CHAPTER ONE
INTRODUCTION

1.1 Background

Induction motors are relatively rugged and inexpensive machines. Therefore much attention is given to their control for various applications with different control requirements. An induction machine, especially squirrel cage induction machine, has many advantages when compared with DC machine. First of all, it is very cheap. Next, it has very compact structure and insensitive to environment. Furthermore, it does not require periodic maintenance like DC motors. However, because of its highly non-linear and coupled dynamic structure, an induction machine requires more complex control schemes than DC motors. Traditional open-loop control of the induction machine with variable frequency may provide a satisfactory solution under limited conditions. However, when high performance dynamic operation is required, these methods are unsatisfactory. Therefore, more sophisticated control methods are needed to make the performance of the induction motor comparable with DC motors. The most popular induction motor drive control method has been the Field Oriented Control (FOC) in the past two decades. The objective of field orientation is to make the induction motor emulate the separately excited dc machine as a source of adjustable torque .Furthermore; the recent trend in FOC is towards the use of sensor-less techniques that avoid the use of speed sensor and flux sensor. The sensors in the hardware of the drive are replaced with state observers to minimize the cost and increase the reliability [1].

1.2 Problem Statement

The previous control strategies have good steady-state but poor dynamic response oscillation resulted from the air gap flux. Field oriented control (FOC) overcame the poor dynamic response.

1.3 Objectives

The objectives of the research are**:**

- Using FOC for motor applications which can operate smoothly over the wide speed range, can produce full torque at zero speed, and is capable of quick acceleration and deceleration”
- Make modeling to the system by using MATLAB/SIMULINK

1.4 Methodology

The methodology used to achieve research objectives are as follow:

Task one: review of previous studies and collecting of information related to the research and building of cemented background to achieve research objectives.

Task two: investigate of various control techniques such as field oriented control method and implementation of the technique in software program to be sure the technique is robust and effective.

Task three: Analysis the result by using MATLAB/SIMULINK program or design the project and compare between the specifications and result of the project.

1.5 Project Outline

The thesis includes five chapters organized as follow:

Chapter two presents the general theory of induction Motors, with focus on the chapter also different speed control of induction motor.

Chapter three the review the variable frequency drive of induction motor and mainly focused on field oriented control also describe the voltage source inverter.

Chapter four describe the layout has been used in MATLAB/SIMULINK and show the result of the simulation.

Chapter five discussions the result and recommendations

CHAPTER TWO

INDUCTION MOTOR AND DIFFERENT SPEED CONTROL METHODS

2.1 Introduction

For industrial and mining applications, 3-phase AC induction motors are the prime movers for the vast majority of machines. These motors can be operated either directly from the mains or from adjustable frequency drives. In modern industrialized countries, more than half the total electrical energy used in those countries is converted to mechanical energy through AC induction motors. The applications for these motors cover almost every stage of manufacturing and processing. In the last decade, it has become increasingly common practice to use 3-phase squirrel cage AC induction motors with Variable Voltage Variable Frequency (VVVF) converters for Variable Speed Drive (VSD) applications. To clearly understand how the VSD system works, it is necessary to understand the principles of operation of this type of motor [1].

2.2 Three Phase Induction Motor

The three phase induction motors are also called as asynchronous motors, which are most commonly used type of motor in industrial applications.in particular, the squirrel-cage induction motor are widely used electric motor in home and industrial applications , because these machine are very economical, rugged and reliable. They are available in the ranges of the Fractional Horse Power (FHP) to multi-megawatt capacity .fraction horse power motors are available in single-phase as well as poly-phase(three phase).The three phase machines are used most often in variable-speed drive where the torque requirement is motor. An induction motor or synchronous motor is a type of alternating current motor where power is supplied to rotor by means of electromagnetic induction. An elect motor rotates because of magnetic force exerted between a stationary electromagnet called the stator and rotating electromagnet called the rotor. The current in stator side creates an electromagnetic field which interacts with the secondary to produce a resultant torque, transforming electrical energy into mechanical energy. The cross sectional view of induction motor and its various parts are shown in Figure 2.1.

2.3 Construction

In this section, the construction details of induction motor are discussed. A three phase induction motor mainly consists of two parts, stator and rotor. Stator is the stationary part while the rotor is rotating part of the motor and they are separated by small air gap depending on the rating of the motor.

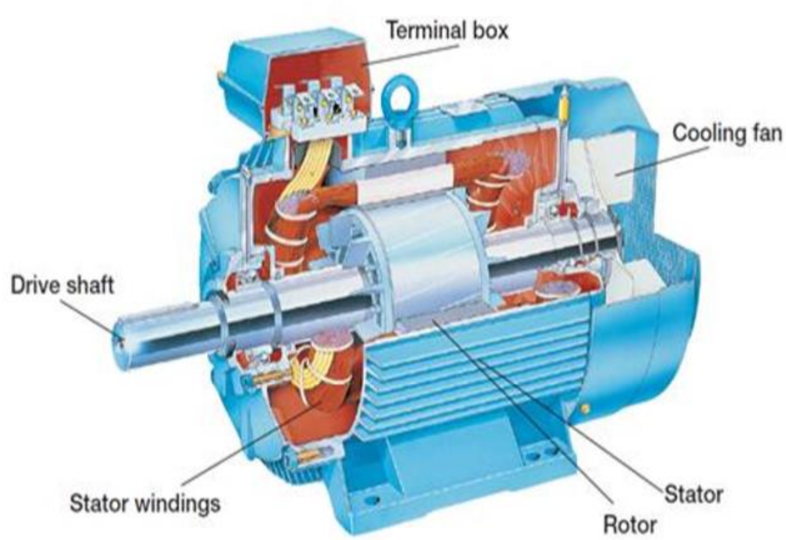


Figure 2.1: Squirrel cage three phase induction motor

2.3.1 Stator

The stator is shown in Figure 2.2, which consists of a steel frame which encloses a hollow cylindrical core made up of thin laminations of silicon steel to reduce eddy current and hysteresis loss. A large number of uniform slots are cut on the inner periphery of the core. The stator conductors are placed in these slots which are insulated from one another and also from the slots. The windings are wound for a definite number of poles depending on the requirement of speed. It is wound for more number of pole, if speed required is less and vice versa. According to the relation

$$N_s = \frac{120f}{p} \qquad (2.1)$$

Where Ns is the synchronous speed in RPM

f is the supply frequency

p is the number of poles

When a three phase supply is given to stator winding a magnetic field of constant magnitude and rotating at synchronous speed is produce. This rotating magnetic field is mainly responsible for producing the torque in the rotor, so that it can rotate at the rated speed.

Figure 2.2: Stator

2.3.2 Rotor

The rotor is rotating part of induction motor and is mounted on the shaft of the motor to which any mechanical load can be connected. Based on the construction of the rotor, induction motors are broadly classified in two categories; squirrel cage motor and slip ring motor. The stator construction is the same in both motors.

A-Squirrel cage motors

Almost 90% of induction motors are squirrel cage motors. This is because the squirrel cage has a simple and rugged construction. Figure 2.3 show the squirrel cage type motor, it is consists of cylindrical laminated core with axially placed parallel slots for carrying rotor conductors. The rotor conductors are heavy bar of copper or aluminum. Each slot carries a copper, aluminum or alloy bar. If slot are semi closed, then these bars are inserted from the end. These rotor bars permanently short circuit at both ends by mean of the end ring, it is not possible to add any external resistance in series with the rotor circuit during starting. The slots are slightly skewed, which helps in two way i.e.

- It reduces noise due to magnetic hum and makes motor run quietly.
- It reduce locking tendency between rotor and stator.

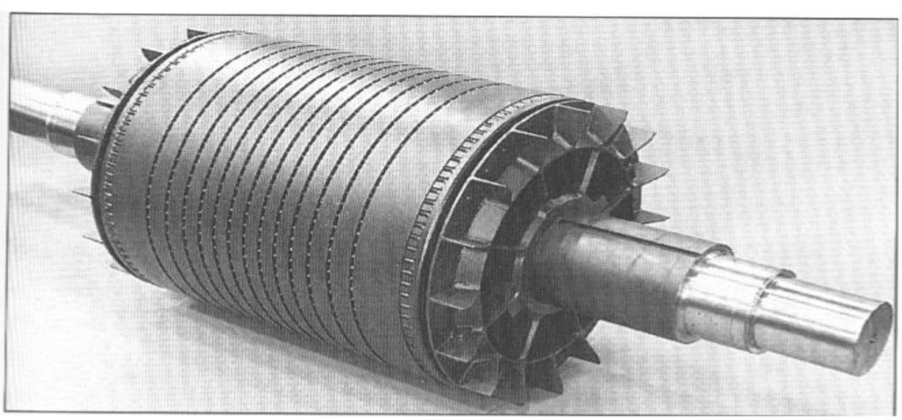


Figure 2.3: Squirrel cage type rotor

Advantages of squirrel cage motor

1. It is simple in construction, rugged and can withstand rough handling.
2. Maintenance cost is low.
3. It is better efficiency and power factor.
4. A simple star delta starter is sufficient to start the rotor.
5. It is explosion proof as there are no slip ring and brushes.

