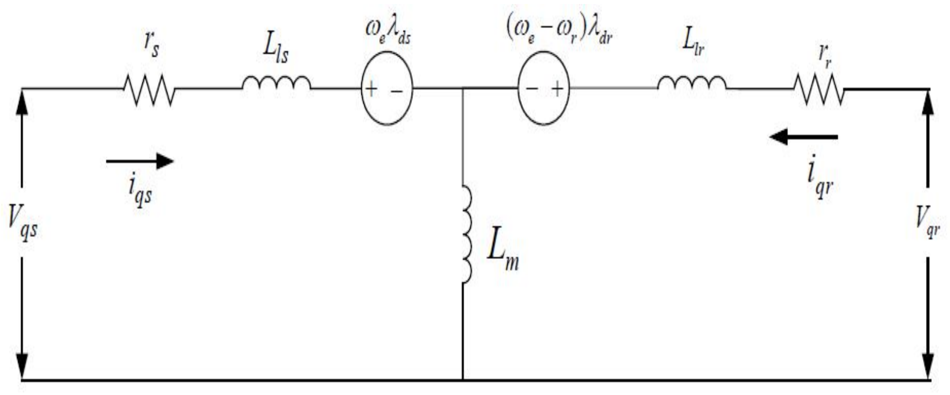

Figure (3.2) Arbitrary reference frame equivalent circuit for a three phase, symmetrical induction machine in the q-axis.

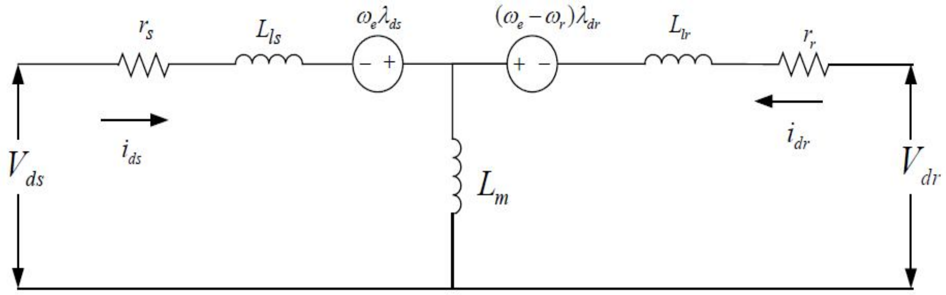

Figure (3.3) Arbitrary reference frame equivalent circuit for a three phase, symmetrical induction machine in the d-axis.

The Induction machine equivalent circuit is useful in the analysis of the machine when the motor settles at the rated speed. The equivalent circuit of the machine in the reference frame variables is formed using the equations from (3.20) to (3.25). The equivalent circuit for the stator is as shown in Figure (3.2) and that of the rotor is as shown in Figure (3.3).

3.3.2 Free acceleration characteristics

The variables of the induction machine during free acceleration or on no-load are observed which gives a deeper insight as to how the machine operates. The nonlinear differential equations as given in equations from (3.20) to (3.25) are used. The machine is simulated with either flux or currents as a state variable. Choosing flux as the state variable the equations are less complicated, thus flux is chosen to be the state variable and later from the flux equations the currents are obtained. The equations for the computer simulation in terms of flux linkages that is λ_{qs}, λ_{ds}, λq_r, λ_{dr} are given from (3.40) to (3.45).

$$p\lambda_{qs} = V_{qs} - \frac{r_s L_r}{K}\lambda_{qs} - \omega\lambda_{ds} + \frac{r_s L_m}{K}\lambda_{qr} \quad (3.40)$$

$$p\lambda_{ds} = V_{ds} - \frac{r_s L_r}{K}\lambda_{ds} - \omega\lambda_{qs} + \frac{r_s L_m}{K}\lambda_{dr} \quad (3.41)$$

$$p\lambda_{dr} = V_{dr} - \frac{r_r L_s}{K}\lambda_{dr} + \frac{r_r L_m}{K}\lambda_{ds} + (\omega - \omega_r)\,\lambda_{qr} \quad (3.42)$$

$$T_{\mathrm{e}} = \left(\frac{3p}{4}\right)\frac{L_m}{L_r}\left(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}\right) \quad (3.43)$$

$$p_{\omega_r} = \frac{p}{2J}(T_e - T_L) \quad (3.44)$$

$$K = L_s L_r - L_m^2 \tag{3.45}$$

Where ω reference frame speed, ω can be any reference frame, it can be synchronous ($\omega = \omega_r$) or the stator reference ($\omega=0$) frame depending on which reference frame will make the analysis simple. Since the induction machine is symmetric in the both the stator and the rotor in the sense the stator and the rotor have the same kind of winding choosing any reference frame will not make any difference to simplify the analysis.

After solving for the flux expression current be obtained from them as

$$i_{qs} = \frac{1}{K}\left(L_r \lambda_{qs} - L_m \lambda_{qr}\right) \tag{3.46}$$

$$i_{ds} = \frac{1}{K}\left(L_r \lambda_{ds} - L_m \lambda_{dr}\right) \tag{3.47}$$

$$i_{qr} = \frac{1}{K}\left(L_s \lambda_{qr} - L_m \lambda_{qs}\right) \tag{3.48}$$

$$i_{dr} = \frac{1}{K}\left(L_s \lambda_{dr} - L_m \lambda_{ds}\right) \tag{3.49}$$

3.4 Simulink Model

The induction machine whose parameters are given in Appendix A is simulated using Matlab/Simulink. Figure (3.4) shows the model of induction motor

