Design Algorithm of an Induction Motor for Fault diagnosis

A THESIS

Submitted to the
Department of Electronics and Power Engineering of
Pakistan Navy Engineering College
National University of Sciences and Technology
by

Syed Nazim Hussain

In partial fulfillment of the requirements
for the degree of
Master of Science in Electrical Engineering

2015

Title of Thesis:

Control and Fault Diagnosis of an Induction Motor using Pattern Recognition

Submitted by:

Syed Nazim Hussain

Supervised by:

Cdr Dr Sajjad Haider Zaidi

Assistant Professor

Guidance and Examination Committee:

Cdr Dr Attaullah Yousuf Memon

Assistant Professor

Cdr Dr Aleem Mushtaq

Assistant Professor

Dr Bilal Khan

Assistant Professor

ABSTRACT

Control and Fault progression of a three Induction Motor

By

Syed Nazim Hussain

Owing to their extensive use and waste presence in different procedures and processes, induction machines are rightly called as the work horses of the industry. Adequate and timely maintenance, fault finding and repair of these machines is a mandatory requirement for efficient working. In literature, extensive work has been presented exploring induction machine faults their symptoms and remedies. Broken rotor bar is one of the highly investigated. Due to the complexity involved in observing this fault, indirect methods to detect its presence are employed. Simulation is a modern tool to analyze machines under different operating conditions. However, in case of a faulty machine, model becomes different as compares to the normal mode. A three phase induction machine model is presented having broken rotor bars. Moreover, comparative analysis is performed between faulty and healthy case. An easy to comprehend model of an induction motor in *abc* frame is described to understand the parametric change of a faulty model of an induction motor. The implementation of both healthy and faulty model is done using Matlab/Simulink software. First, the healthy motor is simulated and then the results of faulty motor are compared with the healthy motor to understand the change in response of faulty

and healthy motor. Consideration is on broken rotor bar fault but other faults like bearing fault, phase imbalance and mechanical faults can also occur because of broken rotor bar. As the motor is the backbone of the process of an industry a short time shut down of a plant is avoided, the method proposed can be helpful in understanding the current and frequency response of an induction motor which can be use to avoid breakdown maintenance. A three phase motor is examined in an experimental setup with load and no load conditions so that model's responses could be validate. Broken rotor bar in hardware is done by drilling of bars so that different numbers of broken bar could be analyze. A pattern observed in model can be visualize and can be used as a comparative technique to find the number of broken rotor bar broken.

This work is dedicated to Imam Mahdi (a.s)…

ACKNOWLEDGEMENTS

Sincere gratitude to my supervisor, Syed Sajjad Haider Zaidi for his kind support and availability. The way he taught me to ask honest questions is a great advancement for my future endeavors.

I am thankful to GEC members Dr. Ataullah Y.Memon, Dr. Aleem Mushtaq and Dr. Bilal Khan for their guidance and support whenever I need and to appreciate my work.

I would like to thank PNEC,NUST a well known engineering institute and HEC for providing an ideal atmosphere by mean of highly qualified teaching staff, digital libraries and well equipped laboratories as my thesis research included hardware.

Thanks to the lab staff of PNEC, NUST for their kind support by guiding me via physical and verbal means.

My friends who supported me throughout my studies and always helped me out to solve the problems and strengthen by encouraging me. I am thankful to Adeel, Usman, Hazwer and Khizer.

Special thanks to my family and to those not less than the family Gohar, Mehwish, Shakir, Yasir, Owais and Raweem as their encouragement and devotion enforced me to achieve my career goal and milestone. I am thankful for their availability, belief and to support wherever they can.

Finally, my parents and their belief is the reason of completion of thesis. Their prayers brought me to the level that I am able to complete my master’s work as they always loved and believed in me, specially my father who never let me face any problem and always asked me to focus on my studies.

Above all, thanks to the most merciful and most beneficial Allah for his divine intervention to achieve academic endeavors. Muhammad(s.a.w.w) and Ahlul Bayt(a.s) for showing me the way to work hard with dedication and consistency.

Table of Contents

LIST OF FIGURES

This page is intentionally left blank

CHAPTER 1. INTRODUCTION

In an industry, induction motor is considered as the backbone as it is the prime mover of an industrial process. These motors are generally reliable. But manufacturing and installation, heavy load parameters and environmental factors sometimes lead to internal fault occurrence. These faults occurred in stator, bearing, accessories and in rotor. Bearing and accessories faults are often and can be resolved without affecting the production, as they are less time consuming and can be maintained on the working floor at plant. Faults like stator core or winding, rotor breakage, damage lamination or air gap eccentricity are time consuming faults as maintenance engineer has to remove the motor from the field and fix it on the working table in the lab, as it need special care and tools. If there isn't a stand by motor, production has to suffer which is a loss and can lead to heavy loss in case of large scale production.

DC motor drives with an advantage of simple control scenario were introduced earlier. The drawbacks of DC motors were known, but the preference of these motor appreciated in most applications. Although, AC motors were existed but considered in open loop operations only at that time. The discovery of inverter technology diverted the situation in favor of AC motor. The feature like reliability, ruggedness and long term cost effectiveness compelled the plant designer to choose AC motors over DC. As the usage is directly proportional to fault occurrence.AC induction motor occurred faults which diverted the concentration of engineers and researchers to look into these faults. A huge database of research literature is dedicated to these faults and increasing efforts are being made day by day.

Earlier mentioned faults are potential hazards to the operational safety and can affect the operational cost of the system. Broken rotor bar is often in an industrial setup. The causes of these faults are described above. Although, these faults aren't initially causes motor failure but can affect the efficiency by lowering it and can shorten the life of an AC induction motor. Machine breakdown may occurred eventually if insulation or winding damages. Motor operating with broken rotor bar causes sparking which is a fatal hazard in petroleum, mining or petrochemical industry as flammable gases are present in such operations.

Preventive measures should be adopted to avoid such faults as a vital parameter. Predicting such faults is desiring by the maintenance team as it's not only helpful in reducing operational cost but allows scheduling of maintenance provisionally as well, which in result minimize the down time. A vast research is studied in condition monitoring and fault diagnosis of an induction motor. However, the key feature is diagnosing the fault of an AC induction motor by monitoring the operational parameters of machine. By monitoring the condition, the evaluation is continuously performed throughout the serving life of an AC induction motor. A complete diagnosing cycle of condition monitoring compromises of following tasks.

1- Transduction

2- Data acquisitioning

3- Signal processing

4- Fault diagnosing

Measuring and analyzing method may differ as per the type of fault . Whereas, electrical quantities are most appropriate measuring parameter. Motor current, voltage and leakage flux are the most usually investigated parameters in condition monitoring and fault diagnosis. The presented work is to investigate and analyze motor’s stator current and its representation with varying number of broken rotor bar. The speed torque curve is included as well, to visualize the change in speed and torque of , an AC induction motor with varying number of broken rotor bar. There are several other methods like temperature of core and level of bearing vibration adopted to diagnose other fault conditions like defect in insulation, partial discharge, bearing degradation and other score temperature or bearing vibration.

1.1 Importance of Current Signature Analysis for Fault Finding

Fault diagnosis and condition monitoring of an induction motor are of prime importance to identify a specific fault and to identify an authentic approach to obtain a practical online system. Researchers have found that motor’s stator current depicts overall condition of an induction motor by mean of frequency component in current signature. Thus, investigating stator's current spectrum, fault diagnosis can be accomplished[1]. Motor Current Signature Analysis (MCSA) is an effective approach to monitor motor's condition and fault, adopted widely in the end of 20th century.

A MCSA system is consist of current lead, a signal processing system and an algorithm of fault detection. A MCSA system for detection of broken rotor bar is illustrated in figure 1.1

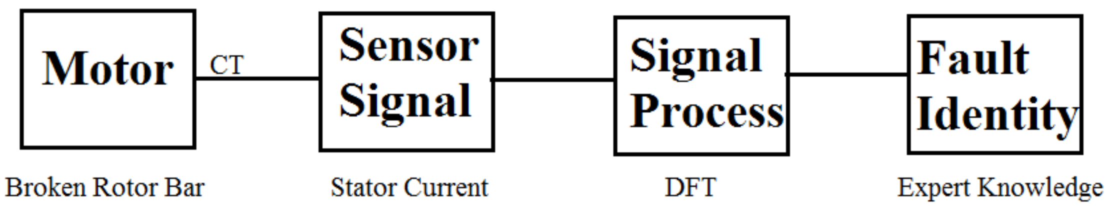


Fig 1.1 A typical flow chart of MCSA system for broken rotor bar diagnosis.

A Current Transformer(CT) is used to measure the stator current of motor's stator. The signal is then processed for spectral analysis. In signal processing system signal is passed through low pass filter then analog to digital (A/D) conversion is applied and transformed into frequency domain. At the end of the procedure frequency components can be visualize either manually of using pattern recognition technique, fault detection could be done.

There are several merits of MCSA system, some of them are

1- An online approach is desirable as it doesn’t interrupt the production of an industry
2- Applying CT for the measurement of current in inaccessible location or hazardous environment in the plant area is demanding, as it need to be done at the time of plant installation and not needed in routine which is a mandatory schedule to keep the system in working condition, by the maintenance team.
3- Physical Impairment of motor is not further required, as it’s a non-intrusive technique

Researchers have dedicated their efforts recent years to the Induction Motor’s broken rotor bar fault[2][3]. It can be done using MCSA system. The thesis covers detection, modeling, impacts and causes of a broken rotor bar in an Induction Motor. The model is dynamic and can be used to visualize the model of different rating.

1.2 Motivation

The symptoms of broken rotor bar of an Induction Motor for the purpose of diagnosis is the presence of frequency component on either side of the fundamental frequency [4]. Referred to as rotor bar’s side band frequency. The components sideband frequency are close usually, to the fundamental frequency and small amplitude relatively. A frequency selection technique is difficult because of low signal to noise ratio.

A classical technique to analyze spectrum is Discrete Fourier Transform (DFT). A fast algorithm of computation is Fast Fourier Transform (FFT), has adopted in implementing of MCSA[5][6]. However, there are limitations in its application, such as side lobe leakage impacts and frequency resolution limitation. Sideband frequencies of broken rotor bar moves with the rotor speed variation, load condition of motor is influential as well. In the condition of light load, sideband frequency may become very close to fundamental frequency. The motor's load condition are dynamic usually, which variants frequency component current signal. Such factors, in result make the data windows enlargement quite difficult or close to impossible. Thus, in most literature reported the machine's load is kept fix usually at full load in MCSA system, in DFT of signal processing system.

The visual for the current analysis and/or speed-torque is either a stronger tools either to decide manually by an experienced maintenance personnel, or the pattern recognition technique is a powerful tool to analyze the fault's severity and type.

A model is built in simulink using tools and techniques to implement and simulate the operation of an Induction Motor with broken rotor bar. The factor motivated to simulate is the simple yet strong approach to implement different number of broken rotor bar and varying load conditions, as well as econo mical factors are also motivating. The validity of such readings can be confirmed via experimental results of real motor.

1.3 Synopsis of thesis

The research is to address the hypothesis that broken rotor bar can be detected via spectrum of stator current, a model of an Induction Motor with broken rotor bar can be modeled and simulation can be performed as per the effects of stator current. There are unique and strong techniques to visualize the faults in an Induction Motor. While formulating the investigation plan for hypothesis, some questions arise and will be answered in the thesis.

The indicators of broken rotor bar's stator current will be investigated. The description of broken rotor bar fault in the model will be performed. The traditional methods and their limitations will be discussed. Improvement in classical techniques will be enlightened. The effect on performance and factors effecting the performance will be covered in the thesis.

1.4 Thesis organization

The thesis is organized in 6 chapters. Chapter 1 is a brief introduction to broken rotor bar faults and motivation

In chapter 2 an introduction to the induction motor will be given and the literature review is included with existed work, chapter 3 consist of induction motors model, chapter 4covers the introduction to broken rotor bar and its application in model. The model can be used to study impacts of broken rotor bar in an Induction Motor and to identify the different faults as per process need. The broken rotor bar is implemented in chapter 5 using simulation techniques, based on visual of different data sets. the results and their identification is performed and lastly the thesis is concluded in chapter 6.

CHAPTER 2. Literature Review

This chapter describes basic, physical phenomena related to induction motor and it's fault. Moreover, explanation of physical phenomena of induction motor with broken rotor bars is included.

2.1 Induction Motors

Induction motors referred as "working horse" are electro-mechanical devices used extensively in industrial processes worldwide, in conversion of electrical energy into mechanical energy. Induction motors are widely used because of their robustness, easy installation, controlling, and adaptability in many industrial applications such as pumps, conveyer belts, ball-mills, fans, air compressors, machine tools and many other applications. The supply of an induction motor is may be direct from a constant frequency which is sinusoidal power supply or may be by an ac variable frequency drive. There are many types and applicationsof an induction electric large range of types and applications of electric motors, the focus of this discussion will be on those studied in this thesis. In other words, the focus is on the three-phase squirrel cage induction motor, which is a type of asynchronous motor. As is common in the literature, a three-phase squirrel cage induction motor is referred to as an induction motor throughout this thesis

2.1.1 Components

An induction motor has several parts but it is essentially composed of a squirrel cage rotor and a wound stator [7].

The rotor is consist a squirrel cage or wound rotor, a shaft, and a lamination stack as shown in Fig. The main part of the rotor in an induction motor is the squirrel cage, which is composed of two end rings and bars. The rotor bars which are conductive are short-circuited on both sides by the end rings. The electric current circulates from one side to other side of the squirrel cage rotor. The bars are enveloped by iron core lamination, which concentrates the magnetic flux from the stator in the rotor. This lamination mechanically supports the rotor shaft as well. On both sides of the rotor shaft there are bearings which allow the rotor to spin inside the stator freely.

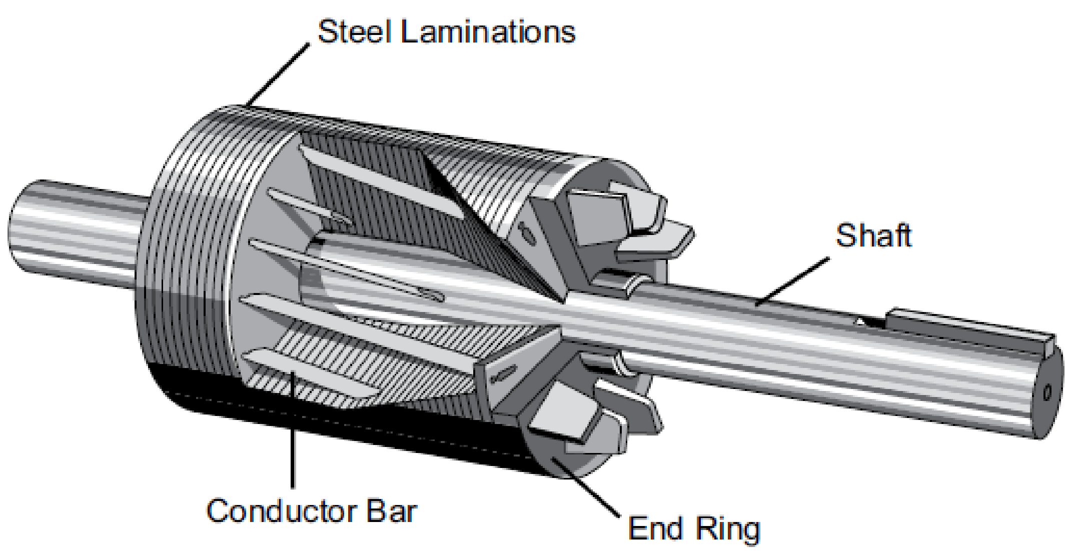


Fig.2.1 Cutaway View of Squirrel Cage Rotor

The stator is consist three parts:

frame, lamination core and windings. The frame provides mechanical support to the stator and the rotor shaft bearings.