B-Slip ring motors

In the slip ring motor, the windings on the rotor are terminated to three insulated slip ring mounted on the shaft with brushes resting on them. This allows an introduction of an external resistor to rotor winding. The external resistor can be used to boost the starting torque of the motor and change the speed torque characteristic. When running under normal condition, the slip rings are short circuit, using an external metal collar, which is pushed along the shaft to connect the rings. In normal condition, the slip ring motor functions like a squirrel cage motor.

2.4 Operation principle of 3-phase induction motor

When three phase supply is given to the three phase stator winding, a magnetic field of constant magnitude and rotating at synchronous speed Ns is produce. This rotating magnetic field sweeps across the rotor conductor and hence an Electro Motive Force (EMF) is induction in rotor conductor. As the rotor conductors are short circuit on themselves the induce EMF step up a current in the rot r conductors in such a direction as to produce a torque, which rotates the rotor in the same direction as magnetic field so that relative speed decreases. The speed of gradually increases and tries to catch up with the speed of rotating magnetic field, but it fails to reach synchronous speed, because if it catches up with the rotor conductors, the speed of magnetic field, relative speed becomes zero and hence no EMF will be induce in the rotor conductor, the torque become zero . Hence, rotor will not be able to catch up with the speed of magnetic field but rotates at a speed Nr which is slightly less than the synchronous speed.

2.4.1 Equivalent circuit

The equivalent circuit is shown in Figure 2.4 from equivalent circuit diagram the various power expressions can be written as follow:

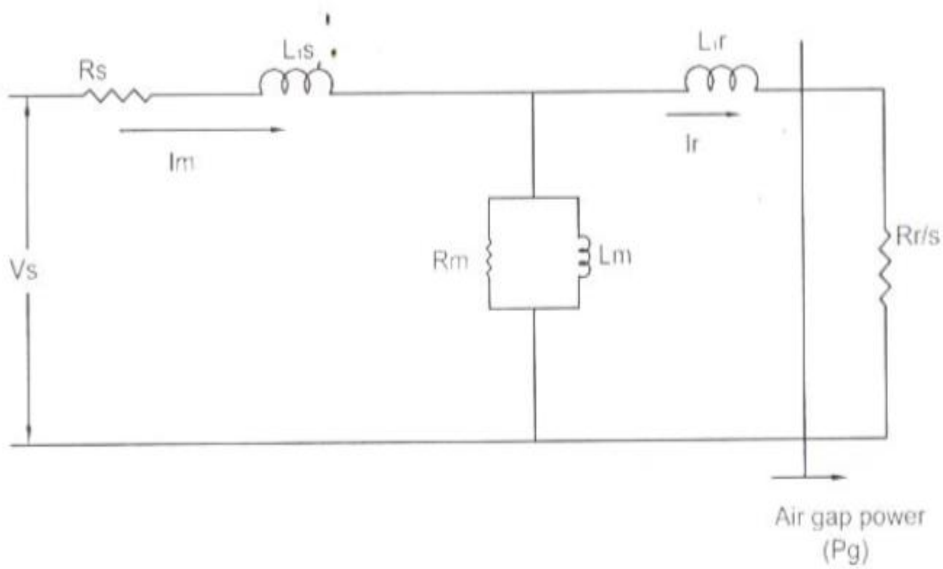


Figure 2.4: Per Phase Equivalent Circuit of Induction Motor

Input power = $3V_s I_s \cos(\emptyset)$ (2.2)

Stator copper loss= $P_{Is} = 3I_s^2 R_s$ (2.3)

Core loss= $\frac{3V_m^2}{R_m}$ (2.4)

Power across air gap: $P_g = 3\frac{R_r}{s} I_r^2$ (2.5)

Rotor copper loss: $P_{Ir} = 3I_r^2 R_r$ (2.6)

Output power: $P_o = P_g - P_{Ir} = \frac{3I_r^2 R_r(1-s)}{s}$ (2.7)

Since the output power is the product of developed torque T_e and speed ω_m, T_e can be expressed as

$$T_e = \frac{P_o}{\omega_m}$$

$$T_e = \frac{3}{\omega_m} I_r^2 R_r \left(\frac{1-s}{s}\right) = 3\left(\frac{P}{2}\right) I_r^2 \frac{R_r}{s\omega_e} \quad (2.8)$$

From the equivalent circuit, the approximate equivalent circuit can be obtained as shown in Figure 2.5, where the core loss resistor R_m has been dropped and the magnetizing inductance Lm has been shifted to the input. This approximation is easily justified for an integral horsepower machine, where $(R_s + j\omega_e L_{Is}) \ll \omega_e L_m$

The performance prediction by the simplified circuit typically varies within 5 percent from the actual machine

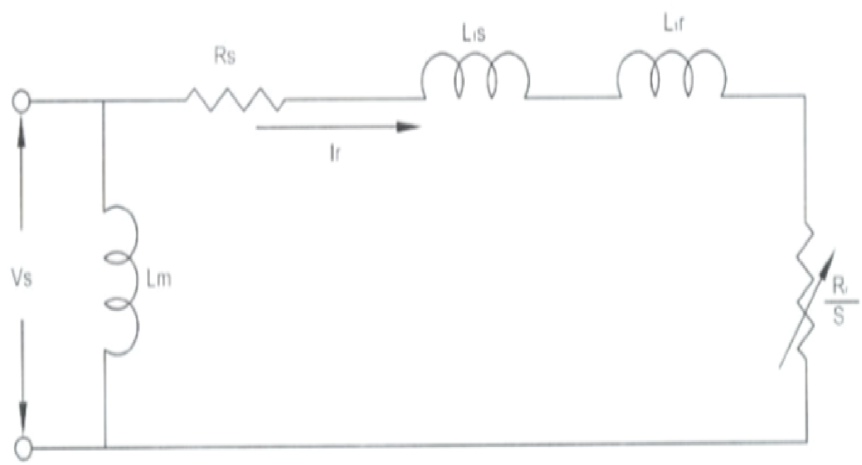


Figure 2.5: Approximate per phase equivalent circuit of IM

In Figure 2.5,the current I_r is figured out by:

$$I_r = \frac{V_s}{\sqrt{\left(R_s+\frac{R_r}{s}\right)^2+\omega_e^2(L_{ls}+L_{lr})^2}} \tag{2.9}$$

Substituting Equation (2.9) in (2.8) yields

$$T_e = 3\left(\frac{p}{2}\right)\frac{R_r}{s\omega_e}\frac{V_s^2}{\left(R_s+\frac{R_r}{s}\right)^2+\omega_e^2(L_{ls}+L_{lr})^2} \tag{2.10}$$

A further simplification of the equivalent circuit of Figure 2.4 can be made by neglecting the stator parameter R_s and l_{Is} . This assumption is not unreasonable for an integral horsepower machine, particularly if the speed is typically above 10 percent. Then, the Equation 2.10 can be simplified as

$$T_e = 3\left(\frac{P}{2}\right)\left(\frac{V_s}{\omega_e}\right)^2\left(\frac{\omega_{sl}R_r}{R_r^2+\omega_{sl}^2L_{lr}^2}\right) \tag{2.11}$$

Where $\omega_{sl} = s\omega_e$

The air gap flux can be given by

$$\Psi_m = \frac{V_s}{\omega_e} \tag{2.12}$$

In low slip region, Equation 2.11 can be approximated as

$$T_e = 3\left(\frac{P}{2}\right)\frac{\Psi_m^2\omega_{sl}}{R_r} \tag{2.13}$$

Where $R_r^2 \gg \omega_{sl}^2L_{lr}^2$ Equation 2.13 is important because it indicated that at constant flux $\Psi_m$the torque T_e is proportional to slip frequency ω_{sl} ,or at constant slip frequency ω_{sl},torque T_e is proportional to Ψ_m^2.

2.4.2 Slip

The slip can be defined as the difference between the synchronous speed and actual speed of the machine. Based on this slip speed , the voltage induce in the rotor winding change, which in turn changes the rotor current and also the torque .A slip increase, the rotor current and torque also increase. The rotor moves in the same direction as that of the rotating magnetic field to reduce the induced current (Lenz's law).The slip can be expressed as given below:

Slip $s = \frac{N_s - N_r}{N_s}$ (2.14)

Or slip $s = \frac{\omega_e - \omega_r}{\omega_e} = \frac{\omega_{sl}}{\omega_e}$ (2.15)

Or rotor speed $N_r = N_s\ (1\text{-}S)$ (2.16)

Synchronous speed is given by $N_s = 120f/p$ (2.17)

Where p represents the number of pole and f is stator frequency in Hz.

Therefore equation (2.16) become,

Rotor speed $N_r = 120f\ (1\text{-}S)/p$ (2.18)

Thus, the speed of an induction motor depends on slip 'S', stator frequency 'f' and the number of pole 'p' for which the winding are wound.