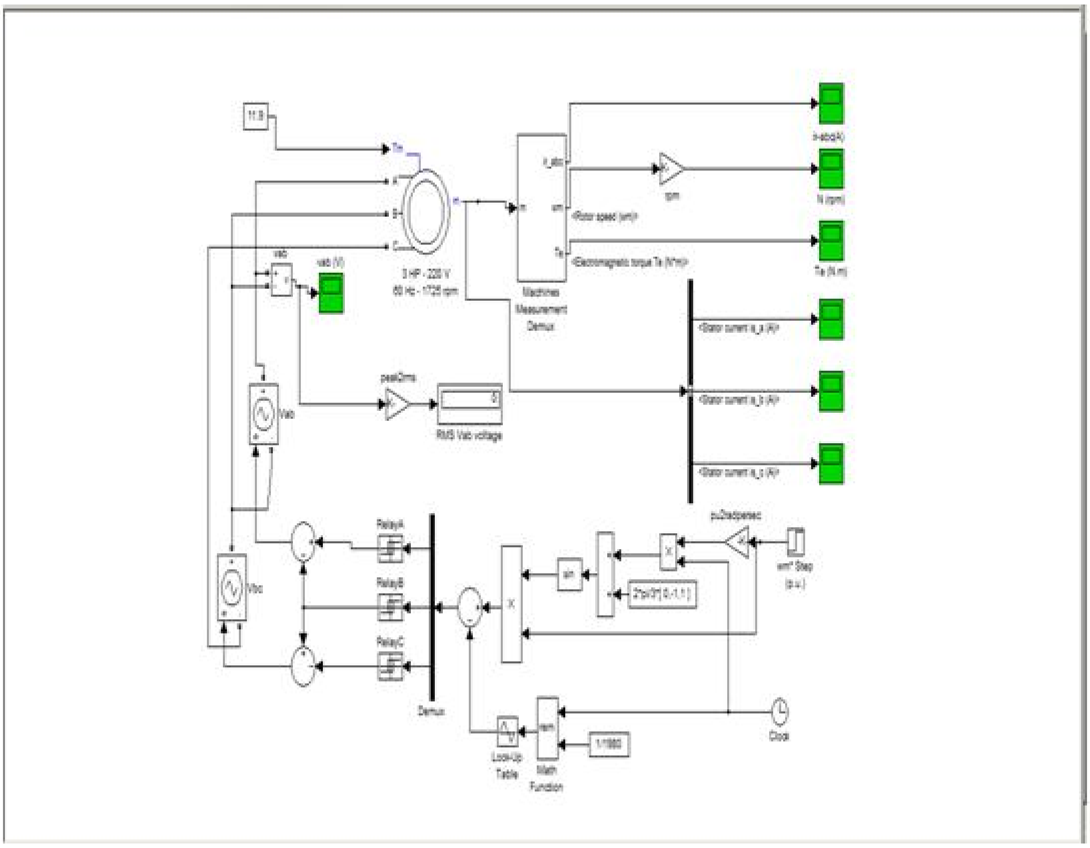

Figure (3.4)Simulink model of induction motor

3.5 Fuzzy Controller Design

Fuzzy control system design essentially amounts to: (1) Choosing the fuzzy controller inputs and outputs, (2) Choosing the preprocessing that is needed for the controller inputs and possibly post processing that is needed for the outputs, and (3) Designing each of the four components of the fuzzy controller as shown in Figure (2.14). There are standard choices for the fuzzification and defuzzification interfaces. Moreover, most often the designer settles on an inference mechanism and may use this for many different processes. Hence, the main part of the fuzzy controller that we focus on for design is the rule-base. The rule-base is constructed so that it represents a human expert “in-the-loop.” Hence, the information that we load into the rules in the rule-base may come from an actual human expert who has spent long time learning how best to control the process. In other situations there is no such human expert, and the control engineer will simply study the plant dynamics (perhaps using modeling and simulation) and write down a set of control rules that makes sense. As an example, in the cruise control problem discussed above it is clear that anyone who has experience driving a car can practice regulating the speed about a desired set point and load this information into a rule-base. For instance, one rule that a human driver may use is "If the speed is lower than the set-point, then press down further on the accelerator pedal." A rule that would represent even more detailed information about how to regulate the speed would be "If the speed is lower than the set-point AND the speed is approaching the set-point very fast, and then release the accelerator pedal by a small amount." This second rule characterizes our knowledge about how to make sure that we do not overshoot our desired goal (the set-point speed). Generally speaking, if we load very detailed expertise into the rule-base, we enhance our chances of obtaining better performance. By editing "fuzzy" in workspace a window of FIS editor appears as in Figure (3.1).

3.5.1 Fuzzy basic FIS editor

The FIS editor displays high-level information about a fuzzy inference System shown in Figure (3.5). At the top is a diagram of the system with each input and output clearly labeled? By double-clicking on the input or output boxes, you can bring up the membership function editor. Double-clicking on the fuzzy rule box in the center of the diagram will bring up the rule editor. Just below the diagram is a text field that displays the name of the current FIS. In the lower left of the window are a series of popup menus that allow you to specify the various functions used in the fuzzy implication process. In the lower right are fields that provide information about the current variable. The current variable is determined by clicking once on one of the input or output boxes.

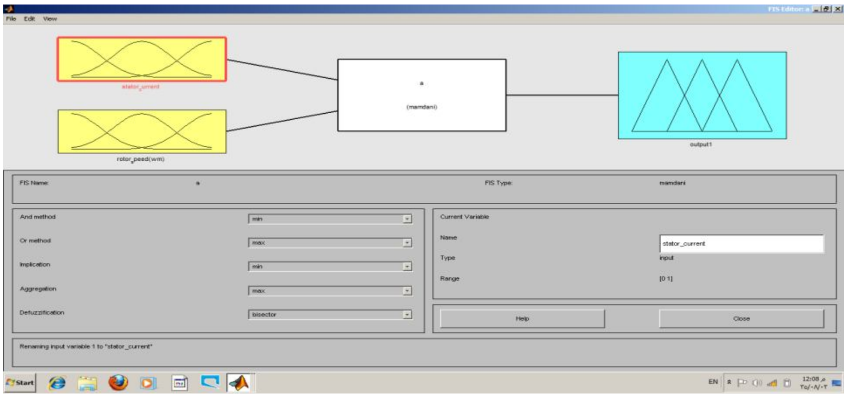

Figure (3.5): FIS editor

By adding INPUT variable from edit men u then FIS give two inputs variable which one is error (e) and another is change of error (ce) etch one consist of five membership functions to give 25 rules.

3.5.2 Membership function editor

The mfedit('a') generates a membership function editor shown in figure (3.6) that allows you to modify all the membership functions for your FIS stored in the file a.FIS. mfedit (a) operates on a MATLAB workspace variable for a FIS structure a. mfedit alone opens the membership function editor with no FIS loaded. The Membership Function (MF) Editor is used to create, remove, and modify the MFs for a given fuzzy system. On the left side of the diagram is a "variable palette" region that you use to select the current variable by clicking once on one of the displayed boxes. Information about the current variable is displayed in the text region below the palette area. To the right is a plot of all the MFs for the current variable. It could select any of these by clicking once on the line or name of the MF. Once selected, It could modify the properties of the MF using the controls in the lower right. MFs are added and removed using the edit menu.

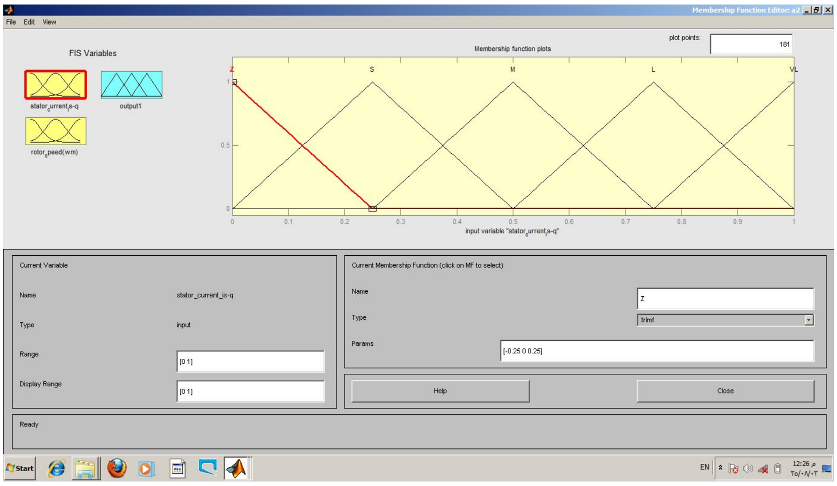

Figure (3.6): Membership function

3.5.3 Rule editor

The rule editor shown in Figure (3.7), when invoked using rule edit ('a'), is used to modify the rules of a FIS structure stored in a file, a.fis. It can also be used to inspect the rules being used by a fuzzy inference system. To use this editor to create rules, you must first have all of the input and output variables you want to use defined with the FIS editor. You can create the rules using the list box and check box choices for input and output variables, connections, and weights.

The syntax rule edit (a) is used when you want to operate on a workspace variable for a FIS structure called a. On the rule editor, there is a menu bar that allows you to open related GUI tools open and save systems, and so on. The file menu for the rule editor is the same as the one found on the FIS editor. Refer to the reference entry fuzzy for more information. By using the edit menu items:

Undo: to undo the most recent change.

By using the View menu items:

Edit FIS properties... to invoke the FIS editor.

Edit membership functions... to invoke the membership function editor.

View rules... to invoke the rule viewer.

View surface... to invoke the surface viewer.

