A PROJECT REPORT

ON

"SPEED CONTROL OF THREE PHASE INDUCTION MOTOR USING TWO LEVEL VECTOR CONTROL"

Submitted to

UNIVERSITY OF MUMBAI

In Partial Fulfillment of the Requirement for the Award of

BACHELOR'S DEGREE IN

ELECTRICAL ENGINEERING

BY

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This is to certify that Mr. ______________________________

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Has satisfactorily completed his Project Work entitled "Speed Control of Three Phase Induction Motor using Two Level vector control" along with his batch mate's fulfillment for the BACHELOR OF ELECTRICAL ENGINEERING during the academic year of 2018-2019

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Acknowledgements

It is indeed a matter of great pleasure and proud privilege to be able to present this project on **"Speed Control of Three Phase Induction Motor Using Two Level Vector Control".**

The completion of the project work is a millstone in student life and its execution is inevitable in the hands of guide. We are highly indebted the project guide **MRS SHRADDHA V. HULE** (Assistant Professor at AIKTC), **SHRI B.M BARAPATRE** along with his colleague **SHRI G.K DAS** for his invaluable guidance and appreciation for giving form and substance to this report. It is due to his enduring efforts; patience and enthusiasm, which has given a sense of direction and purposefulness to this project and ultimately made it a success.

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Really it is highly impossible to repay the debt of all the people who have directly or indirectly helped us for performing the project.

Project Approval for Bachelor of Engineering

This project entitled "**Speed Control of Three Phase Induction Motor Using Two Level Vector Control**" by *SIDDIQUI SHABBIR AHMED (16DEE84), KHAN HUSSAIN I. PATHAN (16DEE67), MAHFUZ ALAM (16DEE62) TAHIR SHAIKH(14EE40)* is approved for the degree of ***Bachelor of Engineering in Department of Electrical Engineering.***

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Declaration

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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PREFACE

We take an opportunity to present this project report on **"Speed Control of Three Phase Induction Motor Using Two Level Vector Control."** and put before readers some useful information regarding our project.

We have made sincere attempts and taken every care to present this matter in precise and compact form, the language being as simple as possible.

We are sure that the information contained in this volume would certainly prove useful for better insight in the scope and dimension of this project in its true perspective.

The task of completion of the project though being difficulty was made quite simple, interesting and successful due to deep involvement and complete dedication of our group members.

ABSTRACT

The main objective of this project is to introduce the non-conventional approach of speed control of ac induction machine that is vector control or field oriented control of induction motor. The advantages of vector control and need of vector control is explained, also the need of field oriented control of induction motor is mentioned and the various methods of FOC is illustrated.

The project entitled "Speed Control of Three Phase Induction Motor Using Two Level Vector Control" is conducted at control and instrumentation division of one of the premier research institute of India **Bhabha Atomic Research Centre, Trombay, Mumbai** where we implemented the dynamic modelling of three phase induction motor and two level space vector pulse width modulation is also implemented on matlab Simulink along with the detailed study of field oriented control of three phase induction motor.

Induction motor or asynchronous motor is the most extensively used in the industrial, commercial, residential settings as these motors are simple and robust in construction having low cost and minimum maintenance, high dependability and sufficiently high proficiency due to these conveniences ACIM are most widely used in industrial applications. However, control of ACIM is more difficult than the control of DC machines, with the help of scalar methods speed can be control as it is simple to implement but it has the coupling effect thus it is responsible for slow response which leads to oscillations due to higher order effect. But in many operations and machinery in industries sensitive revolutions and torque adjustment have to be peripheral with high accuracy, so dc motor drives were generally used variable speed drives because of the simplicity of control due to decoupling between armature current and the field current. This study has been undertaken to investigate the speed control ACIM using field oriented control. The principle of vector control of electric drives is based on the control of both the magnitude and the phase of each phase current and voltage. for this purpose, the study of available conventional and non-conventional approaches has been presented. This report also presents a clear study which illustrates introduction of efficient vector control of ACIM.

Keywords- ACIM-ac induction motors, vector control, barc, scalar control, dc motor drives

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"Speed Control of Three Phase Induction Motor using Two Level Vector Control."

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Chapter 1

Introduction

In industry today, induction motors are preferred due to some superior properties such as their having a cheap and simple structure compared to other motors, their capability to operate under all and every harsh ambient conditions including explosions, and their being maintenance-free and they are usually used in variable-speed drive systems. The variable-speed control of induction motors can be performed in two different manner scalar and vector. In the scalar speed control method, the steady state model of the motor is used and the speed control is carried out with the ratio of the voltage to the frequency (V/f) kept fixed. This speed control method is used because of its easy implementation. The fundamental property of this method is to keep ratio of the voltage, which is supplied to the stator at speed between zero and the rated value, to the frequency (V/f), and therefore the air gap flux and the induced torque as fixed. Speed control may be carried out keeping the voltage fixed and increasing the frequency at speeds greater than the rated speed, therefore weakening the air gap flux. The greatest disadvantage of scalar control is that the rated torque is reduced as a result of the relative effect of the voltage, which decreases with the stator resistance at low voltages of 3-5 Hz, on the phase voltage. Thanks to the developments in the microprocessor technology, vector control systems became applicable for the pulse width modulation (PWM) control of three-phase inverters. In many operations and machinery in industry, sensitive revolution and torque adjustments have to be performed with high accuracy. Field-oriented control of the alternative current motor adjusts the component that constitute the flux and the torque independently in closed loop and enables obtaining high torque even in low speed in addition to many other advantageous that cannot be achieved in scalar mode.