2.5 Different Speed Control Methods

From Equation 2.18, the rotor speed of IM can be varied by varying the slip 'S' or number of pole 'p' or frequency of supply. The different methods of speed control of induction motor can be broadly classified in to scalar and vector control methods. In this work, scalar control methods are used. Hence only details of scalar methods are discussed here. The explanation of vector control method is beyond the scope of thesis. The scalar methods of speed control can be classified as

- stator voltage control
- frequency control
- stator voltage and frequency control i. e volts Hertz control
- rotor voltage control

The first three methods are the basic methods of speed control and explained in detail as follows:

2.5.1 Stator Voltage Control Method

Avery simple and economical method of speed control is to vary the stator voltage at constant supply frequency. The three phase stator voltage at line frequency can be controlled by controlling the switches in the inverter. As seen from Equation 2.10 the developed torque proportional to the square of the stator supply voltage and a reduction in stator voltage will produce a reduction in speed. Therefore, continuous speed control may be obtained by adjustment of the stator voltage without any alteration in stator frequency.

$$T_e = 3\left(\frac{p}{2}\right)\frac{R_r}{s\omega_e}\frac{V_s^2}{\left(R_s+\frac{R_r}{s}\right)^2+\omega_e^2(L_{ls}+L_{lr})^2} \qquad (2.19)$$

The Torque speed curves with variable stator voltage control are shown in figure 2.6.

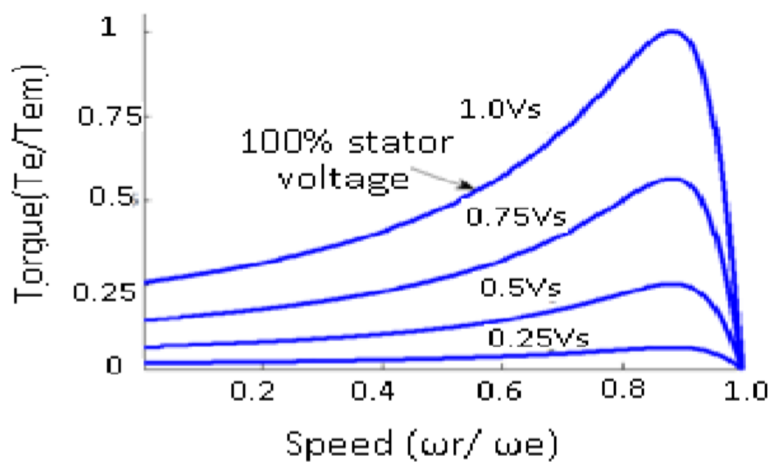


Figure 2.6: Speed torque characteristics with variable voltage

The salient features of stator voltage control method are:

- For low slip motor, the speed range is very low.
- Not suitable for constant torque load.

- Poor power factor.

Used mainly in low power application, such as: fans, blower, centrifugal, pumps, etc.

2.5.2 Frequency control method

The torque and speed of induction motor can be controlled by changing the supply frequency but keeping the voltage constant. If the frequency is decrease keeping voltage constant, then saturation of air gap flux take place. At low frequency, the reactor will decrease and the motor current may be too high. If the frequency is increased above its rated value, then the air gap flux and current decrease correspondingly, the developed torque also decrease. Due to these reason this method of control is rarely used. The torque speed characteristics with frequency control are show in Figure 2.7.

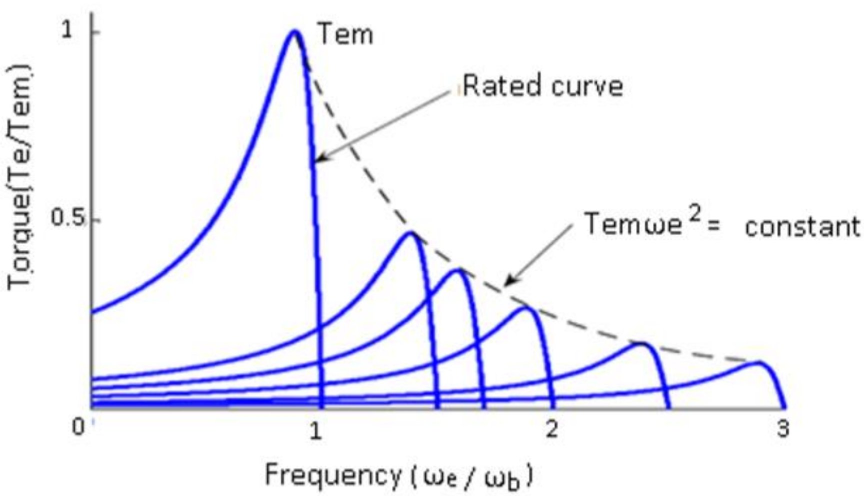


Figure 2.7: Speed torque curve with variable frequency

2.5.3 Voltage Hertz control method

The constant V/F control method is the most popular method of scalar method control. If an attempt is made to reduce the supply frequency at rated supply voltage, the air gap flux Ψ_m will tend to saturate, causing excessive stator current and direction of flux wave. Therefore, the region below the base or rated frequency should be accompanied by the proportional reduction of stator voltage so as to maintain the air gap flux constant. If the ratio of voltage to frequency is kept constant, the flux remains constant. By varying the voltage and frequency the torque and speed can be varied. The torque is normally maintained constant while the speed varied. This arrangement is widely used in the locomotives and industrial applications. The purpose of the volt hertz control scheme is to maintain the air-gap flux of AC induction motor constant in order to achieve higher run-time efficiency. The Magnitude of stator flux remain constant and motor torque depends upon slip frequency. In variable -frequency, variable –voltage operation of a drive system, the machine usually has low slip characteristics (i. e low rotor resistance), giving high efficiency. In spite of the low inherent starting torque for base frequency operation, the machine can always be started at maximum torque as induction in Figure 2.8. The absence of high in rush starting current in direct-start drive reduce stress and therefore improve the efficiency life of the machine. By far the majority of variable-speed ac drive operates with a variable-frequency, variable-voltage power supply. Figure 2.8 shows the torque-speed characteristics of the machine with constant V/F control method. Other than the variation in speed, the torque-speed characteristics of the machine with constant V/F control reveal the following:

- The starting current low.
- The stable operation region of the motor is increased. Instead of simply running at its base/rated speed (N_B), the motor can run typically from 5% of the synchronous speed (Ns) up to the base speed. The torque generated by the motor can kept constant throughout this region.

- Since almost constant rated torque is available over the entire range, the speed range the motor become wider. User can set the speed as per the load requirement, thereby achieving the efficiency.
- One of the most advantages is soft start capability in which motors are ramped up to speed instead of being abruptly thrown on line.

This useful feature reduces mechanical stress on the motor and leads to lower maintenance cost as well as a longer motor life .Because of above reasons V/F control method is proposed in the work.

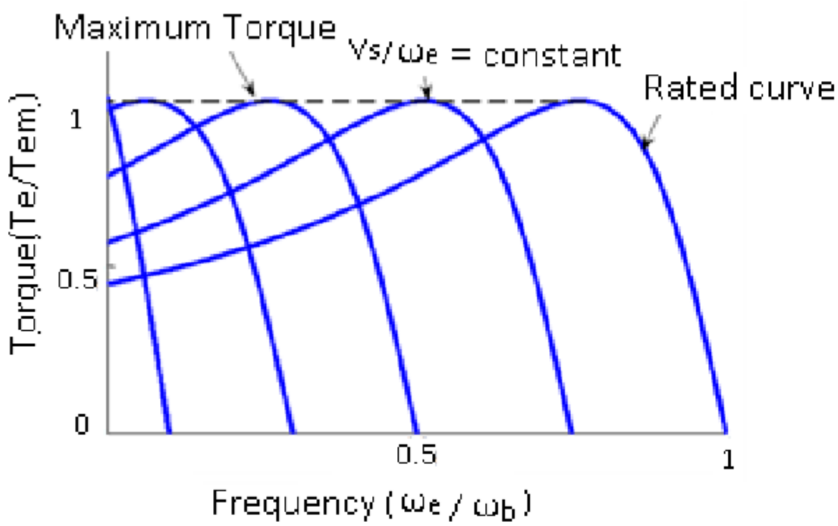


Figure 2.8: Speed torque curve with constant V/F ratio

CHAPTER THREE

VARIABL FREQUENCY DRIVE AND FIELD ORIENTED CONTROL METHOD

3.1 Introduction

Most of the energy consumed in industry by induction motors can be traced to high-powered but relatively unsophisticated machinery such as pumps, fans, blowers, grinders, or compressors. Clearly, there is no need for high dynamic performance of these drives, but speed control can bring significant energy savings in most cases. Consider, for example, a constant-speed blower, whose output is regulated by choking the air flow in a valve. The same valve could be kept fully open at all times (or even disposed of) if the blower were part of an adjustable-speed drive system. At a low air output, the motor would consume less power than that in the uncontrolled case, thanks to the reduced speed and torque. High-performance induction motor drives, such as those for machine tools or elevators, in which the precise torque and position control is a must, are still relatively rare, although many sophisticated control techniques have already reached the stage of practicality. For better drive ability, high-performance adjustable-speed drives are also increasingly used in electrical traction and other electric vehicles.[1]

3.2 Scalar and vector control methods

Induction motors can be controlled in many ways. The simplest methods are based on changing the structure of stator winding. Using the so-called wye-delta switch, the starting current can easily be reduced. Another type of switch allows emulation of a gear change by the already-mentioned pole changing, that is, changing the number of magnetic poles of the stator. However, in modem ASDs, it is the stator voltage and current that are subject to control. These, in the steady state, are defined by their magnitude and frequency; and if these are the parameters that are adjusted, the control technique belongs in the class of scalar control methods. A rapid change in the magnitude or frequency may produce undesirable transient effects, for example a disturbance of the normally constant motor torque. This, fortunately, is not important in low-performance ASDs, such as those of pumps, fans, or blowers. There, typically, the motor speed is open-loop controlled, with no speed sensor required (although current sensors are usually employed in overcurrent protection circuits). In high-performance drive systems, in which control variables include the torque developed in the motor, vector control methods are necessary. The concept of space vectors of motor quantities will be explained later. Here, it is enough to say that a vector represents instantaneous values of the corresponding three-phase variables. For instance, the vector of stator current is obtained from the currents in all three phases of the stator and, conversely, all three phase currents can be determined from the current vector. In vector control schemes, space vectors of three-phase motor variables are manipulated according to the control algorithm. Such an approach is primarily designed for maintaining continuity of the torque control during transient states of the drive system.