The windings are comprised of three distributed coils along the stator core lamination which are connected to three-phase power supply.

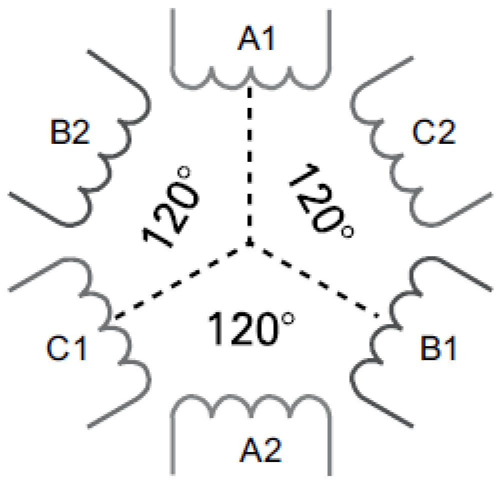


Fig.2.2 2-Pole Stator Winding

The stator is connected to the power supply. It would be described later in this chapter that there is space between stator and rotor which is known as the air gap. laminations are stacked together to form a hollow cylinder. Coils of wire which are insulated, are inserted into slots of the core.

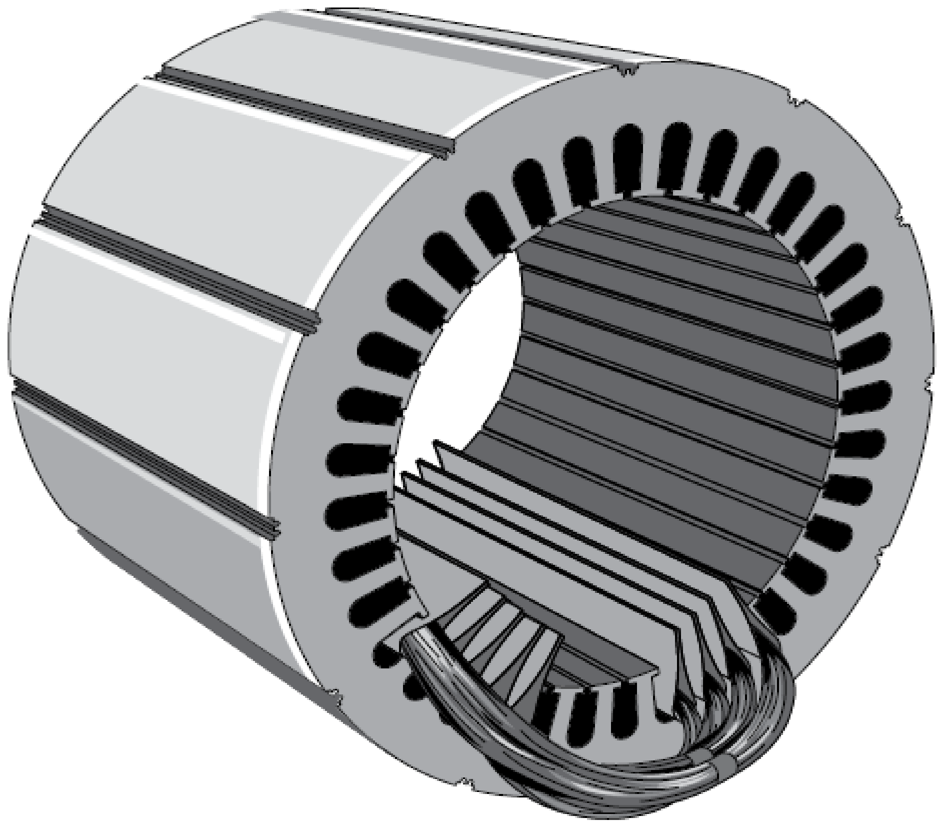


Fig.2.3 Stator Winding Partially Completed

Bearing are mounted on the shaft which supports the rotor and allow it to turn . Shown below is a motor’s cutaway view. It is mounted with a fan on the rotor’s shaft to cool down the motor when rotating.

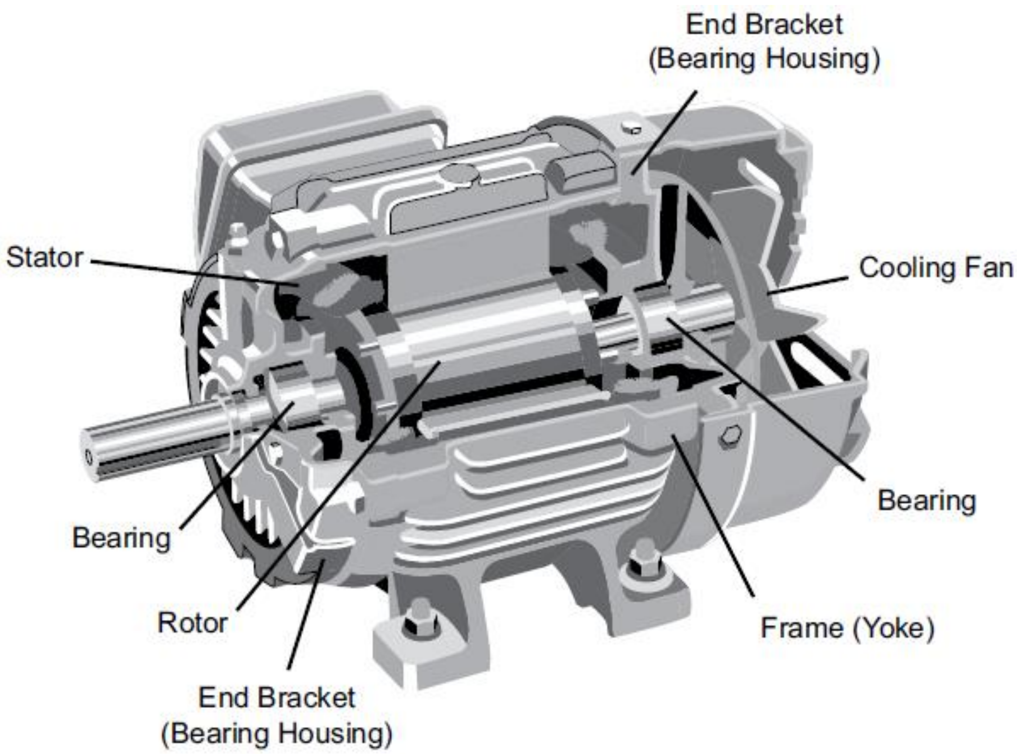


Fig.2.4 Cutaway View of an Induction Motor

2.1.2 Comparison of Induction Motors

There are many types and applications of an electric motor. The focus of this discussion is on those studied in the thesis. The focus is on the 3-Phase squirrel cage induction motor, which is an asynchronous motor.

AC machines are of various types and its depend on their structure and principle of operation. The synchronous machine has a distinguished feature which differs them from asynchronous as their rotor field is produced by a separately excited source. In synchronous machines, the rotor's movement is synchronized with the stator because the flux of rotor tend to aligns itself with stator field. The winding and rotor structure of an

Induction Motor can be viewed in Figure which shows the stator winding and rotor structure of an Induction Motor

There are many advantages associated with an Induction Motor as compared to other electric motors. The independency of brushes as in DC motor, makes an/induction Motor quite robust to work in harsh environment, and such maintenance is not required. AC Induction Motor is less expensive than that of other types of electric motor, mainly because it don't need any permanent magnet. These magnets associated in electric motor are also susceptible to high value of temperature and therefore make permanent magnet dependent motors less robust in harsh thermal environment and conditions. Another drawback is that inability to access or control rotor flux as its depends on permanent magnet. These problems with their affects make the choice easier for maintenance engineer as these parameters are required in situations like improving efficiency and power factor.

Despite of such serious advantages there are some disadvantages associated with Induction Machine. The existence of rotor winding in wound rotor makes Induction Motor sensitive to rotor electrical losses which effects and degrade the improvement in efficiency of these motors. Due to rotor winding, these motors require large space for dissipation of heat. On the other hand, this results in reduced size of motor. In permanent magnet motors the stator current doesn't need to produce rotor flux as the permanent magnets used in place of rotor winding or bars. This produces a complete utilization of stator current for the production of torque. Furthermore, the sinusoidal distribution of winding produce torque and current ripples.

2.1.3 Area of application

Induction motors are most widely used in industrial purposes as these motors are rugged and robust robust machines and can in harsh environment. These machines are used not only for general purpose but in hazardous locations and in severe environments as well. General purpose applications of an induction motor include pumps, centrifugal machines, presses, conveyors, machine tools, elevators, packaging equipment and others.

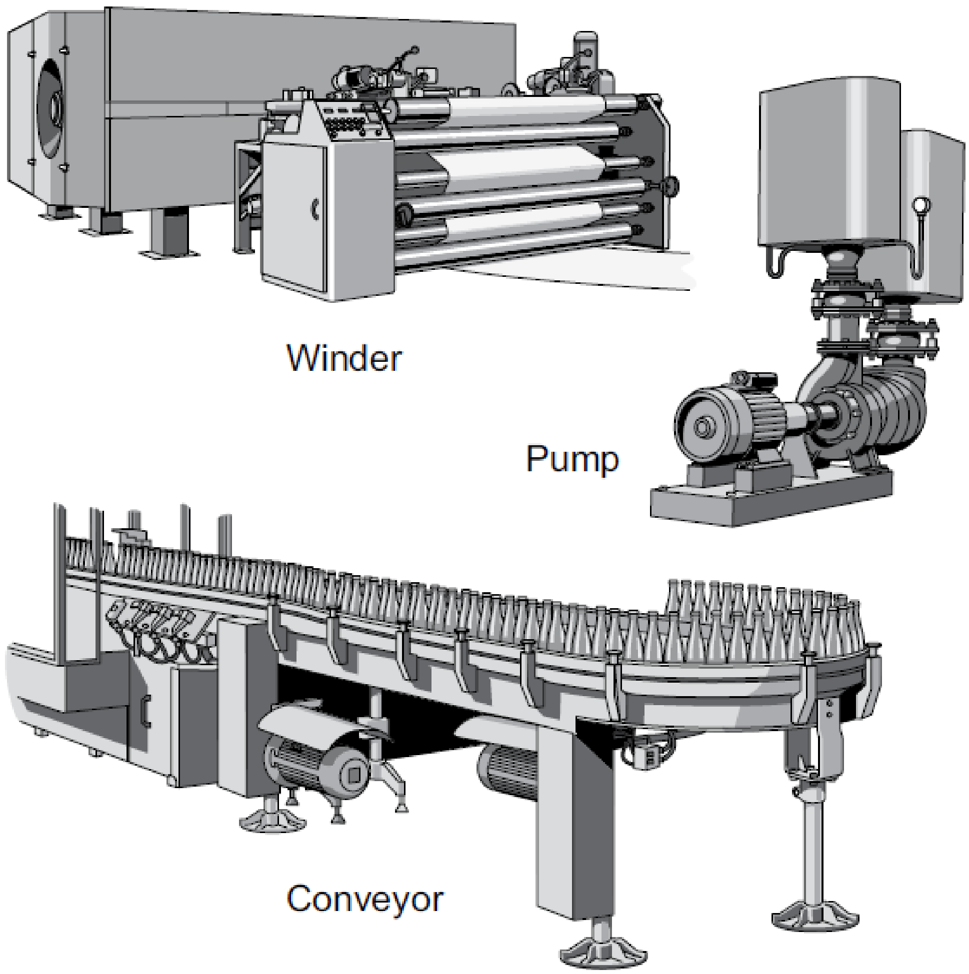


Fig.2.5 Applications of Induction Motor

Applications in hazardous locations include petrochemical and natural gas plants, whereas severe environment application of an induction motor include elevators, coal plant’s equipment & shredder. As an induction motor is reliable with good efficiency and requires low maintenance. A high margin of power, which is in megawatt(MW) is consumed by induction motors which satisfies the production need of process in an industry.

2.2 Induction Motor Operation

The principle of operation of an induction motor is based on the synchronous rotation of the magnetic field [10]. The stator is consist of three electrically shifted windings by 120º. Source of three phase AC is connected to the stator such that A1 and A2 are connected to phase A, B1 and B2 are connected to phase B and C1 and C2 are connected to phase C. the separation between each electrical phase is 120º. Here, A1, B1 and C1 are also 120º apart as can be seen in the figure given below.

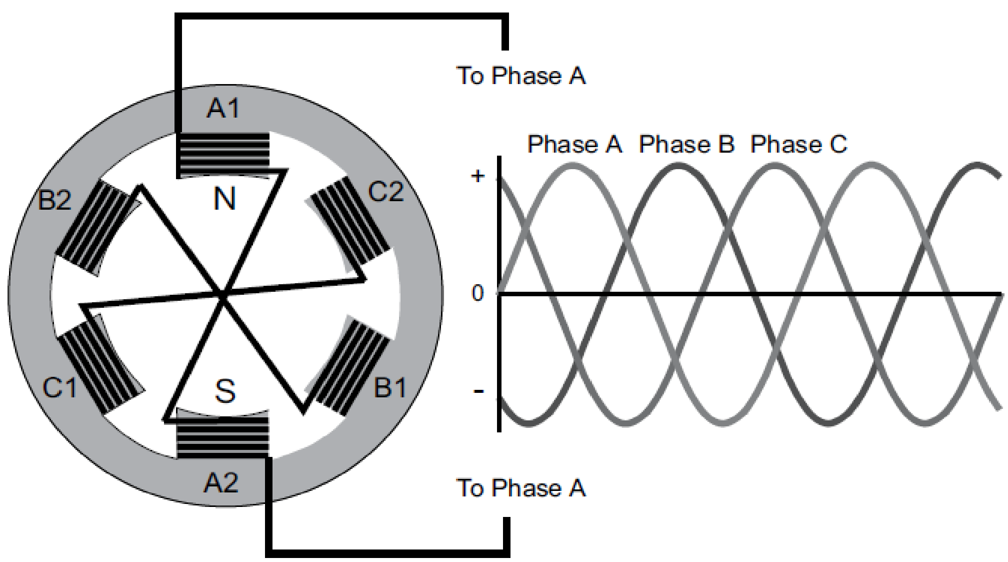


Fig.2.6 Three Phase Distribution in Stator

A three phase AC power is supplied to the windings. A current *I* when passes through a coil, inducing a magnetic field in the coil with two poles (north and south). The magnetic field *H* which is generated is proportional to the current *I*. The magnetic field *H* is characterized with a sinusoidal spatial distribution, and it inverts polarity by 180° in each period. As a result of three phase stator current I_A, I_B and I_C three magnetic fields H_A, H_B and H_C are generated. The three phase with a phase shift of 120° on stator currents of an induction motor generates a phase shift of 120° in magnetic fields. These magnetic fluxes are generated through the lamination of rotor and stator. The equivalent sum of these magnetic fields is the resultant magnetic field, at each time instant. The resultant magnetic field's rotation is shown in Fig.