By using the options menu items:

Language to select the language: English, Deutsch, and Francoise

Format: to select the format: verbose uses the words *if* and *then* and so on to create actual sentences

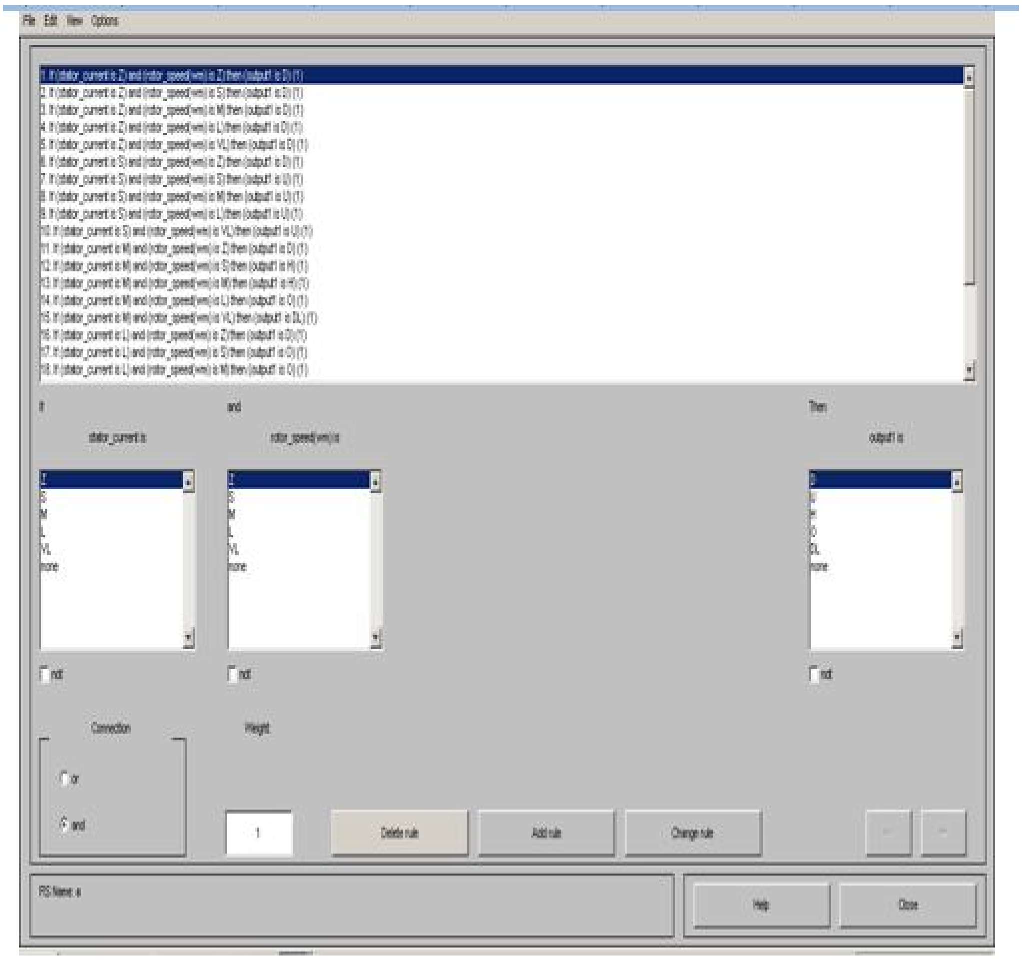

Figure (3.7): Rule editor

Table (3.1): Rule base for FIVE membership function

Is - Speed	NS	NM	Z	PS	PM
NS	NS	NS	NS	NM	Z
NM	NS	NM	NM	Z	PS
Z	NS	NM	Z	PS	PM
PS	NM	Z	PS	PS	PM
PM	Z	PS	PM	PM	PM

3.5.4 Rule viewer

The rule viewer displays shown in Figure (3.8), in one screen, all parts of the fuzzy inference process from inputs to outputs. Each row of plots corresponds to one rule, and each column of plots corresponds to either an input variable (yellow, on the left) or an output variable (blue, on the right). It could change the system input either by typing a specific value into the Input window or by moving the long yellow index lines that go down each input variable's column of plots.

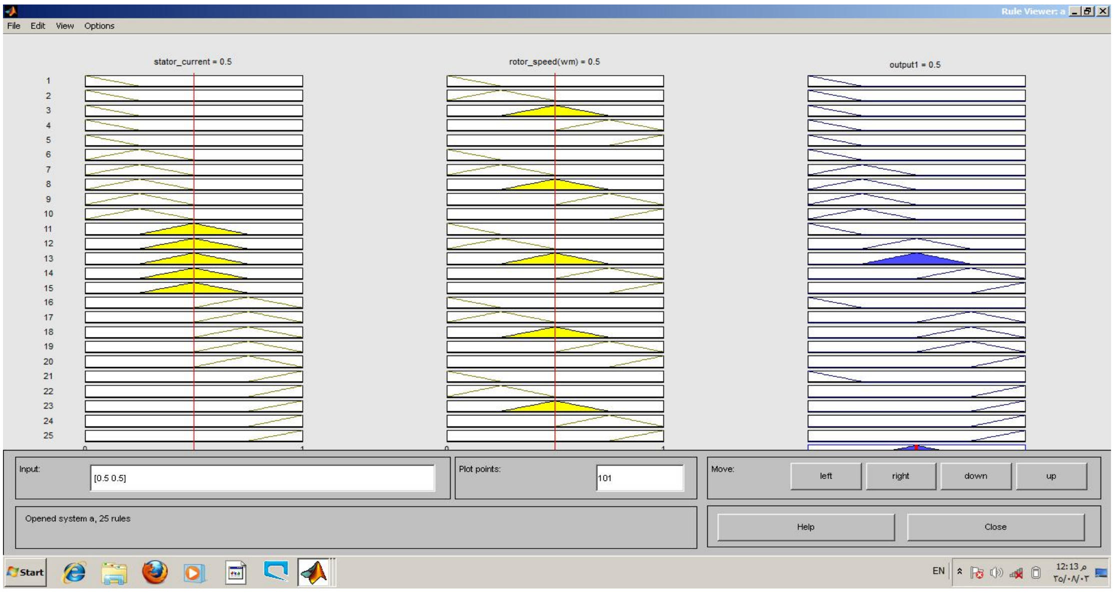

Figure (3.8): Rule viewer

3.5.5 Output surface viewer

The surface viewer shown in Figure (3.9) invoked using surf view('a') is a GUI tool that lets you examine the output surface of a FIS, a.fis, for any one or two inputs. Since it does not alter the fuzzy system or its associated FIS matrix in any way, it is a read-only editor. Using the pop-up menus, you select the two input variables you want assigned to the two input axes (X and Y), as well the output variable you want assigned to the output (or Z) axis. Select the Evaluate button to perform the calculation and plot the output surface. By clicking on the plot axes and dragging the mouse, you can actually manipulate the surface so that you can view it from different angles. If there are more than two inputs to your system, you must supply, in the reference input section, the constant values associated with any unspecified inputs.

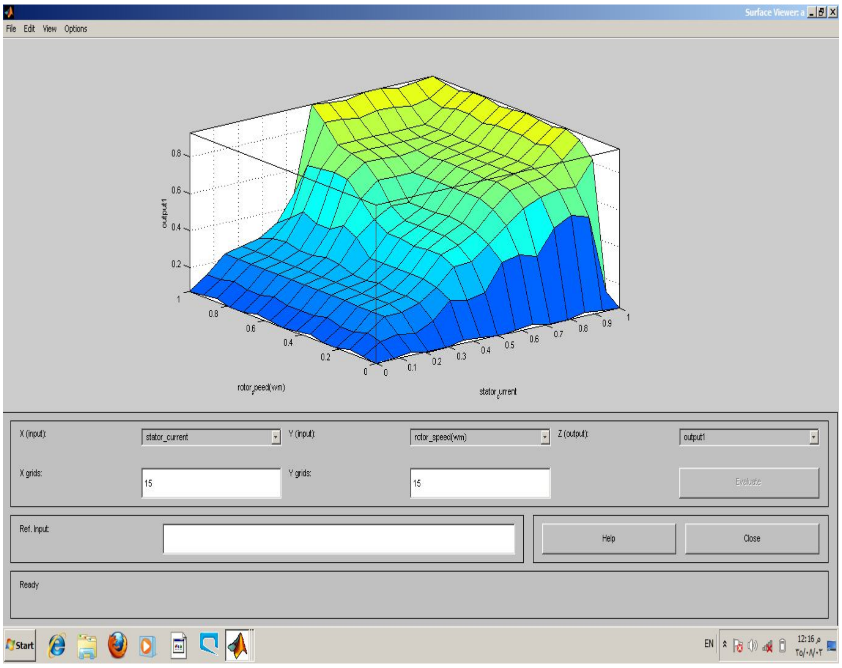

Figure (3.9): Surface viewer

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSIONS

4.1 Simulation Results for Normal Operation

Simulation study is performed as shown in Figure (4.1) of the induction motor. Figure (4.2) shows the represent of rotor speed, Figure (4.3) shows torque of the induction motor. Figure (4.4) shows stator current Ia , Ib , Ic and Figure (4.5) shows rotor current (abc) in normal conditions.