1.1 Feasibility studies

This study has been undertaken to investigate the speed control ACIM using field oriented control. The principle of vector control of electric drives is based on the control of both the magnitude and the phase of each phase current and voltage. For this purpose, the study of available conventional and non-conventional approaches has been presented. This report also presents a clear study which illustrates introduction of efficient vector control of AC induction machine (ACIM).Below figure illustrates the classification of electric motors.

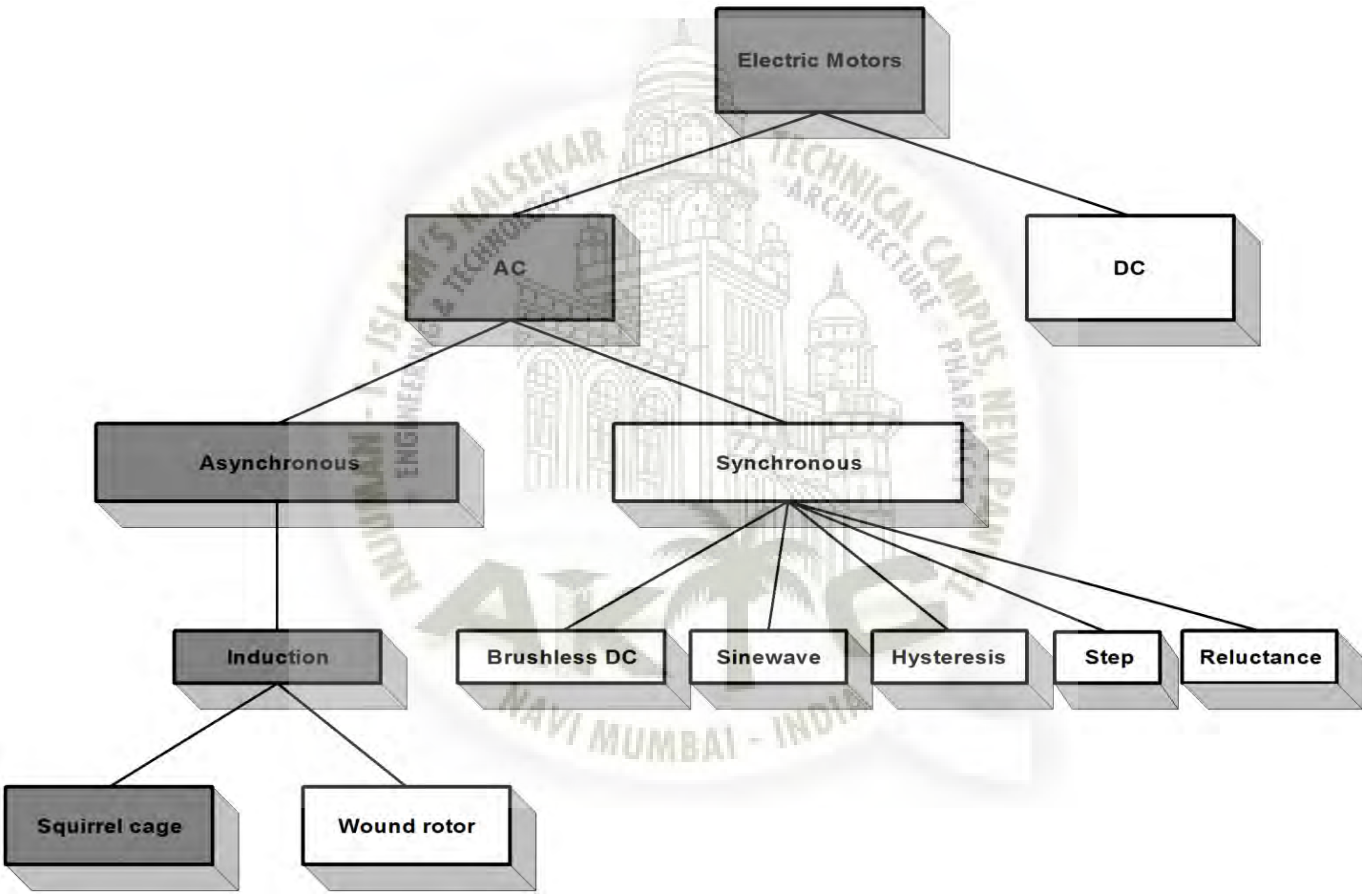

Figure 1: Electric Motors

1.2 Problem Statements:

1.2.1 Scalar Control Methods:

Scalar control methods are convenient for applications where the speed changes slowly, except for low speeds. However, it is not possible to use it in applications where sensitive speed and torque adjustments are required.