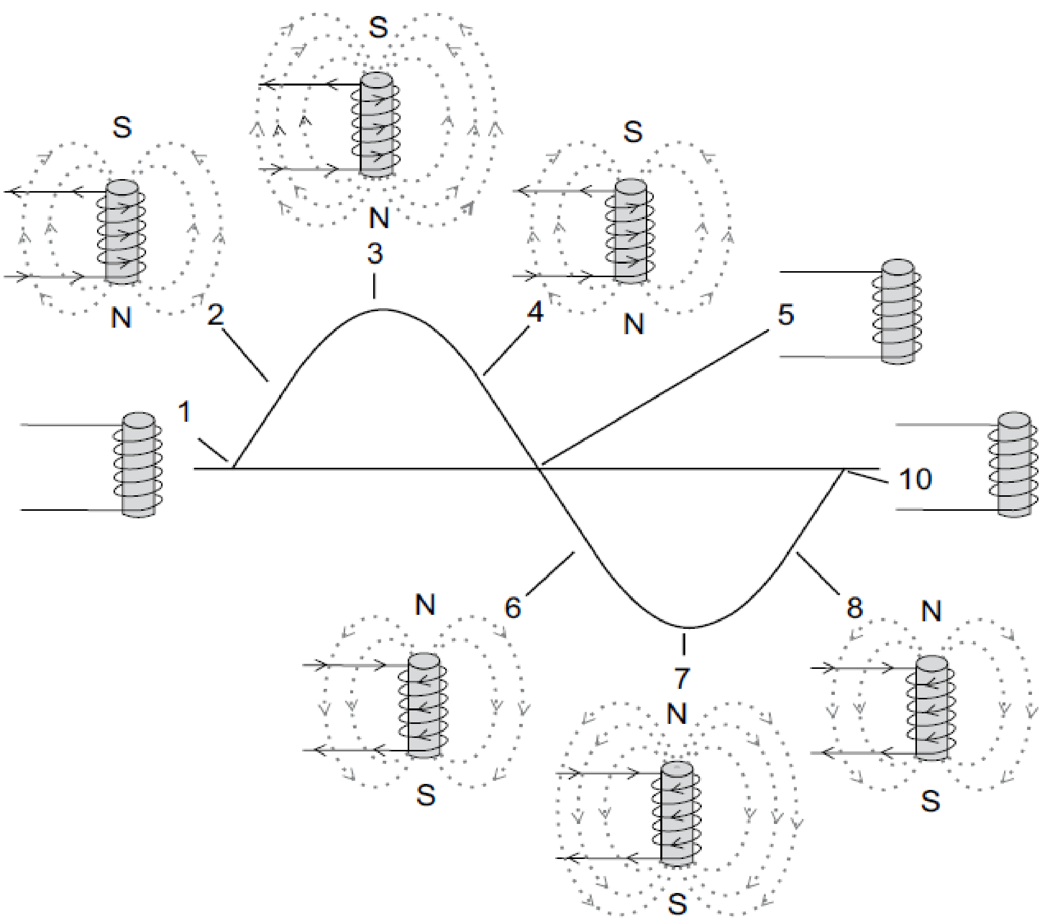


Fig.2.7 Magnetic Field Production

At time 1, no current flows through the coil so that no magnetic field is produced. At time 2, current is flows in positive direction and a magnetic field builds up. At time 3, current is flowing at it’s peak. At time 4, current starts decreasing hence magnetic field starts decreasing as well. In the positive half cycle the south pole is on the top and north at bottom. At time 5, no current flows so that no magnetic field is generated. At time 6, current is in negative half cycle and increasing negatively. The negative cycle is followed until time 7 and 8. The current then returns to zero and again no magnetic field is present. The negative half cycle contains the polarity such that the north pole is on the top and south at bottom.

For an AC source of 50 Hz, the process repeats itself 50 times.

This generated, rotating magnetic field induces electrical current in rotor of an induction motor that’s why we name this machine an induction machine. The induced current in the rotor bars generates magnetic field on it which is in opposite polarity of that of stator. As a result, the rotor which is movable, follows the magnetic field which is rotating as unlike poles attract each other.

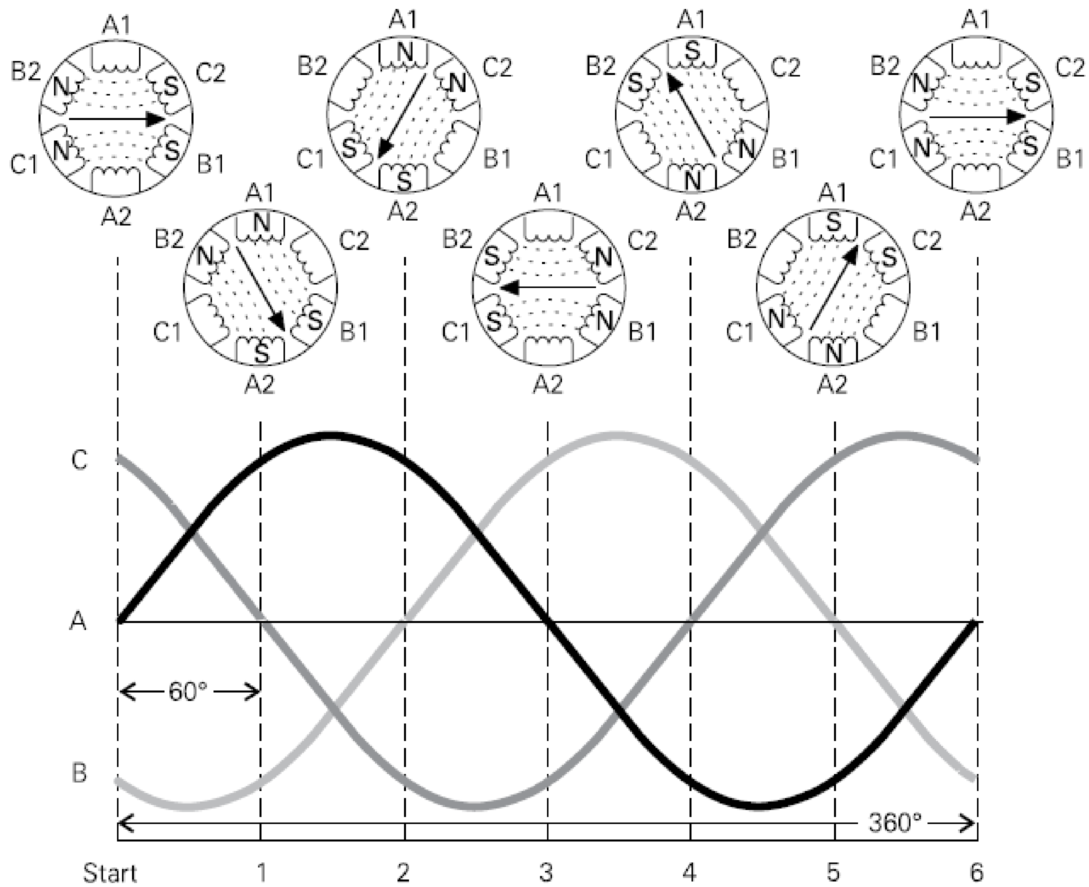


Fig.2.8 Rotating Rotor Bar with respect to magnetic field

The pole formation, as can be seen in the figure above, tends to move the rotor 360°which is complete revolution.

There is a difference between the speed of rotating magnetic field in stator and rotor rotating speed as rotor is following stator magnetic field. This difference is referred as “slip”. The required torque can be produced by a small slip speed which is required to produce rotor current that’s needed as the resistance of bar of rotor is very small[9]. The torque developed is proportional to the product of currents of rotor and stator.

2.3 Induction of Motors Parameter

2.3.1 Current and Voltage

An induction motor is supplied by a source of AC three-phase in which the phase shift between phase of currents is 120º or 2π/3 (electrical radians). The three phase currents are defined as[10].

$$i_a = I_m \cos(\omega t - \varnothing)$$
$$i_b = I_m \cos(\omega t - \varnothing - \frac{2\pi}{3})$$
$$i_c = I_m \cos(\omega t - \varnothing + \frac{2\pi}{3})$$

Where,

i_a is the current of phase A,

i_b is the current of phase B,

i_c is the current of phase C,

I_m is the peak fundamental frequency current of each phase current,

ω is the fundamental angular electrical frequency in (rad/s),

φ is the lag power factor angle in rad

and t is time in second.

Due to the symmetric phase-shift in phase current of 120º in the phase currents, the sum of three phase currents is zero(0) as given.

$$i_a + i_b + i_c = 0$$

The phase voltages are also shifted by 120º or 2π/3 rad. Considering, phase voltage, v_a as reference, the three phase voltages are defined as.

$$v_a = V_m \cos(\omega t)$$

$$v_b = V_m \cos(\omega t - \frac{2\pi}{3})$$

$$v_c = V_m \cos(\omega t + \frac{2\pi}{3}) = V_m \cos(\omega t - \frac{4\pi}{3})$$

where, v_a is the phase voltage of phase *A*,

v_b is the phase voltage of phase *B*,

v_c is the phase voltage of phase *C*, and

V_m is the peak fundamental frequency voltage of the phase voltage.

Similar to current the symmetric shift of 120º in the phase voltages, the sum of three phase voltages is zero as given by.

$$v_a + v_b + v_c = 0$$

2.3.2 Synchronous speed, asynchronous speed, and slip speed

The magnetic rotating field speed is the synchronous speed. For an induction motor with poles P, the synchronous speed in r/min is given as

$$n_{syn} = \frac{120 f}{P}$$

where,

f is the stator frequency in Hertz and

n_{syn} is the synchronous speed in r/min

However, the rotation of rotor is in asynchronous speed, which’s slight slower than the synchronous speed. This difference is called the slip speed as mention earlier and given as.

$$n_s = n_{syn} - n_{asyn}$$

where,

n_{asyn} is the asynchronous speed in r/min and

n_s is the slip speed in r/min.

Moreover, the slip speed can be defined in per unit system also, given as

$$s_{pu} = \frac{n_{syn} - n_{asyn}}{n_{syn}}$$

As mentioned earlier, the synchronous speed of an induction motor which is connected to a constant frequency sinusoidal ac power supply, it depends on the frequency and number of poles. The number of poles in an induction motor can be two, four, six, or eight, etc. Whereas, the rotor speed which is asynchronous depends not only on the frequency and poles but also on load torque. As a result, a high torque results in a high slip and a slow rotor speed. Hence, an induction motor which is connected to a sinusoidal power supply of constant frequency runs at one asynchronous speed and provides no mean of speed control. Consequently, an induction motor can run at a constant speed, and can be used in applications with fixed speed such as constant flow pumps, air compressors, fans, constant speed conveyor belts, mixers, and drills.

2.3.3 Torque

Torque is the force needed to turn a shaft times its arm length to the axis of rotation. The torque (T) is given by.

$$T = Fr$$

Where,

F is the force in Newtons (N) applied to a shaft and

r is the arm length of the force

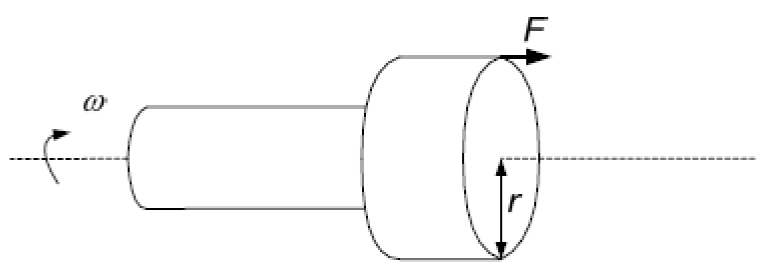


Fig.2.9 Torque applied to shaft

2.4 Speed Torque Analysis of an Induction motor

The torque in an induction motor can be produced by the interaction of the resultant air gap flux and *mmf* (magnetomotive force) of either the stator winding or the rotor [10]. Torque is produced on motor's shaft only if the rotor is running at lower speed lower than synchronous speed, i.e. if the slip speed is a not zero.

Different expressions can be used to compute the torque of an induction motor [11]

Following expression can be used to compute the air gap torque profile [12]

$$T = \frac{P}{2\sqrt{3}}[(i_a - i_b)\psi_{ca} - (i_c - i_a)\psi_{ab}]$$

A torque-speed characteristic curve of an induction motor is shown below

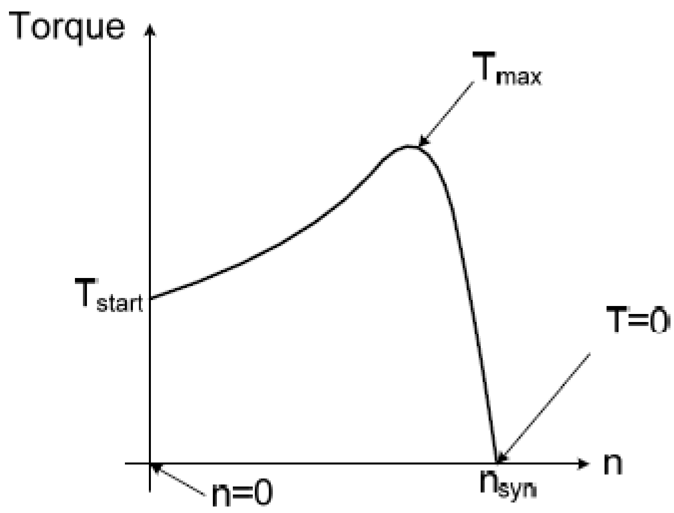


Fig.2.10 Induction Motor and its torque speed analysis

3-Phase induction motor's rotor is categorized on the basis of its construction. There are two types of rotor being manufactured:

i. Squirrel Cage Induction Motor

ii. Wound Rotor or Slip Ring Induction Motor

Both types of rotor has a stator which consist of a 3-phas-e balanced winding with distributed phase. Each phases are distributed mechanically in space by 120° from other windings of phase. The rise in magnetic field which is rotating when current flows, is due this space in windings.

In an Induction machine with rotor type of squirrel cage, the rotor is consist of longitudinal bar of electrical conductor bars. These bars are connected to circular rings of conductor and are short.

In an induction machine with rotor type of wound rotor, the rotor is consist of a 3-Phase balanced winding distributed equally as well. Number of poles are same as that on the stator winding.

Considering balanced 3-Phases , the analysis of a 3-Phase induction machine can be accomplished by analyzing any one of the phase. The per phase equivalent circuit of an induction machine is given below:

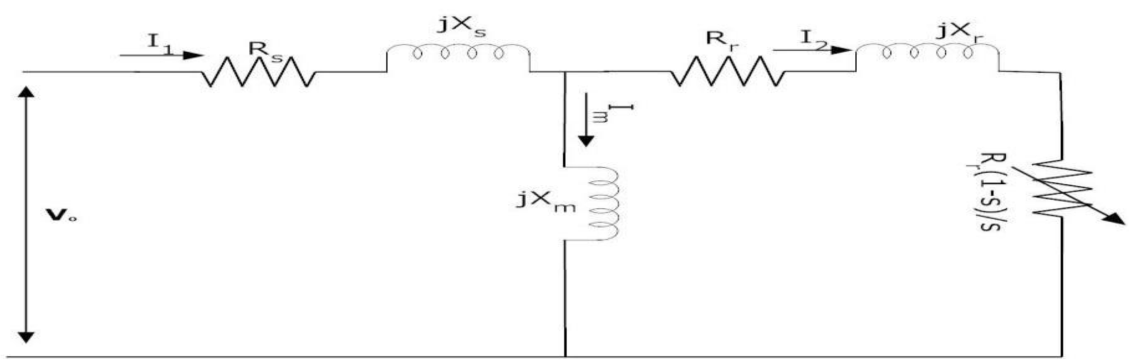


Fig.2.11 Per phase equivalent circuit

R_2 and X_2 are stator referred values of rotor resistance R_1 and rotor reactance X_1. Slip is defined by

$$s = \frac{(\omega_s - \omega_m)}{\omega_s}$$

where, ω_m is rotor speed and ω_s is synchronous speed.