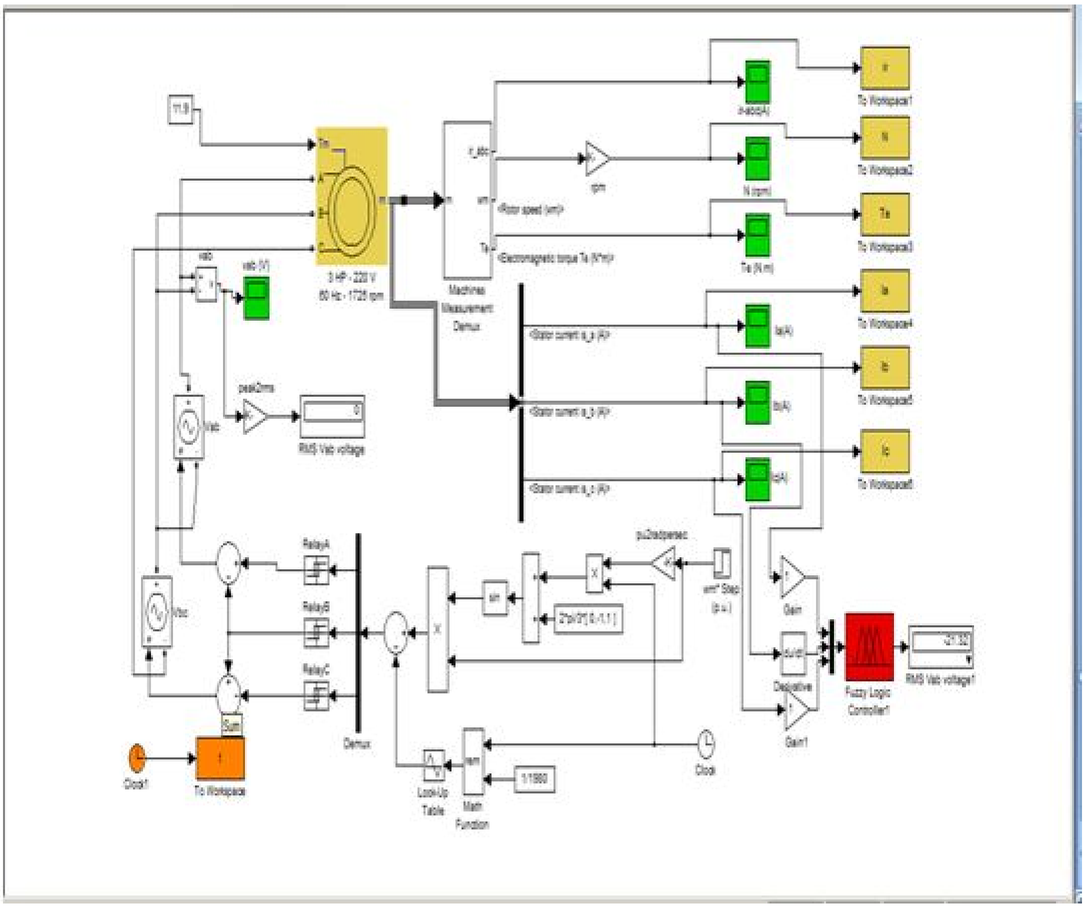

Figure (4.1) Induction motor modeling with fuzzy logic controller

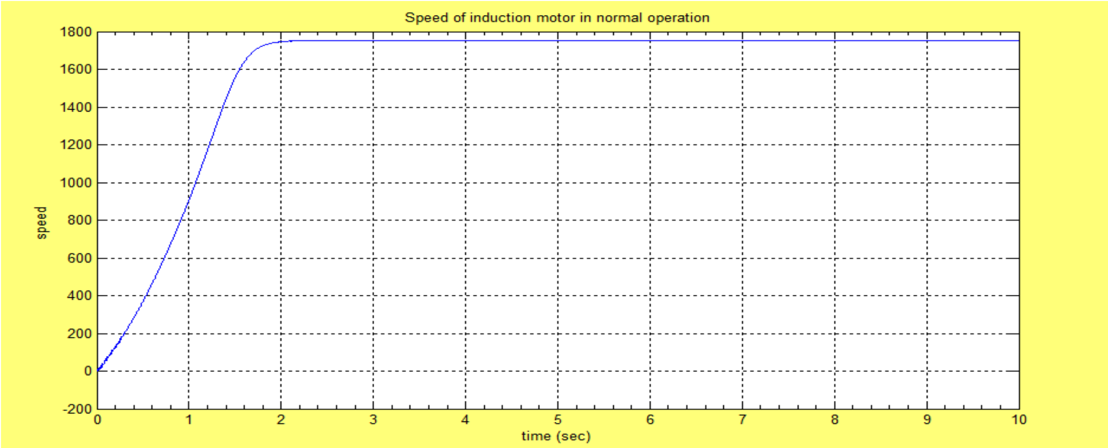

Figure (4.2) Speed of the motor (normal operation)

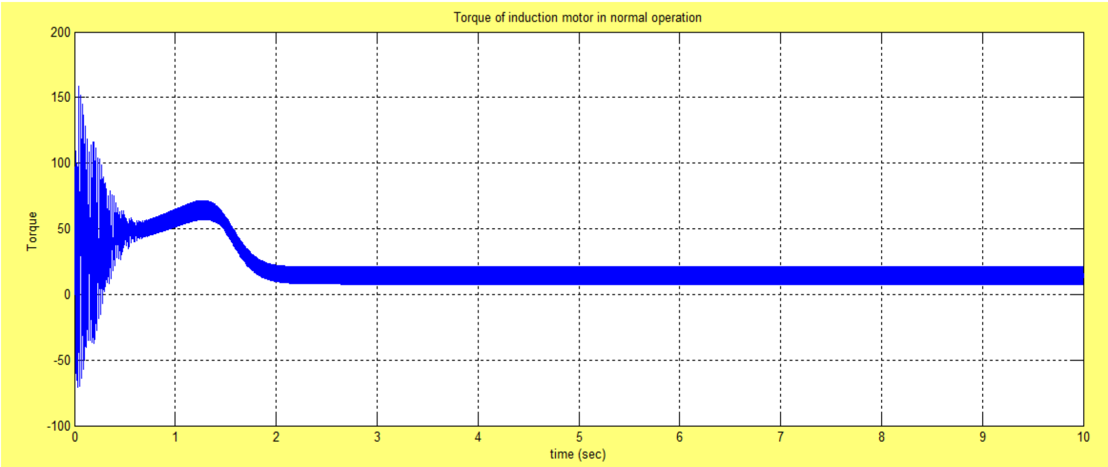

Figure (4.4) Torque of the motor (normal operation)

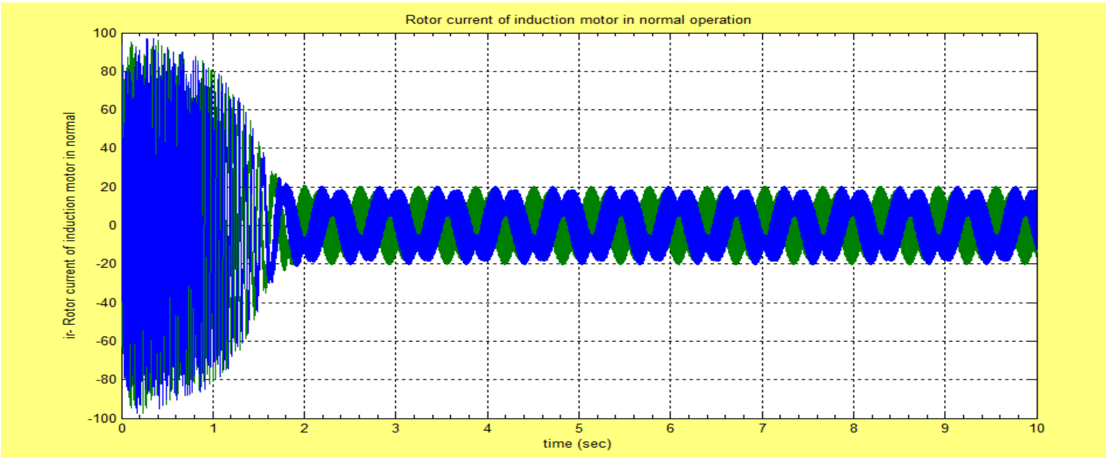

Figure (4.3) Rotor current of the motor (normal operation)