The Speed of Induction Motor is changed from Both Stator and Rotor Side. The speed controls of three phase induction motor from stator side are further classified as:

V / f control or frequency control

Changing the number of stator poles

Controlling supply voltage

Adding rheostat in the stator circuit

The speed controls of three phase induction motor from rotor side are further classified as:

Adding external resistance on rotor side

Cascade control method

Injecting slip frequency emf into rotor side

1.2.2 Speed Control from Stator Side

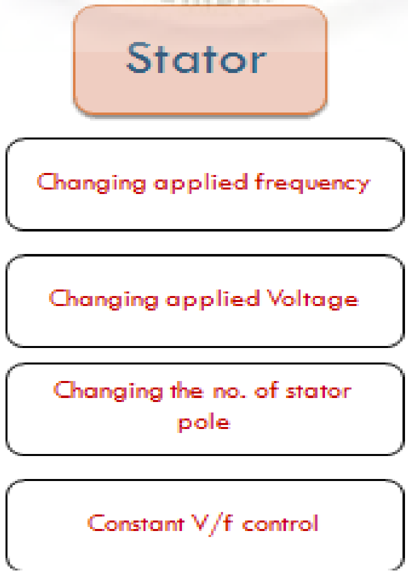

Figure 2: Speed Control Methods from Rotor Side

- **V / f Control or Frequency Control**

  Whenever three phase supply is given to three phase induction motor *rotating magnetic field* is produced which rotates at synchronous speed given by $N_S = \frac{120f}{P}$. In three phase induction motor emf is induced by induction similar to that of *transformer* which is given by $V = 4.44\emptyset KTf$ Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of *flux* causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, it's important to maintain flux , φ constant and it is only possible if we change *voltage*. i.e. if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

- **Controlling Supply Voltage**

  The torque produced by running three phase induction motor is given by $T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$. In low slip region $(sX_2)^2$ is very very small as compared to R_2. So, it can be neglected. So torque becomes $T \propto \frac{sE_2^2}{R_2}$. since rotor resistance, R_2 is constant so the equation of torque further reduces to $T \propto sE_2^2$. We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$. The equation above clears that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same, and it is only possible if we increase the slip and if the slip increases the motor will run at a reduced speed. This method of speed control is rarely used because a small change in speed requires a large reduction in voltage, and hence the current drawn by motor increases, which cause overheating of the induction motor.

- **Changing the number of stator poles**:

  The stator poles can be changed by two methods

1. Multiple stator winding method.
2. Pole amplitude modulation method (PAM)

1. **Multiple Stator Winding Method**

   In this method of speed control of three phase induction motor, we provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. Disadvantages of this method are that the smooth speed control is not possible. This method is costlier and less efficient as two different stator windings are required. This method of speed control can only be applied to squirrel cage motor.

2. **Pole Amplitude Modulation Method (PAM)**
In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

Let $f_1(\theta)$ be the original mmf wave of induction motor whose speed is to be controlled. $f_2(\theta)$ be the modulation mmf wave. P_1 be the number of poles of induction motor whose speed is to be controlled. P_2 be the number of poles of modulation wave.

$$f_1(\theta) = F_1 \sin\frac{P_1\theta}{2}$$

$$f_2(\theta) = F_2 \sin\frac{P_2\theta}{2}$$

After modulation resultant mmf wave $F_r = F_1 F_2 \sin\frac{P_1\theta}{2} \sin\frac{P_2\theta}{2}$

Apply formula for $2\sin A \sin B = \cos\frac{A-B}{2} - \cos\frac{A+B}{2}$

So we get, resultant mmf wave $F_r(\theta) = F_1 F_2 \frac{\cos\frac{(P_1-P_2)\theta}{2} - \cos\frac{(P_1+P_2)\theta}{2}}{2}$

Therefore, the resultant mmf wave will have two different number of poles i.e. $P_{11} = P_1 - P_2$ and $P_{12} = P_1 + P_2$
Therefore, by changing the number of poles we can easily change the speed of three phase induction motor.

- **Adding Rheostat in Stator Circuit**
In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped. In case of three phase induction motor torque produced is given by $T \propto sV_2^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

1.2.3 Speed Control from Rotor Side

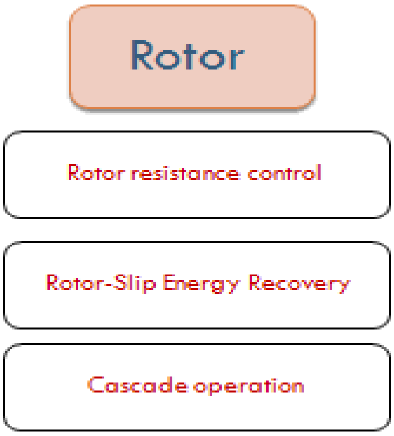

Figure 3: Speed Control Methods from Rotor Side

- **Adding External Resistance on Rotor Side**

  In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is $T \propto \frac{sE_2^2R_2}{R_2^2+(sX_2)^2}$.

  The three-phase induction motor operates in a low slip region. In low slip region term $(sX)^2$ becomes very small as compared to R_2. So, it can be neglected. And also E_2 is constant. So the equation of torque after simplification becomes,

$$T \propto \frac{s}{R^2}$$

  Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further result in the decrease in rotor speed. Thus by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

1. The speed above the normal value is not possible.
2. Large speed change requires a large value of resistance, and if such large value of resistance is added in the circuit, it will cause large copper loss and hence reduction in efficiency.
3. Presence of resistance causes more losses.
4. This method cannot be used for squirrel cage induction motor.

