

Libyan Academy

Tripoli - Libya



**School of Applied Sciences and Engineering
Department of Electrical and Computer Engineering**

Model-Predicted Three-Phase Induction Motor Behavior under Shorted Turns Fault

By:

Fathi Mahmud Albuni

***A Dissertation Submitted to the Department of Electrical and
Computer Engineering in Conformity with the
Department Requirements as partial Fulfillment
for the Degree of Master Of Engineering Sciences.***

Supervised by:

Dr. Abdel hamed Farag Saleh

Copyright © January 2014

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿يَرْفَعِ اللَّهُ الَّذِينَ ءَامَنُوا مِنْكُمْ وَ الَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ﴾

صَدَقَ اللَّهُ الْعَظِيمُ

من الآية (11) سورة المجادلة

ACKNOWLEDGEMENTS

In the name of Allah the beneficent and the merciful.

I would like to thank my supervisor, Dr. Abdel hamed Farag Saleh, for his advice, guidance and patience through the process until the completion of this dissertation.

I would like to thank my family especially my parents and my wife, for their support and encouragement.

I would like to thanks all my friends, for their help and support.

Table of Contents

List of Figures	v
List of Tables.....	vii
Abbreviations	viii
Variables	ix
Chapter One: Introduction	1
1.1-General.....	2
1.2- Problem statement.....	2
1.3- Methodology	2
1.3.1-Condition Monitoring of Induction Machine	3
1.3.2-Motor Current Signature Analysis (MCSA)	4
1.4-Objectives	5
1.5-Thesis Organization	5
Chapter Two: Three-Phase Induction Motor.....	7
2.1-General.....	8
2.2-Construction.....	8
2.2.1-Stator	8
2.2.2- Rotor.....	9
2.3-Principles of Operation.....	10
2.4-The Equivalent Circuit	10
2.5- Power Flow Relation.....	12
Chapter Three: Electrical Faults in Three Phase Induction Motor.....	13
3.1-General.....	14
3.2-Stator Faults	15
3.2.1-Turn to turn fault.....	15
3.2.2-Coil to coil short on the same phase	17
3.2.3- Phase to phase short	17
3.2.4-Open circuit in one phase	18
3.2.5-Phase to earth fault.....	18
Chapter Four: Induction Motor Model under Different Operating Condition	19
4.1-General.....	20

4.2-Induction Motor Voltage Equations.....	20
4.3-Basic Principle of Mutual Inductance between Coils.....	21
4.4-Modeling of Healthy Three Phase Induction Motor.....	21
4.4.1-Self-inductance of motor.....	22
4.4.2-Mutual inductance of motor	22
4.4.3-Mutual inductance between stator and rotor	23
4.4.4-Resistance matrix for the stator and rotor phases	24
4.4.5-Induction motor model with inter-turn stator short circuit.....	24
4.4.6-Transformation from ABC to dq reference frame	26
4.5- Implementation	30
Chapter Five :Results and Discussions	32
5.1- General.....	33
5.2- Model Performance under Normal Condition.....	34
5.2.1- Model Performance at no-load under normal operating conditions	34
5.2.2- Model Performance at Half load Condition	35
5.2.3- Model Performance at Full load Condition.....	36
5.3- Model Performance under Difference Number of Shorted Turns	37
5.3.1- Model Performance under No Load and Difference Number of Shorted Turns..	37
5.3.2- Model Performance under Half Load and Difference Number of Shorted Turns	40
5.3.3- Model Performance under Full Load and Difference Number of Shorted Turns	42
Chapter Six: Conclusion and Future Work	46
6.1- Conclusion	47
6.2-Future Work:.....	47
List of Reference	49
Appendixes	51
1-Appendix A: Matrix elements for induction motor	52
2-Appendix B :Program code of motor simulation for inter turn fault	53

List of Figures

Figure (1.1): The on-line condition monitoring	3
Figure (1.2): Overall MCSA Strategy.....	5
Figure (2-1): Typical stator	8
Figure (2.2): Wound rotor machines.....	9
Figure (2.3): Squirrel cage machines	9
Figure (2.4): Per-phase equivalent circuit of an induction machine	10
Figure (2.5): Per-phase equivalent circuit of an induction machine referred to stator ..	11
Figure (2.6): Thevenin per-phase equivalent circuit.....	12
Figure (3.1): Chart of induction machine faults	14
Figure (3.2): Turn to turn fault	15
Figure (3.3): Stator winding failures.....	16
Figure (3.4): Coil to coil fault.....	17
Figure (3.5): Phase to phase fault	17
Figure (3.6): Open circuit fault.....	18
Figure (3.7): Phase to earth fault	18
Figure (4.1): Mutual between two electrical coils	21
Figure (4.2): Modeling of healthy three phase induction motor	22
Figure (4.3): Modeling of faulty three phase induction motor.....	24
Figure (4.4): d,q axes superimposed onto a three-phase induction motor	26
Figure (4.5): Flow chart of the simulation program	31
Figure (5.1a, b): Simulated for rotor speed and stator currents during starting up and steady state	34
Figure (5.2): Current spectrum for the stator current phase (A) at no load	35

Figure (5.3a, b): Simulated for rotor speed and stator currents during starting up and steady state	35
Figure (5.4): Current spectrum for the stator current phase (A) at half load	36
Figure (5.5a, b): Simulated for rotor speed and stator currents during starting up and steady state	36
Figure (5.6): The current spectrum for the stator current phase (A) at full load.....	37
Figures (5.7a, b, c, d): The current spectrum under healthy and different number of shorted turn at no load.....	39
Figure (5.8): Estimations of shorted turns at no load	40
Figure (5.9a, b, c, d): The current spectrum under healthy and different number of shorted turn at half load	41
Figure (5.10): Estimations of shorted turns at half load	42
Figures (5.11a, b, c, d): The current spectrum under healthy and different number of shorted turn at full load	43
Figure (5.12): Estimations of shorted turns at full load	44

List of Tables

Table(4.1): Induction motor parameters	31
Table(5.1): Frequency components magnitude for a different number of shorted turns at different loads	44

Abbreviations

ESA	Electrical Signature Analysis
Emf	Electrical magnetic force
AC	Alternative current
MCSA	Motor current signature analysis
FFT	Fast Fourier Transform
LF	Line frequency
MCC	Motor control center
IPSA	Instantaneous Power Signature Analysis

Variables

f_{st}	Components that are a function of shorted turns.
f_1	Supply frequency
n	1, 2, 3...
k	1, 3, 5...
p	Pole Paris
m_2	Number of phases
I_a	Armature current in Ampere
I_1	The current in stator
r_1	Resistance of stator winding
x_1	Reactance of stator winding
R_M	The core loss resistor
X_M	The magnetic inductance
E_1	The voltage at primary side
E_{2s}	The voltage at secondary side
r_2/s	Resistance of rotor winding
x_2	Reactance of rotor winding
N_s	Number of stator turns
N_r	Number of rotor turns
I_2	The current in rotor
s	Slip
V_1	Voltage on stator
Z_1	Leakage impedance
K_i	Ratio current
K_v	Ratio voltage.
P_1	Input power
P_{12}	Flow power from stator to rotor
P_2	Output power
$\cos\phi$	Power factor

ΔP_{cu2}	Power loss in rotor copper
ΔP_m	Power loss due to frication
μ	The efficiency of induction machine
R_s	Resistance of stator
L_{ss}	Leakage inductance between phases of stator
L_{sr}	Leakage inductance between phases of stator and rotor
R_r	Resistance of rotor
I_s	Stator current
I_r	Rotor current
θ	Rotor position
ρ	Is copper resistivity and equal ($1.8 \times 10^{-8} \Omega m$ at $25 c^o$)
A_c	Actual conductor area
N_a	Number of turn/ phase
L_e	Stack length of turn
θ_r	Position of rotor
T_s	Parks transform for stator
T_r	Parks transform for rotor
T_e	The electrical torque
T_L	Load torque
J	Moment of inertia
P	Number of poles the motor (an even integer)
L_m	Mutual inductance
ω_s	Synchronous speed
ω_r	Rotor speed
R	Resistance for one turn

Abstract

Motors are critical components for electric utilities and process industries. A motor failure can result in the shutdown of a generating unit or production line, or require that redundant plant be utilized to circumvent the problem. One major cause of failures is breakdown of the turn insulation (Turn to turn fault). This is fault must be detected in an early stage before propagating to a phase to ground or a phase-to-phase fault and occurring complete damage in motor. The condition monitoring of the faulty machines can significantly reduce the costs of maintenance by allowing the early detection of faults, which could be expensive to repair.

Turn fault detection is based on the principal that symmetrical (un faulted) motors powered by symmetrical multiphase voltage sources, two cases for simulation by MATLAB of three phase induction machines having symmetrical winding and inter-turn short circuit on the stator (asymmetrical winding).The first case assumes that each stator phase winding has same number of turns. The second case assumes stator phase (As) has number of shorted turns. For represented a model without using additional sensor using monitors the spectrum content of stator currents to detect the fault.

In this thesis, the applied method is the so-called motor current signature analysis (MCSA) is used to detect this fault and experimental results for healthy and faulty motors have been shown and discussed.

ملخص الرسالة

المحركات الحثية تعتبر من أهم مكونات الصناعات العملية وخاصة مرافق الكهرباء كمحطات التوليد، أي عطل مفاجئ في إحدى المحركات سوف يؤدي إلى خروج وحدة توليد أو خط إنتاج. ومن أهم هذه الأعطال عطل ملفات العضو الثابت (Turn to turn fault) وهو من أكثر الأعطال الشائعة الحدوث في المحرك الحثي . ويتسبب هذا العطل في انهيار العزل بين الملفات المتجاورة. ولحماية المحرك يجب اكتشاف العطل في المرحلة الأولى قبل أن ينتشر ويتسبب في حدوث أعطال أكثر تعقيدا وهذه تسبب في تلف المحرك بالكامل واهم هذه الأعطال عطل طور لطور أو طور للأرض.

هذه الأطروحة تقدم حالتين باستخدام المحاكاة بواسطة الماتلاب للمحرك الحثي في الحالة الأولى فرضنا أن المحرك سليم من جميع الأعطال وان عدد اللفات للأطوار الثلاثة متساوي وتمت المحاكاة والحالة الثانية فرضنا وجود عطل في احد الأطوار للعضو الثابت وليكن الطور (A) وذلك بتغير عدد اللفات لهذا الطور وأيضا تمت المحاكاة ،حيث كان هذا التصور بدون إضافة أجهزة استشعار خارجية، وذلك باستخدام طريقة التحليل الطيفي لتيار العضو الثابت (MCSA) . وبمقارنة هذه الحالتين أظهرت النتائج بوضوح تأثير هذا العطل على التحليل الطيفي لتيار العضو الثابت لطور (A).

Chapter One: Introduction

1.1-General

Induction motors are by far the most numerous of electric machines, accounting for 80% of the motors in use and it is one in which alternating current is supplied to the stator directly. In world industry the three-phase induction motor is widely used for reasons of economy robust construction and reliability. They are used to drive gas compressors, seawater, injection pumps, machine tools, washing machine and oil exporting pumps, etc.

1.2- Problem statement

In modern industrial facilities, thousands of electric motors work together in the manufacturing process. A great percentage of the applied motors are essential to the process. An unscheduled shutdown occurs if one of these motors were failing. If it were possible to detect a developing fault, it would be possible to schedule an orderly shutdown of the complete process with more efficient utilization of material and labor. Because of the great expense associated with unscheduled downtime, it may be cost effective to continuously monitor the critical motors for certain incipient faults before one of these motors become inoperable[1].

People who work on condition monitoring of induction motors often need an accurate model to predict performances and to extract faults signature. Early detection of abnormalities in the motor will help to avoid expensive failures.

1.3- Methodology

The modern industry has widely used reliability-based and condition-based maintenance strategies to reduce unexpected failures and downtime. Many predictive techniques are applied to these motors to reduce the number of unplanned outage. These techniques are most useful if they can be implemented on-line along with a planned maintenance program to prevent unscheduled plant interruptions. The machine parameters which are most often monitored include vibration, leakage flux, and line current. These three features are common in monitoring techniques used today. Vibration analysis not only provides information on the motors in a system but can be used on gear boxes. Line current is probably the most convenient of the three since in an industrial environment it is the most accessible parameter, can be measured remotely if needed, and requires simple instrumentation. The monitoring of line current forms the basis of the work presented in this thesis. The analyses based on mechanical concepts are established.

These techniques can increase the time between planned shutdowns for standard maintenance, reduce maintenance and operational costs.

1.3.1-Condition Monitoring of Induction Machine

Machine condition monitoring is a vital component of preventative and predictive maintenance programs that seek to avoid unplanned downtime and the costs of maintenance by allowing the early detection of faults, which could be expensive to repair. One of the most frequently used fault detection methods is the motor current signature analysis (MCSA).

Condition monitoring is used for increasing machinery availability and machinery performance, reducing consequential damage, increasing machine life, reducing spare parts inventories, and reducing breakdown maintenance. The electric motors have attracted increasing attention during the last decade, during which a considerable number of studies on the detection of stator and rotor faults have been made. There are many published techniques[1]and many commercially available tools to monitor induction machines to insure a high degree of reliability uptime.

On-line condition monitoring uses measurements taken while a machine is in use, to determine if a fault exists. Figure (1.1) shows a block diagram of the general approach. Different types of sensors can be used to measure signals to detect these faults. Current signal processing techniques can be applied to these sensor signals to extract particular features which are sensitive to the presence of faults. Finally, in the fault detection stage, a decision needs to be made as to whether a fault exists or not [2].

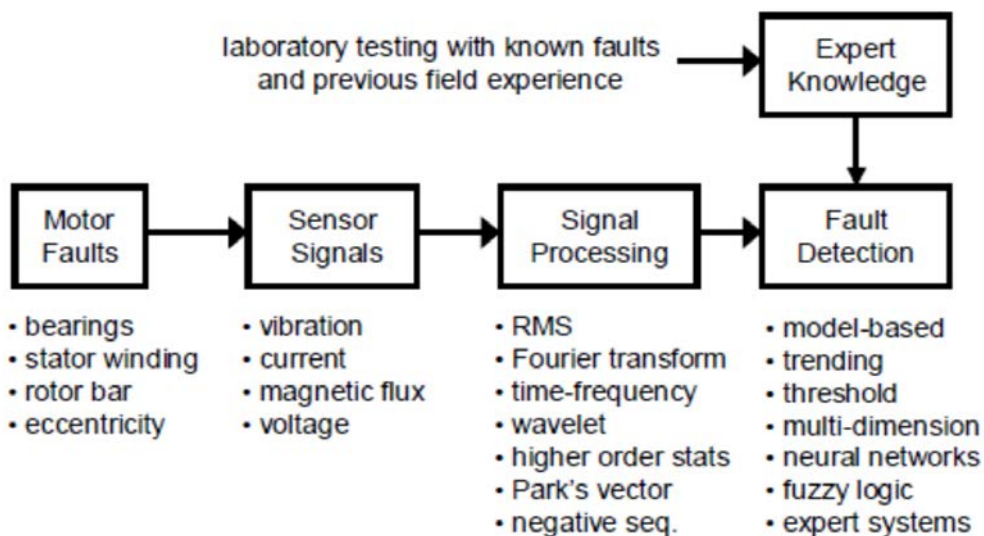


Figure (1.1): The on-line condition monitoring

Previous research in electrical monitoring as W.T. Thomson used online current monitoring to detect inter-turn stator winding faults [3]. Fault severity can be controlled by the number of shorted turns and an optional current limiting resistance to short circuit the windings. It was shown that an indicator of inter-turn winding faults. It has been suggested that it would be worthwhile developing an on-line current monitoring strategy which could reliably detect inter-turn winding faults.

Acosta and Verucchi, [4] have utilized two techniques. One of these techniques resorts to spectrum analysis of machine line current. Another non-invasive technique is the Extended Park's Vector Approach, which allows the detection of inter-turn short circuits in the stator winding.

1.3.2-Motor Current Signature Analysis (MCSA)

MCSA used in induction machine fault diagnosis, it is one of the most frequently used fault detection methods. This technique depends upon locating by spectrum analysis specific harmonic components in the line current produced of unique rotating flux components caused by faults such as broken rotor bars, air-gap eccentricity and shorted turns in stator windings, etc.

Howard and Penrose[5]. MCSA is used the electric motor as a transducer, allowing the user to evaluate the electrical and mechanical condition from the Motor Control Center MCC or disconnect. For accurate analysis, MCSA systems rely upon FFT analysis, much the same as vibration analysis. Most MCSA systems also rely upon analysis of demodulated voltage and/or current, which involves the removal of the fundamental frequency LF.

William and Ronald [6], it is proved that the MCSA is a condition monitoring technique that is now widely used to diagnose problems such as broken rotor bars, abnormal levels of air gap eccentricity ,shorted turns in low voltage stator winding ,and certain mechanical problems. This thesis sets out to present the fundamentals on MCSA plus data interpretation and the presentation of industrial case histories.

Neelam and Ratna[7] have utilized the fundamentals of current spectrum plus condition monitoring of the induction motor for detection fault as figure(1.2), the figure illustrates the key elements for the successful application of MCSA and in clouded fundamental understanding of the design and operation of 3-phase induction motor .MCSA spectrum analyzer to present the signature patterns and it is the drive operator who has to make the final decision to either immediately remove the motor for repair or let it run and prepare for a planned outage to rectify the problem.