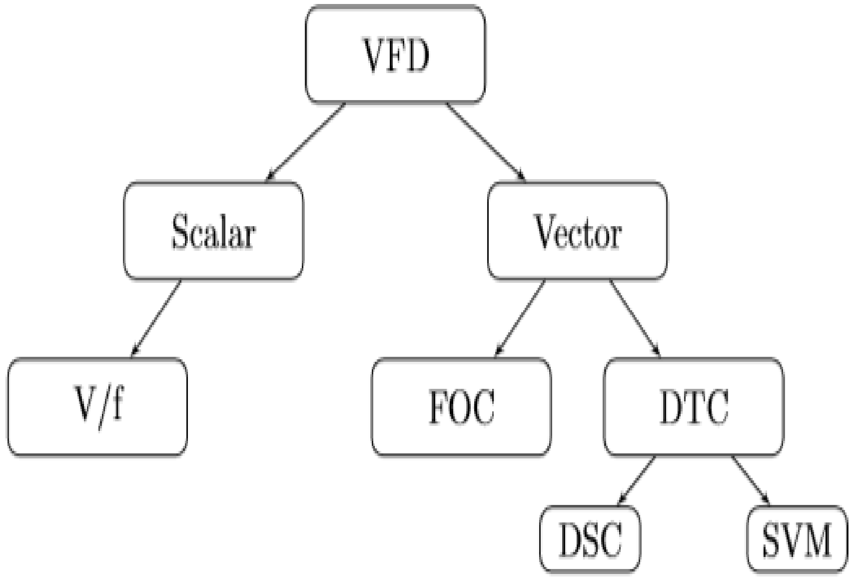


Figure 3.1: Variable frequency drive classification

3.3 Direct torque control

The induction motors in field-orientation ASDs are current controlled, that is, the control system produces reference values of currents in individual phases of the stator. Various current control techniques can be employed in the inverter supplying the motor, all of them based on the feedback from current sensors. Operation of the current control scheme results in an appropriate sequence of inverter states, so that the actual currents follow the reference waveforms. Two ingenious alternative approaches to control of induction motors in high-performance ASDs make use of specific properties of these motors for direct selection of consecutive states of the inverter. These two methods of direct torque and flux control, known as the Direct Torque Control (DTC) and Direct Self-Control (DSC), are presented in the subsequent sections. The torque developed in an induction motor can be expressed in many ways. One such expression is

$$\boldsymbol{T_M} = \frac{\frac{2}{3}p_p L_m}{L_\sigma^2} \boldsymbol{I_m}(\boldsymbol{\lambda_s}\boldsymbol{\lambda_r^*}) = \frac{\frac{2}{3}p_p L_m}{L_\sigma^2} \boldsymbol{\lambda_s}\boldsymbol{\lambda_r} \boldsymbol{sin}(\boldsymbol{\theta_{sr}}) \quad (3.1)$$

Where $\boldsymbol{\theta_{sr}}$ denotes the angle between space vectors, $\boldsymbol{\lambda_s}$ and $\boldsymbol{\lambda_r}$ of stator and rotor flux, subsequently called a torque angle. Thus, the torque can be controlled by adjusting this angle. On the other hand, the magnitude,$\boldsymbol{\lambda_s}$ of stator flux, a measure of intensity of magnetic field in the motor, is directly dependent on the stator voltage . To explain how the same voltage can also be employed to control $\boldsymbol{\theta_{sr}}$ simple qualitative analysis of the equivalent circuit of induction motor.

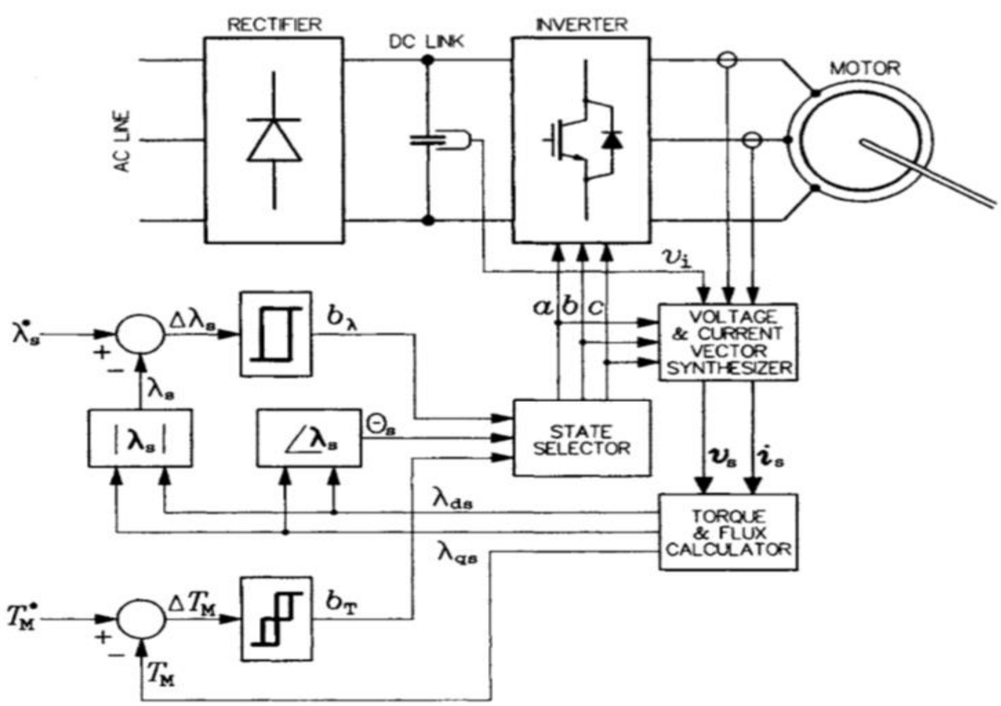


Figure 3.2: Block diagram of the DTC drive system

The basic premises and principles of the Direct Torque Control (DTC) method, proposed by Takahashi and Noguchi in 1986, can be formulated as follows:

- Stator flux is a time integral of the stator EMF. Therefore, its magnitude strongly depends on the stator voltage.
- Developed torque is proportional to the sine of angle between the stator and rotor flux vectors.
- Reaction of rotor flux to changes in stator voltage is slower than that of the stator flux.

Consequently, both the magnitude of stator flux and the developed torque can be directly controlled by proper selection of space vectors of stator voltage, that is, selection of consecutive inverter states.

3.4 Field oriented control

Field orientation, consisting in the alignment of a revolving reference frame with a space vector of selected flux, allows the induction motor to emulate the separately excited dc machine. In this machine, the magnetic field and developed torque can be controlled independently. In addition, the torque is produced under the optimal condition of orthogonality of the flux and current vectors, resulting in the maximum possible torque per-ampere ratio.

Classification of field oriented control:

It classified to two categories according to feedback techniques are

A- Direct field oriented control

Knowledge of the instantaneous position (angle) of the flux vector, with which the revolving reference frame is aligned, constitutes the necessary requirement for proper field orientation. Usually, the magnitude of the flux vector in question is identified as well, for comparison with the reference value in a closed-loop control scheme. Identification of the flux vector can be based on direct measurements or estimation from other measured variables. Such an approach is specific for schemes with the so-called Direct Field Orientation (DFO),

B- Indirect field oriented control

In an alternative approach to direct flux orientation, the Indirect Field Orientation (IFO), the angular position, 0p of the rotor flux vector is determined indirectly as

$$\theta_r = \int_0^t \omega_r^* \, dt + p_P \theta_M \qquad (3.2)$$

To examine the application of field-oriented control to induction machines, we begin with the dq0 transformation. This transformation transforms both the stator and rotor quantities into a synchronously rotating reference frame. Under balanced-three-phase, steady-state conditions, zero-sequence quantities will be zero and the remaining direct- and quadrature-axis quantities will be constant. Hence the flux-linkage current relationships become

$$\lambda_D = L_S i_D + L_m i_{DR} \qquad (3.3)$$

$$\lambda_Q = L_S i_Q + L_m i_{QR} \qquad (3.4)$$

$$\lambda_{DR} = L_m i_D + L_R i_{DR} \qquad (3.5)$$

$$\lambda_{QR} = L_m i_Q + L_R i_{QR} \qquad (3.6)$$

In these equations, the subscripts D, Q, DR, and QR represent the constant values of the direct- and quadrature-axis components of the stator and rotor quantities respectively. It is a straight-forward matter to show that the inductance parameters can be determined from the equivalent-circuit parameters as

$$L_m = \frac{X_{m0}}{\omega_{e0}} \tag{3.7}$$

$$L_S = L_m + \frac{X_{10}}{\omega_{e0}} \tag{3.8}$$

$$L_R = L_m + \frac{X_{20}}{\omega_{e0}} \tag{3.9}$$

Where the subscript (0) indicates the rated-frequency value. The transformed voltage Equations become

$$v_D = R_a i_D - \omega_e \lambda_Q \tag{3.10}$$

$$v_Q = R_a i_Q + \omega_e \lambda_D \tag{3.11}$$

$$0 = R_{aR} i_{DR} - (\omega_e - \omega_{me}) \lambda_{QR} \tag{3.12}$$

$$0 = R_{aR} i_{QR} + (\omega_e - \omega_{me}) \lambda_{DR} \tag{3.13}$$

For the purposes of developing a field-oriented-control scheme, we will begin with the torque expression

$$T_{mech} = \frac{3}{2}\left(\frac{poles}{2}\right)\left(\frac{L_m}{L_R}\right)(\lambda_{DR} i_q - \lambda_{QR} i_d) \tag{3.14}$$

For the derivation of the dq0 transformation, the angular velocity of the reference frame was chosen to the synchronous speed as determined by the stator electrical frequency we. It was not necessary for the purposes of the derivation to specify the absolute angular location of the reference frame. It is convenient at this point to choose the direct axis of the reference frame aligned with the rotor flux (λ_{QR}=0).