1.2.4 Cascade Control Method

In this method of speed control of three phase induction motor, the two three-phase induction motors are connected on a common shaft and hence called cascaded motor. One motor is the called the main motor, and another motor is called the auxiliary motor. The three-phase supply is given to the stator of the main motor while the auxiliary motor is derived at a slip frequency from the slip ring of the main motor. Let N_{S1} be the synchronous speed of the main motor. N_{S2} be the synchronous speed of the auxiliary motor. P_1 be the number of poles of the main motor. P_2 be the number of poles of the auxiliary motor. F is the supply frequency. F_1 is the frequency of rotor induced emf of the main motor. N is the set speed, and it remains same for both the main and auxiliary motor as both the motors are mounted on the common shaft. S_1 is the slip of main

$$S_1 = \frac{N_{S_1} - N}{N_{S_1}}$$

$$f_1 = S_1 f$$

$$f_1 = f_2$$

The Auxiliary Motor is supplied with same frequency as the main motor

$$N_{S_2} = \frac{120 f_2}{P_2} = \frac{120 f_1}{P_2}$$

i.e. $N_{S_2} = \frac{120 S_1 f}{P_2}$

Now put the value of $S_1 = \frac{N_{S_1} - N}{N_{S_1}}$

We get, $N_{S_2} = \frac{120(N_{S_1} - N) f}{N_{S_1} P_2}$

At no load, the speed of auxiliary rotor is almost same as its synchronous speed i.e. $N = N_{S_2}$

$$N = \frac{120(N_{S_1} - N) f}{N_{S_1} P_2}$$

Now rearrange the above equation and find out the value of N, we get

$$N = \frac{120 f}{P_1 - P_2}$$

This cascaded set of two motors will now run at new speed having number of poles *(P1 + P2)*. In the above method the torque produced by the main and auxiliary motor will act in same direction, resulting in number of poles *(P1 + P2)*. Such type of cascading is called cumulative cascading. There is one more type of cascading in which the torque produced by the main motor is in opposite direction to that of auxiliary motor. Such type of cascading is called differential cascading; resulting in speed corresponds to number of poles *(P1 - P2)*. In this method of speed control of three phase induction motor, four different speeds can be obtained

When only main induction motor work, having speed corresponds to $N_{S_1} = \frac{120f}{P_1}$

When only auxiliary induction motor work, having speed corresponds to $N_{S_2} = \frac{120f}{P_2}$

When cumulative cascading is done, then the complete set runs at a speed of $N = \frac{120f}{P_1+P_2}$

When differential cascading is done, then the complete set runs at a speed of $N = \frac{120f}{P_1-P_2}$

- **Injecting Slip Frequency EMF into Rotor Side**

  When the speed control of three phase induction motor is done by adding resistance in rotor circuit, some part of power called the slip power is lost as I^2R losses. Therefore, the efficiency of three phase induction motor is reduced by this method of speed control. This slip power loss can be recovered and supplied back to improve the overall efficiency of the three-phase induction motor and this scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit. The injected emf can either oppose the rotor induced emf or aids the rotor induced emf. If it opposes the rotor induced emf, the total rotor resistance increases and hence the speed is decreased and if the injected emf aids the main rotor emf the total rotor resistance decreases and hence speed increases. Therefore, by injecting induced emf in the rotor circuit, the speed can be easily controlled. The main advantage of this type of speed control of three phase induction motor is that a wide range of speed control is possible whether it is above normal or below normal speed.

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Chapter 2

Literature Review

2.1 Introduction:

This chapter presents a comprehensive review of the control techniques for high performance IM drives. Moreover, the different implementation techniques for IM drives are also reviewed. Moreover, the literature related to adaptive, intelligent, and nonlinear speed controller for high performance IM drives is explored. Finally, the theoretical bases including mathematical model of IM for Indirect Field Oriented Control (IFOC), induction motor equation.

Keywords: literature review, direct vector control, indirect vector control, Space Vector Pulse width Modulation (SVPWM)

2.2 Literature Survey

1. Mathematical Modeling of 3-Phase Induction Motor Using MATLAB-Simulink- Mr. Punit L. Ratnani, Dr. A. G. Thosar have explained dynamic analysis of symmetrical induction machines in the arbitrary reference frame has been intensively used as a standard simulation approach from which any particular mode of operation may then be developed. The dynamic modeling sets all the mechanical equations for the inertia, torque and speed versus time.
2. Design and Application of A New Sensorless Induction Motor Drive Impelemented by Using Field Oriented Vector Control Method- Ibrahim Senol, Nur Bekiroglu, Selin Ozeira have explained a three-phase induction motor drive using field-oriented vector controlled algorithm was designed and implemented. Sensorless speed control was achieved via vector control. The control algorithm was carried out using real-time application.
3. Field Orientated Control of 3-Phase AC-Motors by Texas Instruments (TI) have explained principle of vector control of electrical drives is based on the control of both the magnitude and the phase of each phase current and voltage. For as long as this type of control considers the three phase system as three independent systems the control will remain analog and thus present several drawbacks.