Further, $\omega_s = \dfrac{120 f}{P}$

Where f is the frequency of the supply and is denoting number of poles.

As we know that, impedance drop in stator is generally negligible as compared to terminal voltage V, the simplified equivalent circuit can be shown as:

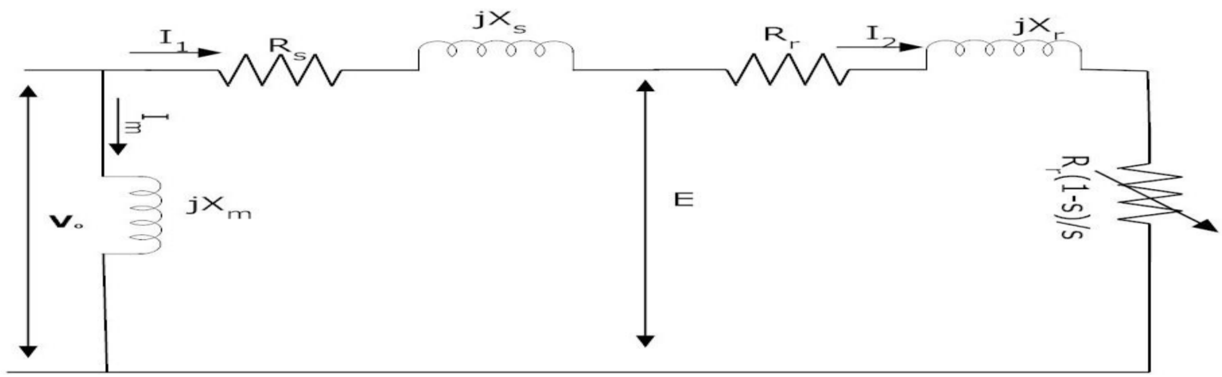


Fig.2.12 Per phase approximate equivalent circuit

Rotor current is given by,

$$I_2 = \frac{v_0}{[(\mathrm{R}_s + \frac{R_r}{s}) + \mathrm{j}(\mathrm{X}_s + \mathrm{X}_r]}$$

Power transferred to rotor (or air-gap power) is given by,

$$P_g = 3I_2 \frac{R_r}{S}$$

Rotor copper loss is given by,

$$P_{cu} = 3I_2 R_r$$

Electrical power converted into mechanical power

$$P_m = P_g - P_{cu} = 3I_2{}^2 R_r (\frac{1-s}{s})$$

Developed torque in motor is given by,

$$T = \frac{P_m}{\omega_m}$$

Thus,

$$T = \frac{3I_2{}^2 R_r}{s\omega_s}$$

By substituting the value of I2 equation above, we get,

$$T = \frac{\frac{3V_0{}^2 R_r}{s}}{\omega_s[(\mathrm{R}_s + \frac{R_r}{s})^2 + (\mathrm{X}_s + \mathrm{X}_r)^2]}$$

By differentiating 'T' with respect to s we get the slip for maximum torque

$$s_m = \pm \frac{R_r}{\sqrt{[\mathrm{R}_s{}^2 + (\mathrm{X}_s + \mathrm{X}_r)^2]}}$$

By substituting the value of Sm in T we get maximum torque,

$$T_{\max} = \frac{3V_0^2}{2\omega_s[\mathrm{R}_r \pm \sqrt{(\mathrm{R}_r{}^2 + (X_s + X_r)^2)}]}$$

CHAPTER 3. Modeling of Induction Motor with Broken Rotor Bar

A dynamic model of an induction motor is developed to investigate the impacts of broken rotor bar and to compare the generated signal via hardware setup with the models signal. Consequently, the level of difference or similarity can be achieved so that a model with precision could be obtained for such faults and other faults related to an Induction motor. The modeling is a powerful tool for engineers, researchers and scientist. Beside economical benefits, the need of manpower with such training is hard to find. Further the cost of manpower and that of motor makes such work harder and complex, as a simple experimental setup consumes a lot more time than a model in software which is economical as well. The breakage of rotor bar in a model is somehow easier than that of physically breaking it in an experimental setup. In MATLAB it's the matter of understanding and implementing formulas and adding new blocks. It could be tough but not that much that in an experimental setup. Breaking such bars need manual dismantling, breaking the bars by mean of drilling or other method than installing the motor again. Repetition may be needed if number of broken rotor bar are dynamic. Sometimes, the motor of high rating and power are huge and need special equipments to handle them. The model on the other hand is flexible. The parameters of the machines could be change, the number of broken rotor bar can be varied, the load conditions are handy and other.

3.1 Introduction

A model which should be reliable and realistic for accurate prediction and simulation of fault is needed. The designed model must be dynamic to execute the dynamic characteristics and should be able to simulate healthy motor and defective motor as well. The simulated desired current stator should be able to reflect broken rotor bar's impact and its influence. The model designed should be easy to understand, manipulate and should be dynamic and accessible. Different approaches have used for the development of dynamic model of an Induction motor[13][14]. A mathematical model is designed is this chapter then broken rotor bar is modeled in the design specifically, which is done by unbalancing the rotor resistance.

For engineers MATLAB is a powerful tool to implement and simulate and it is easy to use as well[15]. The motor's model is simulated in MATLAB. Whereas, the simulations result are analyzed to study the broken rotor bars and it's impact on the motor and current. The results of the modeled motor are compared with the experimental results, so that the validation of the model could be accomplished.

3.2 Mathematical Modeling

The stator and rotor of an induction motor are coupled written in magnetically. An induction motor in matrix notation can be written in terms of voltage, in *abc* frame of reference as[22]

$$v_s^{abc} = r_s i_s^{abc} + \frac{d\lambda_s^{abc}}{dt}$$

$$v_r^{abc} = r_r i_r^{abc} + \frac{d\lambda_r^{abc}}{dt}$$

and,

$$\lambda_s^{abc} = L_{ss}^{abc} i_s^{abc} + L_{sr}^{abc} i_r^{abc}$$

$$\lambda_r^{abc} = L_{rr}^{abc} i_r^{abc} + L_{rs}^{abc} i_s^{abc}$$

Where, $v_s^{abc}, i_s^{abc}, \lambda_s^{abc}, v_r^{abc}, i_r^{abc}$ and λ_r^{abc} represents voltages, current and flux linkage in stator or rotor respectively. In the equations above superscript *abc* represents three phase and subscript s and r represents rotor and stator. The notation r_s and r_r are the stator and rotor resistance which is equivalent of single phase. The resistance in each phase is considered equal in ideal induction motor.

$$r_{s,r} = \begin{bmatrix} r_{s,r} & 0 & 0 \\ 0 & r_{s,r} & 0 \\ 0 & 0 & r_{s,r} \end{bmatrix}$$

L_{ss}^{abc} and L_{rr}^{abc} notifies the self inductance of stator and rotor windings, respectively. Whereas, L_{sr}^{abc} and L_{rs}^{abc} are the stator to rotor and rotor to stator mutual inductances, respectively.

The sub-matrices of self inductances are

$$L_{ss}^{abc} = \begin{bmatrix} L_{ls} + L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ls} + L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ls} + L_{ss} \end{bmatrix}$$

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr} + L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{lr} + L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{lr} + L_{rs} \end{bmatrix}$$

L_{ls} is the stator winding leakage inductance and L_{lr} is the rotor winding leakage resistance.

The stator to rotor and rotor to stator winding mutual inductances are

$$L_{sr}^{abc} = \left[L_{rs}^{abc} \right]^T = L_{sr} \begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ c\cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r \end{bmatrix}$$

In the equation above L_{sr} and L_{rs} is the peak value stator to rotor and rotor to stator mutual inductances. θ_r is the electrical angle between stator and rotor. It is called rotor angle as rotor is the rotating only not stator.

In the equations above rotor and stator voltages equations are related by mean of mutual inductance and is a function of rotor angle and varies with the variance of rotor position and time.

As mathematical transformations are used to study the rotating electric machinery because voltage equations are time-varying.

Park's transformation is used to transform *abc* to *qd0* frame of reference with θ is the stator transformation angle between *q*-axis of arbitrary frame of reference and *a*-axis of stationary stator winding

$$\theta(t) = \int_0^t \omega(\zeta)d\zeta + \theta(0)$$

The rotor angle may expressed as

$$\theta_r(t) = \int_0^t \omega_r(\zeta)d\zeta + \theta_r(0)$$

Here , $\theta(0)$ and $\theta_r(0)$ are the initial angular values of transformation angle and rotor angle, respectively.

State variable transformation can be written as,

$$\mathrm{f}_{qd0}(\theta) = \mathrm{T}_{qd0}(\theta)\,\mathrm{f}_{abc}$$

Here the elements of column vectors f_{qd0} and f_{abc} can be flux linkages, current or phase voltages. T_{qd0} is the transformation matrix which is

$$\mathrm{T}_{qd0}(\theta) = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

The inverse transformation equation can be written as

$$f_{abc} = T_{qd0}(\theta)^{-1} f_{qd0}$$

Where ,

$$T_{qd0}(\theta)^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \end{bmatrix}$$

Transformation of machine voltage and flux linkage equation from *abc* to *dq0* reference of frame by applying transformation function is done by

$$v_s^{qd0} = T_{qd0}(\theta) r_s T_{qd0}^{-1}(\theta)\, \mathrm{i}_s^{qd0} + T_{qd0}(\theta) \frac{d\left[T_{qd0}^{-1}(\theta)\lambda_s^{qd0}\right]}{dt}$$

$$v_r^{qd0} = T_{qd0}(\theta-\theta_r) r_r T_{qd0}^{-1}(\theta-\theta_r)\, \mathrm{i}_r^{qd0} + T_{qd0}(\theta-\theta_r) \frac{d\left[T_{qd0}^{-1}(\theta-\theta_r)\lambda_r^{qd0}\right]}{dt}$$

Substituting the matrices of transformation and rearranging we get,

$$v_s^{qd0} = r_s^{qd0} i_s^{qd0} + E_s^{qd0} + \frac{d\lambda_s^{qd0}}{dt}$$

$$v_r^{qd0} = r_r^{qd0} i_r^{qd0} + E_r^{qd0} + \frac{d\lambda_r^{qd0}}{dt}$$

where,

$$E_s^{qdo} = \omega \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_s^{qd0}$$

$$E_r^{qdo} = (\omega - \omega_r) \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \lambda_r^{qd0}$$

and,

$$\omega = \frac{d\theta}{dt}, \omega_r = \frac{d(\theta_r)}{dt}$$

and,

$$r_s^{qd0} = r_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, r_r^{qd0} = r_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The $\frac{d\lambda}{dt}$ term denotes the rate of exchange of magnetic field between windings.

The application of park's transformation in the equations of flux linkage will be such that

$$\lambda_s^{qd0} = T_{qd0}(\theta)(\mathrm{L}_{ss}^{abc}\, i_s^{abc} + L_{sr}^{abc} i_r^{abc})$$

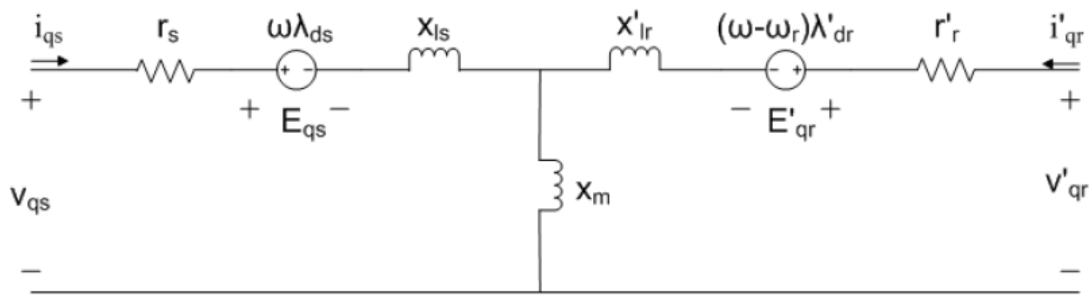
and,

$$\lambda_r^{qd0} = T_{qd0}(\theta)(\mathrm{L}_{rr}^{abc}\, i_r^{abc} + L_{rs}^{abc} i_s^{abc})$$

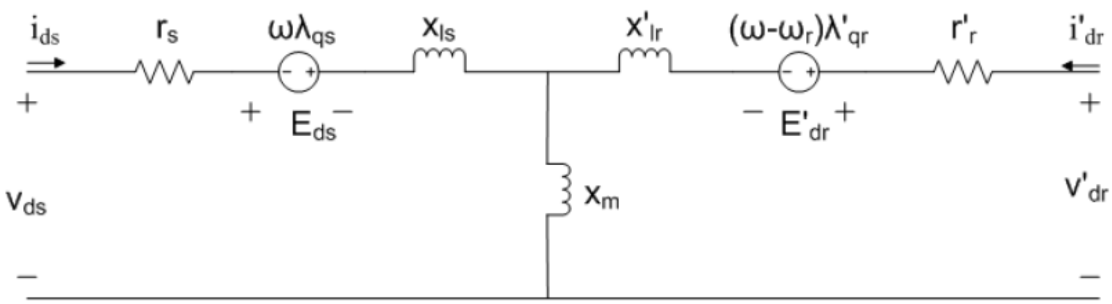
The final matrix by arrangement of equations we get,

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \\ \lambda_{qr}^{'} \\ \lambda_{dr}^{'} \\ \lambda_{0r}^{'} \end{bmatrix} = \begin{bmatrix} L_{ls}+L_m & 0 & 0 & L_m & 0 & 0 \\ 0 & L_{ls}+L_m & 0 & 0 & L_m & 0 \\ 0 & 0 & L_{ls} & 0 & 0 & 0 \\ L_m & 0 & 0 & L_{lr}^{'}+L_m & 0 & 0 \\ 0 & L_m & 0 & 0 & L_{lr}^{'}+L_m & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{lr}^{'} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i_{qr}^{'} \\ i_{dr}^{'} \\ i_{0r}^{'} \end{bmatrix}$$

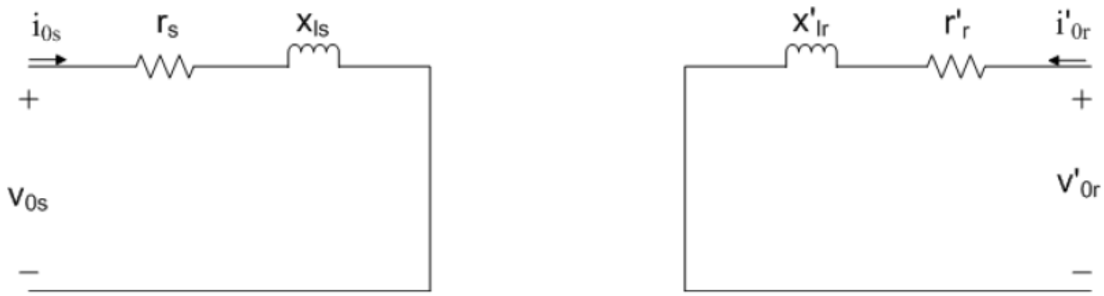
The equivalent circuit of an induction machine is shown below with arbitrary frame of reference.



a- q-axis



b- d-axis



c- zero sequence

Fig. 2.13. Equivalent circuit of an induction motor in arbitrary frame of reference

As the induction motor is symmetrical machine, any fault can effect the symmetry of the machine. Broken bar effects the resistance of the machine which consequently impacts magnetic field between rotor and stator. The alteration in rotor resistance will be such that,

$$r_r^* = \begin{bmatrix} (r_r + \Delta r_{ra}) & 0 & 0 \\ 0 & (r_r + \Delta r_{ra}) & 0 \\ 0 & 0 & (r_r + \Delta r_{ra}) \end{bmatrix}$$

The change in resistance due to broken rotor bar is as[5],

$$\Delta r_{ra,b,c} = \frac{3n_{bb}}{N_b - 3n_{bb}} r_r$$

Here, n_{bb} and N_b are the number of broken rotor bar and total number of bars, respectively.