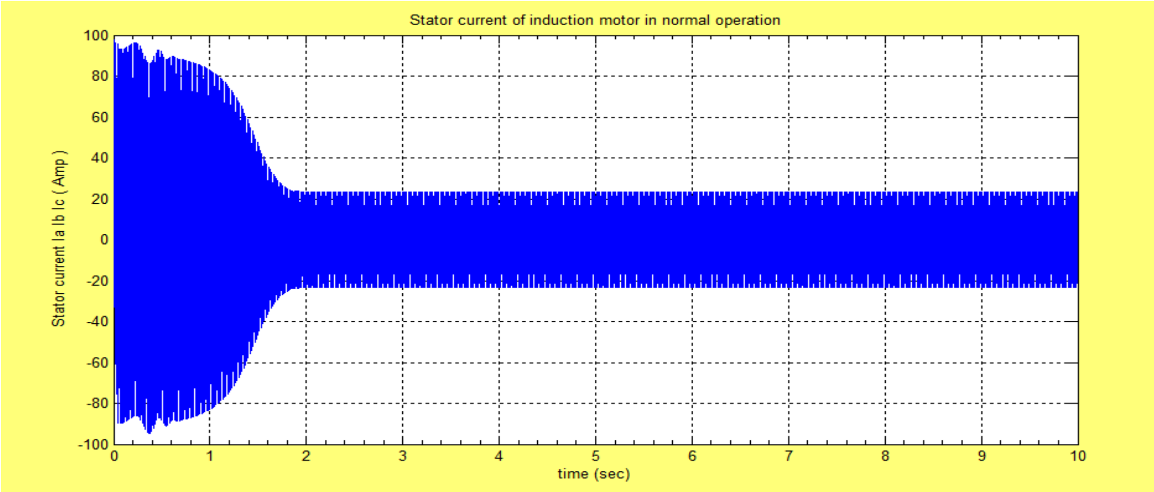

Figure (4.5) Stator current Ia Ib Ic of the motor

4.2 Simulation Results for Various Faults

Simulation of the above motor is also performed by considering various faults Conditions like turn to turn short in one phase winding break in stator winding and unbalance in input voltage.

4.2.1 Turn-Turn short in one phase winding

After the simulation for normal operation of the induction motor model, simulation for the short circuit in the part of the winding in R phase has been carried out. At this condition the value of the stator resistance at short circuit fault is equal to Rstator, fault = 0.00542Ω, we can find the value of the inductance at the fault state by using the ratio between the value of the resistance at both state (normal and fault). Thus the value of the inductance is

$$\frac{R_{Stator,normal}}{R_{Stator,fault}} = n = \frac{L_{Stator,normal}}{L_{Statorn,falut}}$$

0.7384/0.00542 = 0.003045/x

X = 0.0000223

Where : X = inductance of the motor in fault

The simulation is started-up with normal state parameter. After obtaining steady state at 0.15 second the turn fault has been created by changing the above said parameters. Figure (4.6) shows model of induction motor with fuzzy logic controller in fault turn-turn short in one phase, Figure (4.7) shows rotor current of the motor during fault, Figure (4,8) shows torque of the motor during fault and Figure (4.9) shows Ia Ib Ic stator current of the motor during fault.

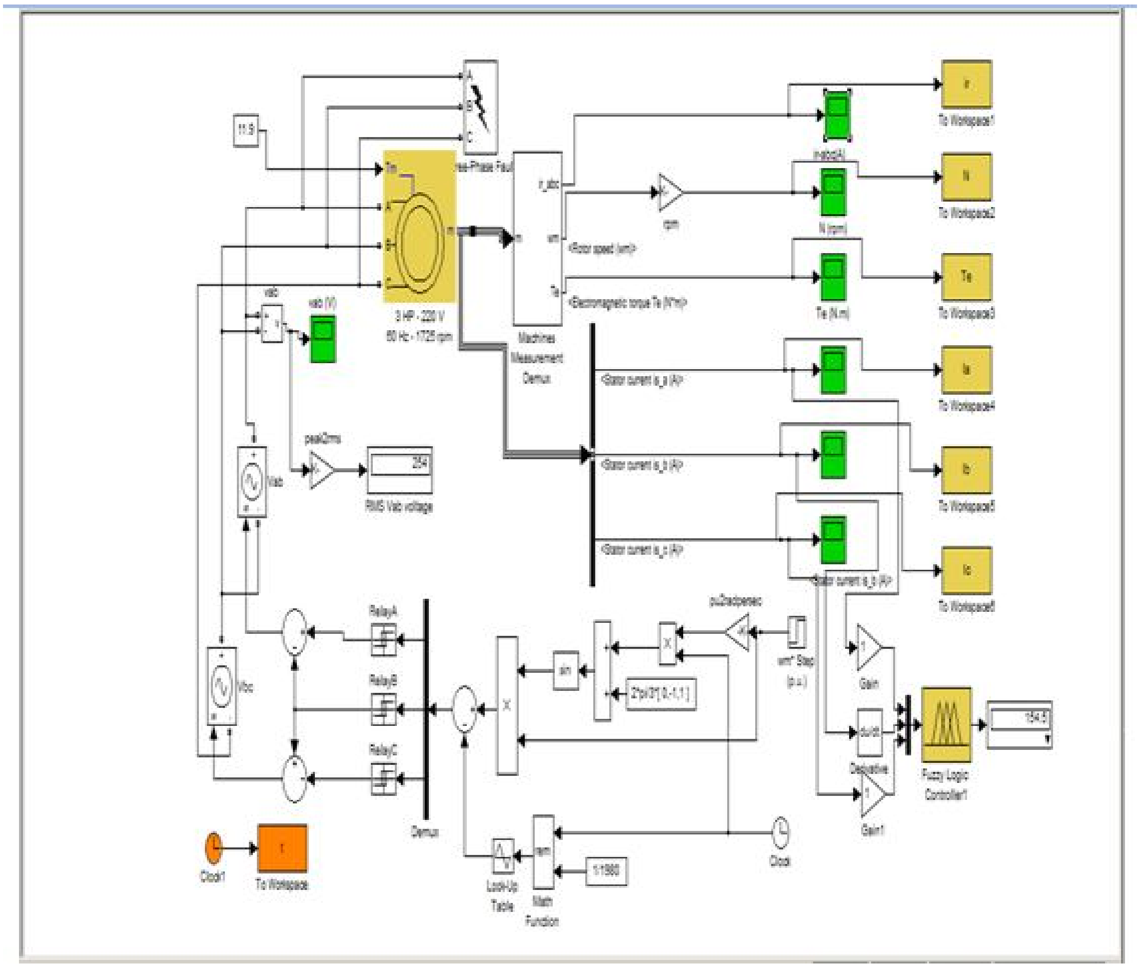

Figure (4.6) Model of induction motor with fuzzy logic controller in fault turn-turn short in one phase