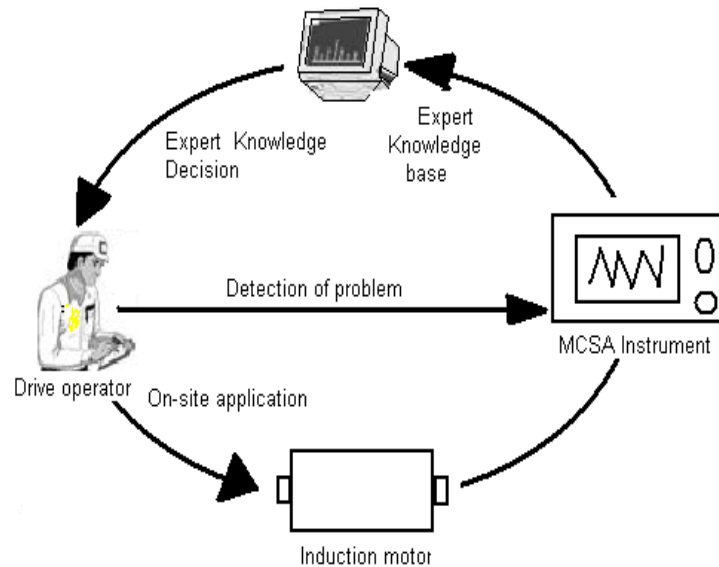


Figure (1.2): Overall MCSA Strategy

The objective is to identify current components in the stator winding that are only a function of shorted turns and are not due to any other problem or mechanical drive characteristic. MCSA is the on-line analysis of current to detect problems in a three-phase induction motor drive while it is still operational and in service. This method is based on detection of sidebands at certain frequencies. For these latter techniques, it is assumed that the current measurements can be modulated like multi-component mixtures whose magnitudes change when a failure occurs[4].

1.4-Objectives

The main objectives of this research are as follows:

1. Surveys the electrical faults and electrical faults on stator.
2. Modeling of induction machine in steady state and with shorted turns.
3. Simulating the model of steady state and transient behavior of motor using MATLAB software.
4. Detecting inter-turn shorted circuit with two cases, the increased amplitude components around 125Hz and 175Hz and increase the magnitude of third harmonic component 150Hz.
5. Evaluation of number of inter turn short by know the magnitude of third harmonic component 150Hz.

1.5-Thesis Organization

In this chapter gives the background, literature review and their detection techniques was presented for detect the stator winding turn faults.

Chapter two presents the types, construction and the principles of operation three phase induction motor. It is also shows the relationship between stator and rotor which been derived from the equivalent circuit.

A survey on induction motor common faults and electrical failure on the stator are presented in chapter three.

System modeling of the induction machine is presented in chapter four. A fault indicator is proposed.

Simulation and results for the operation motor under normal, inter-turn short circuit condition and three different loads, validate the reliability of the model and the fault indicator are given in chapter five.

The conclusions and future work are given in chapter six.

Chapter Two: Three-Phase Induction Motor

2.1-General

The induction machine is basically an AC poly phase machine. The AC power source is, in general, three phases but it may also be single phase. In both cases the winding arrangement on the part of the machine the primary connected to the grid (the stator in general) should produce a traveling field in the machine air gap.

The rotor winding may be multiphase (wound rotors) or made of bars short circuited by end rings (cage rotors). All primary and secondary windings are placed in uniform slots stamped into thin silicon steel sheets called laminations[8].

2.2-Construction

Three phase induction motor has two main parts stator and rotor. The rotor is separated from the stator by a small air-gap which ranges from 0.2 to 3 mm[8], depending on the power of the motor.

2.2.1-Stator

The stator is made up of several thin laminations of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in Figure (2-1)[9]. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of induction motor depends on the internal connection of the stator windings.

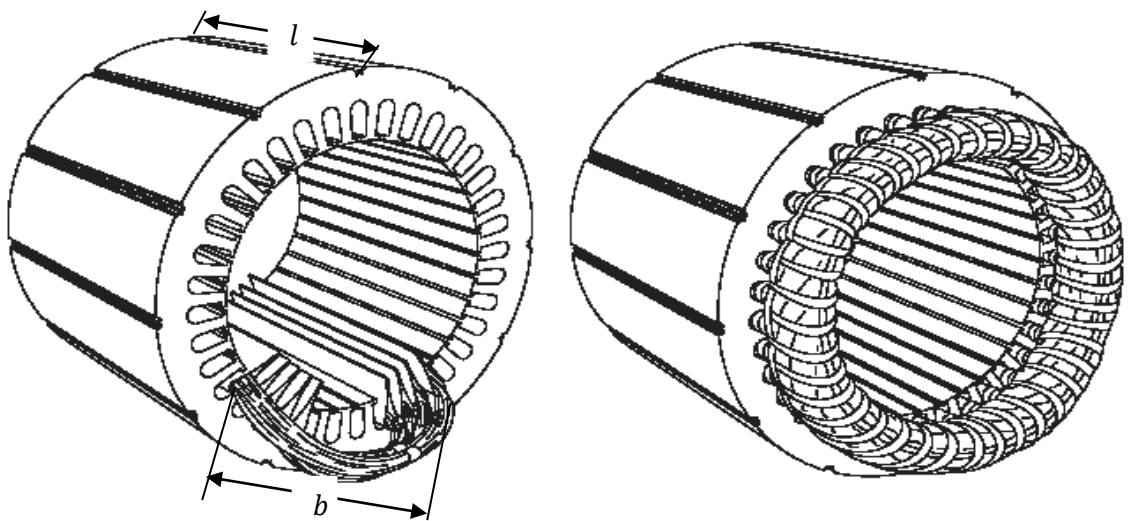


Figure (2-1): Typical stator

2.2.2- Rotor

The rotor mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

-Wound rotor machines

Three phase distributed winding on the rotor with the same number of poles as the stator and number of phases $m_2 = 3$. This windings are usually connected in star with ends of winding brought out to three slip rings as show in figure (2.2).

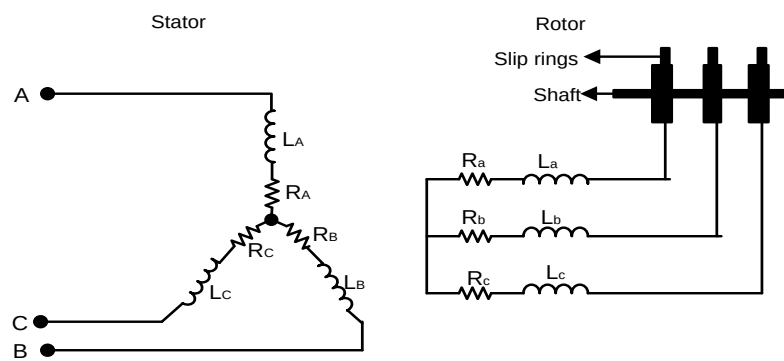


Figure (2.2): Wound rotor machines

-Squirrel cage machines

The rotor of a squirrel cage machine carries a winding consisting of a series of bars in the rotor slots which are shorted by end rings at each end of the rotor as in figure (2.3), it has the number of loops N_2 .

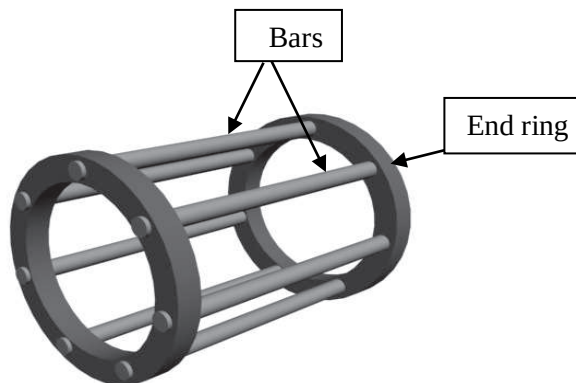


Figure (2.3): Squirrel cage machines

2.3-Principles of Operation

The operation principle of electric machines is based on the interaction between the magnetic fields and the currents flowing in the windings of the machine. When the induction machine is fed in the stator from a three-phase balanced power source, the three-phase currents produce a traveling field in the air gap. This traveling field will induce voltages in conductors on the part of the machine not connected to the grid (the rotor, or the mover in general) the secondary. If the windings on the secondary (rotor) are closed, AC currents occur in the rotor. The interaction between the primary field and secondary currents produces torque from zero rotor speed onward. The rotor speed at which the rotor currents are zero is called the ideal no-load (or synchronous) speed. This field produces emfs both in the stator and in the rotor windings. The equivalent circuit is cleared method to estimate the load and efficiency of an in-service motor.

2.4-The Equivalent Circuit

The performance of the three phase induction motor from the parameters of its equivalent circuit is evaluated in the usual way. The equivalent circuit parameters in figure (2.4) and power losses are known at rated voltage and rated frequency. The following relationship for the motor [10].

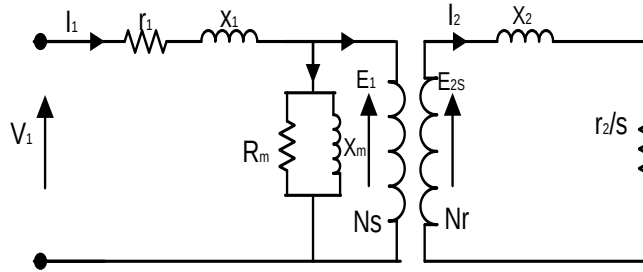


Figure (2.4): Per-phase equivalent circuit of an induction machine

In the familiar equivalent circuit of the induction motor, shown in Fig. (2.4), the impedance (Z_1), the stator voltage (V_1) as

$$V_1 = E_1 + I_1 Z_1 = E_1 + I_1 (r_1 + jx_1) \quad (2-1)$$

The current in secondary circuit associated rotor is

$$I_2 = \frac{E_2}{r_2/s + jx_2} \quad (2-2)$$

The secondary circuit for motor has resistance active (r_2/s). It change with change slip and equal:

$$\frac{r_2}{s} = r_2 + r_2 \frac{1-s}{s} \quad (2-3)$$

This gives per-phase equivalent circuit reduced to the stator. The stator and magnetizing branch components may be reduced to an equivalent circuit small. The rotor impedance may now be transferred to the stator using the relationships of equations

$$I_1 \times N_s = I_2 \times N_r \quad (2-4)$$

For reduced equivalent circuit must connected primary side with secondary side. That is

$$E'_2 = E_2 \times K_v \quad (2-5)$$

$$I'_2 = \frac{I_2}{K_i} \quad (2-6)$$

The resistance transferred to primary is:

$$r'_2 = \left[\frac{N_s}{N_r} \right]^2 \times r_2 \quad (2-7)$$

The figure (2.5) show the small circuit after the parameters in secondary transferred to primary, the circuit is

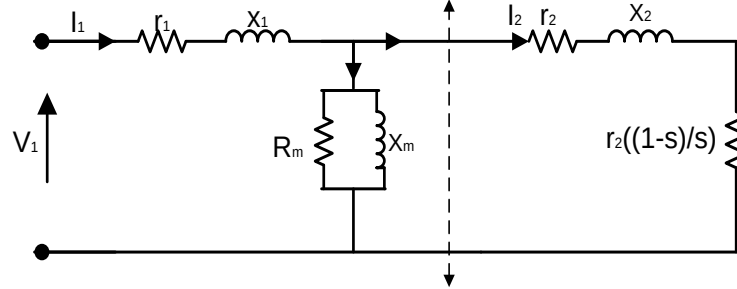


Figure (2.5): Per-phase equivalent circuit of an induction machine referred to stator

By used an equivalent thevenin circuit the rotor at the air gap line of figure (2.6), to given the thevenin equivalent is

$$Z_m = R_m + jX_m \quad (2-8)$$

$$Z_1 = r_1 + jX_1 \quad (2-9)$$

The voltage of thevenin circuit is:

$$V_t = V_1 \left| \frac{Z_m}{Z_m + Z_1} \right| \quad (2-10)$$

And impedance is:

$$Z = \frac{Z_m \cdot Z_1}{Z_m + Z_1} \quad (2-11)$$

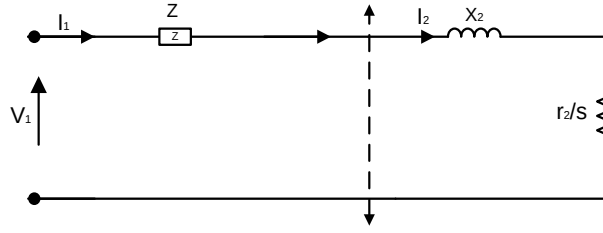


Figure (2.6): Thevenin per-phase equivalent circuit

2.5- Power Flow Relation

The output power (P_2) that can be delivered to the rotor is the power delivered across the air gap (P_{12}) minus the rotor copper losses.

When induction machine is running it takes power from the network

$$P_1 = 3 \cdot V_1 \cdot I_1 \cdot \cos \phi \quad (2-12)$$

A part from this power loss in stator copper via heating (ΔP_{cu1}), other part loss in iron magnetic (ΔP_{fe}). The power electromagnetic which transferred to the rotor via air gap (P_{12}) as

$$P_{12} = P_1 - \Delta P_{cu1} - \Delta P_{fe} \quad (2-13)$$

The mechanical power is

$$P_m = P_{12} - \Delta P_{cu2} \quad (2-14)$$

The output power P_2 can be calculated from

$$P_2 = P_m - \Delta P_m \quad (2-15)$$

The last calculation to consider is to determine the motor efficiencies. These can be calculated by comparing the losses to the total power input of the motor.

The efficiency (μ) of induction machine can be calculated as:

$$\mu = \frac{P_2}{P_1} \cdot 100\% \quad (2-16)$$

Chapter Three: Electrical Faults in Three Phase In- duction Motor

3.1-General

Faults and failures of induction motors can lead to excessive downtimes and generate large losses in terms of maintenance and lost revenues, and this motivates the examination of on-line condition monitoring. These faults are the main types and there are many secondary faults. This chapter presented the major faults which occur on induction motors and special on the stator and behavior motor under operated normal condition.

Induction machine failure surveys [2, 11] have found the most common failures in induction machines see Figure (3.1). These have been categorized according to the main components of a machine stator related faults, rotor related faults, bearing related faults and other faults.

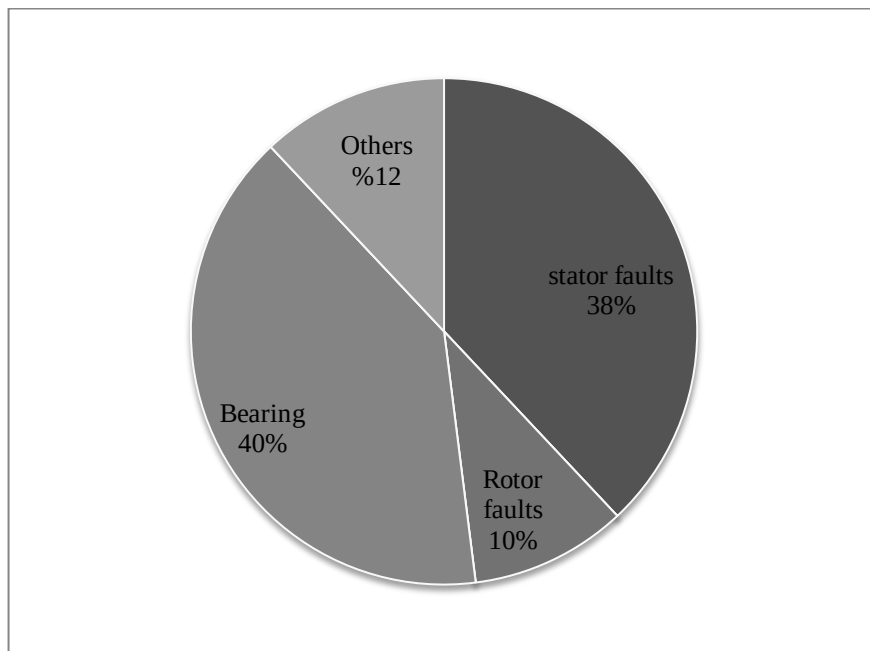


Figure (3.1): Chart of induction machine faults

The failures are unavoidable, and failure statistics has reported that the percentage of failures in induction motor components is as follows:

1. Bearing related faults: 40%
2. Stator winding related faults: 38%
3. Rotor related faults: 10%
4. Other faults: 12%

In general, the induction motor is subjected to many primary types of fault. The sources of motor faults may be internal, external or due to environmental. Internal faults can be classified with reference to their origin, electrical and mechanical or to their location, stator and rotor. Usually, other types of fault, bearing and cooling faults, refer to the

rotor faults because they belong to the moving parts. Stator fault is important to note that even if the stator fault account makes up 38 % of the all faults, it is very important to spot them in time because they can lead to the total destruction of the motor. A reliable system for the detection of such a fault should be able to detect the fault at an early stage, monitoring the motor condition online.

3.2-Stator Faults

Stator is subjected to some types of fault, such as winding faults and core faults. Winding faults are due to turn to turn, phase to phase or winding to earth short circuit, et. While core faults are due to core slacking, laminations short circuit and rotor strike.