The increment Δr can be represented as

$$\Delta r = r_r^* - r_r = \frac{3n_{bb}}{N_b - 3n_{bb}} r_r$$

A general model of a three phase induction motor is described with computer implementation [16] in SIMULINK is shown below in sub-model's form The sub-model to implement three phase into two axes transformation (3/2) of stator voltages, currents calculation is shown in equation (1)

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \qquad (1)$$

V_{as} V_{bs} V_{cs} are three phase stator voltages whereas, V_{ds} and V_{qs} is transformation of stator voltage in two axes transformation of vector V_s.

Currents equations of three phase induction motor in two axes stator reference frame is given in equation (2). Where, the values of inductance and resistance of rotor and stator and mutual inductance is kept constant where as they might be slightly change in real time motor mechanism.

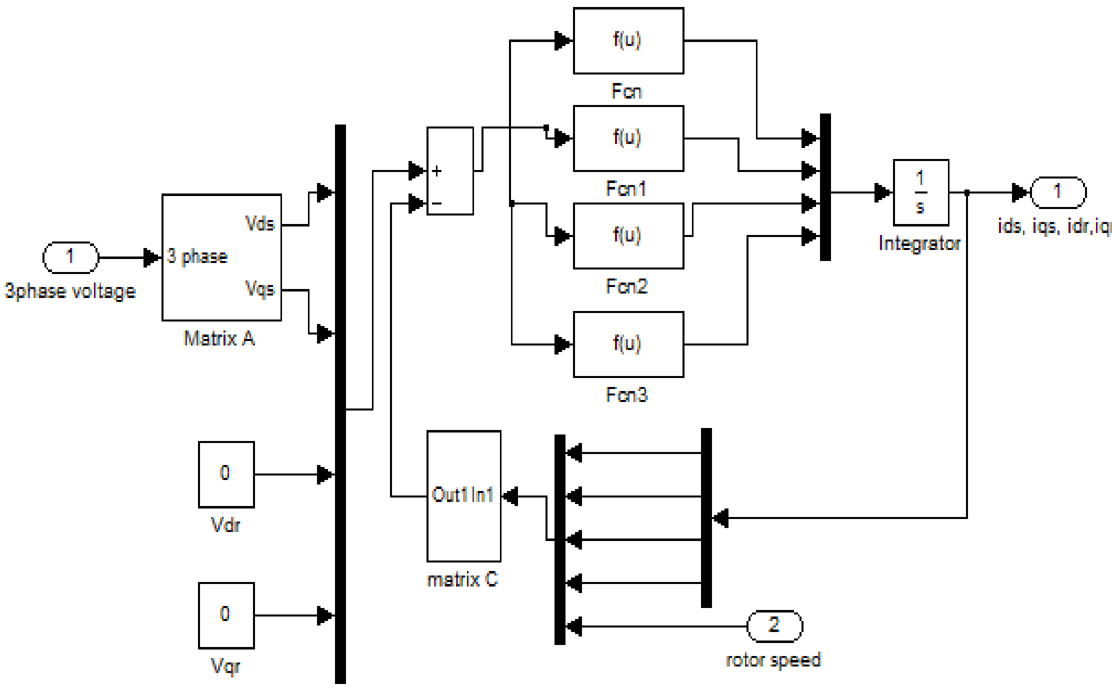


Fig. 3.1. Electrical model of an induction motor in SIMULINK

$$I = \int_{\tau=0}^{t} \{L^{-1} \times (V - R \times I)\} d\tau \qquad (2)$$

Where,

$$I = \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}, \mathrm{L} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}, \mathrm{V} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix},$$

$$
\mathrm{R} = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & \frac{P}{2}\omega_0 L_m & R_s & \frac{P}{2}\omega_0 L_r \\ -\frac{P}{2}\omega_0 L_m & 0 & -\frac{P}{2}\omega_0 L_r & R_r \end{bmatrix}
$$

Implementation of equation (2) is such that the input is $\begin{bmatrix} V_{as} & V_{bs} & V_{cs} \end{bmatrix}$ and $\begin{bmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr} \end{bmatrix}$ are the output current of stator and rotor from the model shown in figure 2. Here, $V_{dr} = 0$ and $V_{qr} = 0$ due to the short circuited winding of cage rotor.

Torque sub-model of the motor is implemented using equation (3) and mechanical sub-model using equation(4)

$$
T = \frac{PL_m}{3}\left(i_{dr} i_{qs} - i_{qr} i_{ds}\right) \tag{3}
$$

$$
\omega_0 = \int_{\tau=0}^{t} \frac{T - T_L}{J}\, d\tau \tag{4}
$$

The torque and mechanical sub-model is implemented as shown in figure 3 and figure 4 respectively.

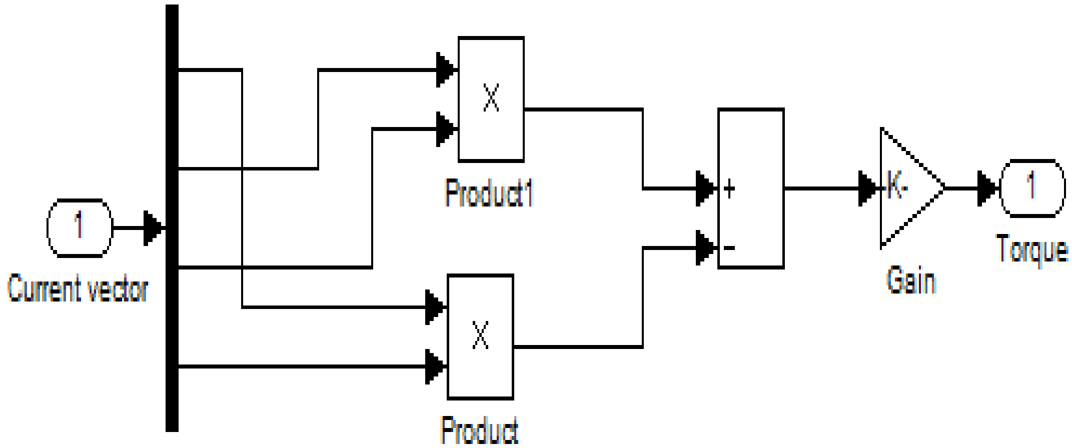


Fig. 3.2. Torque sub-model

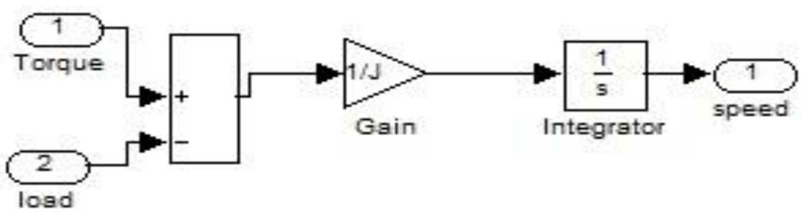


Fig. 3.3. Mechanical sub-model

Output sub-model of the stator current of three phase induction motor is calculated using equation (5) and could be implemented using ‘Fcn’ block of SIMULINK.

$$\left|i_s\right| = \frac{2}{3}\sqrt{\left(i_{ds}^{e}\right)^2 + \left(i_{qs}^{e}\right)^2} \qquad (5)$$

The complete block diagram of three phase induction motor is using equations (1-5) is given in figure 5.

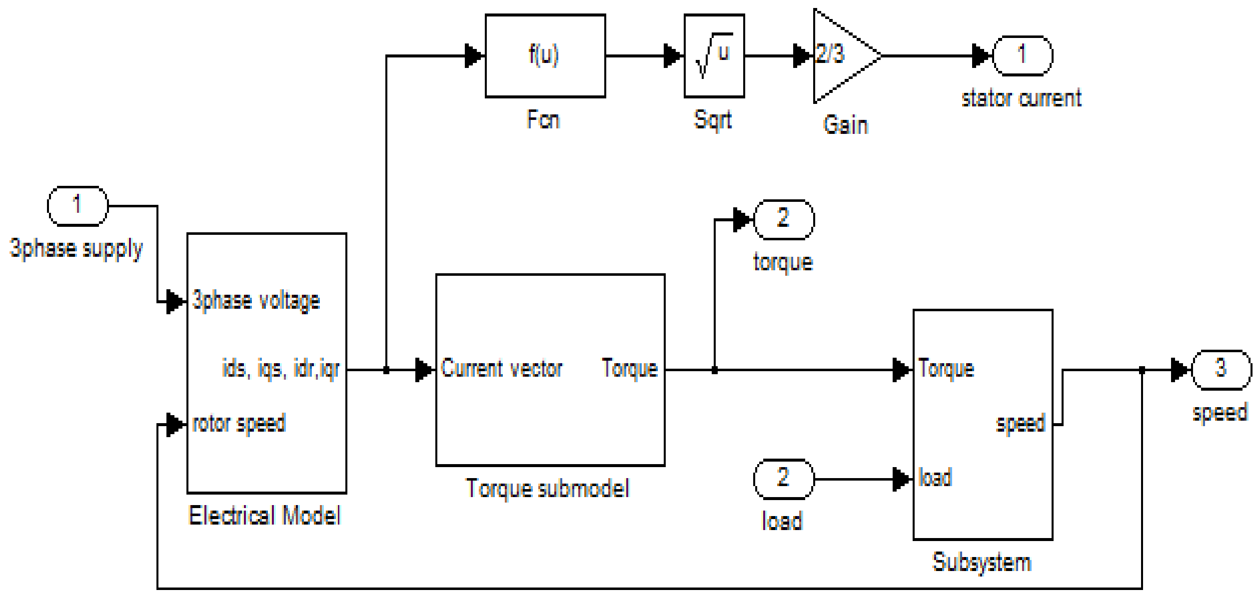


Fig. 3.4. Induction motor

A three phase sinusoidal voltage generation is achieved using equation (6) as |V| is the amplitude of the terminal voltage, Q is initial phase angle and w is the supply frequency

$$\begin{cases} V_{as} = |V| Cos(\omega t + \theta) \\ V_{bs} = |V| Cos\left(\omega t - \frac{2\pi}{3} + \theta\right) \\ V_{cs} = |V| Cos\left(\omega t + \frac{2\pi}{3} + \theta\right) \end{cases} \qquad (6)$$

Three phase voltage model is shown in

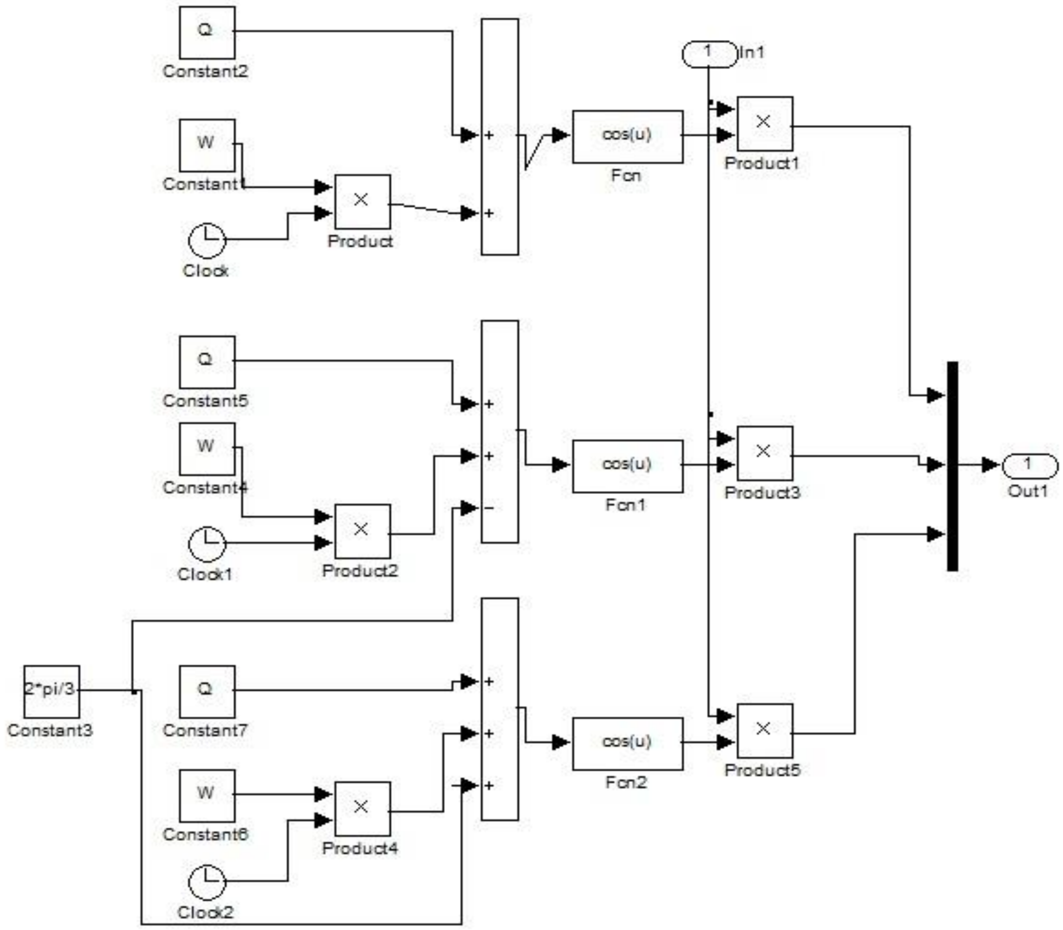


fig.3.6

Fig. 3.5. Three phase supply sub-model

The terminal voltage is given by equation (7) due to the supply cable's voltage drop and it's implementation is shown in figure 7.

$$|V| = E - R_c |i_s| \quad (7)$$

Where E is supply voltage and R_c is cable resistance

The complete presentation of power supply for a three phase induction model is shown in figure 8 using equation (6) and (7).

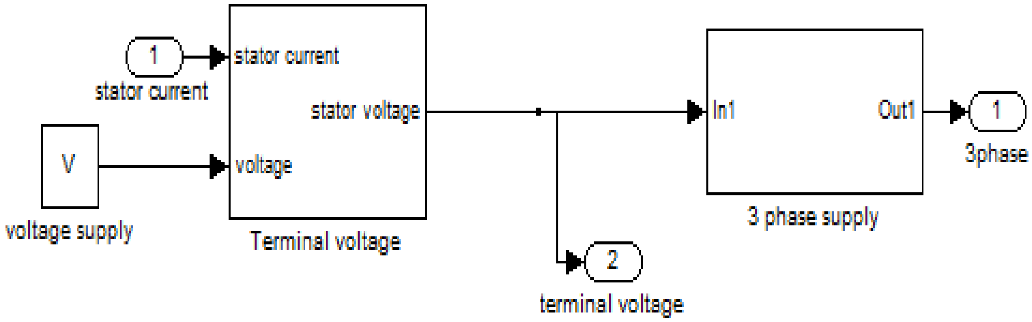


Fig. 3.6. Power supply sub-model

Using power supply sub-model and induction motor sub-model a complete representation of the system is implemented as shown in fig.3.9.