4. Sensorless Speed Control of a Three-phase Induction motor: An experiment approach by Vo Thanh Ha, Nguyen Van Thang, Duong Anh Tuan, Pham Thi Hong Hanh, this paper represents a method of estimating the speed of an induction motor. This method is based on speed sensorless estimation of vector controlled induction motor drive and adaptive control theory. A flux observer of an induction motor with a parameter adaptive scheme will be proposed. The parameters identified adaptively are stator and rotor resistance. The theoretical basis of indirect field oriented vector control is explained in detail and it is implemented in Matlab, Simulink.

5. Space Vector Based Synchronized PWM Strategies for Field Oriented Control of VSI fed Induction Motor- Mohammed Shafi kp, Joseph Peter, Rijil Ramchand have explained The space vector approach in real time pulse width modulation offers variety of switching patterns for effective control of induction motor drives. In high power motor drives switching frequency of the inverter is very less due to increased losses. The harmonic distortion in the stator current due to low switching frequency can be reduced by using synchronized PWM strategies. In this paper space vector based synchronized PWM strategies are applied to field oriented control of induction motor. Two synchronized PWM strategies are analyzed in this paper, conventional space vector strategy and basic bus clamping strategy. The performances of these strategies are analyzed for different operating conditions in terms of total harmonic distortion of no load current. A combination of PWM strategies can be used to reduce the distortion in line current of the drive operating under different conditions. Synchronization of PWM pulses after the transient period is achieved by generating carrier wave form according to the zero crossing of modulating wave in a phase locked manner.
6. Dynamic d-q Model of Induction Motor Using Simulink by Anand Bellure, Dr. M.S Aspalli, In this paper discuss about a dynamic d-q model of a three phase induction motor in state space form and its computer simulation in MATLAB/SIMULINK. The details on the construction of sub models for the induction motor are given and their implementation in SIMULINK delineated. The required equations are stated at the beginning and then a d-q model of induction motor is developed. This plan could be led to other engineering systems.
7. SVPWM Based Speed Control of Induction Motor with Three Level Inverter Using Proportional Integral Controller by Vikramarajan Jambulingam have explained the design and implementation of an induction in Simulink is uncomplicated and trouble free. In general speed control techniques are

essential in flexible speed drive system. To achieve this it requires variable frequency and supply voltage. Even though there are numbers of pulse width modulations scheme is used to obtain variable frequency and voltage supply from an inverter. It is less used than the space vector pulse width modulation. In the space vector pulse modulation method with proportional integral control of induction motor drive is widely used in high performance drive system. It is due to its characteristics like good power factor and high efficiency.

8. Implementation of Space Vector Modulation for Two Level Inverter and its Comparison with SPWM- Simran Bhalla, Dr.Jagdish Kumar, this paper focuses on step by step development of MATLAB/SIMULINK model of SVPWM.Firstly model of a three-phase VSI is discussedbased on space vector representation.
9. Mathematical Modelling of Dynamic Induction Motor and Performance Analysis with Bearing Fault by Ashish Kamal and V.K. Giri have explained the modelling of 3 phase induction motor having bearing fault is being carried out with the help of dq0 axis transformation. The theory of axis transformation is widely used to create such model because it reduces the complexities of time-varying variables. In the present work, a step by step Simulink implementation of an induction machine using dq0 axis transformations of the stator and rotor variables in the arbitrary reference frame has been carried out.

Chapter 3

Vector Control Method

We can overcome the uncertainties and demerits of scalar method very efficiently by choosing vector methods to control the speed parameters.

3.1 Proposed Methods:

3.1.1 Vector control methods

When it is considered that the quantities to be controlled are the amplitude, phase, and frequency of the current, the defined control quantity becomes the current vector. This control is called the vector control in the literature and arises with the development of space vector theory [7,8]. With this theory, the current vector can be separated into two components. These two components consist, as in the direct current motors, of the component that constitutes the torque and the component that constitutes flux. Thus, the induction motor can be control just like a direct current motor. The fact that the induction motors contain a non-linear structure necessitates more complex control and transformation algorithms compared to the control of direct current motors. In vector control, the control carried out depending on the selection of the flux vectors included in the induction motor.