Almost 38% of all reported induction machine failures fall into this category. The stator winding consists of coils of insulated copper wire placed in the stator slots. They are often caused by insulation failure between two adjacent turns in a coil. This is called a turn-to-turn fault or shorted turn. The resultant induced currents produce extra heating and cause an imbalance in the magnetic field in the low voltage three-phase induction motors, inter turn fault can be classified as follow:

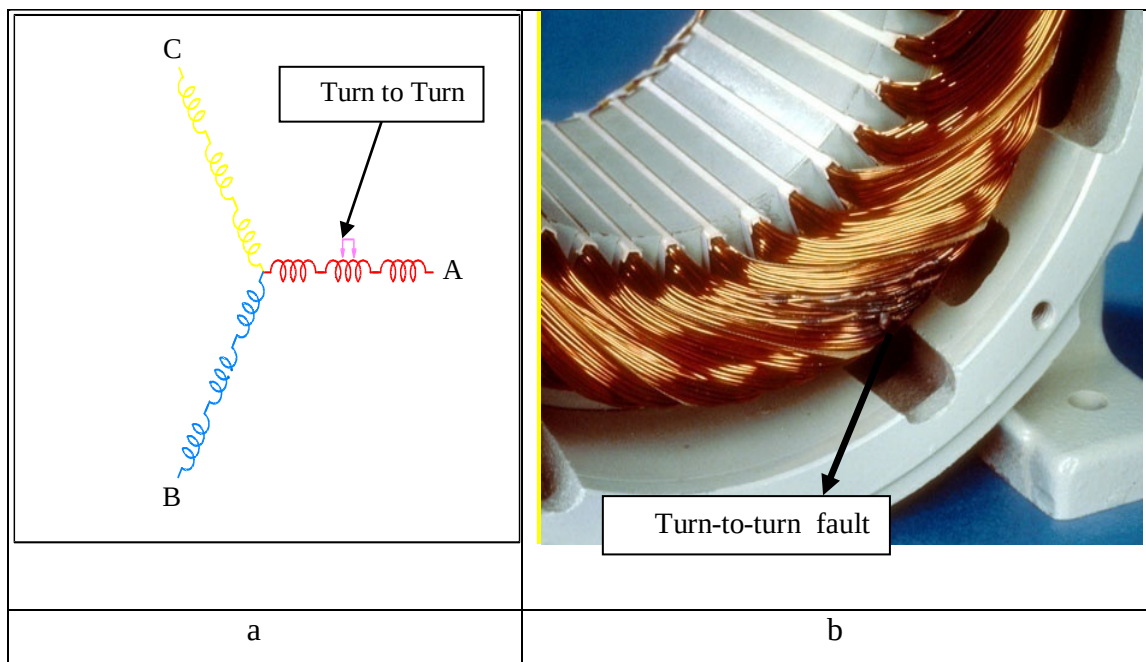


Figure (3.2): Turn to turn fault

3.2.1-Turn to turn fault

An inter-turn fault denotes an insulation failure between two windings in the same phase of the stator. The insulation failure problems in the motor totalize 11% of the total of motor failures, and they are shown in figure (3.3)[12].

Turn to turn fault within a coil (inter-turn short circuit), the motor will continue to operate, the induction motor with inter-turn fault is represented in figure(3.2b)[7]. It is one of the most common faults in the electrical motors. The increased heat due to this fault may also lead to turn-to-turn and turn to ground faults. It is mostly caused by mechanical stress, moisture and partial discharge. The majority of stator winding fault is caused by the breakdown of turn-to-turn insulation as a result of the voltage, current or thermal stress acted on the stator winding. In early stage of this failure, the motor may still operate. However, such a fault can be rapidly propagated to more stator turns since it makes a large circulating current in the shorted path, yielding excessive heat. Therefore an early detection of inter-turn short during motor operation is quite important to avoid subsequent damage to adjacent coils and stator core.

A turn to turn fault is one of the most difficult failures to detect, depending on the type of motor protection, the motor may continue to run, but the heating in the shorted turns will soon cause severe faults like phase to phase or coil to ground faults. Warning before catastrophic failure can only be achieved if turn to turn faults within a coil can be initially diagnosed via online diagnostic techniques [2]. This is the main objective of this thesis.

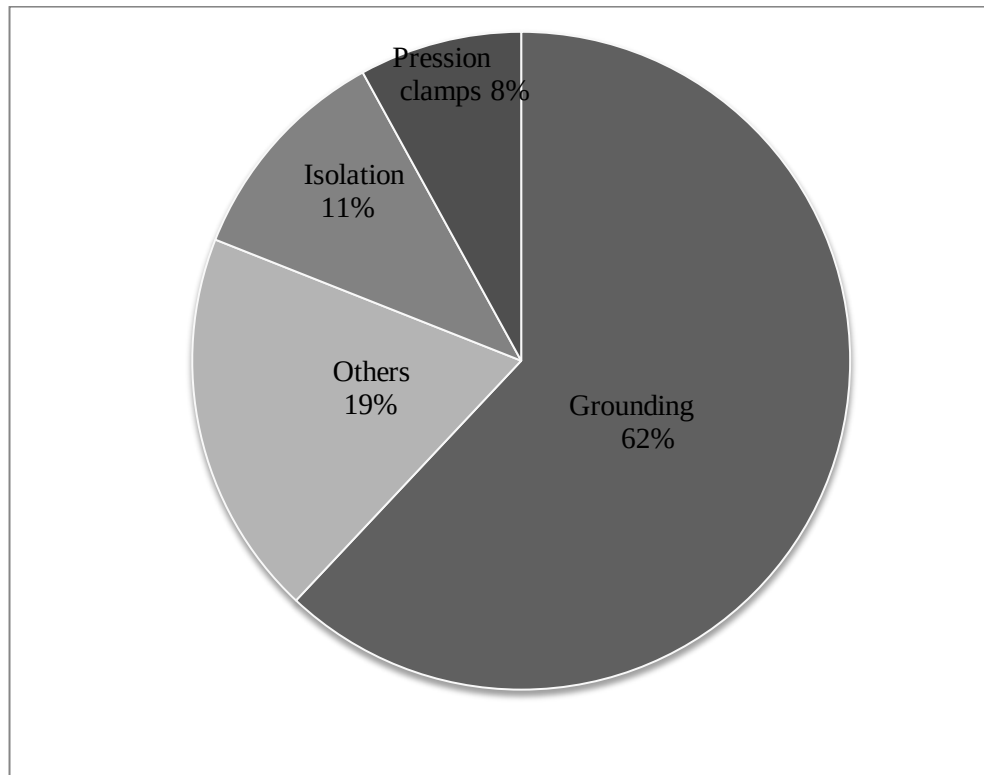


Figure (3.3): Stator winding failures

3.2.2-Coil to coil short on the same phase

When Shorts occur between coils of the same phase, the motor can continue to operate. Show in figure (3.4).

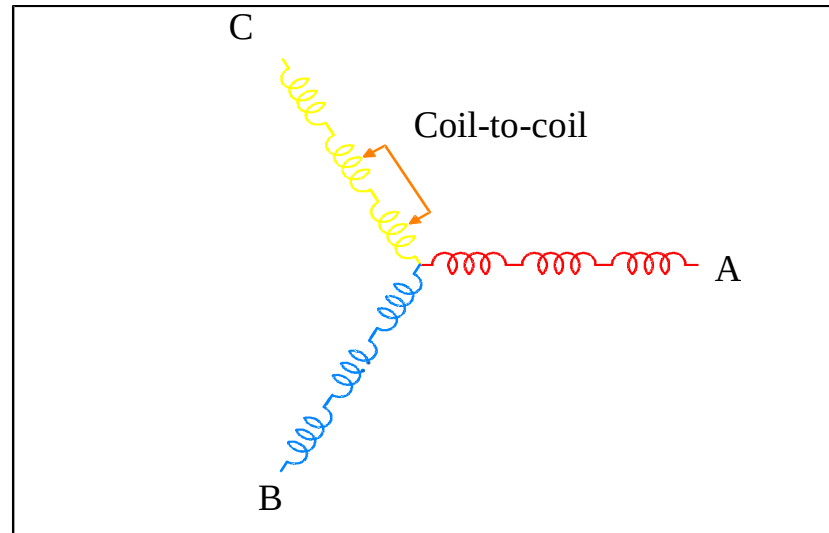


Figure (3.4): Coil to coil fault

3.2.3- Phase to phase short

When two of the three-phase in induction motor are shorted, the motor fails and protection equipment disconnects the supply figure (3.5).

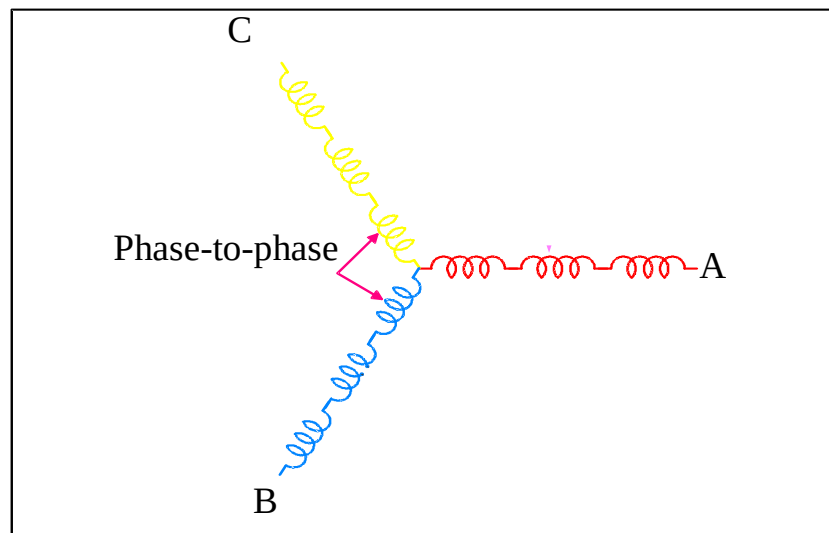


Figure (3.5): Phase to phase fault

3.2.4-Open circuit in one phase

When one of the three-phases to the motor is open, single phasing situation occurs. This result increased positive and negative sequence currents and hence excessive heating. Motor may continue to operate, depending on the load conditions. It can see in figure (3.6).

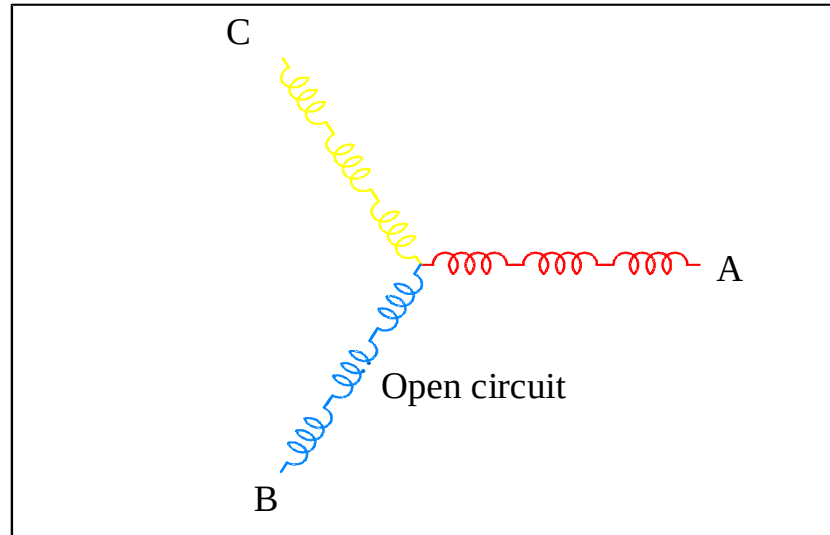


Figure (3.6): Open circuit fault

3.2.5-Phase to earth fault

When one of the three-phases in induction motor is connected with earth the motor fails and protection equipment disconnects the supply figure (3.7).

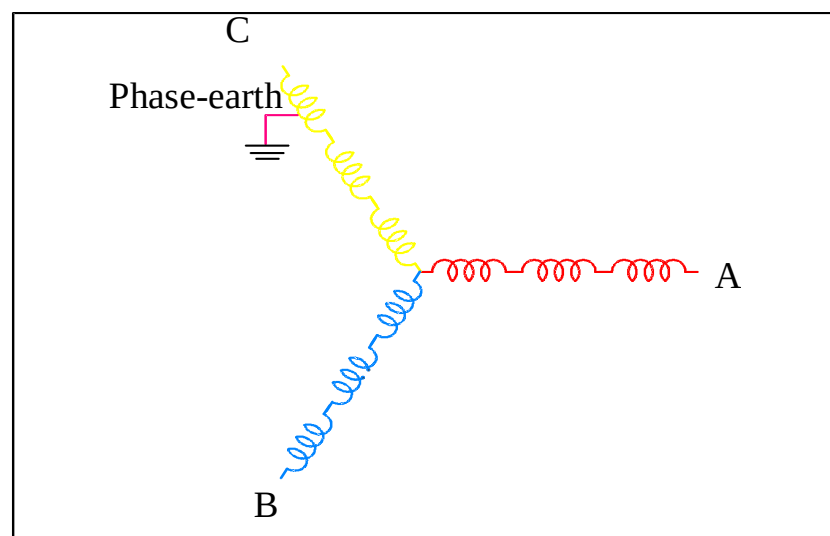


Figure (3.7): Phase to earth fault

Chapter Four: Induction Motor Model under Differ- ent Operating Condition

4.1-General

For symmetrical three-phase induction machine model and a symmetrical model of stationary defects such as short circuit between turns in the same phase, we introduce only in the matrix the coefficient of resistance, inductance of stator and in the mutual inductance stator-rotor. This coefficient take account the number of turns in short-circuit deducted from the total number of turns in the same phase. A state space model is developed based on d-q axis theory, which can represent both the healthy and faulty conditions.

4.2-Induction Motor Voltage Equations

Using the coupled circuit approach and motor notation, the voltage equations of the magnetically coupled stator and rotor circuits[13], general motor voltage equation can be written

$$[V] = [R][I] + [L] \frac{d[I]}{dt} + [I] \frac{d[L]}{dt} \quad (4-1)$$

Stator voltage equations:

$$[V_s] = [R_s][I_s] + [L_s] \frac{d[I_s]}{dt} + \frac{d[L_s]}{dt} [I_s] + [L_{sr}] \frac{d[I_r]}{dt} + \frac{d[L_{sr}]}{dt} [I_r] \quad (4-2)$$

Rotor voltage equations:

$$[V_r] = [R_r][I_r] + [L_{sr}]^t \frac{d[I_s]}{dt} + \frac{d[L_{sr}]^t}{dt} [I_s] + [L_r] \frac{d[I_r]}{dt} + \frac{d[L_r]}{dt} [I_r] \quad (4-3)$$

Where

$-v_s$ -and v_r are the stator and rotor voltage (v). and equal

$$[v_s] = \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix}, \quad [v_r] = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$-I_s$ -and I_r are the stator and rotor current (A).and equal

$$[I_s] = \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}, \quad [I_r] = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$-R_s$ -and R_r are the stator and rotor resistance (Ω). Appendix A

$-L_{ss}$ -and L_{rr} are the stator and rotor resistance (H). Appendix A.

$-L_{sr}$ -the mutual inductance between stator and rotor phases (H). Appendix A

And current equation is [13]

$$\frac{d[I]}{dt} = [L]^{-1}[V] - [R][I] + [I]\frac{d[L]}{dt} \quad (4-4)$$

$$\frac{d}{dt} \begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} L_s & 0 \\ 0 & L_r \end{bmatrix}^{-1} \begin{bmatrix} V_s \\ V_r \end{bmatrix} - \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}^{-1} \left[\begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix} \right] \begin{bmatrix} I_s \\ I_r \end{bmatrix} \quad (4-5)$$

The mutual inductance matrix is a function in rotor position θ

$$\omega = \frac{d\theta}{dt} \quad (4-6)$$

Equation (4-5) can be rewritten as:

$$\frac{d}{dt} \begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} L_s & 0 \\ 0 & L_r \end{bmatrix}^{-1} \begin{bmatrix} V_s \\ V_r \end{bmatrix} - \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}^{-1} \left[\begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} + \omega \frac{d}{d\theta} \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix} \right] \begin{bmatrix} I_s \\ I_r \end{bmatrix} \quad (4-7)$$

4.3-Basic Principle of Mutual Inductance between Coils

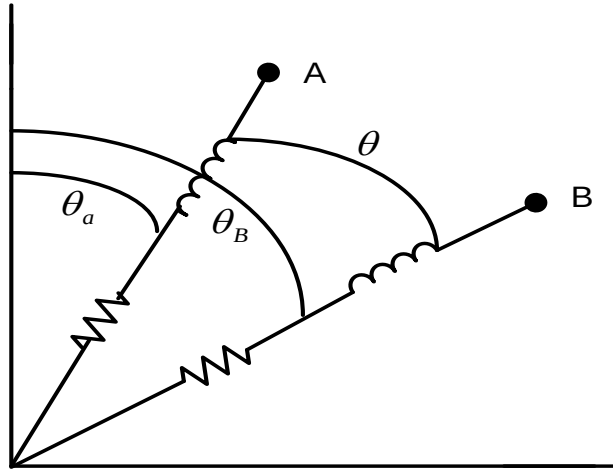


Figure (4.1): Mutual between two electrical coils

$$L_{ab} = L_m \cos(\theta_a - \theta_b) + L_2 \cos(\theta_a + \theta_b)$$

L_2 - appears only in salient pole synchronous machine.