The XY-graph block is used to get the torque/speed characteristic of the three phase induction motor

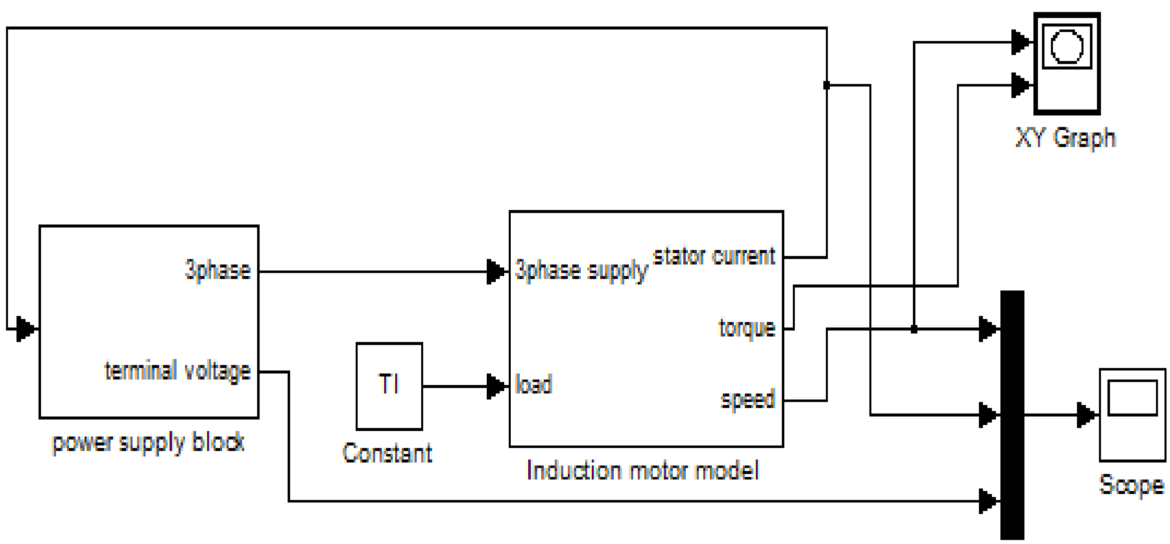


Fig. 3.7. Induction motor model

Broken rotor bar faults occurred generally in induction motor due to different reasons some of them are thermal stress, magnetic tension, bearing failure, dynamic pressure and load variation [17], [18]. The present work is a comparative analysis of a healthy and a faulty motor (broken rotor bar fault). Considering dynamic resistance of the rotor as its depending upon the number of bars broken. There are several methods and models to identify the resistance of broken rotor bar, we are considering one of the model[19] to identify the value of that changed resistance as the rotor broke and the value of that resistance is change as number of broken rotor bars change.

$$\Delta \mathrm{R} = \frac{n_b}{\frac{N}{3} - n_b} R_r \tag{8}$$

In the equation above R_r is the rotor resistance when no bar is broken, N is the number of total bars in rotor, n_b is the number of rotor bars broken in rotor. This change in rotor resistance is used to simulate the model of healthy and faulty rotor of an induction machine.

CHAPTER 4. Implementation on Hardware

4.1 Introduction

Implementation of modeled motor in hardware setup is done using a mechanical structure on which motor of 1H.P is mounted and the readings are extracted using an electronics circuit which will be explained in this chapter later. Further, these reading are evaluated and analyzed the designed model so that impacts of different scenarios could be visualized and discussed. First, the healthy motor with no bar broken is demonstrated and illustrated. Then, rotor bar are broken so that further analysis could be performed. In the end, a comparison is made between different fault conditions and presented.

The current extraction performed using a hardware setup in the laboratory. This chapter include following steps.

- To illustrate Data acquisition from motor without disturbing its operation and at a sampling rate which could visualize current peaks changing in ms.
- The motor and its parameter so that motor selection could be and its impact.
- Fault injection in motor.
- Overall hardware setup formation.

4.2Components

4.2.1Arduino

There are several methods to extract the current from a system. The method adopted is to use the analog port of Arduino MEGA 2560. As it is simple, reliable and portable device, it can be used to get the current spectrum of any device at the desired level of sampling. Arduino Omega 2560 is programmed to get the current with sampling frequency adopted at 1Khz, 10Khz and 20Khz and chose the suitable one to analyze the effects of fault on spectrum.

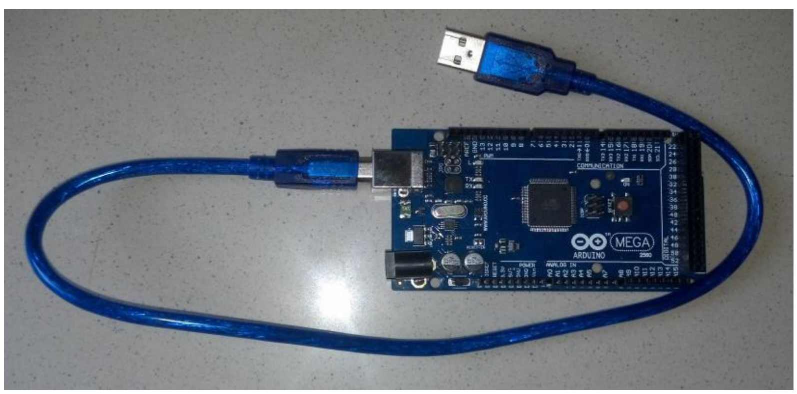


Fig. 4.1. Arduino Mega 2560 Controller

Analog port1 is used to get the analog data from hall effect sensor 712S with a range up to 20A.

4.2.2 Hall effect sensor :

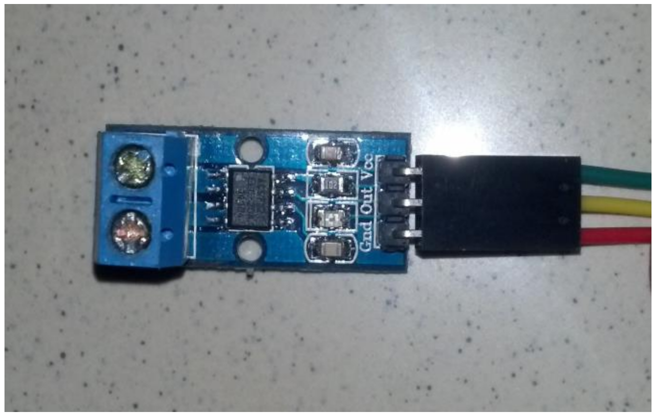


Fig. 4.2. Hall Effect Sensor Module

Hall effect sensor which is a transducer varies it's output voltage in response to a magnetic field. Hall effect sensors are used for different applications like switching, positioning, speed detection, and current sensing applications. It has a bandwidth of 50KHz with error in accuracy of about 1.5%. It is an easy to implement module for sensing of AC or DC currents.

4.2.3 Three Phase Induction Motor:

A single HP SIEMENS three phase induction motor is used to perform the analysis using a mechanical structure to mechanically fix the motor so that vibration and safety issues could be resolved. The motor has 2 poles and 14 rotor bars to induce the field in it.

Fig. 4.3 Induction Motor’s Rotor and Stator

4.3 Connectivity

Hall effect sensor after connected with Arduino Omega 2560, using lines of command can extract the current from the device at desired frequency so that close analysis could be performed. Analog current from hall effect sensor is adopted through Arduino then transmitted to the computer via serial port. Serially received current is then saved and analyzed in MATLAB. The Arduino software can be used to read the signal serially through Arduino and can easily stored way the data serially through serial port and saves the incoming data into .txt format easily. The can be stored and then analyzed for experiments.

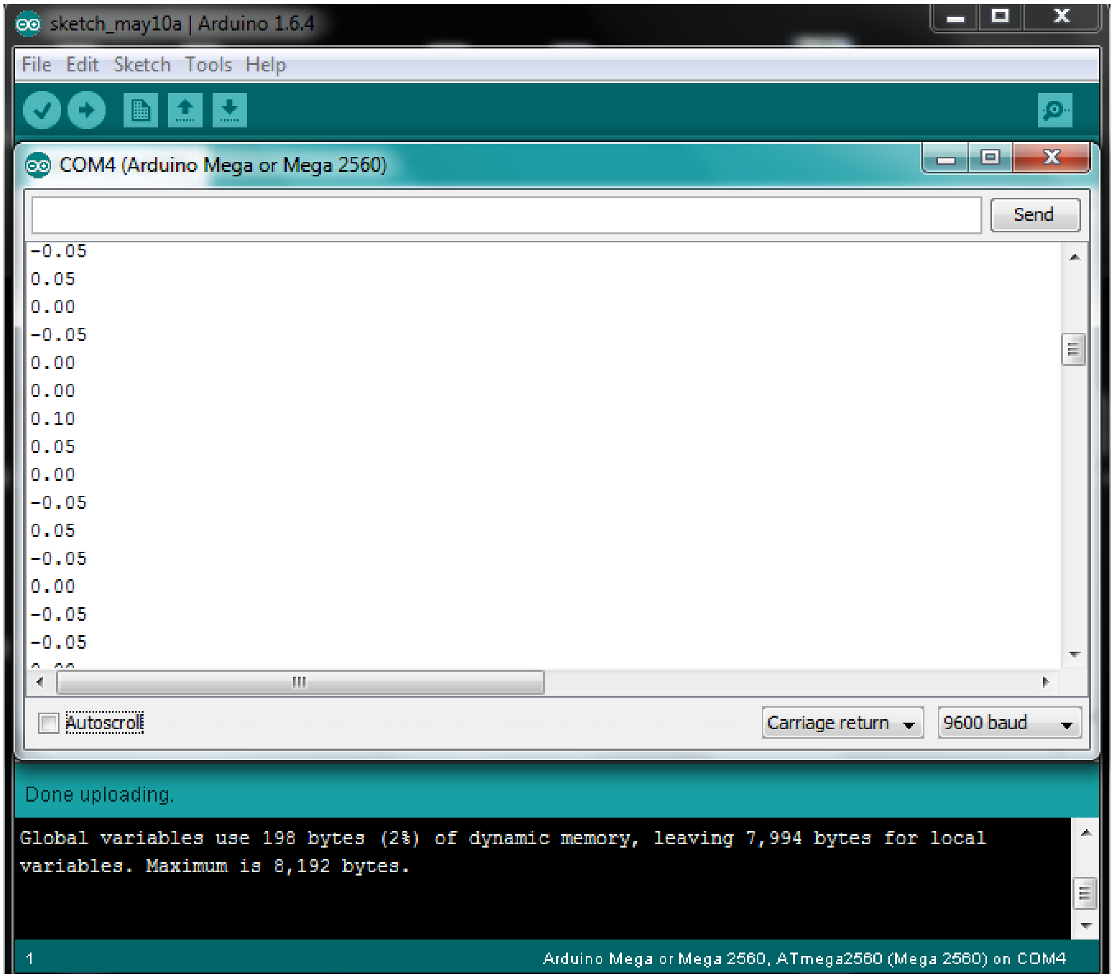


Fig. 4.4. Data Acquisition From Motor

The text(.txt) file can be loaded into the MATLAB using simple line of commands. Once the data is uploaded into the MATLAB, the experiment on different scales can be performed. MATLAB provides a dynamic setup to analyze the data using different tools and techniques. Frequency and time domain analysis are then performed on the basis of these readings to find the difference in response on different fault conditions.

4.4 Fault Injection in the Rotor:

Fault in induction motor is injected by mean of drilling the rotor bar in such manners that only bar should be broken and no other part of that rotor should be affected. It is performed in the mechanical workshop where a drilling machine is used to drill the bar to break it and increasing the number of broken bar. In some cases the size of drilling bit can matter so the selection of the bit is an important factor as in case of smaller size the bar may not break completely and can effect the results and in case of bigger size the surrounded area of bar i.e iron core may be effected and can cause a change in current parameters.

Fig. 4.5. Fault Injection by Mean of Drilling the Rotor Bar

4.5 Effects of Injected faults

There can be several effects occurred while motor is operating under fault condition whereas, it depends on the level of fault and it type as the phase imbalance, bearing fault, mechanical and broken rotor bar, all of these faults have different impacts on operation.

4.5.1 Impact on Current

The main consequence of any fault variates the current. This variation could be from mA to A. The change in current spectrum and its pattern is highly investigated and still under consideration in condition monitoring and fault finding techniques. The change in current occurred after breaking the rotor's bar and this variation is increased with respect to the number of broken rotor bar.

4.5.2 Impact on leakage flux

As the number of broken rotor bar broke the leakage flux at a particular frequency was increased. The flux which has to be induced in the bar of the rotor is broken is leaked out and was sensed using the ACS712 "Hall Effect" sensor which Is used to sense the current as well. The reading indicates the rise in peaks of the flux.

4.5.3 Impact on Sound

The change in sound was observed. When the number of broken rotor's bar increased the sound of the motor become weird proportionally. The loudness of the sound could be experienced as normally in industry the maintenance technicians observe the sound of the motor closely and report the engineer if any change in sound is heard, it is the most traditional way on the working floor to identify that motor or it's operation has some defect. The sound which was actually the noise of the motor is so observed because the electromagnetic induction on rotor's bar was not uniformly distributed and due to that humming of the magnetic field the sound became louder.

4.5.4 Impact on vibration

Vibration analysis is performed on an induction motor in to monitor the condition on an induction motor in several literatures. As the motor was becoming faulty the vibrational parameters were observed as well. With the increase in number of broken rotor bar, the vibration of the motor was increasing as it was smooth when there was no fault. In presence of vibration sensors, a close look on the vibration and it's parameter could be analyzed. Whereas, a person can normally experience the rise in vibration as the motor becomes more defected.

CHAPTER 5. Results of Simulations & Experiments

5.1 Introduction

The induction motor chosen for the simulation studies has the following parameters:

Type: three-phase, 2-pole, wye-connected, induction motor with,

R_s=0.088 Ω/ph R_r=0.187 Ω/ph

L_s=0.0425 Ω/ph L_m=0.04 Ω/ph

L_r=0.0425 Ω/ph J=0.4 kg m^2

J_L=0.4 kg m^2

The transient operation of the three phase induction motor is illustrated using the simulation study of direct-on-line starting. At t=0, the motor, previously de-energized and at standstill connected to a 380 V, 50 Hz three-phase power supply through a cable.

Motor's stator current reflects the overall condition of an induction motor by representing frequency parameters of that current signal. Thus, fault diagnosis by mean of stator current spectrum investigation[20] for a healthy and a faulty motor is done.

Since, in an induction motor mechanical angular speed of a rotor is less than the rotating electrical fiend of a stator. Therefore, the slip is always less than '1' in running condition.

$$S = \frac{\omega_{sm} - \omega_{rm}}{\omega_{sm}} \tag{9}$$

As fault become more severe there is an arise in higher order harmonics which is clearly understandable that rotor bar is defected and the number of defected bars can be estimated by analyzing the overall response of stator current spectrum. As the number of broken rotor bars increase, current's flow increases which in turn dissipated in the form of heat which is not only affecting the efficiency of motor but damages the winding as well.

Further, Torque-Speed curve can be a supportive parameter which will be altered as per the number of broken rotor bar.

A speed-torque curve of an induction motor with overall healthy condition and no bar broken can be visualize that the traditional speed –torque curve is attained.

As the number of broken bar increased a change in speed-torque curve can be observed. The speed-torque curve of induction motor with 5 broken bar can be visualize to see the drastic change in the response

Current samples obtained from the model described above are used to identify the response and spectrum changes between healthy and faulty motor with one or more than one broken rotor bars. As shown , the increase in number of broken rotor bar is increasing the spectral changes in the stator current spectrum. As the number of broken bar increase the speed-torque curve shows the effect on speed which is stabilizing with certain perturbations. Whereas, the current response or difference between rated and operational current can be observe to get the clear understanding of number of broken rotor bar.

By comparing healthy motor with a faulty, we can understand that in a healthy motor speed-torque curve is showing smoothness as the rotor gets the speed. Whereas, in a faulty motor with broken rotor bars, the speed-torque curve is in continuous variation as can be visualized.