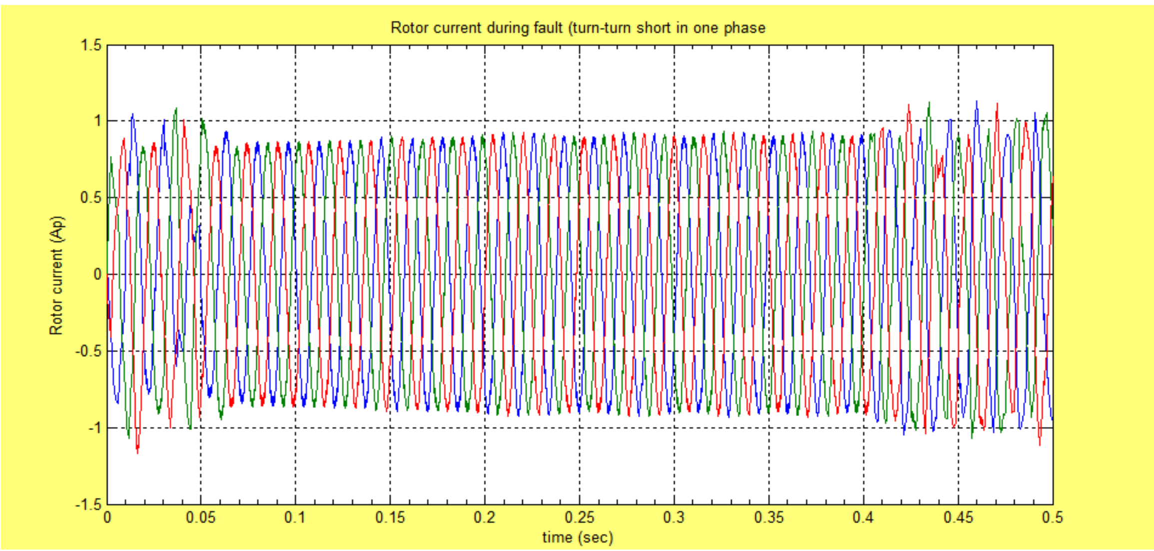

Figure (4.7) Rotor current of the motor during turn-turn fault

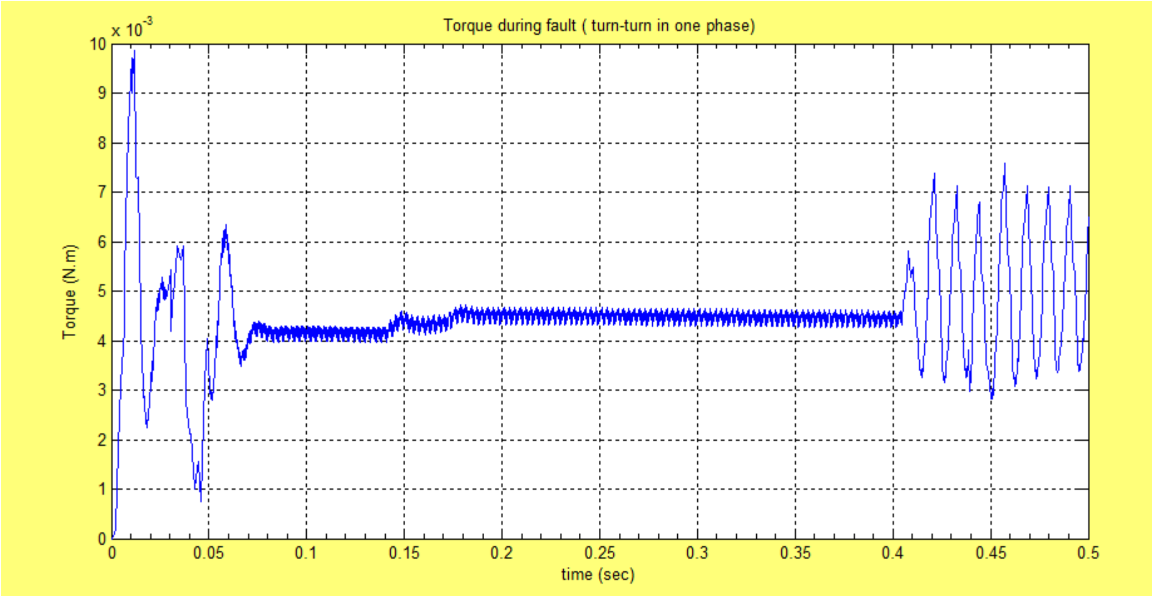

Figure (4.8) Torque of the motor during turn-turn fault

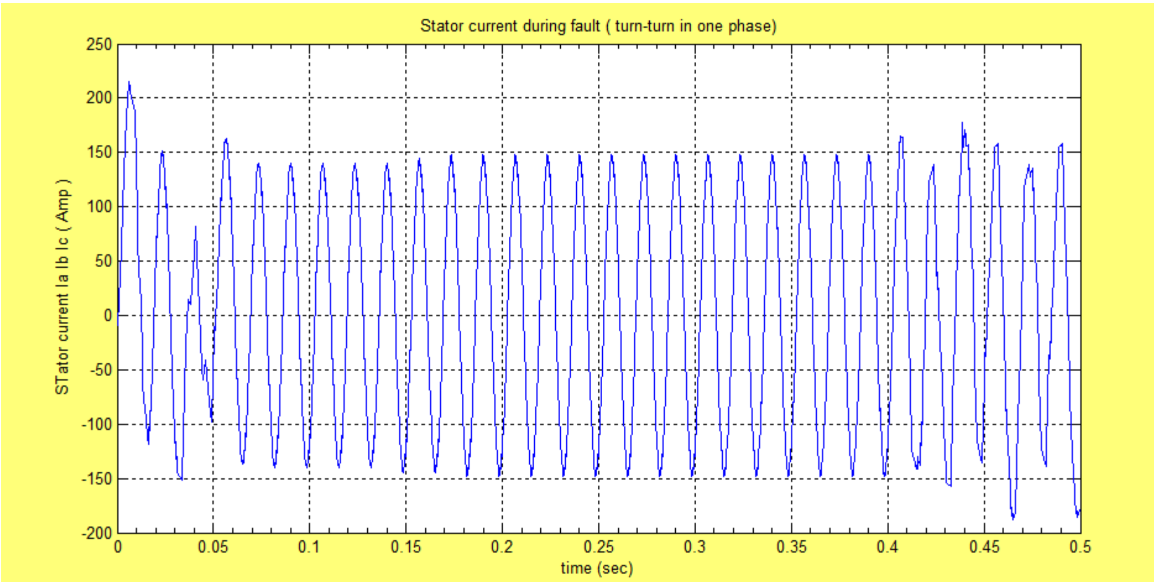

Figure (4.9) Stator current Ia Ib Ic of the motor during turn- turn fault.

4.2.2 Break in stator winding

For simulation of the break fault in the stator winding at R phase, it is not possible to apply a break in the phase by putting the value of the stator resistance and the stator inductance to infinity. It is assumed that the value of the stator resistance is very large and corresponding to this value we can calculate the value of the inductance by this equation:

$$\frac{R_{Stator,normal}}{R_{Stator,falut}} = n = \frac{L_{Stator,noral}}{L_{Stator,fault}}$$

0.7384/30000 = 0.003045/x

X = 123.71

Where : X = Inductance of the motor in faults

Replacing the values of the stator resistance and stator self-inductance in phase R by these values, the fault state results can be obtained. Figure (4.10) shows the rotor current of the motor during break in winding fault, Figure (4.11) shows torque of the motor during break in winding fault and Figure (4.12) shows stator current Ia Ib Ic of the motor during break in winding fault