But in induction machines and turbo synchronous machines the air gap is uniform so the magnetic path is constant and $L_2=0$.

4.4-Modeling of Healthy Three Phase Induction Motor

Usually reference is magnetic axis of stator current phase (as)

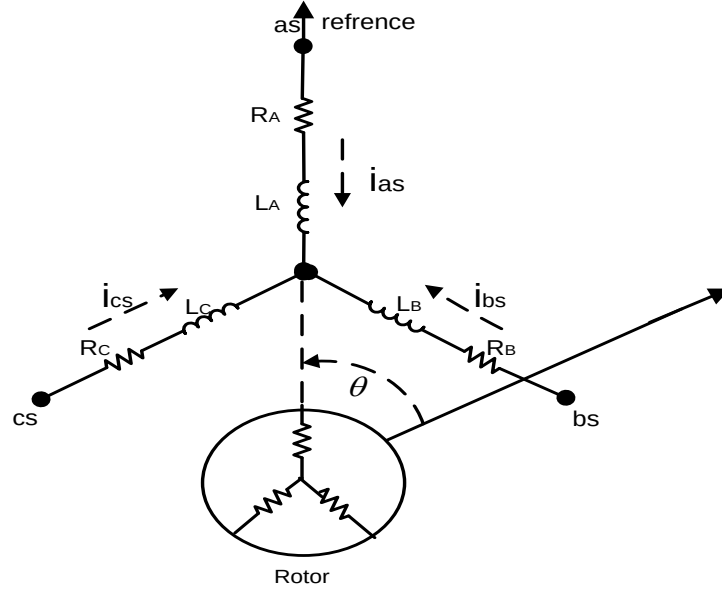


Figure (4.2): Modeling of healthy three phase induction motor

$$\left. \begin{aligned}
 \theta_{as} &= 0 & \theta_{ar} &= 0 \\
 \theta_{bs} &= \frac{2\pi}{3} & \theta_{br} &= \theta + \frac{2\pi}{3} \\
 \theta_{cs} &= -\frac{2\pi}{3} & \theta_{cr} &= \theta - \frac{2\pi}{3}
 \end{aligned} \right\} \quad (4-8)$$

The model for symmetrical three-phase induction motor is well known .To derive equations for symmetrical stator winding and rotor, are the following

4.4.1-Self-inductance of motor

a) Self-inductance of stator

$$\left. \begin{aligned}
 L_{asas} &= L_{ls} + L_m = \frac{N_a^2}{N_s^2} \left(l_{ls} + \frac{2}{3} l_m \right) = N_a^2 \cdot l_{mls} \\
 L_{bsbs} &= L_{ls} + L_m = N_b^2 \cdot l_{mls} \\
 L_{cscs} &= L_{ls} + L_m = N_c^2 \cdot l_{mls}
 \end{aligned} \right\} \quad (4-9)$$

$$\text{Where: } l_{mls} = \frac{1}{N_s^2} (l_{ls} + l_m)$$

b) Self-inductance of rotor

$$\left. \begin{aligned}
 L_{arar} &= L_{lr} + L_m \\
 L_{arar} &= L_{brbr} = L_{crcr} = L_{lr} + L_m
 \end{aligned} \right\} \quad (4-10)$$

4.4.2-Mutual inductance of motor

a) Mutual inductance of stator

$$\begin{aligned}
L_{asbs} &= L_m \cos(\theta_{as} - \theta_{bs}) = -0.5L_m = \left(-\frac{1}{2}N_a N_b\right) \left(\frac{2}{3} \frac{l_m}{N_s^2}\right) \\
&= N_a N_b l_{mss} \\
L_{ascs} &= L_m \cos(\theta_{as} - \theta_{cs}) = -0.5L_m = N_a N_c l_{mss} \\
L_{bscs} &= L_m \cos(\theta_{bs} - \theta_{cs}) = -0.5L_m = N_b N_c l_{mss}
\end{aligned} \tag{4-11}$$

b) Mutual inductance of rotor

As the same as in the stator we get it as the following:

$$L_{arbr} = L_{arcr} = L_{brcr} = -0.5L_m \tag{4-12}$$

4.4.3-Mutual inductance between stator and rotor

a) Mutual between phase a in stator and rotor phases:

$$\begin{aligned}
L_{asar} &= L_m \cos(\theta) = \frac{2}{3} \frac{N_a N_r}{N_s^2} \cdot l_m = N_a \cdot l_{msr} \\
L_{asbr} &= L_m \cos(\theta + 120) = \frac{2}{3} \frac{N_a N_r}{N_s^2} \cdot l_m = N_a \cdot l_{msr} \\
L_{ascr} &= L_m \cos(\theta - 120) = \frac{2}{3} \frac{N_a N_r}{N_s^2} \cdot l_m = N_a \cdot l_{msr}
\end{aligned} \tag{4-13}$$

b) Mutual between phase b in stator and rotor phases

$$\begin{aligned}
L_{bsar} &= L_m \cos(\theta + 120) = \frac{2}{3} \frac{N_b N_r}{N_s^2} \cdot l_m = N_b \cdot l_{msr} \\
L_{bsbr} &= L_m \cos(\theta) = \frac{2}{3} \frac{N_b N_r}{N_s^2} \cdot l_m = N_b \cdot l_{msr} \\
L_{bscr} &= L_m \cos(\theta - 120) = \frac{2}{3} \frac{N_b N_r}{N_s^2} \cdot l_m = N_b \cdot l_{msr}
\end{aligned} \tag{4-14}$$

$$\text{Where: } l_{msr} = \frac{2}{3} \frac{N_r}{N_s^2} \cdot l_m$$

c) Mutual between phase c in stator and rotor phases

$$\begin{aligned}
L_{csar} &= L_m \cos(\theta + 120) = N_c \cdot l_{msr} \\
L_{csbr} &= L_m \cos(\theta - 120) = N_c \cdot l_{msr} \\
L_{cscr} &= L_m \cos(\theta) = N_c \cdot l_{msr}
\end{aligned} \tag{4-15}$$

So the total inductance matrix of the healthy induction motor is as follows:

$$L = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} & L_{asar} & L_{asbr} & L_{ascr} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bsar} & L_{bsbr} & L_{bscr} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{csar} & L_{csbr} & L_{cscr} \\ L_{aras} & L_{arbs} & L_{arcs} & L_{arar} & L_{arbr} & L_{arcr} \\ L_{bras} & L_{brbs} & L_{brcs} & L_{brar} & L_{brbr} & L_{brcr} \\ L_{cras} & L_{crbs} & L_{crCs} & L_{crar} & L_{crbr} & L_{crCr} \end{bmatrix} \quad (4-16)$$

By substituting from equations (4.9) to (4.15) in equation (4.16) the result as following:

$$L = \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix} \quad (4-17)$$

4.4.4-Resistance matrix for the stator and rotor phases

$$R = \begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} \quad (4-18)$$

- Calculation of resistance:

The stator resistance phase in induction machine per one turn can be calculation from figure (2-1):

$$R = \rho \times L_e \times \frac{1}{A_c} \quad (4-19)$$

Where: $L_e = 2l + 2b$

The total resistance for one phase example phase (A)

$$R_{sa} = R \times N_a \quad (4-20)$$

4.4.5-Induction motor model with inter-turn stator short circuit

Figures (4.3a, b) show a three phases, 2-poles, induction machine in case of short circuit winding at stator phase (as).

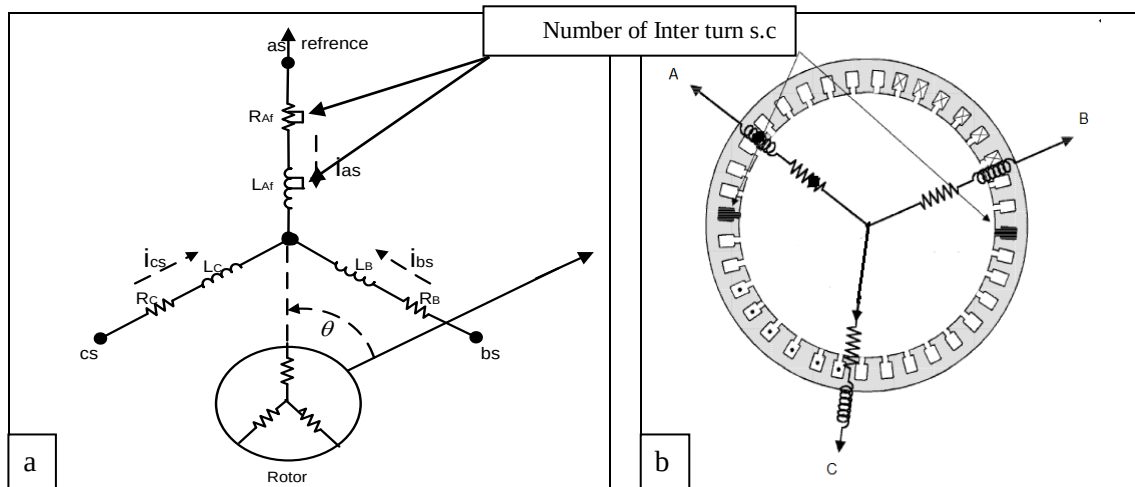


Figure (4.3): Modeling of faulty three phase induction motor

It has been assumed that phase (as) has winding before fault (N_{sa}) and after fault (N_{saf}), the phases (bs) and (cs) have $N_{sb} = N_{sc} = N_s$. The effective number of turns in stator phase (a) is reduce by the number of turns (N_{saf}) shorted turns winding, the motor reference direction of rotation is adopted as shown in figure (4.3)[14],[3].

In the following the modification of equations for the new model is presented. The equations from (4-9) to (4-18) demonstrated the relationships between the per phase stator resistance, self and mutual inductances, the number of per-phase stator turns, and showed that the resistance, self and mutual inductances are highly dependent on the number of turns.

Suppose (k_{sa}) as the ratio of shorted turns (N_{saf}) to total number of phase turns (N_s).

$$k_{sa} = \frac{N_{saf}}{N_s}$$

The number of useful turns for the stator phase (a) is then given by:

$$N_{sa} = N_s - N_{saf} = (1 - k_{sa})N_s = f_{sa}N_s \quad (4-21)$$

The matrixes R_s, L_{ss}, L_{sr} , depend of the coefficient (f_{sa}) are given by the following terms

-Resistance of motor

$$R_{saf} = f_{sa} \times R \times N_a \quad (4-22)$$

The resistance of each stator phase is proportional to the number of useful turns. Appendix A.

-Self-inductance of motor

$$\left. \begin{aligned} L_{asasf} &= f_{sa}^2 \times N_a^2 \cdot l_{mls} \\ L_{bsbs} &= N_b^2 \cdot l_{mls} \\ L_{cscs} &= N_c^2 \cdot l_{mls} \end{aligned} \right\} \quad (4-23)$$

-Mutual inductance of stator

$$\left. \begin{aligned} L_{asbsf} &= f_{sa} N_a N_b l_{mss} \\ L_{ascsf} &= f_{sa} N_a N_c l_{mss} \\ L_{bscs} &= N_b N_c l_{mss} \end{aligned} \right\} \quad (4-24)$$

Mutual between stator phase a and rotor phases

$$\begin{aligned}
 L_{asarf} &= f_{sa} N_a \cdot l_{msr} \\
 L_{ascrf} &= f_{sa} N_a \cdot l_{msr} \\
 L_{asbrf} &= f_{sa} N_a \cdot l_{msr}
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} L_{asarf} \\ L_{ascrf} \\ L_{asbrf} \end{aligned}} \right\} \quad (4-25)$$

So the total inductance matrix of the non-healthy induction motor is as follows:

$$L = \begin{bmatrix} L_{asasf} & L_{asbsf} & L_{ascsf} & L_{asarf} & L_{asbrf} & L_{ascrf} \\ L_{bsasf} & L_{bsbs} & L_{bscs} & L_{bsar} & L_{bsbr} & L_{bscr} \\ L_{csasf} & L_{csbs} & L_{cscs} & L_{csar} & L_{csbr} & L_{cscr} \\ L_{arasf} & L_{arbs} & L_{arcs} & L_{arar} & L_{arbr} & L_{arcr} \\ L_{brasf} & L_{brbs} & L_{brcs} & L_{brar} & L_{brbr} & L_{brcr} \\ L_{crasf} & L_{crbs} & L_{crCs} & L_{crar} & L_{crbr} & L_{crCr} \end{bmatrix} \quad (4-26)$$

The model of a faulty motor can be derived from standard equations (4-2), (4-3). The equations of induction motor with turn-to-turn fault in *abc* system take the following form

$$[V_s] = [R_{sf}][I_s] + [L_{sf}] \frac{d[I_s]}{dt} + \frac{d[L_{sf}]}{dt} [I_s] + [L_{srf}] \frac{d[I_r]}{dt} + \frac{d[L_{srf}]}{dt} [I_r] \quad (4-27)$$

$$[V_r] = [R_r][I_r] + [L_{srf}]^t \frac{d[I_s]}{dt} + \frac{d[L_{srf}]^t}{dt} [I_s] + [L_r] \frac{d[I_r]}{dt} + \frac{d[L_r]}{dt} [I_r] \quad (4-28)$$

4.4.6-Transformation from ABC to dq reference frame

Figure (4.4) shows a schematic diagram of a 3-phase induction motor with the *dq* axes superimposed. The *q*-axes lag the *d*-axes by 90° .

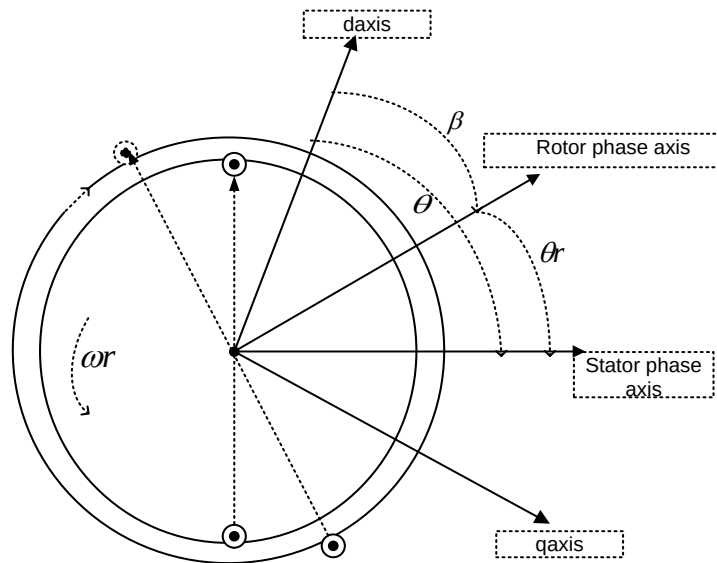


Figure (4.4): *d,q* axes superimposed onto a three-phase induction motor

The dq axes can rotate at an arbitrary speed .There is no relative speed between the four coils ds , qs , dr and qr , the physical significance of showing the dq coils in figure (4.4) is to illustrate that in effect the three phase induction machine with its six coils is replaced by a new machine with four coils .

When $\theta = 0$ this is called the stationary reference frame because the dq axes do not rotate .In addition ,the d -axes is chosen to coincide with the stator phase A axes .Hence from figure (4.4)[13, 15].

$$\omega = p\theta = 0$$

$$\beta = \theta - \theta_r = -\theta_r \quad (4-29)$$

In general for any arbitrary value of (θ) ,the transformation of ABC phase variable to dq variables is carried out through Parks transform $[T]$ as follows[[13],[15]],

$$[T_s] = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}, [T_s]^{-1} = \begin{bmatrix} \cos\theta & \sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

Using this transformation, all variables rotor (flux and currents) can be changed into new variables with the same pulsation that the variables stator. Thus, all parameters of the model will be independent of the angular position.