5.2 Results of Healthy Motor in Frequency Domain

Frequency domain is one the most important tool to analyze and examine the signal and its parameter. Sometimes, time domain analysis can be used to fulfill the analysis need. Whereas, in close change frequency domain analysis is used and variation in different spectral can be observed.

5.2.1 Simulation Results

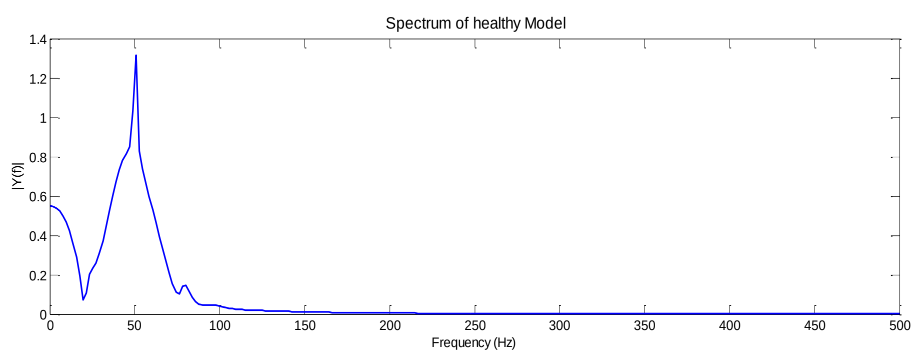


Fig. 5.1. Current Spectrum of Healthy Model

The simulation of the motor with none bar broken injected can be visualize. The peak value is 1.3 but the value may change for the motor with similar power but other parametric change like rotor resistance or stator resistance.

5.2.2 Experimental Results

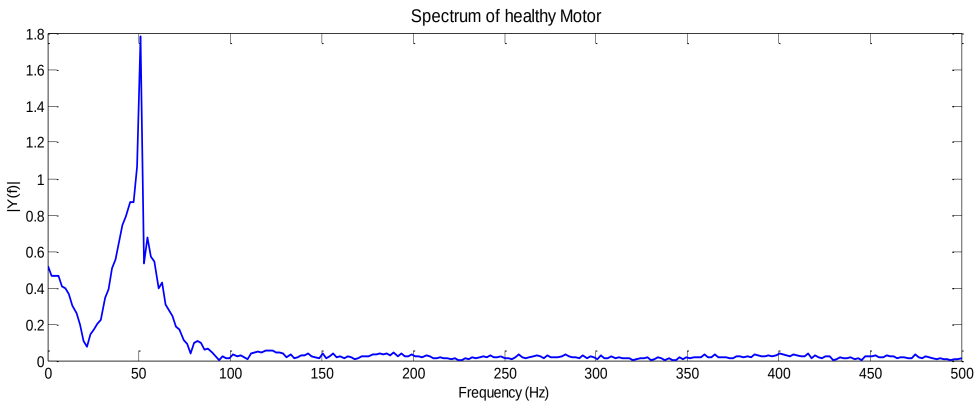


Fig. 5.2. Current Spectrum of Healthy Motor

Hardware results are implemented to examine the response of the motor. As we can see the peak value is at about 1.9. it is more than that calculated by the model but such noise and other factors which were ignored in the model impact the system. Simulation and hardware results can be totally matched or totally different sometimes but mostly they validate each other by minor changes as we have in this model.

5.3 Results of Motor with 3 bar broken in Frequency Domain

5.3.1 Simulation Results

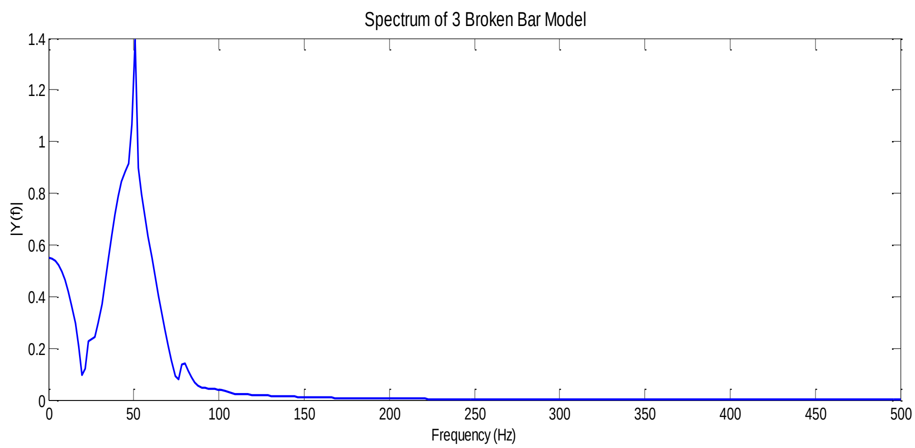


Fig. 5.3. Current Spectrum of Model with 3 Broken Bar

Increase in number of broken rotor bar and its effect can be visualize in fig.5.6 the peak is raised from 1.3 to 1.4 as the consumption of current and electromagnetic induction is increased. As the broken area or the broken rotor bar effect is in such a way that the electromagnetic flux which is not inducing in that bar will accumulate its required current from other bar and hence increased in current observed.

5.3.2 Experimental Results

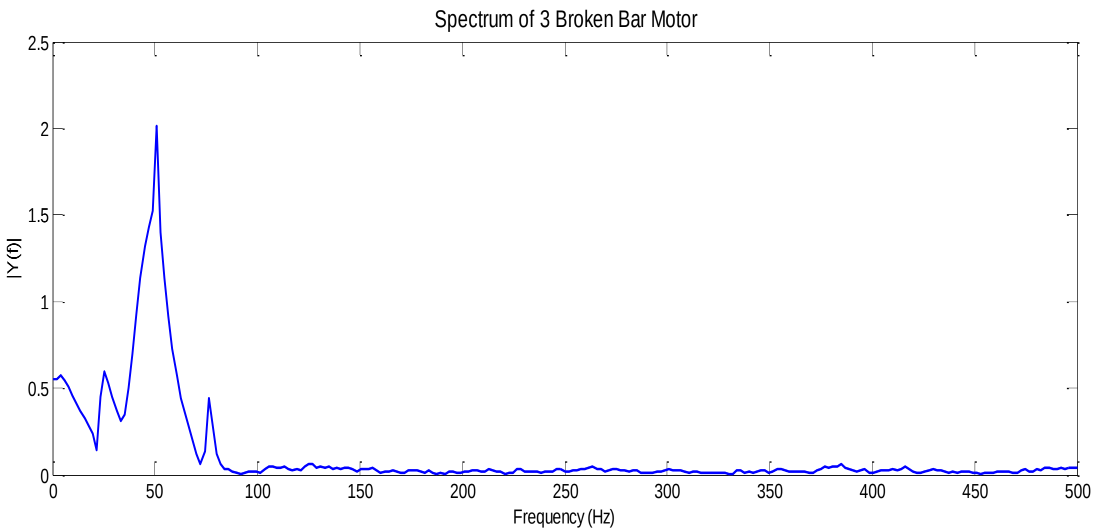


Fig. 5.4. Current Spectrum of Motor with 3 Broken Bar

The change in peak can be seen in the motor as in the model. The difference in motor and model is due the noise and the factors neglected in the model as the real time motor is more sensitive to other factors such as condition of bearing and that of the winding. Fig.5.7 shows the increase in peak as it is 2.0.

5.4 Results of Motor with 5 bar broken in Frequency Domain:

5.4.1 Simulation Results

Broken rotor bar upto that extent is actually effecting the motor and its efficiency as can be seen the peak is now raised to 1.8 as

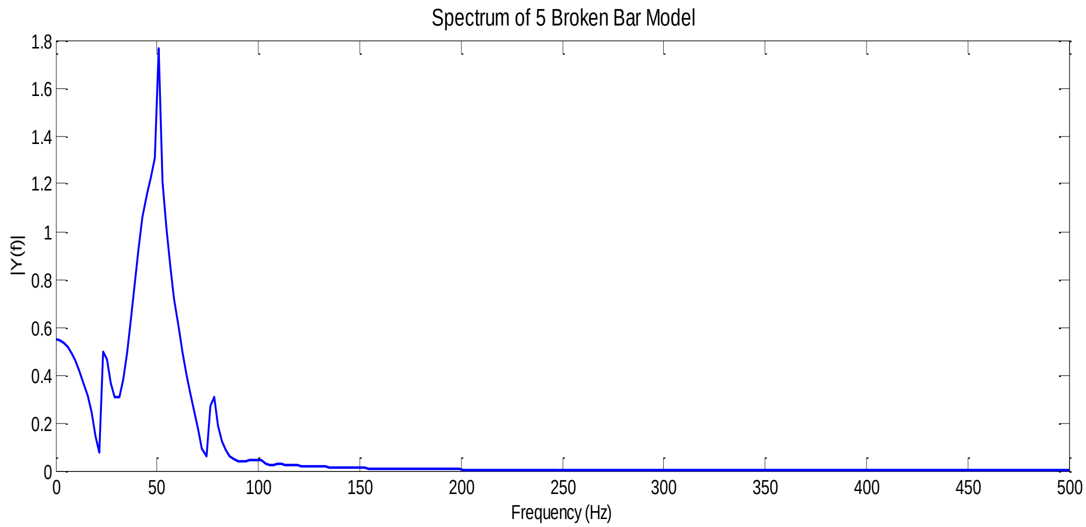


Fig. 5.5. Current Spectrum of Model with 5 Broken Bar

can be observed in fig.5.8. The efficiency of the motor is now degrading.

5.4.2 Experimental Results

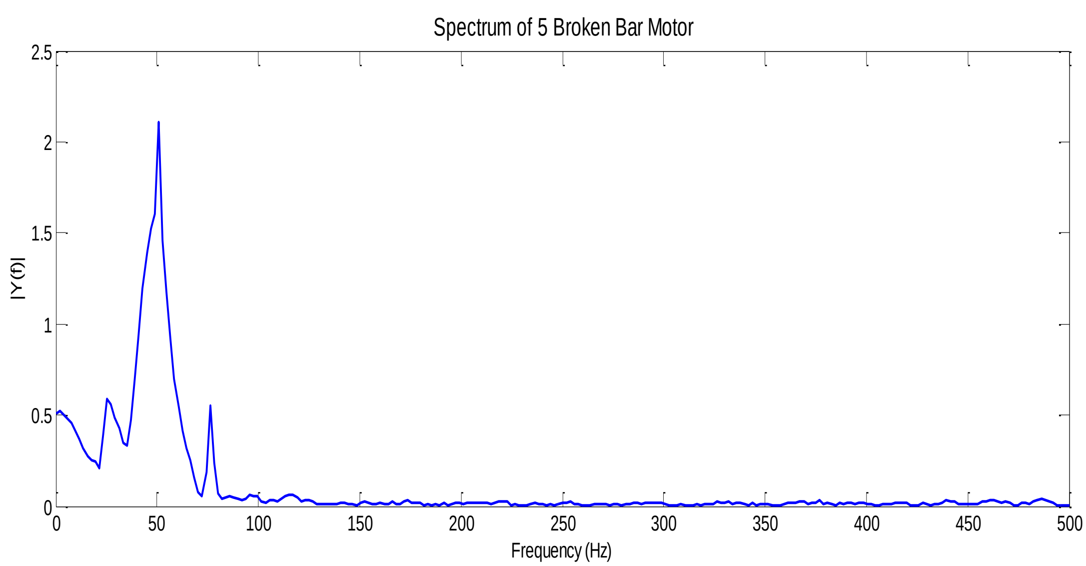


Fig. 5.6. Current Spectrum of Motor with 5 Broken Bar

The peak change in model and motor is due to the factors described earlier and the change in model and motor can be minimized but hardly achievable. The peak of current spectrum is now 2.11 in fig.5.9. which is clearly mentioning the change in response of motor as number of broken bar increased.

5.5 Results of Healthy Motor in Time Domain:

5.5.1 Simulation Results

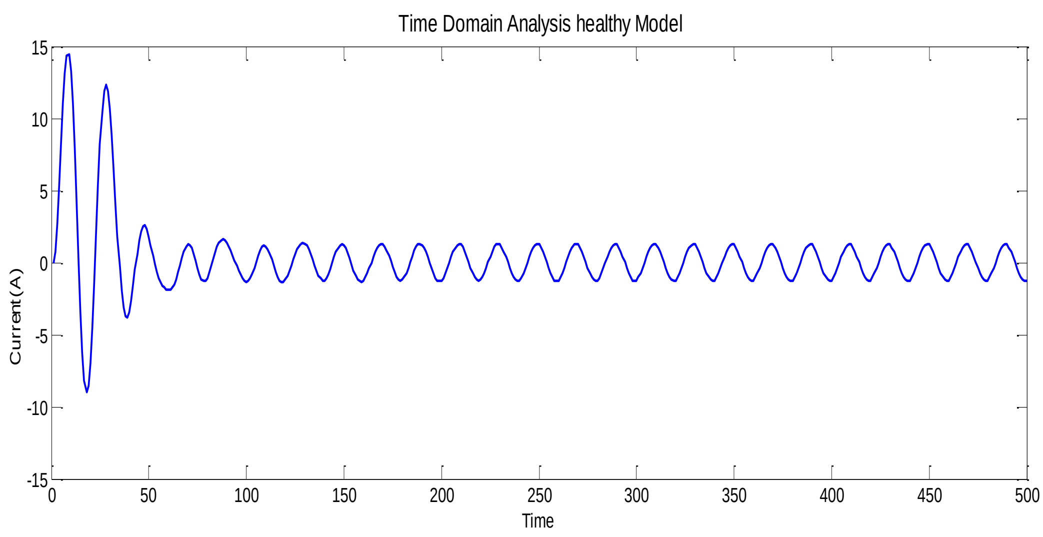


Fig. 5.7. Current in Time Domain of Healthy Model

Time domain analysis is a good tool to analyze certain changes in response of the system but for a small change and complex scenario it is avoided. Here, we can see the time sequence of current consumed by the motor. As it is the model's response it can be variant in real motor. In fig.5.10. the peak current for starting torque is less than 15.

5.5.2 Experimental Results

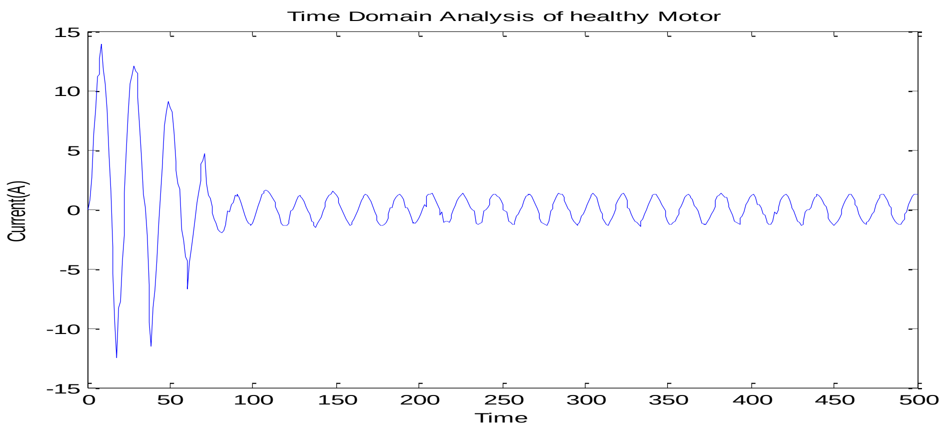


Fig. 5.8. Current in Time Domain of Healthy Motor

In hardware of the prescribed model the current consumed is little change but the change in current response as per the number of broken rotor bar can be seen.