3.1.2 Process flow chart:

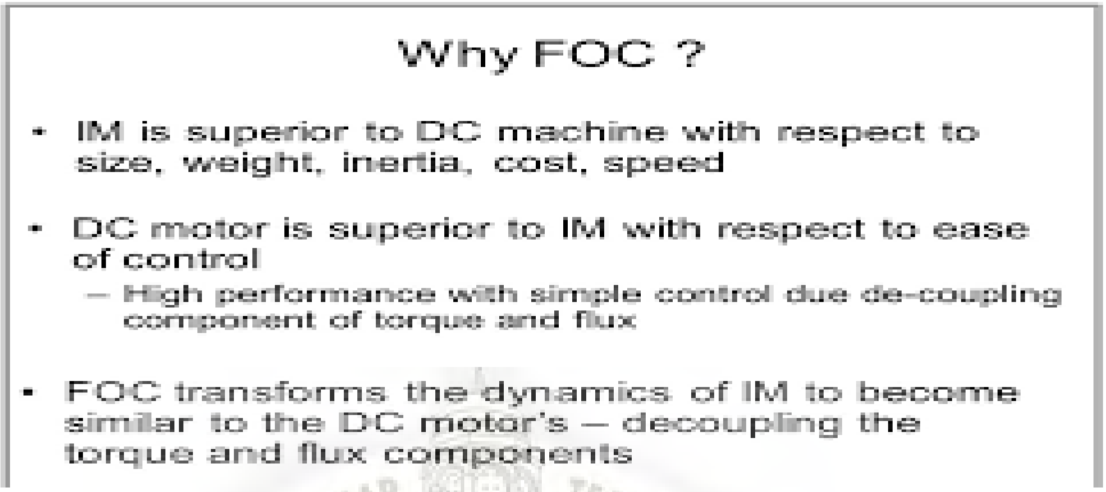


Figure 4: Reason behind FOC

The Field Orientated Control (FOC) consists of controlling the stator current represented by a vector. This control is based on projections which transform a three-phase time and speed dependent system into a two co-ordinate (*d* and *q* co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the *q* co-ordinate) and the flux component (aligned with *d* co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient). The FOC thus solves the classic scheme problems, in the following ways:

- The ease of reaching constant reference (torque component and flux component of the stator current)
- The ease of applying direct torque control because in the (*d, q*) reference frame the expression of the torque is:

  $m \propto \varphi_R i_{sq}$

  By maintaining the amplitude of the rotor flux (ψ_R) at a fixed value we have a linear relationship between torque and torque component (i_{Sq}). We can then control the torque by controlling the torque component of stator current vector.

3.2 Space Vector Definition and Projection:

The three-phase voltages, currents and fluxes of AC-motors can be analyzed in terms of complex space vectors [1][6]. With regard to the currents, the space vector can be defined as follows. Assuming that i_a, i_b, i_c are the instantaneous currents in the stator phases, then the complex stator current vector i_s is defined by:

$$i_s = i_a + \alpha i_b + \alpha^2 i_c$$

Where $\alpha = e^{j\frac{2\pi}{3}}$ and $\alpha^2 = e^{-j\frac{2\pi}{3}}$ represent the spatial operators. The following diagram shows the stator current complex space vector:

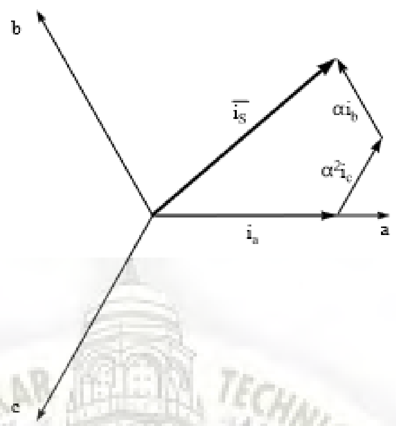


Figure 5: Stator current space vector and its component in (a, b, c)

3 (a, b, c)⇒ (α, β) (the Clarke transformation) which outputs a two co-ordinate time variant system

4 (α, β)⇒ (*d, q*) (the Park transformation) which outputs a two co-ordinate time invariant system

3.2.1 The (a, b, c)-> (α, β) projection (Clarke transformation)

The space vector can be reported in another reference frame with only two orthogonal axis called (α, β). Assuming that the axis-a and the axis-α are in the same direction we have the following vector diagram:

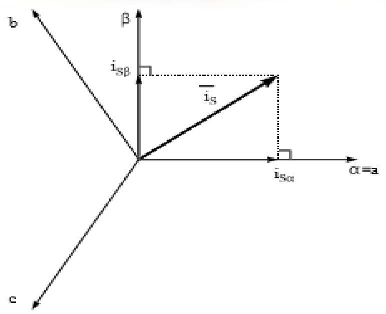


Figure 6: Stator current space vector and its components in (a, b)

The projection that modifies the three phase system into the (α, β) two-dimension orthogonal system is presented below.

$i_{s\alpha} = i_a$

$$i\_s\beta = 1/\sqrt{3}\ i\_b + 2/\sqrt{3}\ i\_c$$

We obtain a two co-ordinate $\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$ system that still depends on time.

3.2.2 The (α, β)-> (d, q) projection (Park transformation)

This is the most important transformation in the FOC. In fact, this projection modifies a two phase orthogonal system (α, β) in the *d, q* rotating reference frame.

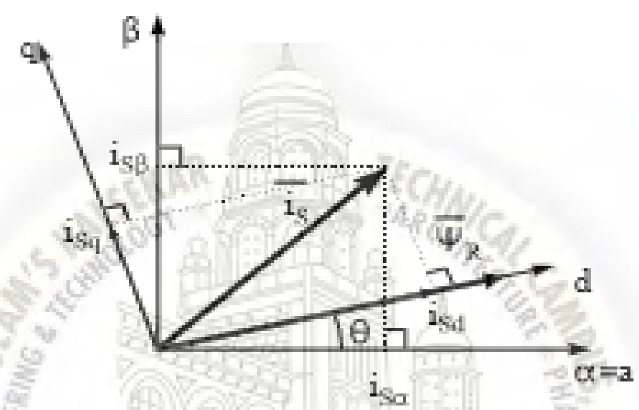


Figure 7: Stator current space vector and its component in (a, b) and in the d, q rotating reference frame