-In Case of Healthy Motor

Applying a stationary reference frame transformation to these equations yields the corresponding qd equations. Eq. (4-2), (4-3) becomes

$$[V_{dq}] = [T][V_{ABC}] \quad (4-30)$$

$$\begin{aligned} V_{dqs} &= [R_s]_{dq} \cdot i_{dqs} + [L_{ss}]_{dq} \cdot p \cdot i_{dqs} + [L_{sr}]_{dq} \cdot p \cdot i_{dqr} \\ &\quad + j\omega [L_{ss}]_{dq} \cdot i_{dqs} + [L_{sr}]_{dq} \cdot i_{dqr} \end{aligned} \quad (4-31)$$

$$\begin{aligned} V_{dqr} &= [R_r]_{dq} \cdot i_{dqr} + [L_{rr}]_{dq} \cdot p \cdot i_{dqr} + [L_{sr}]_{dq} \cdot p \cdot i_{dqs} \\ &\quad + k \cdot [L_{rr}]_{dq} \cdot i_{dqr} + [L_{sr}]_{dq} \cdot i_{dqs} \end{aligned} \quad (4-32)$$

Where: $k = j(\omega - \omega_r)$, $p = \frac{d}{dt}$

And the current equal

$$i_{dqs} = [T_s][i_{ABC}], i_{dqr} = [T_r][i_{ABC}]$$

The matrix $[R_s]_{dq}$, $[L_{ss}]_{dq}$, $[L_{sr}]_{dq}$ can be transformed with the matrix T_{dq} , to dq coordinates as

$$[R_s]_{dq} = [T_s][R_s][T_s]^{-1}$$

$$[R_s]_{dq} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \quad (4-33)$$

$$[L_{ss}]_{dq} = [T_s][L_{ss}][T_s]^{-1}$$

$$[L_{ss}]_{dq} = \begin{bmatrix} L_s - L_m & 0 \\ 0 & L_s - L_m \end{bmatrix} \quad (4-34)$$

$$[L_{sr}]_{dq} = [T_s][L_m][T_r]^{-1}$$

$$[L_{sr}]_{dq} = L_m \cdot \begin{bmatrix} \frac{3}{2} & 0 \\ 0 & \frac{3}{2} \end{bmatrix} \quad (4-35)$$

Similarly from figure(4.4) .The rotor (dq) transformation can be derived as[13]

$$[T_r] = \frac{2}{3} \begin{bmatrix} \cos\beta & \cos\left(\beta - \frac{2\pi}{3}\right) & \cos\left(\beta + \frac{2\pi}{3}\right) \\ \sin\beta & \sin\left(\beta - \frac{2\pi}{3}\right) & \sin\left(\beta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (4-36)$$

$$\text{Where: } \beta = \theta - \theta_r \quad (4-37)$$

Thus the rotor quantities can be expressed as

$$\left. \begin{aligned} V_{dqr} &= [T_r][V_{ABCr}] \\ [R_r]_{dq} &= [T_r][R_r][T_r]^{-1} \\ i_{dqr} &= [T_r][i_{ABCr}] \\ [L_{rr}]_{dq} &= [T_r][L_{rr}][T_r]^{-1} \end{aligned} \right\} \quad (4-38)$$

Equation (4-7) can be rewritten as:

$$\frac{d}{dt} \begin{bmatrix} I_s \\ I_r \end{bmatrix}_{dq} = [L_{dq}]^{-1} \begin{bmatrix} V_s \\ V_r \end{bmatrix}_{dq} - [L_{dq}]^{-1} \left[[R_{dq}] + \omega \frac{d}{d\theta} [L_{dq}] \right] \begin{bmatrix} I_s \\ I_r \end{bmatrix}_{dq} \quad (4-39)$$

$$\text{Where: } [L_{dq}] = \begin{bmatrix} [L_{ss}]_{dq} & [L_{sr}]_{dq} \\ [L_{rs}]_{dq} & [L_{rr}]_{dq} \end{bmatrix} \quad (4-40)$$

Mechanical Dynamic Equation:

The mechanical equation is coupled to

$$J \frac{d^2 \theta_{rm}}{dt^2} + T_L - T_e = 0 \quad (4-41)$$

The electrical torque can be expressed as the partial variation of the co energy with respect to rotor position as:

$$T_e = \left[\frac{dW_{co}}{d\theta} \right]_{(I_s, I_r \text{ constant})} \quad (4-42)$$

In a linear magnetic system the co-energy is equal to the stored magnetic energy and equal

$$W_{co} = \frac{1}{2} I_s^t \cdot L_{ss} \cdot I_s + \frac{1}{2} I_s^t \cdot L_{sr} \cdot I_r + \frac{1}{2} I_r^t \cdot L_{sr} \cdot I_s + \frac{1}{2} I_r^t \cdot L_{rr} \cdot I_r \quad (4-43)$$

The electrical torque that can be calculated (L_{ss}, L_{rr}) are constant

$$T_e = \frac{P}{2} [I_s]_{dq}^t \cdot \left(\frac{d[L_{sr}]}{d\theta} \right)_{dq} \cdot [I_r]_{dq} \quad (4-44)$$

With this manner the mutual inductors matrix become independent of position angle (θ):

$$\begin{aligned} \left(\frac{dL_{sr}}{d\theta} \right)_{dq} &= [T_s] \cdot \left(\frac{d[L_{sr}]_{ABC}}{d\theta} \right) \cdot [T_r]^{-1} \\ \left(\frac{dL_{sr}}{d\theta} \right)_{dq} &= L_m \cdot \begin{bmatrix} 0 & \frac{3}{2} \\ -\frac{3}{2} & 0 \end{bmatrix} \end{aligned} \quad (4-45)$$

-In Case of Inter Turn Shorted Circuit

We show that in faulty case, an induction machine can be characterized by two equivalents modes. The common mode model corresponds to the healthy dynamics of the machine (Park's model) whereas the differential mode model explains the faults. This model, very simple to implement because expressed in Park's frame, offers the advantage to explain the defect through a short circuit element dedicated to the faulty winding. The qd -applied voltage in a reference frame fixed to the stator can be obtained from the stator phase voltage equation(4-31),(4-32) by standard transformation [15]. The qd voltages in case fault are

$$\begin{aligned} V_{dqs} &= [R_{sf}]_{dq} \cdot i_{dqs} + [L_{ssf}]_{dq} \cdot p \cdot i_{dqs} + [L_{srf}]_{dq} \cdot p \cdot i_{dqr} \\ &\quad + j\omega \left[[L_{ssf}]_{dq} \cdot i_{dqs} + [L_{srf}]_{dq} \cdot i_{dqr} \right] \end{aligned} \quad (4-46)$$

$$\begin{aligned} V_{dqr} &= [R_r]_{dq} \cdot i_{dqr} + [L_{rr}]_{dq} \cdot p \cdot i_{dqr} + [L_{srf}]_{dq} \cdot p \cdot i_{dqs} \\ &\quad + k \cdot \left[[L_{rr}]_{dq} \cdot i_{dqr} + [L_{srf}]_{dq} \cdot i_{dqs} \right] \end{aligned} \quad (4-47)$$

The matrix $[R_s]_{dq}$, $[L_{ss}]_{dq}$, $[L_{sr}]_{dq}$ depend on coefficients (f_{sa}) are given by the following terms

$$[R_{sf}]_{dq} = [T_s][R_{sf}][T_s]^{-1}$$

$$[R_{ssf}]_{dq} = \begin{bmatrix} R_s(\frac{2}{3}f_{sa} + \frac{1}{3}) & 0 \\ 0 & R_s \end{bmatrix} \quad (4-48)$$

$$[L_{ssf}]_{dq} = [T_s][L_{ssf}][T_s]^{-1}$$

$$[L_{ssf}]_{dq} = \begin{bmatrix} L_s(\frac{2}{3}f_{sa}^2 + \frac{1}{3}) - (\frac{4}{3}f_{sa} - \frac{1}{3})L_m & 0 \\ 0 & (L_s - L_m) \end{bmatrix} \quad (4-49)$$

$$[L_{srf}]_{dq} = [T_s][L_{srf}][T_r]^{-1}$$

$$[L_{srf}]_{dq} = L_m \cdot \begin{bmatrix} (f_{sa} + \frac{1}{2}) & 0 \\ 0 & \frac{3}{2} \end{bmatrix} \quad (4-50)$$

Equation (4-39) can be rewritten as:

$$\frac{d}{dt} \begin{bmatrix} I_s \\ I_r \end{bmatrix}_{dq} = [L_{dqf}]^{-1} \begin{bmatrix} V_s \\ V_r \end{bmatrix}_{dq} - [L_{dqf}]^{-1} \left[[R_{dqf}] + \omega \frac{d}{d\theta} [L_{dqf}] \right] \begin{bmatrix} I_s \\ I_r \end{bmatrix}_{dq} \quad (4-51)$$

Where

$$[L_{dqf}] = \begin{bmatrix} [L_{ssf}]_{dq} & [L_{srf}]_{dq} \\ [L_{rsf}]_{dq} & [L_{rr}]_{dq} \end{bmatrix}$$

The matrix elements $[R_{sf}]$, $[L_{ssf}]$, $[L_{srf}]$ are given in Appendix A.

Mechanical Dynamic Equation:

The electrical torque for a machine under turn-to-turn fault can be calculated from [13]

$$T_{em} = \frac{P}{2} [I_s]_{dq}^t \cdot \left(\frac{d[M_{srf}]}{d\theta} \right)_{dq} \cdot [I_r]_{dq} \quad (4-52)$$

The mutual inductors matrix become

$$\left(\frac{dL_{srf}}{d\theta} \right)_{dq} = [T_s] \cdot \left(\frac{d[L_{srf}]_{ABC}}{d\theta} \right) \cdot [T_r]^{-1}$$

$$\left(\frac{dL_{srf}}{d\theta} \right)_{dq} = L_m \cdot \begin{bmatrix} 0 & f_{sa} + \frac{1}{2} \\ -(f_{sa} + \frac{1}{2}) & 0 \end{bmatrix} \quad (4-53)$$

4.5- Implementation

Three phase induction motor is adopted as a model example in this thesis. It has 2-pole, power 3hp and their parameters are listed in table (4-1):

Table (4.1): Induction motor parameters

p	2
N_s	182
N_r	28
L_m	0.109 H
L_s	0.20566666667H
L_r	0.13H
D	0.07
J	0.006 kg.m^2
V_{ph}	240v
R_s	1.5Ω
R_e	0.3Ω
R_b	0.3Ω

In the model are $V_s, V_r, L_s, L_r, L_{sr}, R_s, R_r$ in the equation from (4-1),(4-51). The model was then translated into a mat lab code (Appendix B) in which the variables were presented. Figure (4.5) shows the flow chart of the simulation program

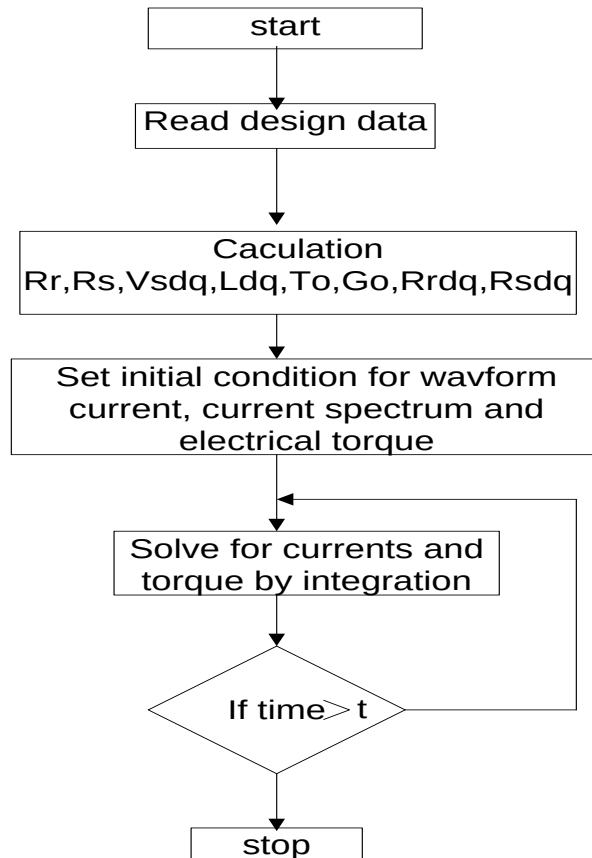


Figure (4.5): Flow chart of the simulation program

Chapter Five: Results and Discussions

5.1- General

This chapter presents the simulations of the proposed model were carried out on a surface mounted permanent magnet motor whose main parameters are shown in Table (4-1).

The study concentrates on the inter-turn short circuit fault occurring in a single coil because this is a common condition. The healthy induction motor was simulated to provide a base for comparison of the spectra of line current between the healthy machine and faulty. The current wave form of the stator phases **a**, **b** and **c** in time domain, at occurs the fault in stator, under case of inter turn fault shorted turn. There is no big difference in stator currents between healthy and faulty conditions. Thus, the waveform did not reveal any information about these small faults presented. Frequency domain analysis of the current signal provides detailed information. For small degree of fault, uncertain information may be obtained, especially if the level of random noise is high and there is fluctuation in the speed, load and supply voltage. Many researchers have proposed a wide variety of techniques to diagnose inter turn faults in three phase induction machine [6, 16]. MCSA is one of the most studied techniques in recent years and it is seen as a good replacement for the widely-spread (method analysis). The principle is to use the stator winding itself as a sensor placed inside the machine. The fault current due to the shorted turn is the source of an additional *mmf* pulse, which also has a space harmonic distribution which is superposed on the main field distribution. From previous considerations, it follows that this will lead to a change in the time harmonics observed in the leakage field. Previous theoretical studies have proved that the following equation gives the components in the air gap flux waveform that are a function of shorted turns [6, 11, 17, and 18].

$$f_{st} = f_1 \left(\frac{n}{p} (1 - s) \pm k \right) \quad (5-1)$$

The induction motor is simulated to operate under different fault levels and different load. The amplitude components on the stator current spectrum as per around 125Hz (with $k=1$, $n=3$), 175 Hz ($k=1$, $n=5$) and magnitude of frequency component (150Hz) appear in spectrum analysis of stator phase current. They are apparent indicators of this fault[6, 19]. The simulation results demonstrate that this approach has effectiveness on fault detection under transient conditions. This advantage has significance on condition monitoring of induction motor, since the induction motor predominantly operate under transient conditions.

The rotor is robust, and (N_r) is generally assumed to be constant, while (N_s) will change value due to deterioration in the stator winding. When (N_s) is variable, (i_s) , (R_s) , (L_s) , and (L_{sr}) become a function of (N_s) . Hence the current in stator is a function of number turns (N_s) and can be expressed as

$$i_s = f(N_s) \quad (5-2)$$

5.2- Model Performance under Normal Condition

In the first step, the machine was run under normal operating condition for a period of 2 seconds under three different loads (0%, 50%, and 100%). The Program used in all the Simulation is reported in Appendix B.

5.2.1- Model Performance at no-load under normal operating conditions

Figure (5.1a) shows the simulated rotor speed (ω_r) which reached the steady state condition after about 0.5 sec and then maintained a constant speed.

Figure (5.1b) shows the simulated stator currents **a,b,c** during motor starting up and steady state at no load, it is clear that the starting current is about five times the full load current during transient stage then decrease to steady state current after 0.5 sec. The model appears to be working well and the speed and current characteristics are as expected. Simulated stator phase currents during the steady state at no load 6.5A, and the maximum value of current at startup is approximately 32.5A.

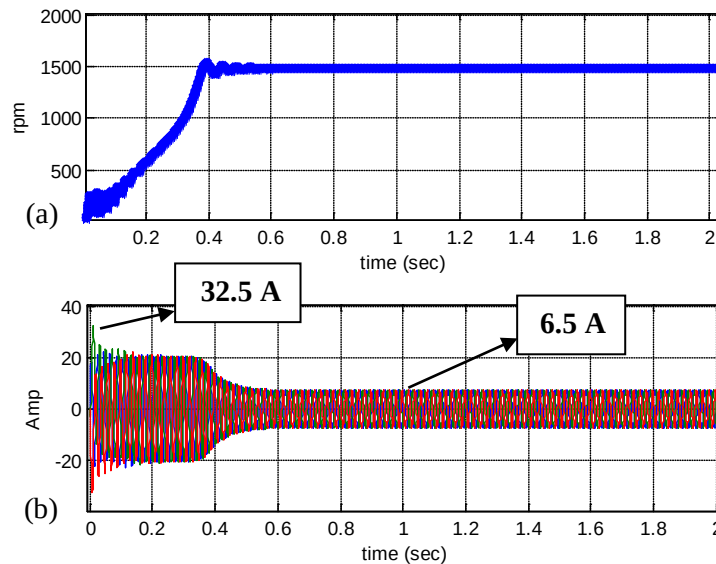


Figure (5.1a, b): Simulated for rotor speed and stator currents during starting up and steady state

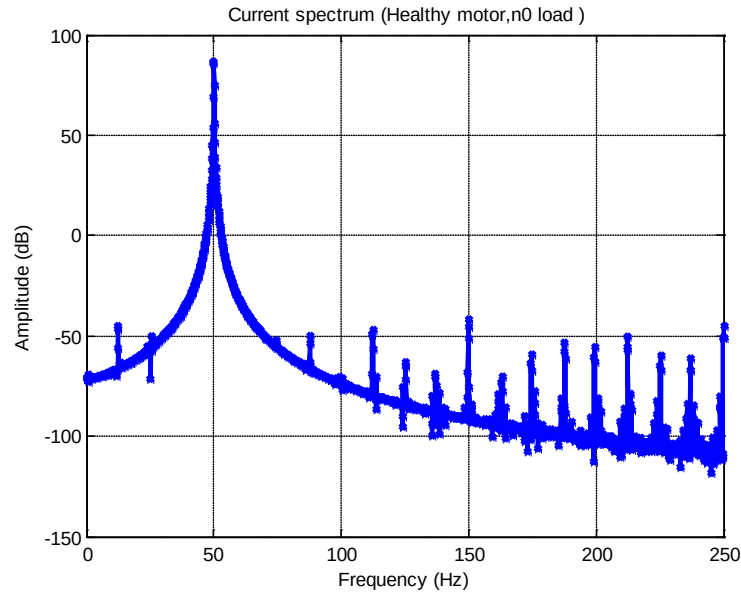


Figure (5.2): Current spectrum for the stator current phase (A) at no load

Figure (5.2) shows the current spectrum waveform for the stator current. The ripples in the current spectrum due to the slots or tooth on stator, since the ripples are due to slotting, they do not move with respect to the conductors but glide over the flux-distribution curve, always opposite the slots and teeth which cause them. [20]. The motor supply line frequency is clearly ($\text{dB} > 0$) apparent only in the current spectrum.