5.6 Results of Motor with 3 bar broken in Time Domain:

5.6.1 Simulation Results

Increase in broken rotor bar is effecting the current as to accumulate the starting torque of the motor but can hardly be seen if the change in

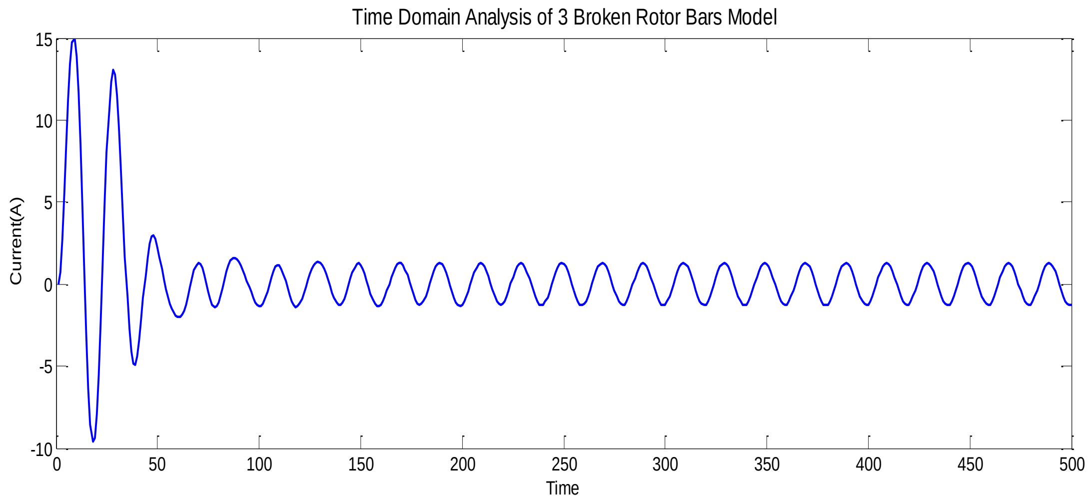


Fig. 5.9. Current in Time Domain of 3 Broken Bar Model

number of broken rotor bar is small hence 3 broken rotor bar response are collected directly. The peak current in fig.11 can be seen has reached to 15 now.

5.6.2 Experimental Results

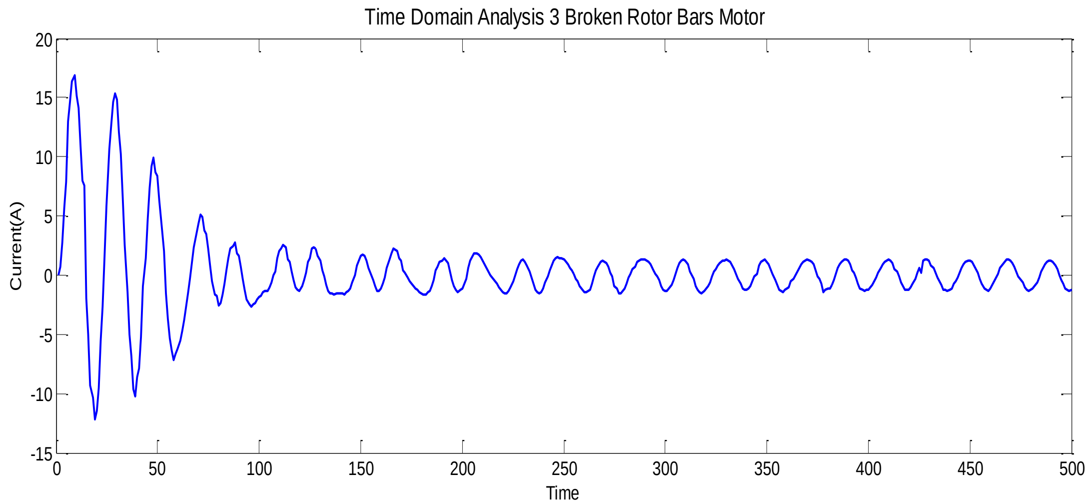


Fig. 5.10. Current in Time Domain of 3 Broken Bar Motor

Experimental results validating the change in current spectrum can be seen in the response of the motor the motor's peak current has now reached to 16 in fig.5.13 and may increase further to fulfill its need of starting torque in case of increase in broken rotor bar

5.7 Results of Motor with 5 bar broken in Time Domain:

5.7.1 Simulation Results

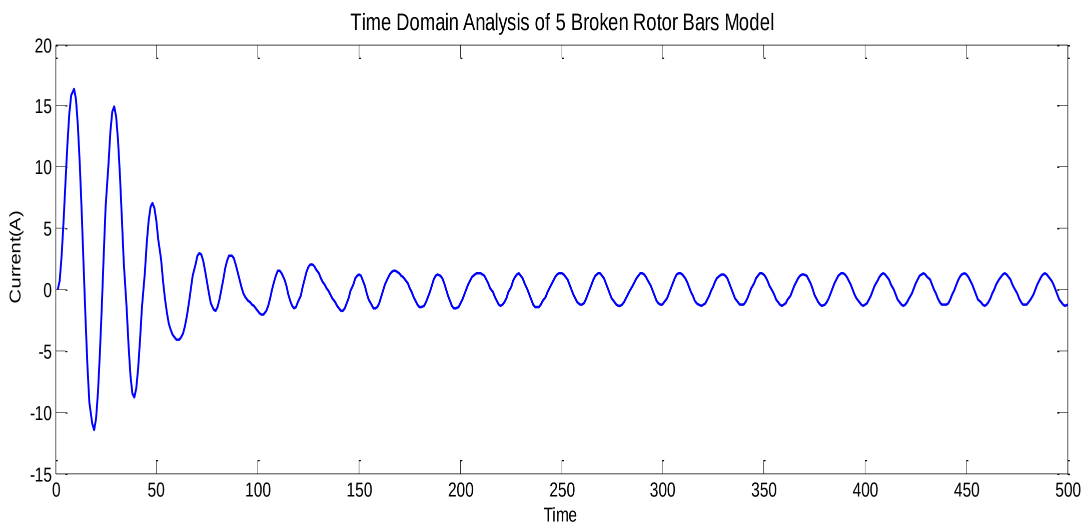


Fig. 5.11. Current in Time Domain of 5 Broken Bar Model

Number of broken rotor bar has increased to 5 and the effects of this increment can be visualize in current spectrum as it is now over 15 in fig.5.14.

5.7.2 Experimental Results

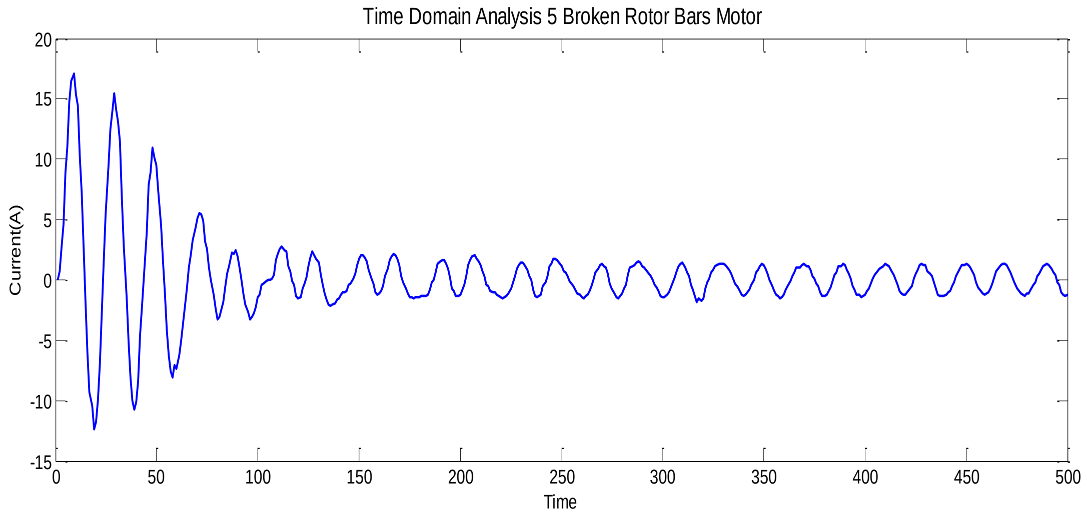


Fig. 5.12. Current in Time Domain of 5 Broken Bar Motor

The hardware results of response of motor with 5 broken bar is attained and plotted the current's peak, is now close to 17 in fig.5.15. the rise in model and motor's current peak and their difference has shown the attitude of current as per the disturbances.

Current and its peak are changing as we are increasing the number of broken rotor bar. It is clearly visible that the effeiciency of the motor is effected. In case of mega motor this change could lead to tens of ampere loss per hour and will part in increased utility bill.

CHAPTER 6. Conclusions

Fault diagnosis and condition monitoring of an induction motor is practically challenging and critical to perform. Identification of broken rotor bar in an induction motor and it diagnosis for research purpose is expensive and difficult to perform as induction motor is of high cost and real efforts are needed to inject such faults in induction motor manually.

The thesis is the study of broken rotor bar it’s impact and possible consequences for that a hardware setup for motor’s operation is investigated. Hence, It can concluded that the change in resistance of rotor which is in accordance with the number of rotor bar broken is translated in form of increased rotor resistance, we can analyze the number of broken rotor bar and can visualize the severity of the fault by mean of current consumption so that preventive maintenance measures could be taken which is comparatively easy for engineers than breakdown maintenance so that production and operation of an industry doesn’t suffer.

6.1 Analysis of Broken Rotor Bar

Hardware implementation of the proposed method has performed using an experimental setup so that live motor and its responses could be visualized to validate the authenticity of the working model.

Time domain analysis is performed and alteration in current spectrums were studied. It was found that initially the current does not change abruptly as the bar broken but when number of broken rotor bar increased the current spectrum changed. Further, the RMS of the motor increased as the number of broken rotor bar increased. Thus, fault severity is playing a major role on the amplitude and RMS of the motor whereas, the minor fault introduced after a single bar broken is unable to find using time domain analysis but in case of more than 3 bars broken in a rotor of 14 bars, these values shows the differences prominently. Hence, can be use in case of small operation and motor with low power or low cost.

Frequency analysis is a key tool to examine small scale deviation in the spectrum. Frequency domain analysis is performed and it authenticate the small scale deviation as a single number of bar is broken. Hence, the frequency analysis shows a good contribution in identifying even a single number of bar broken and can be used in large scale operation as well small scale, depends on the operation.

6.2 Implementation of fault

Fault in induction motor is implemented by manual mean. Motor was disassembled and then the rotor bar is drilled using a drilling machine in mechanical workshop. Being conscious, he drilling should be performed by the person with training else it could be dangerous. Once the drilling is performed the motor should be assemble properly with perfect bearing placement and oiling or it could disturb the actual readings of the stator.

6.3 Future Works

The work presented is on a small scale and can play a little part in diagnosis of faults of an induction machine. Further, several other analysis could be performed using the same setup and techniques with different parameters, some of them are given below

- Wavelet transformation on the signals could be performed in detail, so that more clear differences between slight changes in current spectrum could be visualized.
- Leakage flux, which is adopted using the same sensor could be investigated. It's a detail topic to cover with specific target.
- Other faults like Bearing, ware tare, motor's base bolt, stator could be introduced in the hardware model to further identify the differences between broken bar and other faults.
- A hand-held portable device could be design to perform the preventive maintenance of the induction motor for such industries where online monitoring system is not implemented.

Bibliography

[1] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators", volume 112, issue 1996 of IEEE, by IEEE Power Engineering Society

[2] M. E. H. Benbouzid, :A review of induction motors signature analysis as a medium for fault detection," *IEEE Trans. Ind. Electron.*, vol. 47, pp.984-993, Oct. 2000.

[3] D. R. Rankin, "The industrial application of phase current analysis to detect rotor winding faults in squirrel cage induction motors," *Power Engineering journal*, vol-9, pp. 77-84, 1995.

[4] W. T. Thomson amd M. Fenger, "Current signature analysis to detect induction motor faults." *IEEE In. App. Magazine*, pp.26-34, July/Aug. 2001.

[5] F. Filippetti, M. Martelli, G. Franceschini, and C, Tassoni, "Development of expert system knowledge base to on-line diagnosis of rotor electrical faultsof induction motors," in *Conf. Rec. IEEE IAS Annu. Meeting*, (Houston, TX), pp. 92-99, Oct. 1992.

[6] S. A. S. A. Kazzaz and G. K. Singh, "Experimental investigations on induction machine condition monitoring and faults diagnosis using digital signal processing techniques," *Electric Power Systems Research*, vol. 65, pp. 197-221, Jun. 2003.

[7] WEG, *General Purpose Motors*. Brazil: WEG Electric Motors Corporation, 2004.

[8] B. K. Bose, *Modern power electronics and AC drives*. Upper Saddle River, NJ: Prentice Hall, 2002.

[9] G. R. Slemon, "Electrical machines for variable-frequency drives," *in Proceedings of the IEEE*, vol. 82, pp. 1123-1139, 1994.

[10] B. K. Bose, *Modern power electronics and AC drives*. Upper Saddle River, NJ: Prentice Hall, 2002.

[11] P. C. Krause, *Analysis of electric machinery*. New York: McGraw-Hill, 1986.

[12] J. S. Hsu, "Monitoring of defects in induction motors through air-gap torque observation," *IEEE Transactions on Industry Applications*, vol. 31, pp. 1016-1021, 1995.)

[13] A. L. Orille, G. M. A. Sowilam, and J. A. Valencia, "A new simulation of three phase induction motor under transformation of park," *Computer and Industrial Engineering*, vol.37, pp. 359-362, 1999.

[14]J. F. Bangura and N. A. Demerdash. "Diagnosis amd characterization of effects of broken bars and connector in squirrel-cage induction motors by a time stepping coupled finite element state space modeling approach," IEEE Trans. Energy Conversion, vol. 14, pp. 1167-1176, Dec.1999.

[15] C. M. Ong, *Dynamic Simulation of Electric Machinery Using MATLAB/SIMULINK*, New Jersey: Prentice Hall, 1998.

[16] K. L . SHI, T . F. CHAN, Y. K. WONG and S. L . HO "Modelling and simulation of the three-phase induction motor using Simulink", Int. J. Elect. Enging. Educ., Vol. 36, pp. 163–172, 1999.

[17] S. A. Taher and M. Malekpour, “A novel technique for rotor bar failure detection in single-cage induction motor using FEM and MATLAB/SIMULINK,” vol. 2011, pp. 1–14, 2011.

[18] Nandi and H. A. Toliyat, “Condition monitoring and fault diagnosis of electrical machines-a review,” vol. 1, no. 4, pp. 719–729, 1999.

[19] A. Bellini, F. Filippetti, G. Franceschini, C. Tassoni, and G. Kliman, “Quantitative evaluation of induction motor broken bars by means of electrical signature analysis,” Industry Applications, IEEE Transactions on, vol. 37, no. 5, pp. 1248–1255, 2001.

[20] M. E. H. Benbouzid, “A review of induction motors signature analysis as a medium for faults detection,” *IEEE Trans. Ind. Electron.*, vol. 47, pp.984-993, Oct. 2000.

[21] G. B. L\Kliman, R. A. Koegl, J. Stein, and R. D. Endicott, “Noninvasive detection of broken rotor bars in operating induction motors,” *IEEE Trans. Energy Conversion,* vol. 3, pp. 873-879, Dec. 1988.

[22] P.C. Krause, O. Wasynczuk, and S,D Sudhof, *Analysis of Electric Machinery*. New York: IEEE Press, 1995.