If we consider the *d* axis aligned with the rotor flux, the next diagram illustrates the current vector and the relationship from the two reference frame:

where θ is the rotor flux position. The flux and torque components of the current vector are determined by the following equations:

$$i_{Sd} = i_{S\alpha}\cos\theta + i_{S\beta}\sin\theta$$

$$i_{Sq} = -i_{S\alpha}\sin\theta + i_{S\beta}\cos\theta$$

These components depend on the current vector (α, β) components and on the rotor flux position; if we know the right rotor flux position then, by this projection, the *d, q* component becomes a constant. We obtain a two co-ordinate $\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$ system with the following characteristics:

- Two co-ordinate time invariant system
- With i_{Sd} (flux component) and i_{Sq} (torque component) the direct torque control is possible and easy.

3.2.3 d, q to α, β projection (inverse Park transformation)

Here, we introduce from this voltage transformation only the equation that modifies the voltages in *d, q* rotating reference frame in a two phase orthogonal system:

$$V_{s\alpha ref} = V_{sdref}\cos\theta - V_{sqref}\sin\theta$$

$$V_{s\beta ref} = V_{sdref}\sin\theta + V_{sqref}\cos\theta$$

The outputs of this block are the components of the reference vector that we call V_{ref}

V_r is the voltage space vector to be applied to the motor phases.

3.3 The basic scheme for the FOC

The following diagram summarizes the basic scheme of AC motor control with

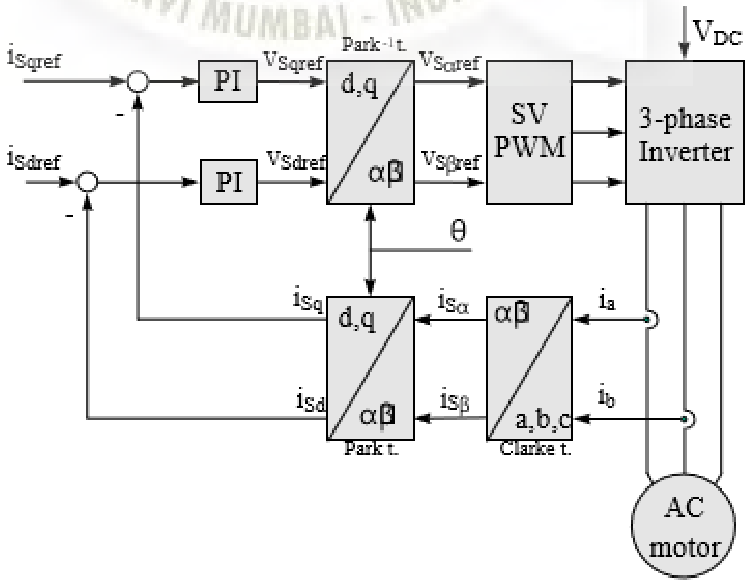


Figure [8]:

Two motor phase currents are measured. These measurements feed the Clarke transformation module. The outputs of this projection are designated $i_{S\alpha}$ and $i_{S\beta}$. These two components of the current are the inputs of the Park transformation that gives the current in the *d, q* rotating reference frame. The i_{Sd} and i_{Sq} components are compared to the references i_{Sdref} (the flux reference) and i_{Sqref} (the torque reference). At this point, this control structure shows an interesting advantage. It can be used to control either synchronous or induction machines by simply changing the flux reference and obtaining rotor flux position. As in synchronous permanent magnet motors, the rotor flux is fixed (determined by the magnets). Hence, when controlling a PMSM, i_{Sdref} should be set to zero. As induction motors need a rotor flux creation in order to operate, the flux reference must not be zero. This conveniently solves one of the major drawbacks of the "classic" control structures: the portability from asynchronous to synchronous drives. The torque command i_{Sqref} could be the output of the speed regulator when we use a speed FOC. The outputs of the current regulators are v_{Sdref} and v_{Sqref}; they are applied to the inverse Park transformation. The outputs of this projection are $v_{S\alpha ref}$ and $v_{S\beta ref}$ which are the components of the stator vector voltage in the α, β stationary orthogonal reference frame. These are the inputs of the Space Vector PWM. The outputs of this block are the signals that drive the inverter. Note that both Park and inverse Park transformations need the rotor flux position. Obtaining this rotor flux position depends on the AC machine type (synchronous or asynchronous machine). Rotor flux position considerations are made in a following paragraph.

Figure 8: Basic scheme of FOC for AC motor

3.3.1 The input for the FOC

Fundamental requirements for the FOC are a knowledge of two phase currents (as the motor is star-connected, the third phase current is also known, since $i_a + i_b + i_c = 0$), and the rotor flux position.

3.3.2 Current sampling

The measured phase currents i_a and i_b are sampled and converted by an A/D converter.

The correct working of the FOC depends on the true measurement of these currents.

3.3.3 Rotor flux position

Knowledge of the rotor flux position is the core of the FOC.