5.2.2- Model Performance at Half load Condition

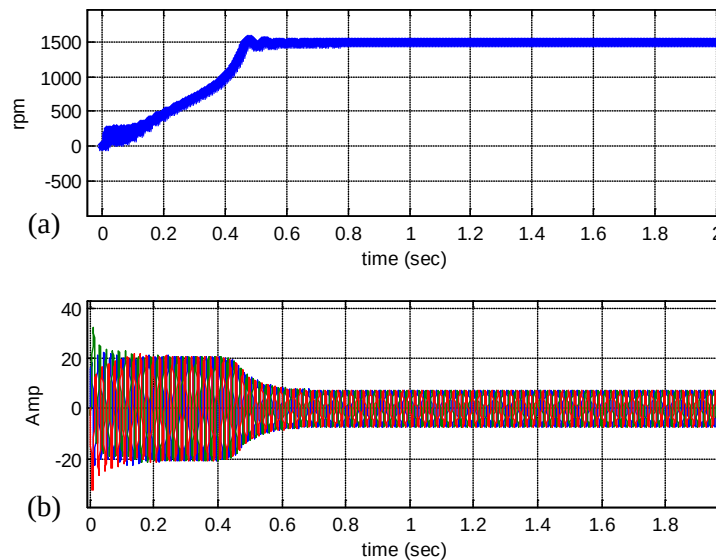


Figure (5.3a, b): Simulated for rotor speed and stator currents during starting up and steady state

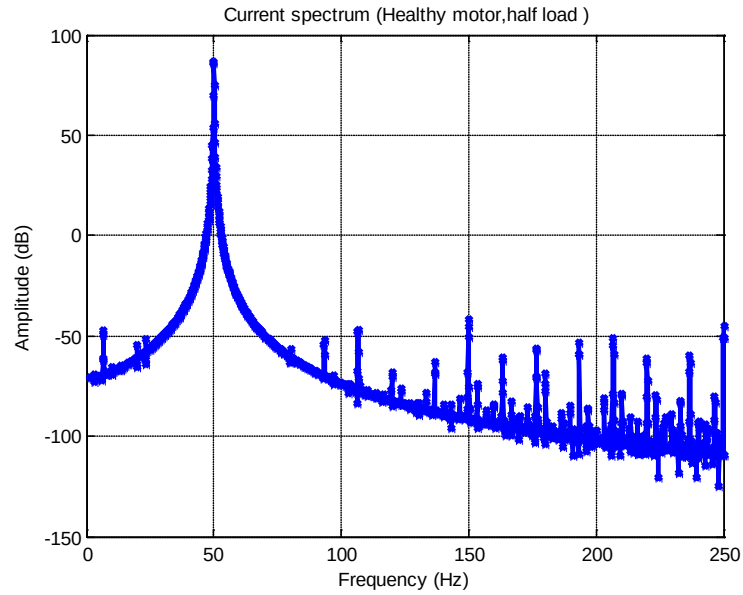


Figure (5.4): Current spectrum for the stator current phase (A) at half load

Figure (5.3a) show the simulated rotor speed (ω_r) which reached the steady state condition after about 0.6 sec and then maintained a constant speed.

Figure (5.3b) show simulated stator **a, b, c** currents during motor starting up and steady state at half load during first two second. It is clear that the currents at starting reach to about five times of steady state current then decays to steady state current, it takes about 0.6 sec.

5.2.3- Model Performance at Full load Condition

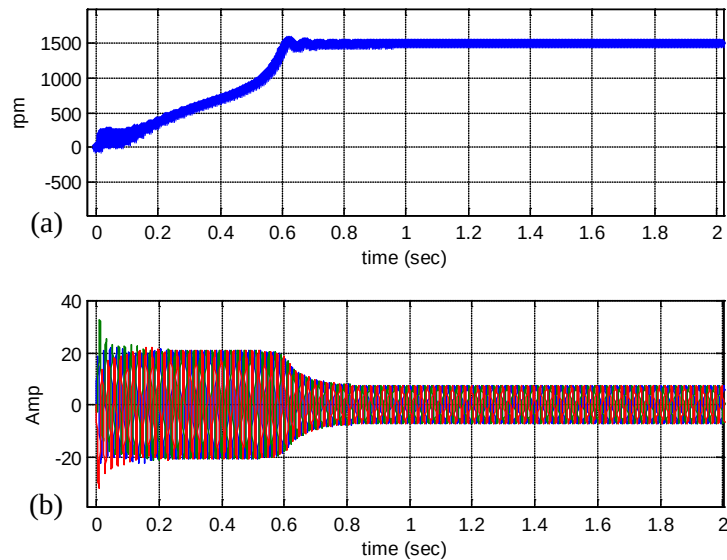


Figure (5.5a, b): Simulated for rotor speed and stator currents during starting up and steady state

Figure (5.5a) show the simulated rotor speed during motor starting up and steady state at full load condition, motor speed started from zero rpm to constant speed at full load after about 0.8 sec.

Stator **a, b, c** currents during transient and steady state stages are shown in figure (5.5b). It is clear that the current reaches about six times of steady state current during transient stage then decrease to steady state current after 0.8 sec. The maximum value of steady state current is approximately 35A.

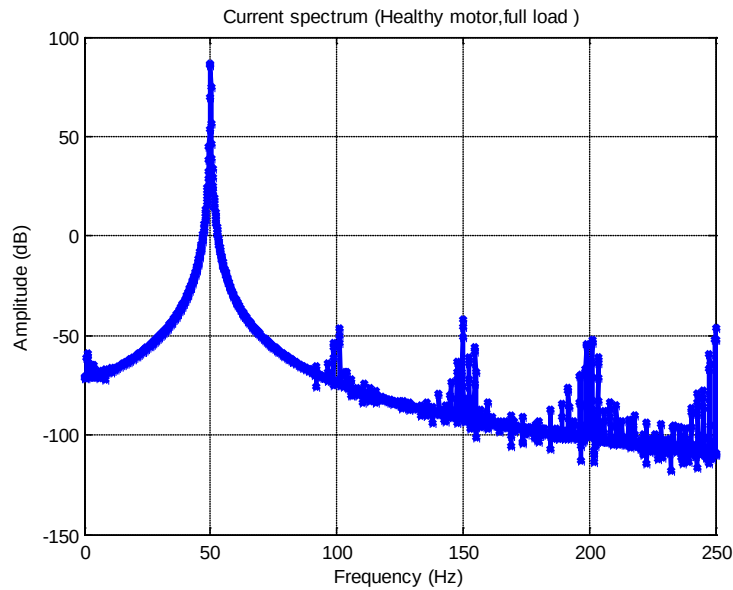


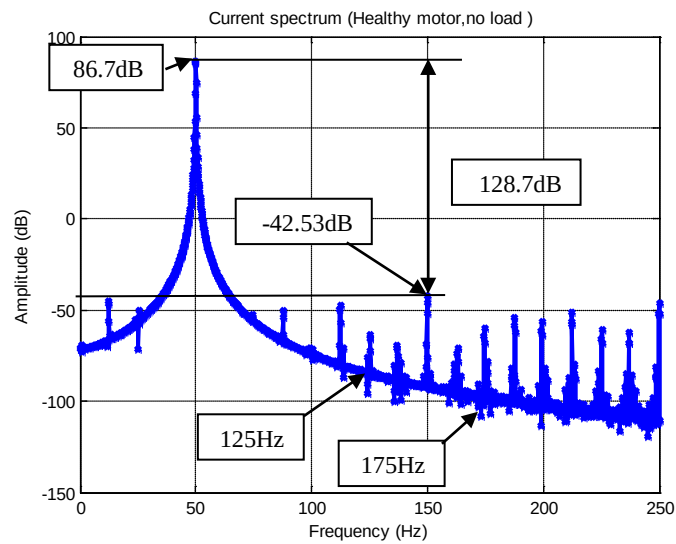
Figure (5.6): The current spectrum for the stator current phase (A) at full load

5.3-Model Performance under Difference Number of Shorted Turns

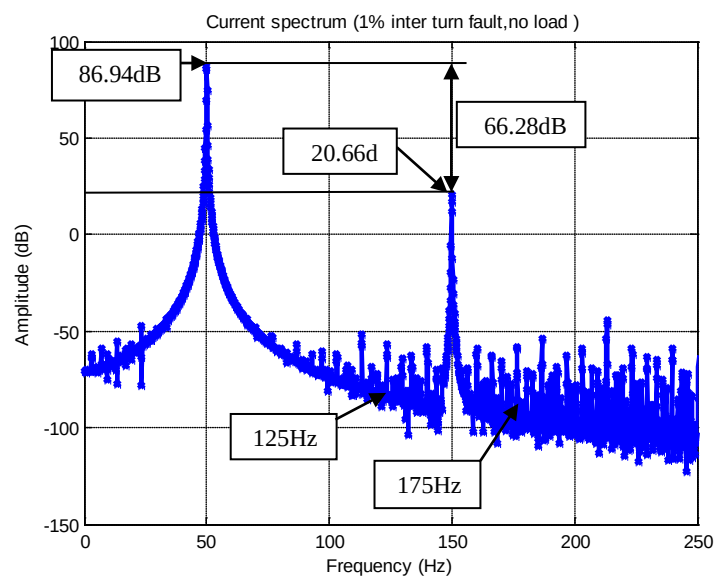
For a shorted turns fault, equation (4-51) according to the fault phase. The study concentrates on the inter-turn short circuit fault occurring in a single coil because this is a common condition. First the healthy machine was simulated above to provide a base for comparison of the spectra of line current between the healthy machine and one with an incipient fault. Many different fault percentages were simulated .Here only four situations are described in detail (0% (Healthy motor), 1%, 1.5%, 2%) shorted turns.

5.3.1- Model Performance under No Load and Difference Number of Shorted Turns

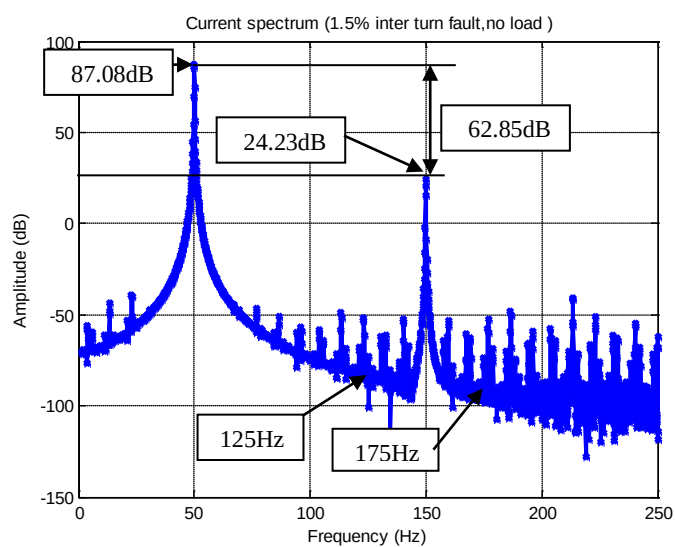
Figures (5.7) show the simulation results for current spectrum [0-250Hz] under the different number of inter-turn and no load.



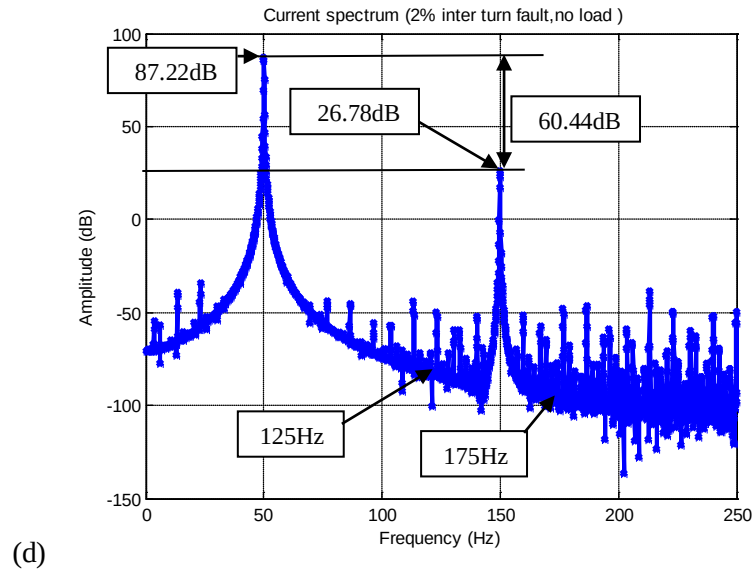
(a)



(b)



(c)



Figures (5.7a, b, c, d): The current spectrum under healthy and different number of shorted turn at no load

The diagnosis of shorted turns via MCSA is based on detecting amplitude around the frequency components given by equation (5-1) in that these rotating flux waves can induce corresponding current components in the stator phase current.

Figure (5.7a) presents the current spectrum while the motor is operated under healthy condition, no amplitude around components on the current spectrum at 125,175 Hz. The obvious change in figures (5.7b, c, d) respectively is that completely new amplitude component exist around 125 and 175 Hz and can only be due to the shorted turn[6]. Note that these components will change in frequency as a function of load. This result agrees with a search carried by [3] [4] [6] in which it demonstrated that stator fault causes are appear in these components.

Figures (5.7a, b, c, d), they can be seen clearly the component frequency 150Hz. This third harmonic results from the interaction of the negative sequence current in the stator phases and the fundamental slip frequency current in the rotor bars. This interaction produces torque pulsating at twice the line frequency. The consequence speed ripple caused flux density component at three times the line fundamental frequency with respect to stator. Finally, this flux produces the third harmonic in the stator current. The magnitude of the third harmonic increases as the fault severity increases [21]. On other hand the (dB) difference between the third component magnitude 150Hz in figure 5-7a and the supply frequency component is 128.7dB, in figure (5.7b) the (dB) difference is decreased by 66.28dB ,either in figure(5.7c,d), the dB difference is decreased respec-

tively by 62.85dB, 60.44dB, this indicate to when inter-turn short circuit happens respectively .

Figure (5.8) show value magnitude at frequency component 150Hz in phase (A) of stator current before and after inter-turn shorted turns. Fault happens in no load operation, the comparison between the serious levels of inter-turn short. Notice that the magnitude (dB) at component frequency (150Hz) is increased by ($\cong 3$ dB). Faulty parameter various to indicate stator level occurring in the motor(1% various to approach 2 turns , 1.5% to approach 3 turns 2% to approach 4 turns).

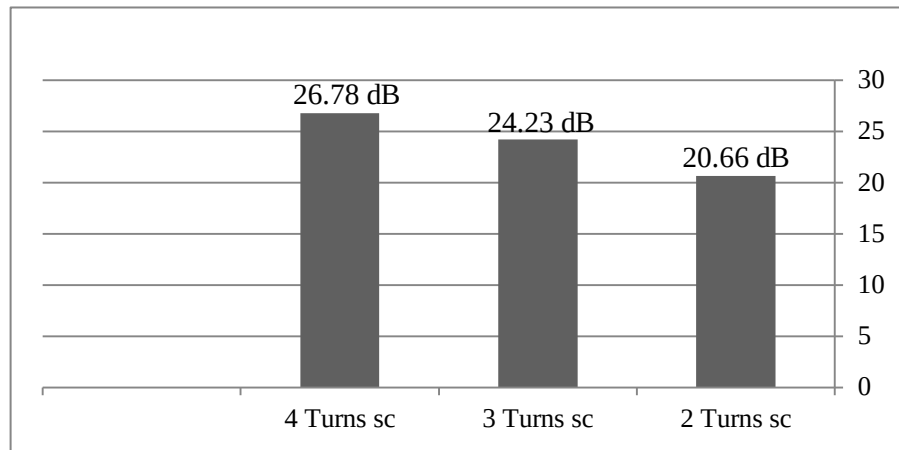
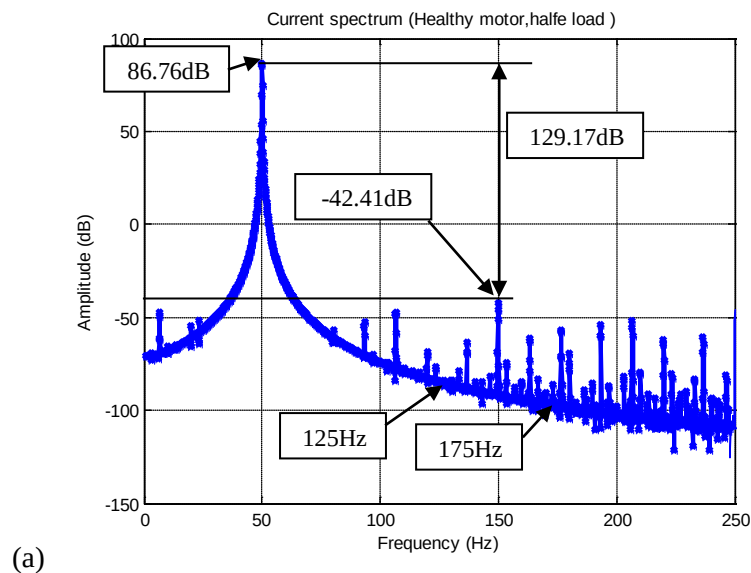


Figure (5.8): Estimations of shorted turns at no load

5.3.2- Model Performance under Half Load and Difference Number of Shorted Turns

The figures (5.9a, b, c, d) shows the fault current spectrum of stator current phase (A) respectively at half load condition. As it can be seen the obvious change in figures (5.9b,c,d), are that completely amplitude frequency component exist around 125 and 175 Hz, and can only be due to the shorted turn magnitude fault current spectrum.