And the torque expression of Equation 3.14 becomes

$$T_{mech} = \frac{3}{2}\left(\frac{poles}{2}\right)\left(\frac{L_m}{L_R}\right)\lambda_{DR} i_q \tag{3.15}$$

From Equation 3.12 are become: $i_{DR} = 0$

And thus

$$\lambda_{DR} = L_m i_D \tag{3.16}$$

And

$$\lambda_D = L_S i_D \tag{3.17}$$

From Equations 3.16 And 3.17 are become that by choosing set $\lambda_{QR} = 0$ and thus aligning the synchronously rotating reference frame with the axis of the rotor flux, the direct- axis rotor flux (which is, indeed, the total rotor flux) as well as the direct-axis flux are determined by the direct-axis component of the armature current. Notice the direct analogy with a dc motor. In a dc motor, the field- and direct-axis armature fluxes are determined by the field current and in this field-oriented control scheme, the rotor and direct-axis armature fluxes are determined by the direct-axis armature current. In other words, in this field-oriented control scheme, the direct-axis component of armature current serves the same function as the field current in a dc machine. The torque equation, Equation 3.15, completes the analogy with the dc motor. We see that once the rotor direct-axis flux λ_{DR} is set by the direct-axis armature current, the torque is then determined by the quadrature-axis armature current just as the torque is determined by the armature current in a dc motor. In a practical implementation of the technique which we have derived, the direct- and quadrature-axis currents i_D and i_Q must be transformed into the three motor phase currents ia(t), ib(t), and ic(t). This can be done using the inverse dq0 transformation which requires knowledge of θ_S, the electrical angle between the axis of phase a, and the direct-axis of the synchronously rotating reference frame. Since it is not possible to measure the axis of the rotor flux directly, it is necessary to calculate θ_S, where $\theta_S = \omega_e t - \theta_0$. Solving Equation 3.13 for ω_e gives

$$\omega_e = \omega_{me} - R_{aR}\left(\frac{i_{QR}}{\lambda_{DR}}\right) \quad (3.18)$$

From Equation 3.6 with λ_{QR} = 0 we see that

$$i_{QR} = -\left(\frac{L_m}{L_R}\right) i_Q \quad (3.19)$$

Equation 3.19 in combination with Equation 3.16 then gives

$$\omega_e = \omega_{me} + \frac{R_{aR}}{L_R}\left(\frac{i_Q}{i_D}\right) = \omega_{me} + \frac{1}{\tau_R}\left(\frac{i_Q}{i_D}\right) \quad (3.20)$$

Where $\tau_R = L_R/R_{aR}$ is the rotor time constant.

We can now integrate Equation 3.20 to find

$$\hat{\theta}_S = \left[\omega_{me} + \frac{1}{\tau_R}\left(\frac{i_Q}{i_D}\right)\right] t + \theta_0 \quad (3.21)$$

Where $\hat{\theta}_S$ indicates the calculated value of θ_S (often referred to as the estimated value of θ_S). In the more general dynamic sense

$$\hat{\theta}_S = \int_0^t \left[\omega_{me} + \frac{1}{\tau_R}\left(\frac{i_Q}{i_D}\right)\right] dt' + \theta_0 \quad (3.22)$$

Note that both Equations 3.21 and 3.22 require knowledge of θ_0, the value of θ_S at t = 0. Although we will not prove it here, it turns out that in a practical implementation, the effects of an error in this initial angle decay to zero with time, and hence it can be set to zero without any loss of generality.

Figure 3.4 a shows a block diagram of a field-oriented torque-control system for an induction machine. The block labeled "Estimator" represents the calculation of Equation 3.22 which calculates the estimate of θ_S required by the transformation from dq0 to abc variables. Note that a speed sensor is required to provide the rotor speed measurement required by the estimator. Also notice that the estimator requires knowledge of the rotor time constant $\tau_R = L_R/R_{aR}$. In general, this will not be known exactly, both due to uncertainty in the machine parameters as well as due to the fact that the rotor resistance R_{aR} will undoubtedly change with temperature as the motor is operated. It can be shown that errors in τ_R result in an offset in the estimate of θ_S, which in turn will result in an error in the estimate for the position of the rotor flux with the result that the applied armature currents will not be exactly aligned with the direct- and quadrature-axes. The torque controller will still work basically as expected, although there will be corresponding errors in the torque and rotor flux. As with the synchronous motor, the RMS armature flux-linkages can be found from

$$(\lambda_a)_{rms} = \sqrt{\frac{\lambda_D^2+\lambda_Q^2}{2}} \tag{3.23}$$

Combining Equations 3.4 and 3.19 gives

$$\lambda_Q = L_S i_Q + L_m i_{QR} = \left(L_s - \frac{L_m^2}{L_R}\right) i_Q \tag{3.24}$$

Substituting Equations 3.17 and 3.24 into Equation. 3.23 gives

$$(\lambda_a)_{rms} = \sqrt{\frac{L_S^2 i_D^2+\left(L_s-\frac{L_m^2}{L_R}\right)^2 i_Q^2}{2}} \tag{3.25}$$

Finally, the rms line-to-neutral armature voltage can be found as

$$V_a = \sqrt{\frac{v_D^2+v_Q^2}{2}} = \sqrt{\frac{\left(R_a i_D-\omega_e\lambda_Q\right)^2+\left(R_a i_Q-\omega_e\lambda_D\right)^2}{2}}$$

$$= \sqrt{\frac{\left(R_a i_D-\omega_e\left(L_s-\frac{L_m^2}{L_R}\right)i_Q\right)^2+\left(R_a i_Q-\omega_e L_S i_D\right)^2}{2}} \tag{3.26}$$

These equations show that the armature flux linkages and terminal voltage are determined by both the direct- and quadrature-axis components of the armature cur- rent. Thus, the block marked "Auxiliary Controller" in Figure 3.3 .which calculates the reference values for the direct- and quadrature-axis currents, must calculate the reference currents (i_D)ref and (i_Q)ref which achieve the desired torque subject to con- straints on armature flux linkages (to avoid saturation in the motor), armature current, $I_{a_{rms}} = \sqrt{\frac{i_D^2+i_Q^2}{2}}$ (to avoid excessive armature heating) and armature voltage (to avoid potential insulation damage).

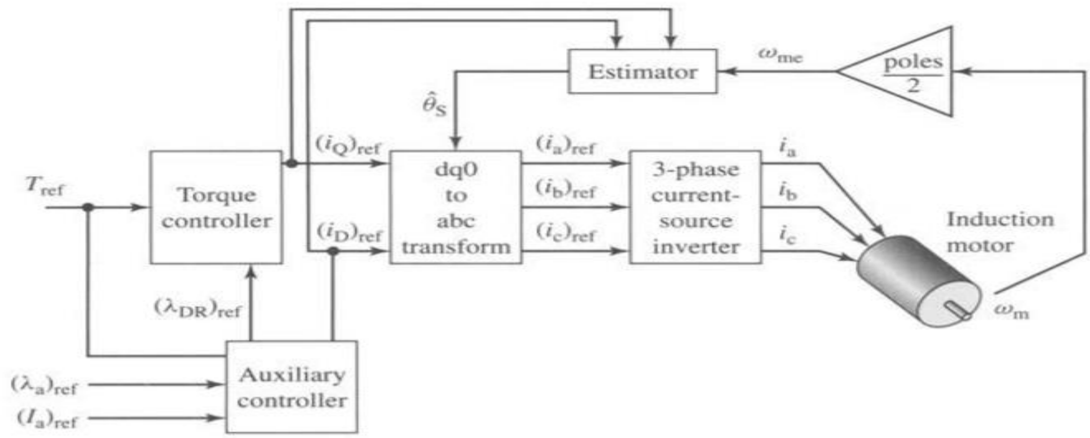


Figure 3.3: Block diagram of a field-oriented torque-control system for an induction motor

3.5 Voltage Source Inverter

Both FOC and DTC strategies require an inverter to convert the low voltage control signals to high voltage to drive the motor. The inverter is connected to the motor terminals as seen in figure 4.6 and is controlled by three signal SA,B,C. Each signal controls both high h and low l side switches of the corresponding phase. When signal SA is high, switch Ah is turned on while switch Al turned off. When signal SA is low, switch Ah is turned off while switch Al turned on. Same method is applied for the other two phases B and C.