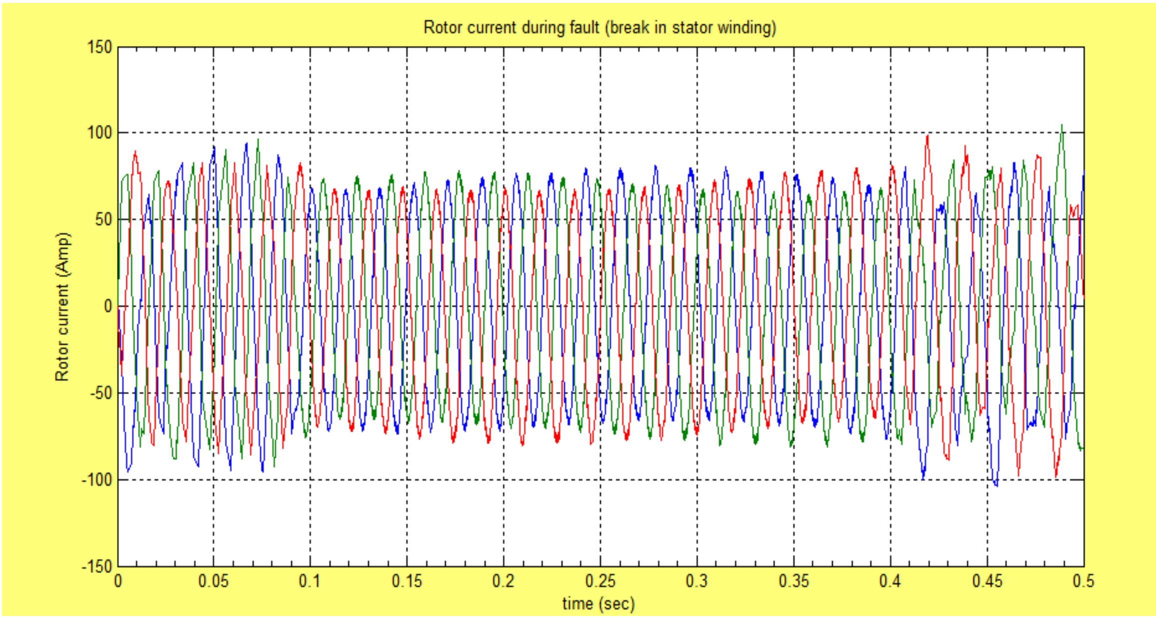

Figure (4.10) Rotor current of the motor during break in winding fault

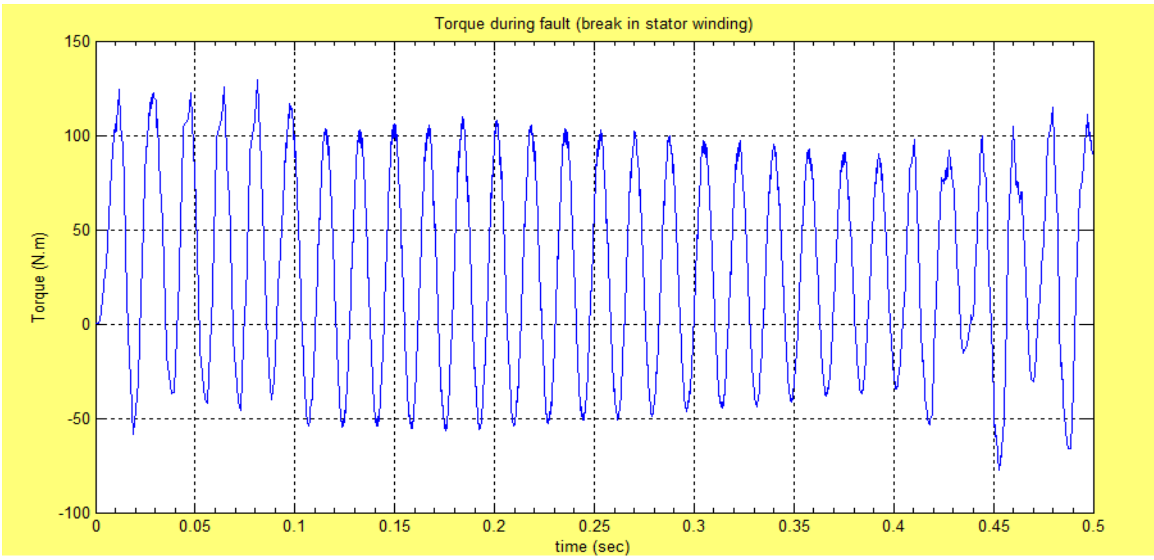

Figure (4.11) Torque of the motor during break in winding fault

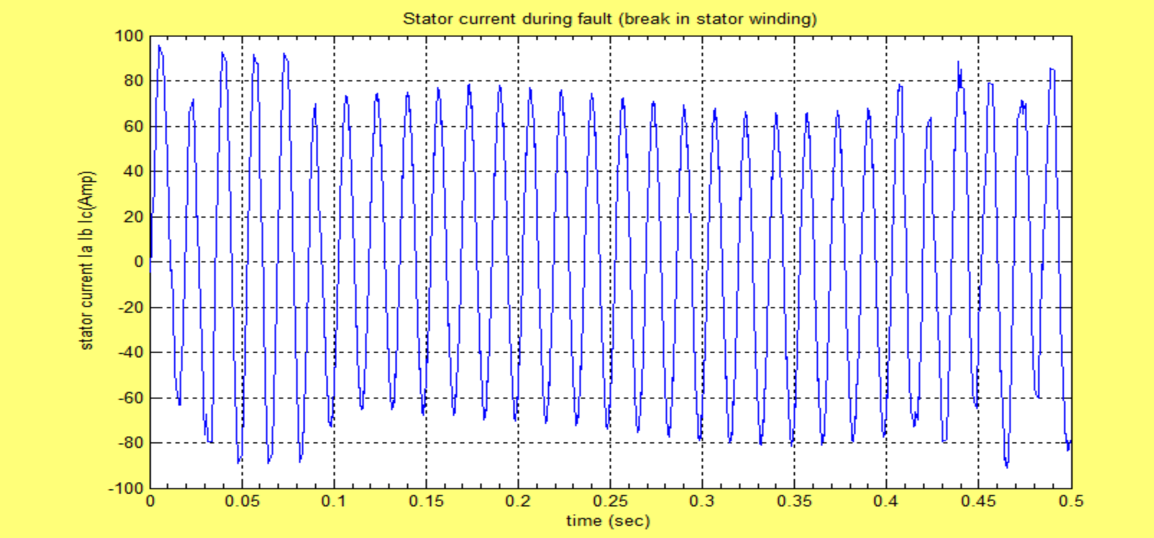

Figure (4.12) Stator current Ia Ib Ic of the motor during break in winding fault

4.2.3 Unbalance in input voltage

The simulation of induction motor with voltage unbalance can be simulated by simply varying the voltage magnitude in any one of the phase, no other parameters need to be changed. As in the previous case, the machine is started up with normal value, and at 10 second, the current takes its steady state value, now the fault has been created by changing the voltage of a phase. Figures (4.13) (4.14) shows rotor current, stator current Ia Ib Ic and torque of the motor during unbalance in input voltage.