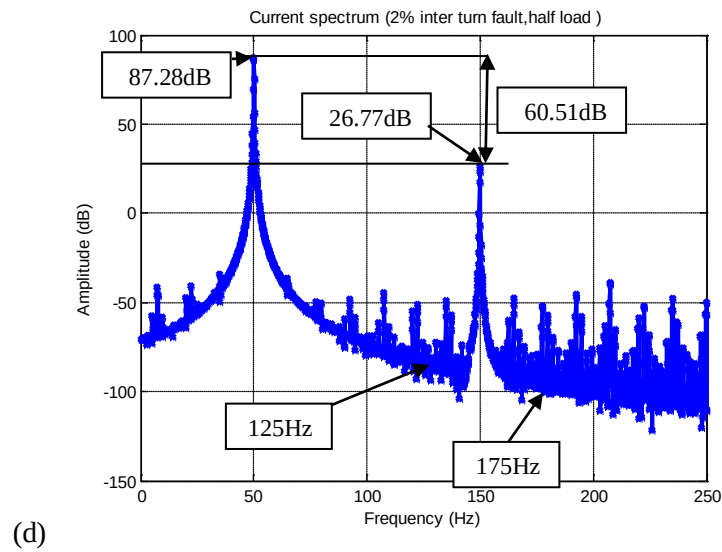
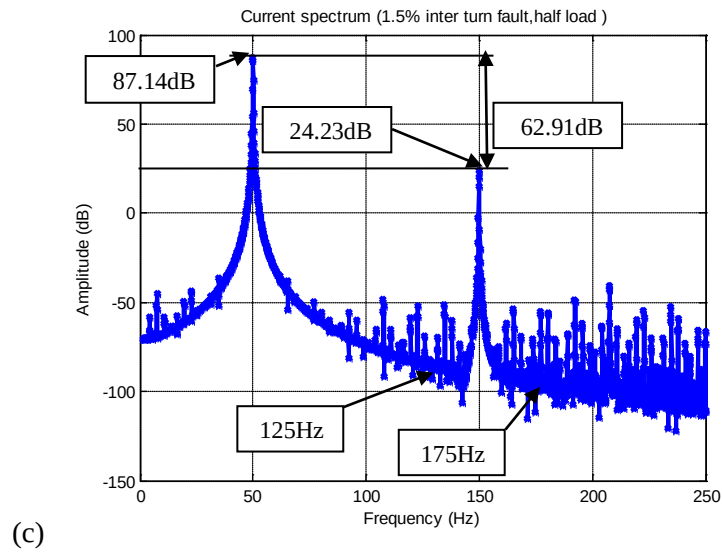
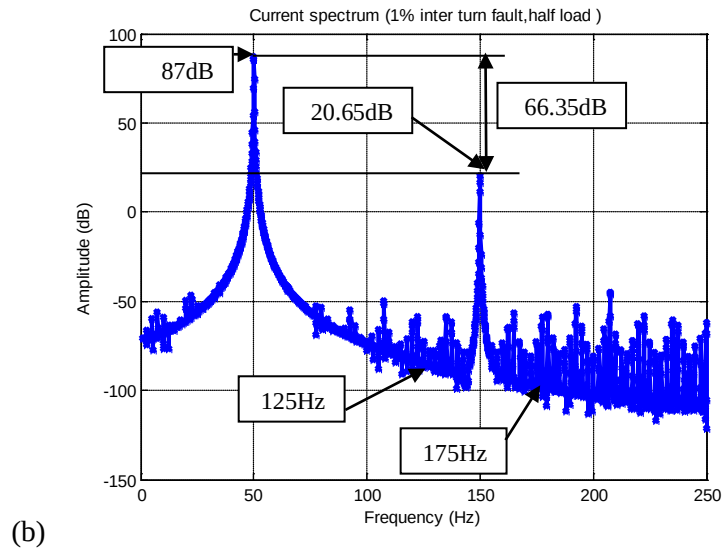


Figure (5.9a, b, c, d): The current spectrum under healthy and different number of short-
ed turn at half load

Figures(5.9a,b,c,d) can be seen clearly at the third component (150Hz), in figure(5.9a) the difference magnitude between (50Hz and 150Hz) is high about (129.17dB),when inter-turn short circuit happens respectively ,the difference in figure(5.9b,c,d) decreased with the serious level of short turns.

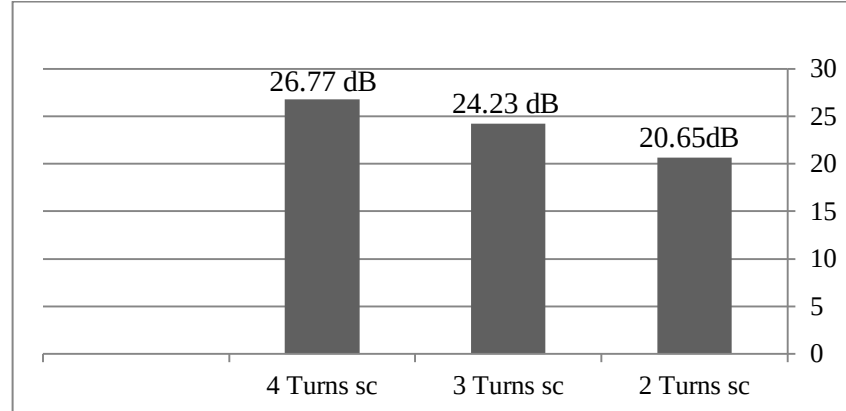
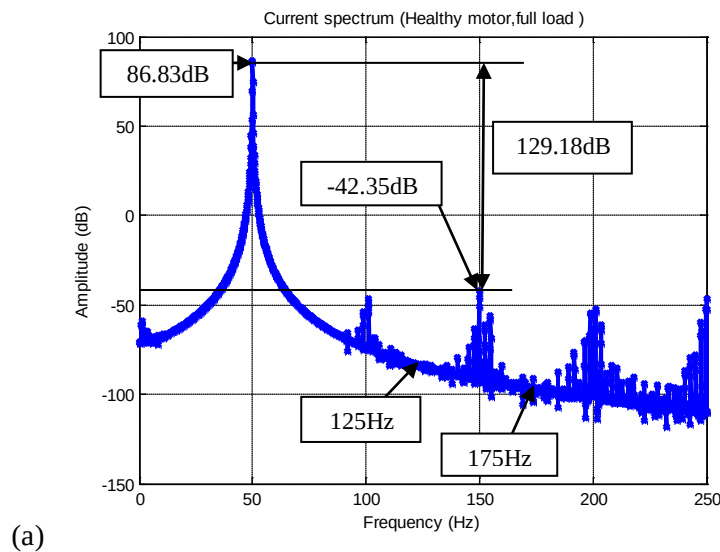


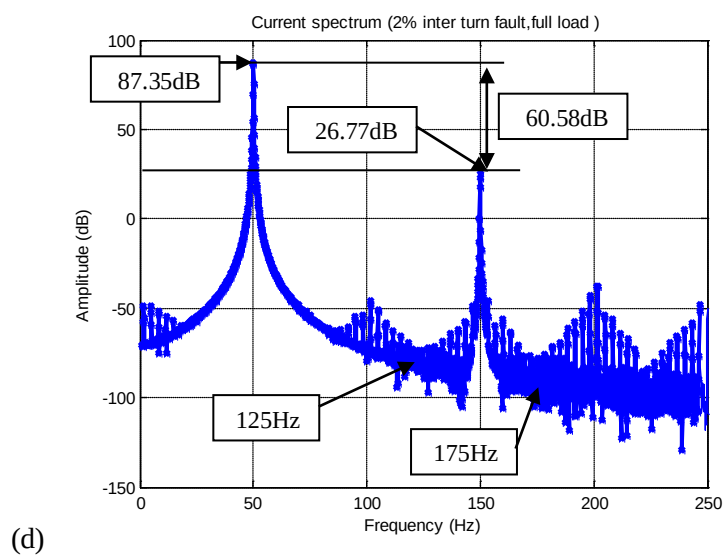
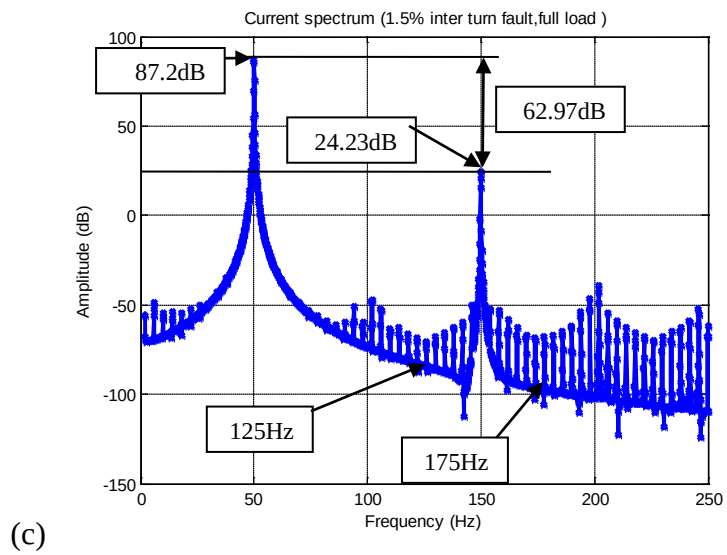
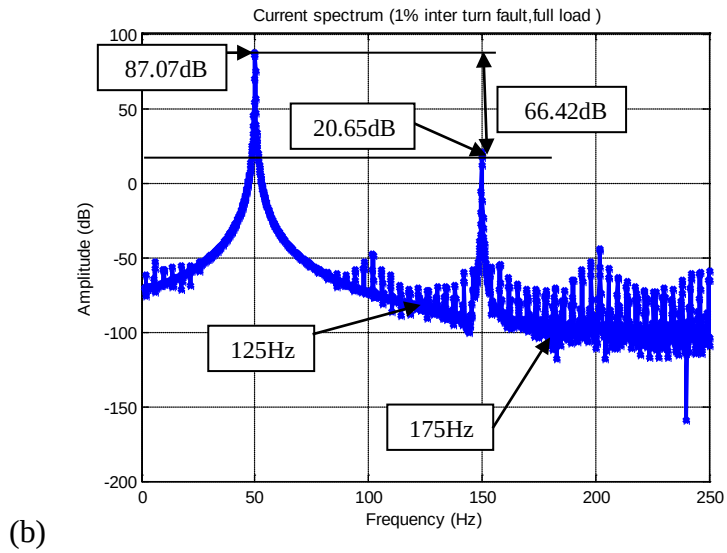
Figure (5.10): Estimations of shorted turns at half load

For more clearly figure (5.10) show magnitude of third harmonic component (150Hz) in one phase of stator after inter-turn short. Fault happens at half load operation, the magnitude in case healthy (-42.4), for the comparison between the serious level of inter-turn fault, notice that the magnitude (dB) at component frequency (150Hz) is increased by ($\cong 3$ dB).

5.3.3- Model Performance under Full Load and Difference Number of Shorted Turns

Figures (5.11a, b, c, d) shows the fault current spectrum for (0%,1%,1.5%,2%) shorted turns respectively at full-load condition .No amplitude component around 125,175 Hz in figure(5.11a), but in figures (5.11b, c, d) found amplitude component around 125,175 Hz, they are respectively increased [15].





Figures (5.11a, b, c, d): The current spectrum under healthy and different number of shorted turn at full load

Figures (5.11a,b,c,d) shows the magnitude for a healthy motor and with a percentage of shorted inter-turn on stator at frequency component (150Hz), the (dB) difference between the third component magnitude (150Hz) in figure(5-11a) and the supply frequency component (50Hz) is appear to be greater in healthy case, when short turns occur, as in figure (5.11b) the difference decreased of this magnitude component (150Hz) approximately (66.42dB) is change (due to 1% shorted turns). It is also seen that the difference between two components in figure (5.11c, d) are decreased respectively.

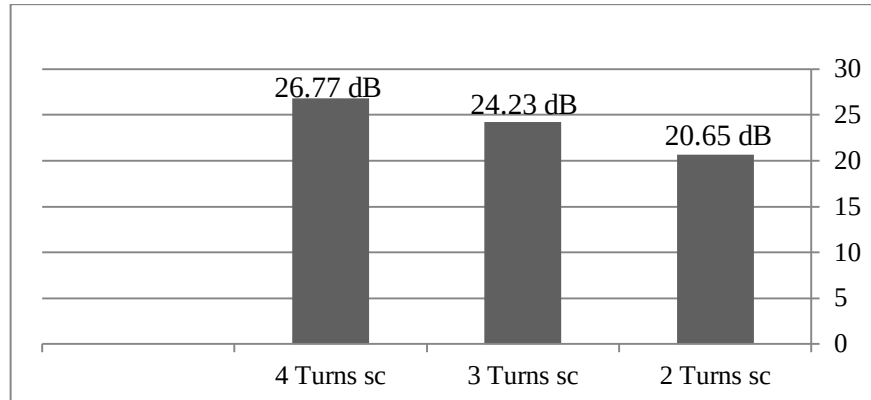


Figure (5.12): Estimations of shorted turns at full load

Generally when compared to the healthy condition at same operating load (circled). The current spectra with no fault and the case with actual shorted turns, the amplitude components that is clearly inductive of shorted turns less than three load conditions around 125,175Hz as per equation (5-1). Note that these components will change in frequency as a function of load and inter turn short. The other hand, the stator fault causes an increase in the magnitude of the third component (150Hz) in current spectrum. They can be seen clearly the (dB) difference between the magnitude (150Hz) component and the supply frequency component, and this is indicative of serious short turns.

Table (5.1): Frequency components magnitude for a different number of shorted turns at different loads

Percentage of inter-turn S.C	Number of turn	Frequency component	No load	Half load	Full load
0%	0	150Hz	-42.5dB	-42.41dB	-42.35dB
1%	2	150Hz	20.66dB	20.65dB	20.65dB
1.5%	3	150Hz	24.23dB	24.23dB	24.23dB
2%	4	150Hz	26.78dB	26.77dB	26.77dB

From above table, the change in the magnitude of the frequency component which is presented at (150Hz) can be taken as a diagnostic and indicator for the number of stator shorted-turns fault.

This comparison is important because it is evident that only faulty parameters change when the faults occur according to prior information.

Chapter Six: Conclusion and Future Work

6.1- Conclusion

In this thesis the feasibility of diagnosing shorted turns in the stator windings by parameter estimation of induction machine. This model takes into account the effects of inter turn faults resulting in the shorting of one phase, and obtains inter turn shorted. A model dedicated to induction motors has been presented for the realistic identification and detection of stator inter turn fault. Simulation tests illustrate the efficiency of this technique for use in on-line stator fault diagnosis of induction motor under varying current spectrum of stator. The estimates of the number of inter turns short circuit windings in different realizations give a good approximation of the fault level in the motor.

The detection is based on monitoring the harmonic component around 125Hz and 175 Hz in the supply line current after eliminating any other cases, and we can know approximately the number of inter shorted-turn by comparison from the magnitudes of the third component 150 Hz. They are apparent indicators of this fault and the number of inter- turn fault.

Both the simulation current spectrum analysis results show a significant rise in the third harmonic components 150 Hz when a turn-to-turn fault is inserted. An online fault estimator based on a transient model for the faulty induction motor is implemented. Therefore, the model is good at simulation, and tests illustrate the good approximation of the real faults and the efficiency of this technique for use in fault diagnosis.

The main conclusions, contributions that could be pointed out of the thesis are:

- 1- Detecting the occurrence of turn-to-turn insulation failure through monitoring amplitude components around 125 and 175 Hz in the spectrum of the line current as per equation (5-1).
- 2- The increasing for the third component magnitude (150 Hz) by different faults and constant load can used diagnostic of turn-to-turn insulation failure and indicate for the number of inter turn short-circuit of the induction motor.
- 3- The (dB) difference between the third component magnitude 150Hz and the supply frequency component at difference faults and constant load can used diagnostic an approximately indicate for the number of inter turn short-circuit.

6.2-Future work:

- In this research has used a single sensor type (motor current of stator) combined with a particular signal processing technique (frequency spectrum) to detect fault. Combining information from multiple sensor types and processing tech-

niques should improve the accuracy of fault detection as temperature sensors monitoring, speed variation, et.

- Developing an observer for the load torque from the measured currents.
- Use of this approach (MCSA) for diagnosing also stator winding faults in three-phase synchronous machines (generators) such as inductive and resistive unbalance in one stator and rotor phase.