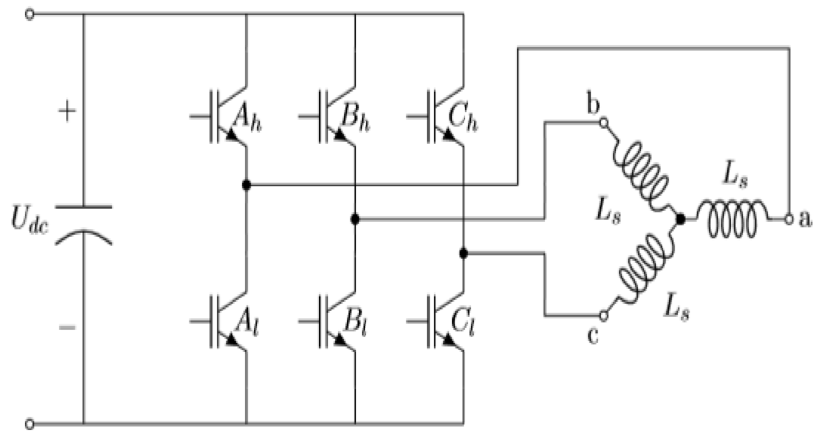


Figure 3.4: Output stage of a two level three phase voltage source inverter with an ideal three phase motor model connected

3.6 Hysteresis Controller

In Figure 3.6. In each phase, the actual current is compared with the reference current, and the difference (current error) is applied to a hysteresis controller, whose output signal constitutes the switching variable for this phase. Taking phase A as an example, the characteristic of the hysteresis controller is given by

$$a = \begin{cases} 0 \quad if \;\; \Delta i_a < -\frac{h}{2} \\ 1 \quad if \;\; \Delta i_a > \frac{h}{2} \end{cases} \tag{3.27}$$

where Δi_a denotes the current error and h is the width of the tolerance band. With the current error within the tolerance band, the value of remains unchanged. The bang-bang current control is characterized by a fast response to rapid changes of the reference current. Many modifications of the basic scheme have been proposed to stabilize the switching frequency and reduce the interaction between phases.

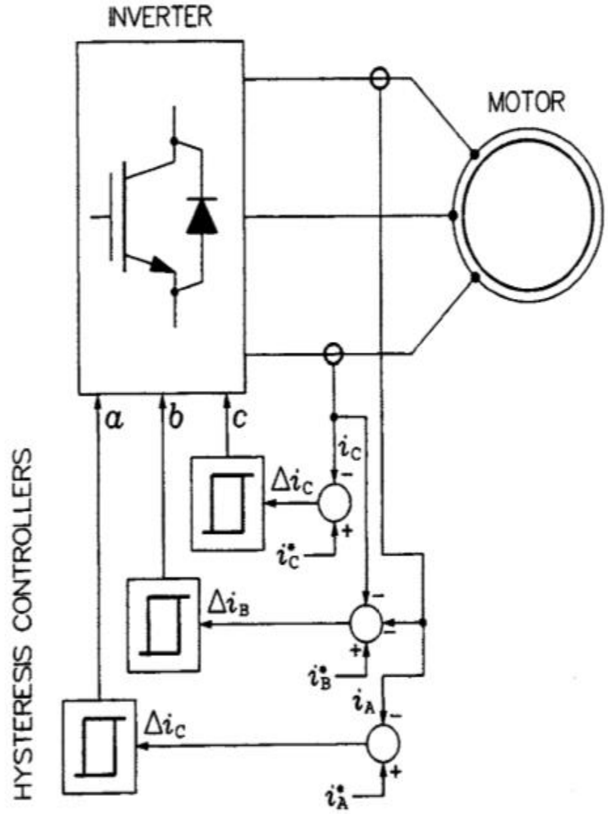


Figure 3.5: Block diagram of hysteresis current controller scheme

CHAPTER FOUR

SIMULATION AND RESLULTS

4.1 Introduction

All simulations have been implemented in Simulink, the software provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement and test a variety of time-varying systems. This makes it simpler to visualize and rapidly develop a control system unlike traditional C or Matlab-code.

4.2 Layout

The control circuit has been implemented in matlab-simulink by using DC source and power electronic inverter to control the speed of three phase induction motor.

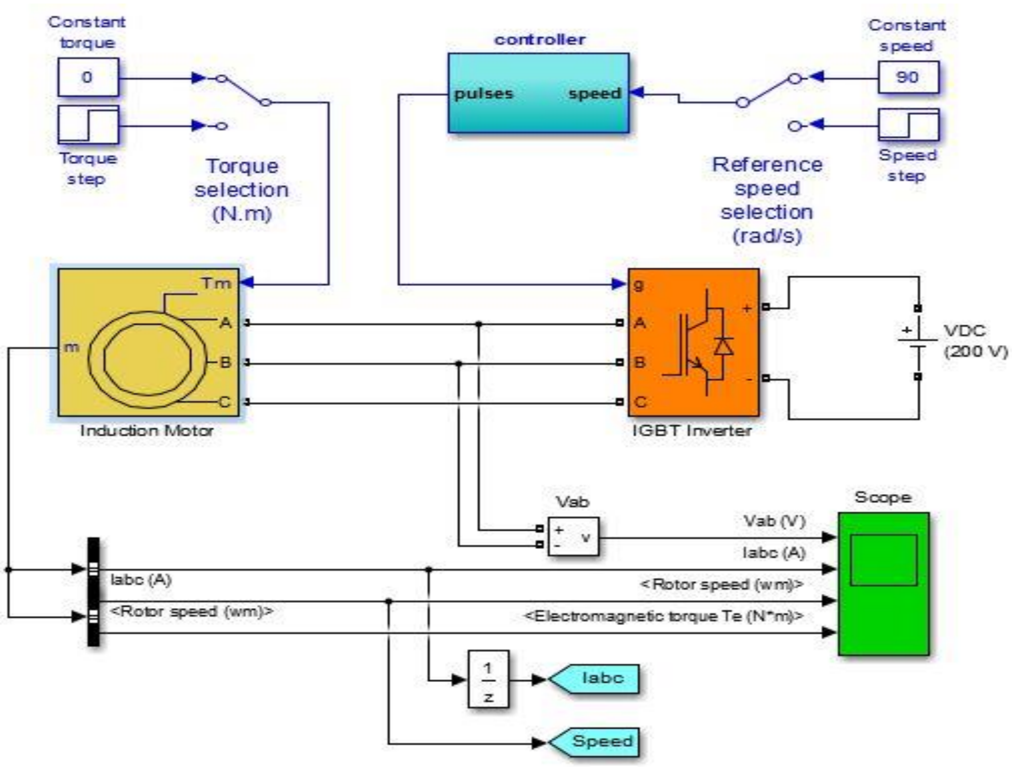


Figure 4.1: schematic diagram of project circuit

4.2.1 Induction Motor

The 0.75 kW machine used in simulations is not representative to all induction machines. The p.u. stator resistance is much higher for such a small machine than for a larger one. However, as a large stator resistance makes flux estimation more difficult at low frequencies, the chosen machine represents a ”near worst case”. The parameter of induction for simulation is shown in Table 4.1

Table.4.1: Induction motor parameters

Type of connection	Δ/Y
Rated power	0.75 Kw
Rated voltage	220/380 V
Rated current	3.63/2.1 A
Rated speed	1390 rpm
Frequency	50 Hz
Cosϕ	0.76
Rs	3.60 Ω
Rr	2.47 Ω
Ls1	0.0128H
Lr1	0.0128 H
Lm	0.148 H
k γ	0.920
LM	0.160 H
LL	0.0291 H
J	2.1*10–3 kg m2
H	37*10–3 s Ψ
V/F	0.57

4.2.2 Power electronic inverter

The power electronic inverter employed to convert a dc supply to an ac level of a definite frequency and value .the controlled semiconductor devices used IGBT/DIODE and the parameter are shown in Table 4.2.