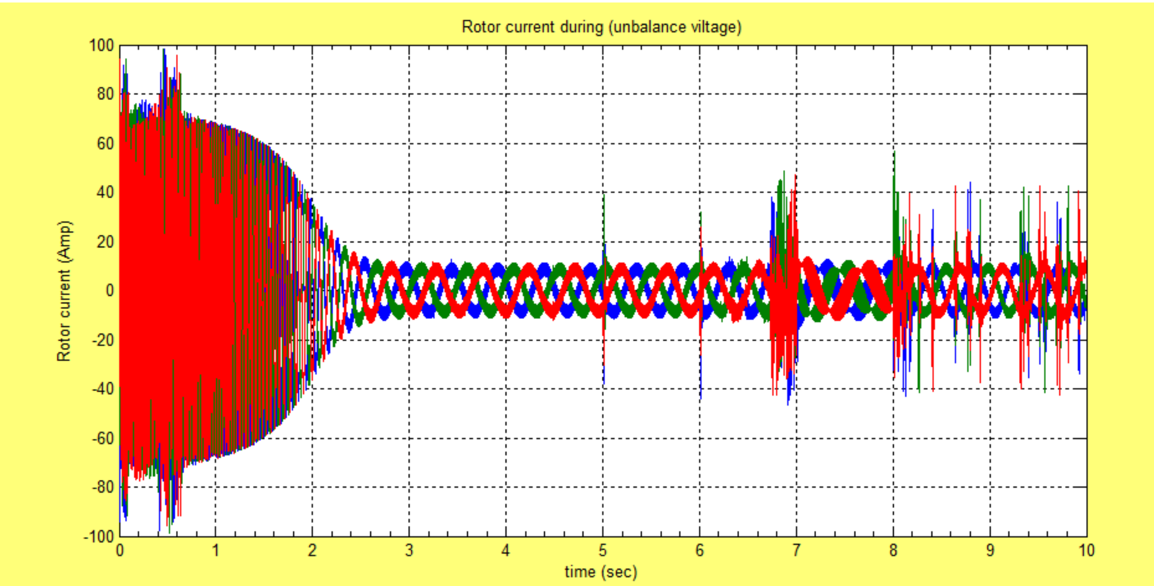

Figure (4.13) Rotor current during unbalance in voltage

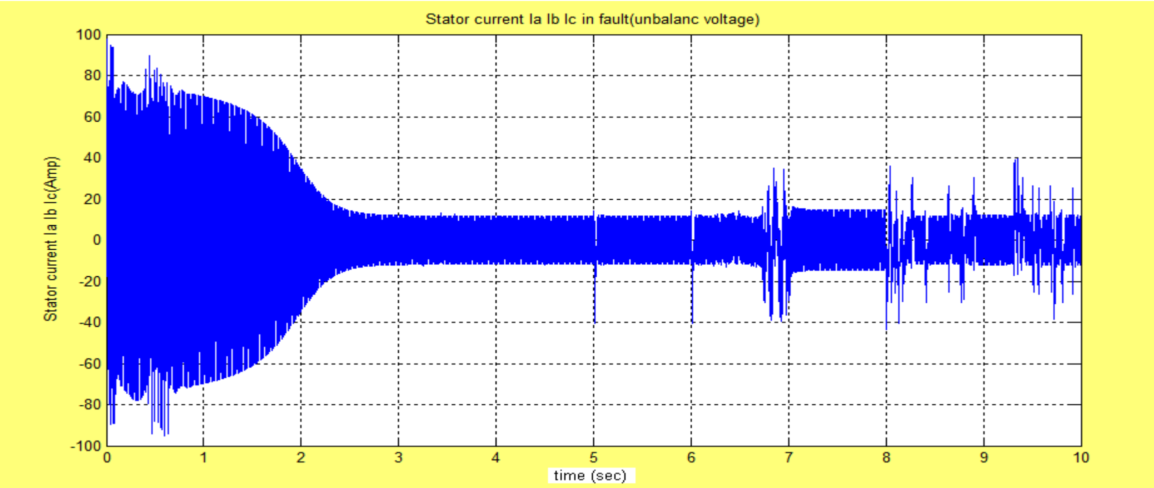

Figure (4.14) Rotor current during unbalance voltage

Figures (4.15) and (4.16) shows the result of speed and torque variation of motor and corresponding stator current amplitudes variation when phase-A is opened among the running condition. The speed and torque are not reaching the steady state positions after opening the phase. The stator current magnitude is zero in phase-A after opening.

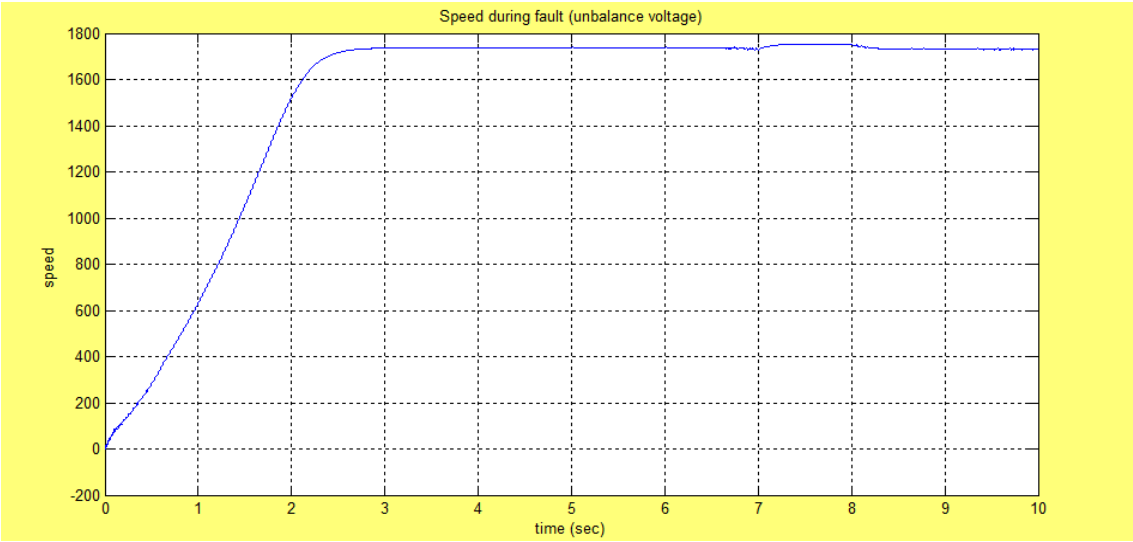

Figure (4.16) Speed of induction motor with unbalance voltage

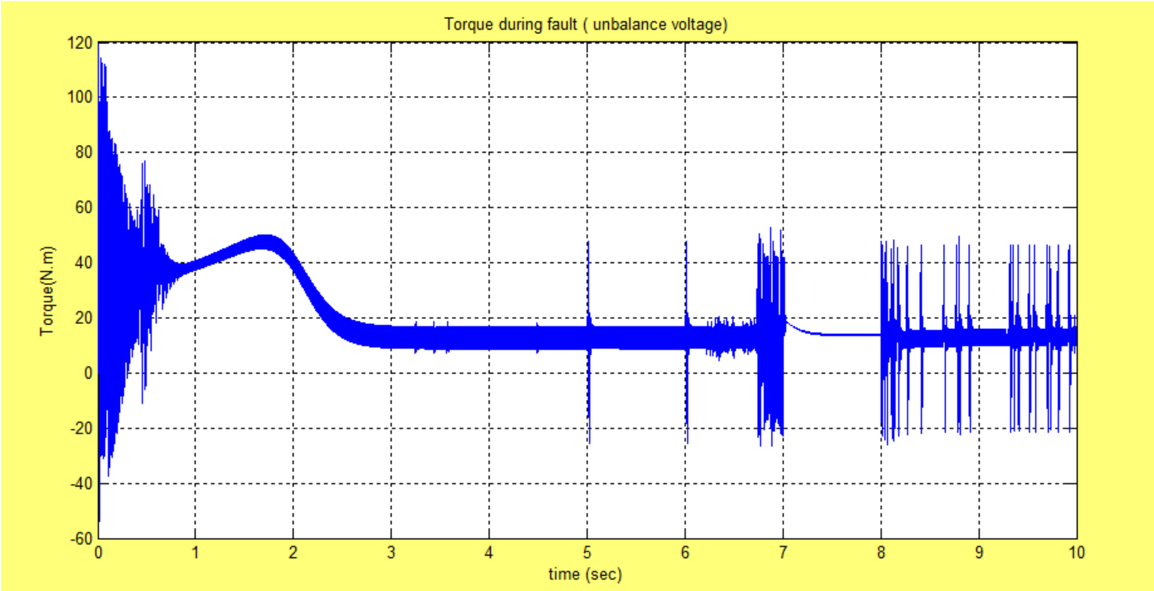

Figure (4.17) Torque of induction motor with unbalance voltage

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this thesis, three phase induction motor under healthy condition, unbalanced fault, break in stator winding and turn-turn short in one phase winding are simulated using fuzzy logic controller. The study is based on the MATLAB/Simulink software platform and mathematical models of the induction motor. By using fuzzy logic over conventional method like Wald's sequential test has several advantages. It provides the important information about system's health in between the thresholds too. It provides information about smooth transition from no fault to faulty condition. This also helps in avoiding false triggers and missing alarms. Fuzzy logic is a good option when there is no general mathematical model available which describes the output fault severity based on the available inputs. The observed knowledge is directly used for fault detection process instead of any detailed modeling. Also this is a highly versatile technology for condition monitoring and fault analysis of motors. It solves the shutdown problems and ensures safe working environment in continuous process industry. It helps in diagnosis of various faults created in the motor as it can detect small changes in the parameters of the motor.

5.2 Recommendations

By the end of his thesis it recommended that further can be done in:

1- Diagnosis fault of induction motor using other techniques like neural network and neuro-fuzzy

2 – Extend it to the induction generator by fuzzy logic algorithm or by any other diagnostic techniques.

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Appendix A

Rating of Testing Induction Motor

Power 50 HP
Frequency= 50 HZ Voltage= 400V Motor speed 1725 rpm Pole pair (p) 2
Stator resistance R_S = 0.7384 Ohm Stator inductance L_s=0.003045H Rotor resistance R_r =0.7402ohm Rotor inductance L_r =0.003045H Mutual inductance= 0.1241 Number of poles p=2 Inertial constant j=0.343 $Kg.m^2$