List of Reference

- [1] J.C. Robertson and C.M. Ong, "Detecting Stator and Rotor Winding Faults in Three-phase Induction Machines," 1995.
- [2] M.L. Sin, W.L. Soong, and N. Ertugrul, "Induction machine on-line condition monitoring and fault diagnosis-A survey," in Book Induction machine on-line condition monitoring and fault diagnosis-A survey, vol. 28, *Series Induction machine on-line condition monitoring and fault diagnosis-A survey*, Editor ed.^eds., City, 2003.
- [3] M. Arkan, D. Kostic-Perovic, and P.J. Unsworth, "Modelling and simulation of induction motors with inter-turn faults for diagnostics," *Electric Power Systems Research*, vol. 75, (no. 1), pp. 57-66, 2005.
- [4] G.G. Acosta, C.J. Verucchi, and E.R. Gelso, "A current monitoring system for diagnosing electrical failures in induction motors," *Mechanical Systems and Signal Processing*, vol. 20, (no. 4), pp. 953-965, 2006.
- [5] H.W. Penrose, "Practical Motor Current Signature Analysis Taking the Mystery Out of MCSA," *Site da Web*, 2003.
- [6] W.T. Thomson and R.J. Gilmore, "Motor current signature analysis to detect faults in induction motor drives-fundamentals, Data interpretation, and industrial case histories," in Book Motor current signature analysis to detect faults in induction motor drives-fundamentals, Data interpretation, and industrial case histories, *Series Motor current signature analysis to detect faults in induction motor drives-fundamentals, Data interpretation, and industrial case histories*, Editor ed.^eds., City, 2003.
- [7] N. Mehla and R. Dahiya, "An approach of condition monitoring of induction motor using MCSA," *International Journal of Systems Applications, Engineering and Development*, vol. 1, (no. 1), pp. 13-17, 2007.
- [8] I. Boldea and S.A. Nasar, *The induction machine handbook*: CRC press, 2001.
- [9] R. Parekh, "AC Induction Motor Fundamentals," *Microchip Technology Inc*, 2003.
- [10] C.S. Indulkar and K. Ramalingam, "Sensitivity Analysis of Induction Motor Performance," *ELECTRICAL INDIA*, vol. 47, (no. 1), pp. 48, 2007.
- [11] W.T. Thomson and M. Fenger, , , "Current Signature Analysis to Detect Induction Motor Faults," *IEEE Industry Applications Magazine*, x, pp. 26-34, July/August 2001.

- [12] E.L. Bonaldi, L.E.d.L. de Oliveira, J.G.B. da Silva, G. Lambert-Torres, and L.E.B. da Silva, "Predictive Maintenance by Electrical Signature Analysis to Induction Motors."
- [13] D.A.h. ALshandoly, "Modelling of Three Phase Induction Motor."
- [14] D.E. Khodja and A. Kheldoun, "Three-phases Model of the Induction Machine Taking Account the Stator Faults," *World Academy of Science, Engineering and Technology*, vol. 52, pp. 21, 2009.
- [15] R.J. Lee, P. Pillay, and R.G. Harley, "D, Q reference frames for the simulation of induction motors," *Electric Power Systems Research*, vol. 8, (no. 1), pp. 15-26, 1984.
- [16] L. Mihet-Popa, "Current signature analysis as diagnosis media for incipient fault detection," *Advances in Electrical and Computer Engineering*, vol. 7, (no. 2), pp. 11-15, 2007.
- [17] W.T. Thomson, "On-line MCSA to diagnose shorted turns in low voltage stator windings of 3-phase induction motors prior to failure," *IEEE International, vol. Electric Machines and Drives Conference*, 2000. IEMDC 2001, 2001.
- [18] J. Penman, H.G. Sedding, B.A. Lloyd, and W.T. Fink, "Detection and location of interturn short circuits in the stator windings of operating motors," *Energy Conversion, IEEE Transactions on*, vol. 9, (no. 4), pp. 652-658, 1994.
- [19] G.M. Joksimovic and J. Penman, "The detection of inter-turn short circuits in the stator windings of operating motors," *Industrial Electronics, IEEE Transactions on*, vol. 47, (no. 5), pp. 1078-1084, 2000.
- [20] M. Liwschitz-Garik and C.C. Whipple, *Alternating-current machines*: van Nostrand, 1961.
- [21] Y. Amara and G. Barakat, "Modeling and diagnostic of stator faults in induction machines using permeance network method," in *Book Modeling and diagnostic of stator faults in induction machines using permeance network method, Series Modeling and diagnostic of stator faults in induction machines using permeance network method*, Editor ed.^eds., City, pp. 1550-1559.

Appendixes

1-Appendix A: Matrix elements for induction motor

A.1. Matrix elements for induction motor

- $L_{ss} = \begin{bmatrix} L_s & -0.5L_m & -0.5L_m \\ -0.5L_m & L_s & -0.5L_m \\ -0.5L_m & -0.5L_m & L_s \end{bmatrix}$
- $L_{rr} = \begin{bmatrix} L_r & -0.5L_m & -0.5L_m \\ -0.5L_m & L_r & -0.5L_m \\ -0.5L_m & -0.5L_m & L_r \end{bmatrix}$
- $L_{sr} = \begin{bmatrix} L_m \cos(\theta) & L_m \cos(\theta + 120) & L_m \cos(\theta - 120) \\ L_m \cos(\theta - 120) & L_m \cos(\theta) & L_m \cos(\theta + 120) \\ L_m \cos(\theta + 120) & L_m \cos(\theta + 120) & L_m \cos(\theta) \end{bmatrix}$
- $R_s = \begin{bmatrix} R_A & 0 & 0 \\ 0 & R_B & 0 \\ 0 & 0 & R_C \end{bmatrix}, R_r = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}$
- $\frac{d[L_{sr}]_{ABC}}{d\theta} = \begin{bmatrix} 0 & -\sin\left(\alpha + \frac{2\pi}{3}\right) & -\sin\left(\alpha - \frac{2\pi}{3}\right) \\ -\sin\left(\alpha - \frac{2\pi}{3}\right) & 0 & -\sin\left(\alpha + \frac{2\pi}{3}\right) \\ -\sin\left(\alpha + \frac{2\pi}{3}\right) & -\sin\left(\alpha - \frac{2\pi}{3}\right) & 0 \end{bmatrix}$

A.2. Matrix elements for induction motor with inter-turn fault

- $[R_{sf}] = \begin{bmatrix} f \cdot R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}$
- $[L_{ssf}] = \begin{bmatrix} f^2 \cdot L_s & -0.5 f \cdot L_m & -0.5 f \cdot L_m \\ -0.5 f \cdot L_m & L_s & -0.5 L_m \\ -0.5 f \cdot L_m & -0.5 L_m & L_s \end{bmatrix}$
- $[L_{srf}] = L_m \cdot \begin{bmatrix} f \cdot \cos\alpha & f \cdot \cos\left(\alpha + \frac{2\pi}{3}\right) & f \cdot \cos\left(\alpha - \frac{2\pi}{3}\right) \\ \cos\left(\alpha - \frac{2\pi}{3}\right) & \cos\alpha & \cos\left(\alpha + \frac{2\pi}{3}\right) \\ \cos\left(\alpha + \frac{2\pi}{3}\right) & \cos\left(\alpha - \frac{2\pi}{3}\right) & \cos\alpha \end{bmatrix}$
- $\frac{d[L_{srf}]_{ABC}}{d\theta} = L_m \cdot \begin{bmatrix} 0 & -f \cdot \sin\left(\alpha + \frac{2\pi}{3}\right) & -f \cdot \sin\left(\alpha - \frac{2\pi}{3}\right) \\ -\sin\left(\alpha - \frac{2\pi}{3}\right) & 0 & -\sin\left(\alpha + \frac{2\pi}{3}\right) \\ -\sin\left(\alpha + \frac{2\pi}{3}\right) & -\sin\left(\alpha - \frac{2\pi}{3}\right) & 0 \end{bmatrix}$

2-Appendix B: Program code of motor simulation for inter turn fault

```
% motor simulation for inter turn fault

% in q-d frame stationary system

clear all

close all

global Lr0 Lss Lrr Lm Rs Rr0 Rr Rdq P D J tL Rdq Rrdq Rb Re

global Nr Ph L0 G0 ua ub uc T0 Tem wr R0s Ls Ls1 Ls2 f R1 Lm1

% P numbers of pole pairs

% D Damping factor

% J mechnaical inertial or rotor system

% tL=external Load

% fs supply frequency

% fb sideband

fs=50;

wb=fs*2*pi;

tL=1;%external load

f=1;%coefficient of S.C

Lm1=0.07266666667;%Lm1=Lss-Ls

Ls=0.205666666667;

Lss=0.133;

Lrr=0.13;

Lm=0.109;

Rs=1.5;

R1=f*Rs;

% Ra=1.2;Rb=1.5;Rc=2.5;

P=2;

D=0.07;

J=0.006;

wm=wb/P; % syncr speed

Ph=3; Nr=28;Ns=182;

Rb=0.3;%68.34e-6; % bar r

Re=0.3;%1.56e-6; % ring seg r in physical stuctrune

% require equivelent R's for equation solving

%rotor matrix

Rr=zeros(Nr,Nr);

for i=1:Nr,%32=Nr+Ph+1 diagnal

Rr(i,i)=2*(Rb+Re);

end

% b. produce -Rb elements

for i=1:Nr,

if i==1,

Rr(i,i+1)=-Rb;Rr(i,Nr)=-Rb;
```

```

elseif i==Nr,
Rr(i,i+1-Nr)=-Rb;Rr(i,i-1)=-Rb;
    else
Rr(i,i+1)=-Rb;Rr(i,i-1)=-Rb;
    end
end
%stator resistance matrix
R0s=zeros(3);
R0s=diag([R1 RsRs]);
y0=zeros(1,5);
% y0(5)=0;
Fs=2000;
datapoints=2^14;
Time=datapoints/Fs;
tspan=[0:1/Fs:Time];
nsx=find(tspan>1.5); % find the instance of steady operation
ns=nsx(1);
T1=Time-1.5;
win=round(T1/tspan(2)); % data points per mech rev
nt=length(tspan);
%win=2.^floor(log2(nt));
nt2=nt-win;
[t y]=ode45('diff_simulation_dq',tspan,y0);
ua=sqrt(2)*240*cos(2*pi*50*t);
ub=sqrt(2)*240*cos(2*pi*50*t-2*pi/3);
uc=sqrt(2)*240*cos(2*pi*50*t+2*pi/3);
ia=y(:,1)*sqrt(2/3);
ib=(-0.5*y(:,1)+(sqrt(3)/2)*y(:,2))*sqrt(2/3);
ic=(-0.5*y(:,1)-(sqrt(3)/2)*y(:,2))*sqrt(2/3);
%Tem=P*(y(1:4)*T0*y(1:4));
figure(1)
subplot(211),
plot(t,y(:,5)*60/2/pi);xlabel('time (sec)');ylabel('rpm');
subplot(212),
plot(t,ia,t,ib,t,ic);xlabel('time (sec)');ylabel('Amp');
grid;zoom on
figure(2)
subplot(211),
plot(t(nt2+1:nt2+win),y(nt2+1:nt2+win,5)*60/2/pi);xlabel('time (sec)');ylabel('rpm');
title('speed')
subplot(212),
plot(t(nt2+1:nt2+win),y(nt2+1:nt2+win,1:4))

```

```

zoom on
figure(3),clf
subplot(211),
plot(t(nt2+1:nt2+win),ia(nt2+1:nt2+win,1))
grid
title('windowed Current Signal for FFt')
fa=(0:win-1)*Fs/win;
Fr=300;
ww=Fr/(Fs/2);
[B,A] = butter(6,ww);
%iaf(:,1) = filtfilt(b,a,ia(nt2+1:nt2+win));
iaf(:,1)=ia(nt2+1:nt2+win);
wc=mean(y(nt2+1:nt2+win,5)); % average speed
s=(wm-wc)/wm;
fb=2*s*fs; % sideband frequency
power=filtfilt(B,A,ua(nt2+1:nt2+win).*iaf);
% .*hanning(win)
figure(4)
subplot(211),
plot(fa,20*log10(fft(iaf.*hanning(win))))
grid
title(' Current spectrum (healthy machine full load )')
xlim([0 400]);xlabel('Frequency (Hz)');ylabel('Amplitude (dB)')
zoom on
subplot(212),
Te=y(:,2).*y(:,3)-y(:,1).*y(:,4);
plot(t,Te);title('electromagnetic torque Healthy machine full load')
xlabel('time');
grid;zoom on
% xlim([0 250]);xlabel('Frequency (Hz)');ylabel('Amplitude (dB)')
% zoom on
% Irms=std(iaf)
speed=y(:,5);
%xs=[t uaubuciaibic speed]

```

```

function iyd=diff_inter turn simulation_dq(t,iy)
% function for healthy and inter turn fault
global Lr0 LssLrr Lm Rs Rr0 Rr P D J tL MM RdqRrdquaubucRb Re M1 M2 M4 M7
global Nr Ph L0 G0 T0 Tem wr R0s f Ls Ls1 Ls2 R1 Rsdq Lm1
% P number of poles
% D Damping factor
% J mechnaical inertial or rotor system

```

```

% tL=external Load
M1=((2/3)*f+(1/3));
M2=((4/3)*f-(1/3));
Ls1=(M1*Ls)-(M2*Lm1);
Ls2=Ls-Lm1;
M4=(f+0.5)*Lm1;
M7=((4/3)*f+(1/6))*Lm1;
Rss=M1*Rs;
i=1;
iy=iy(:);
iyd=zeros(size(iy));
wr=P*iy(5);
ar=2*pi/Nr;
leny=length(iy);
L0=zeros(leny-1,leny-1);
G0=zeros(leny-1,leny-1);
R0=zeros(leny-1,leny-1);
u=zeros(leny-1,1);
ua=sqrt(2)*240*cos(2*pi*50*t);
ub=sqrt(2)*240*cos(2*pi*50*t-2*pi/3);
uc=sqrt(2)*240*cos(2*pi*50*t+2*pi/3);
% tL=0.5*sin(2*pi*50*t);
% votage from three to dq
u(1)=2/3*(ua-1/2*ub-1/2*uc);
u(2)=(ub-uc)/sqrt(3);
% u(1)=sqrt(2/3)*(ua-1/2*ub-1/2*uc);
% u(2)=(ub-uc)*sqrt(2)/2;;
u(3)=0;
u(4)=0;
thtar=wr*t;
%Rotor Transforms to dq
Kr=zeros(2,Nr);
Kr(1,1:end)=cos(thtar+P*(2*pi/Nr*[0:Nr-1]));
Kr(2,1:end)=sin(thtar+P*(2*pi/Nr*[0:Nr-1]));
% Kr(3,1:end)=1/2;
rKr=Kr';
%Kr=Kr*(2/Nr);
% Stator transformation to dq
Ks=zeros(2,Ph);
Ks(1,1:end)=cos(thtar+(2*pi/Ph*[0:Ph-1]));
Ks(2,1:end)=sin(thtar+(2*pi/Ph*[0:Ph-1]));
% Ks(3,1:end)=1/2;

```

```

rKs=Ks';
% L matrix
L0(1,1)=Ls1; L0(1,2)=0; L0(1,3)=M7; L0(1,4)=0;
L0(2,1)=0; L0(2,2)=Ls2; L0(2,3)=0; L0(2,4)=Lm;
L0(3,1)=M7; L0(3,2)=0; L0(3,3)=Lrr; L0(3,4)=0;
L0(4,1)=0; L0(4,2)=Lm; L0(4,3)=0; L0(4,4)=Lrr;
%stator resistans matrix transfered to dq
ReplaceAllRsdq=(2/Nr)*Ks*R0s*rKs;
%rotor resistans matrix transfered to dq
Rrdq=(2/Nr)*Kr*Rr*rKr;
Rrdq=Rrdq;
%motor resistance matrix
% Rdq=zeros(4);
% Rdq(1,1)=Rsdq(1,1);Rdq(2,2)=Rsdq(2,2);
% Rdq(3,3)=Rrdq(1,1);
% Rdq(4,4)=Rrdq(2,2);
%motor resistance matrix
Rdq=zeros(4);
Rdq(1,1)=Rss;Rdq(2,2)=Rs;
Rdq(3,3)=Rrdq(1,1);
Rdq(4,4)=Rrdq(2,2);
% G0 matrix = transformation*inductance matrix(ABC)*inverse of diffrentiation of the
% transformation with respect to thata
G0(1,1)=0; G0(1,2)=0; G0(1,3)=0; G0(1,4)=0;
G0(2,1)=0; G0(2,2)=0; G0(2,3)=0; G0(2,4)=0;
G0(3,1)=0; G0(3,2)=M4; G0(3,3)=0; G0(3,4)=Lrr;
G0(4,1)=-M4; G0(4,2)=0; G0(4,3)=-Lrr; G0(4,4)=0;
% G0(3,:)=L0(4,:);
% G0(4,:)=-1*L0(3,:);
% T matrix
T0=zeros(4,4);
T0(1,4)=0;T0(1,2)=0;T0(1,3)=0; T0(1,4)=-M4;
T0(2,1)=0;T0(2,2)=0;T0(2,3)=M4; T0(2,4)=0;
T0(3,1)=0;T0(3,2)=M4;T0(3,3)=0;T0(3,4)=0;
T0(4,1)=-M4;T0(4,2)=0;T0(4,3)=0; T0(4,4)=0;
rL0=inv(L0);
iyd(1:4)=-rL0*(Rdq+wr*G0)*iy(1:4)+rL0*u;
iyd(5)=(P*(iy(1:4)'*T0*iy(1:4))-D*iy(5)-tL)/J;

```