Table.4.2 Converter parameters

Snubber resistance Rs	1000 Ohms
Snubber capacitance Cs	inf F
R_{on}	0.001 Ohms
Device Vf=0.8 V	0.8V
Diode V_{fd}	0.8V
Fall time T_f	1e-6 sec
Tail time T_t	1e-6 sec

4.2.3 Controller

The schematic diagram controller used for control motor speed is built using hysteresis as shown below

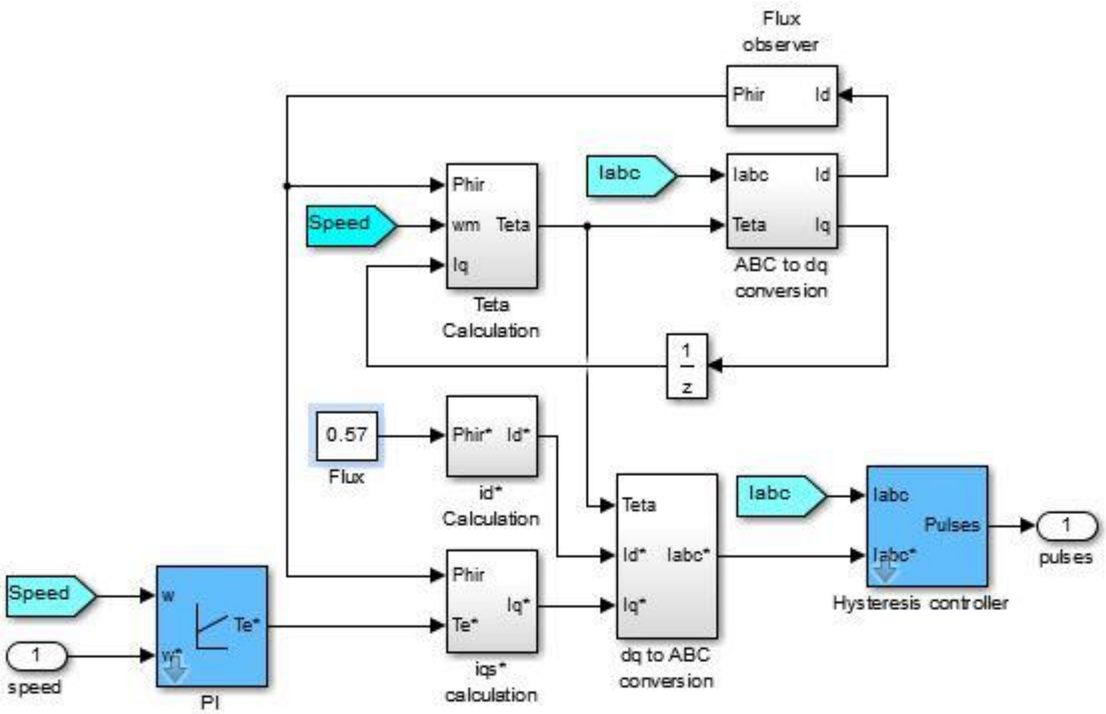


Figure 4.2: Shematic diagram of FOC controller

A- PI controller (speed controller)

It tunes the error signal between reference and actual speed with integral and proportional coefficients and describe by:

$$error(t) = speed\ reference - speed\ actual$$

$$P.I\ output = kp\big(error(t)\big) + ki \int (error(t))dt \qquad (4.1)$$

B- Iq reference calculation

The quadratic current reference is calculated as follow

I_q= (2/3) * (2/p) * (L_r/L_m) * (T_e / Flux) (4.2)

Where

$L_r = Ll'_r + L_m$ (4.3)

C- Id reference calculation (I_d^*)

The direct current reference is calculated as follow

$I_d^* = Flux^* / L_m$ (4.4)

D- Theta calculation (Ɵ)

From the dynamic equations of the induction machine in the synchronous rotating reference frames. The electrical field angle is found as follow

Theta= Electrical angle= integ ($\omega_r + \omega_m$) (4.5)

Where

ω_r = Rotor frequency (rad/s) = $L_m * I_q / (T_r * Flux)$ (4.6)

E- Flux observer

It determine the flux of motor from the time constant of rotor as the following Equation

Flux = $L_m * I_d / (1 + T_r .s)$ (4.7)

F- ABC to dq conversion

It transforms the rotating 3.ϕ into fixed (d,q) axis. The transform matrix is expressed as shown below.

$$\begin{bmatrix} Id \\ Iq \\ Io \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & cos(\theta - 2\pi/3) & cos(\theta - 4\pi/3) \\ sin\,\theta & sin(\theta - 2\pi/3) & sin(\theta - 4\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \quad (4.8)$$

G- dq to ABC Conversion

It transforms the fixed (d,q) axis into rotating 3.ϕ . The transform matrix is expressed as shown below.

$$\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & sin\,\theta & 1/\sqrt{2} \\ cos(\theta - 2\pi/3) & sin(\theta - 2\pi/3) & 1/\sqrt{2} \\ cos(\theta - 4\pi/3) & sin(\theta - 4\pi/3) & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} Id \\ Iq \\ Io \end{bmatrix} \tag{4.9}$$

H- Hysteresis controller

It is compare the reference current with actual current to determine the current error to the following equation

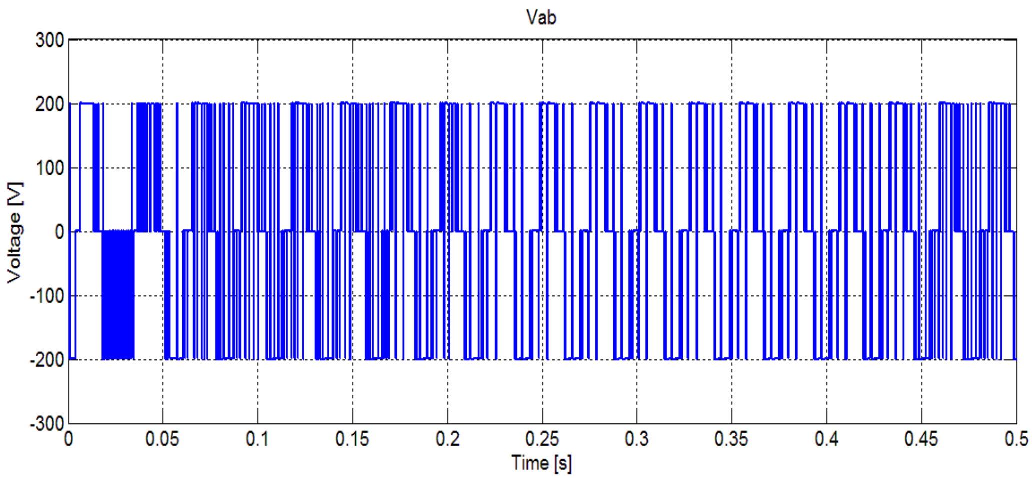
$$a = \begin{cases} 0 \;\; if \;\; \Delta i_a < -\frac{h}{2} \\ 1 \;\; if \;\; \Delta i_a > \frac{h}{2} \end{cases} \tag{4.10}$$

4.3 Scenarios

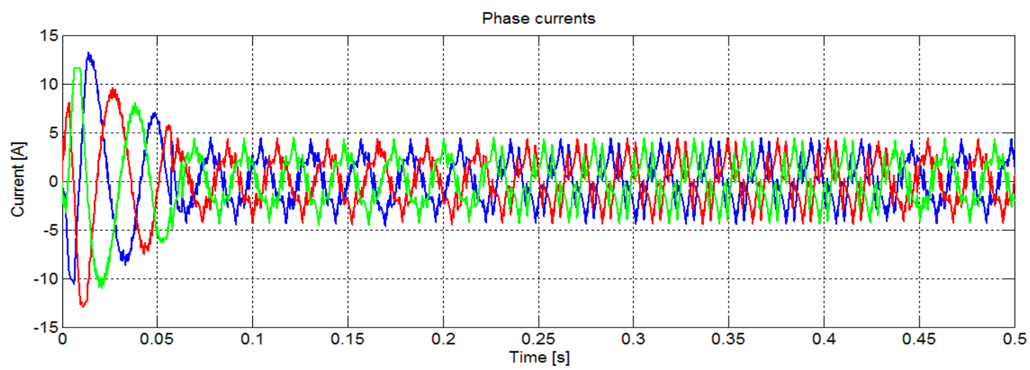
All simulations were done with a DC source voltage of 200V dc an 2μs sample time, the torque is also limited to max 5Nm. Figure 4.3. shows a simulation from stand still up to 120rad/s without load. Figure 4.4 shows the response of torque with operation of varying speed. Figure 4.5 shows the response of speed with operation of varying torque.

4.3.1 Normal operation response

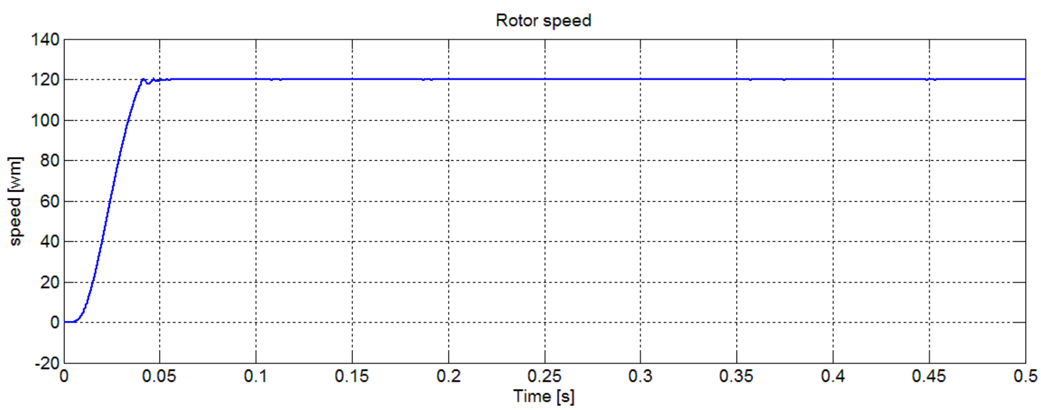
Figure 4.3 shows the stator voltage, the stator current, the torque and the speed waveforms at no-load for a 0.75kw motor. Figure 4.3 c shows that the machine is response and rotates at 120rpm as set by reference speed and the torque its ripple around zero. The time response to reach the rated speed is 0.005s.The simulations have shown that the FOC has high torque ripple but these ripple can be eliminated if PID controller is used instead of hysteresis current control. Also three phase current of the motor is contain multiple of harmonics order and not pure sinusoidal and these require installation of filter to conceal the harmonics. The increase of motor current in first cycles is due to starting and may be controlled using soft starter.



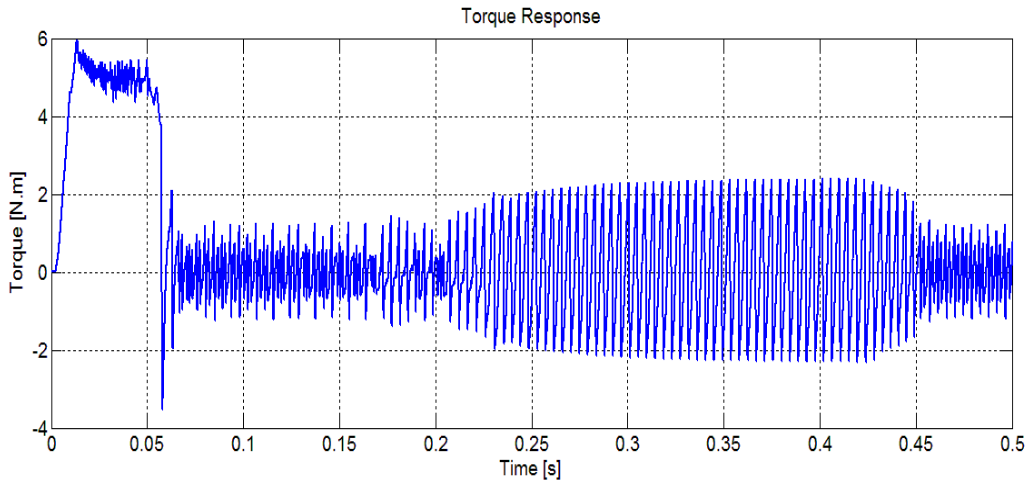
(a) Motor line voltage



(b) Stator current



(c) Motor speed

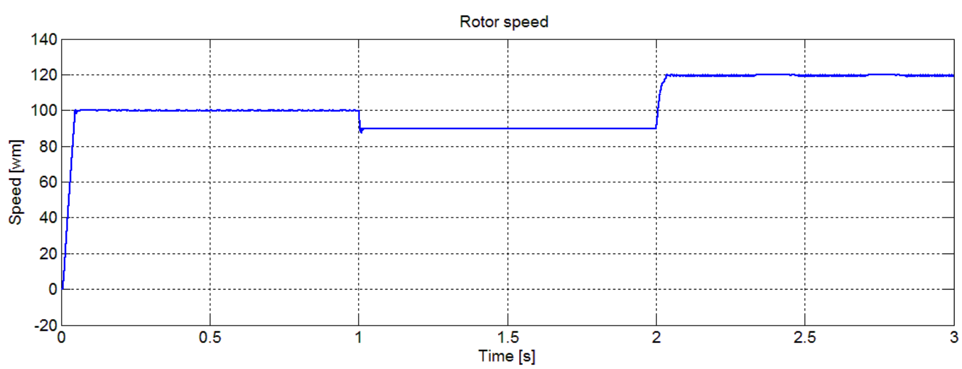


(c) Motor torque

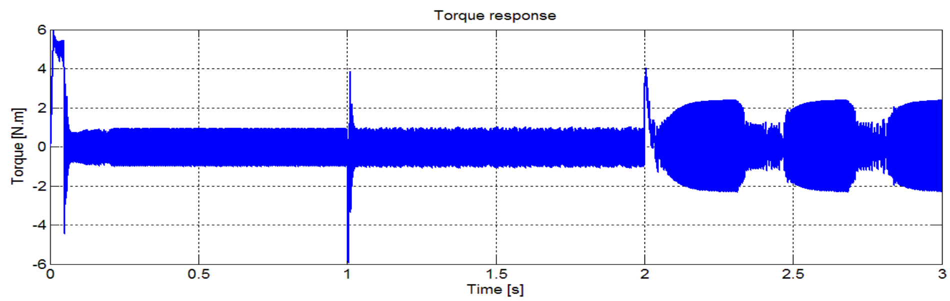
Figure 4.3: Simulation result during normal operation

4.3.2 Response with varying speed

Figure 4.4 shows the stator voltage, the stator current, the torque and the speed waveforms at variable speed of motor and at no-load. Figure 4.4a demonstrates the robustness of the control system which adds possibilities of change speed setting point if required. The motor speed setting point is 100RPM between 0 and 1sed and 90RPM between 1 and 2sec and changed to 120RPM between 2 to 3sec. Fig.4.4a shows that the machine is response and changes its speed according to setting points.



(a) Motor speed

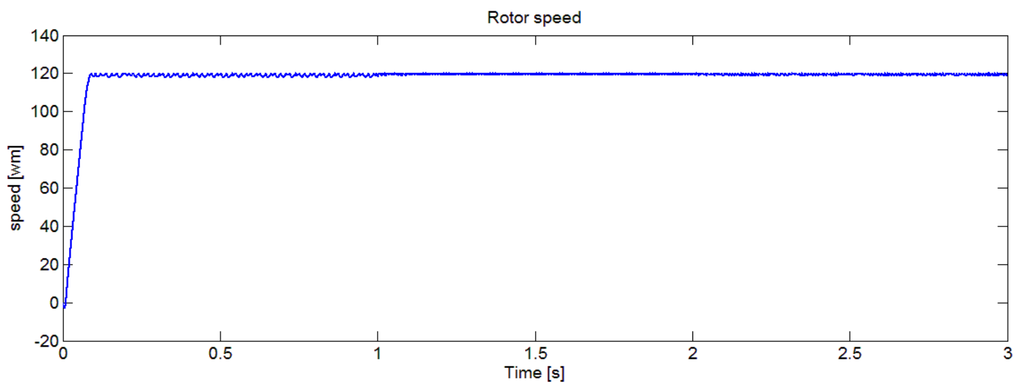


(b) Motor torque

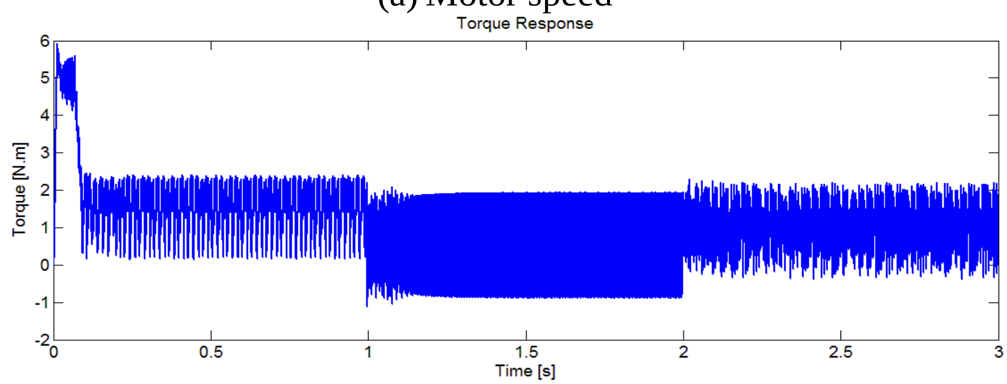
Figure 4.4: Simulation result during variable speed operation

4.3.3Response with varying torque

In Figure 4.6a the motor speed remain constant although the motor torque is increased and varied as shown in Figure 4.6b. The motor torque was 1.5 Nm between 0 and 1s and 0.5Nm between 1 and 2sec and changed to 1Nm between 2 to 3sec. in all case the motor speed remain unchanged (120RPM)



(a) Motor speed



(b) Motor torque

Figure 4.5: Simulation result during variable torque

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 conclusions

In this work, the main aspects of the induction motor are speed control of this machine by power-electronic to improve the performance of the induction motor .the machine has been makes like a DC motor where decomposed to two perpendicular axis direct and quadratic axis. the direct axis contain magnetic component and the quadratic axis contain magnetic motive force component. Therefore any change in the load (mmf component) does not affect in the machine flux. make machine operate with high dynamic response as shows in the results.so Current control of electric motor is important not only for torque control, but also for reaching maximum efficiency. The FOC is normally considered to need more complex calculations to run.

The simulations have shown that the FOC has high torque ripple but these ripple can be eliminated if PID controller is used instead of hysteresis current control. Also three phase current of the motor is contain multiple of harmonics order and not pure sinusoidal and these require installation of filter to conceal the harmonics.

5.2 Recommendation

- Design and implementation of the circuit in laboratory.
- Investigation of other control techniques such as senseless control or Try the project with SPWM or SVPWM and compere the result.

REFERENCES

[1] Malcolm Barnes, “Practical Variable Speed Drives and Power Electronics”, British Library,2003, UK

[2] A. E. Fitzgerald, “Electric Machinery”, McGraw-Hill,2003, United States

[3] Thomas A. L1po, “The Field Orientation Principle in Control of Induction Motors”, Kluwer Academic,1994, New York

[4] N. N. HANCOCK, “Matrix Analysis of Electrical Machinery”, Pergamon Press Ltd, 1974, New York