In fact, if there is an error in this variable the rotor flux is not aligned with d-axis and i_{Sd} and i_{Sq} are incorrect flux and torque components of the stator current. The following diagram shows the (a, b, c), (α, β) and (*d, q*) reference frames, and the

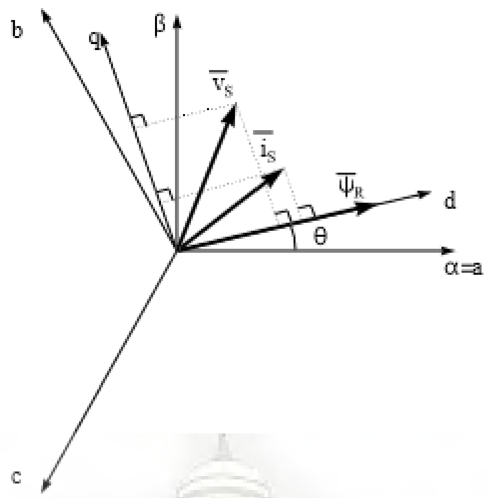


Figure 9: Current, voltage and rotor flux space vectors in the d, q rotating reference frame and their relationship with a, b, c and a, b stationary reference frame

correct position of the rotor flux, the stator current and stator voltage space vector that rotates with *d, q* reference at synchronous speed.
The measure of the rotor flux position is different if we consider synchronous or induction motor.

- In the synchronous machine the rotor speed is equal to the rotor flux speed. Then θ (rotor flux position) is directly measured by position sensor or by integration of rotor speed.
- In the induction machine the rotor speed is not equal to the rotor flux speed (there is a slip speed), then it needs a particular method to calculate θ.

The basic method is the use of the current model [5][6][7] which needs two equations of the motor model in *d,q* reference frame.

3.4 The PI regulator

An electrical drive based on the Field Orientated Control needs two constants as control parameters: the torque component reference I_{Sqref} and the flux component reference $I_{Sdrefef}$. The classic numerical PI (Proportional and Integral) regulator is well suited to regulating the torque and flux feedback to the desired values as it is able to reach constant references, by correctly setting both the P term (K_{pi}) and the I term (K_i) which are respectively responsible for the error sensibility and for the steady state error. The numerical expression of the PI regulator is as follows:

$$U_k = K_{pi}e_k + K_ie_k + \sum_{n=0}^{K-1} e_n$$

which can be represented by the following figure:

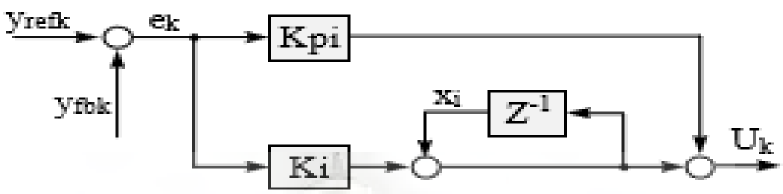


Figure 10: Classical Numerical PI Regulator Structure

The limiting point is that during normal operation, or during the tests, large reference value variations or large disturbances may occur, resulting in saturation and overflow of the regulator variables and output. If they are not controlled, this kind of non-linearity damages the dynamic performance of the system. To solve this problem, one solution is to add to the previous structure a correction of the integral component as depicted in the following diagram:

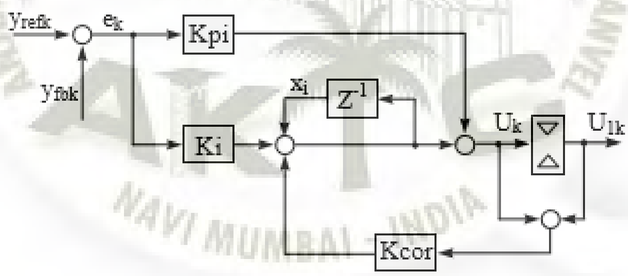


Figure 11: Numerical PI Regulator with Correction of the Integral Term

The integral term correction algorithm in a high level language is given below:

INPUT y_{refk} , y_{fbk}

$e_k = y_{refk} - y_{fbk}$

$u_k = x_i + K_{pi}e_k$

$u_{lk} = u_k$

IF $u_k > u_{max}$ *THEN* $u_{lk} = u_{max}$

IF u_k □ u_{min} *THEN* $u_{lk} = u_{min}$

OUTPUT u_{lk}

$e_{lk} = u_k - u_{lk}$

$$x_i = k_i e_k + k_{cor} e_{lk}$$

With u_{max}, u_{min} we mean the limitations of the output variable.

3.5 Study of FOC Methodologies

3.5.1 Indirect Vector control

There are essentially two general methods of vector control. One, called the direct or feed- back method, was invented by Blaschke and the other, known as the indirect or feed forward method was invented by Hasse. . The two methods differ in the way the rotor angle is determined. In direct FOC the angle is obtained by the terminal voltages and currents, while as in indirect FOC, the angle is obtained by using rotor position measurement and machine parameter's estimation. Field orientation has emerged as a powerful tool for controlling AC machines such as inverter-supplied induction motors/synchronous motors. The complex functions required by field oriented control are executed by intelligent controllers using microcontrollers or digital signal processors (DSP), thus greatly reducing the necessary control hardware. An important requirement to obtain good control performance is to make the motor parameters in the field-oriented controller coincide with the actual parameters of the motor. The ability to inject currents into the motor with a current source opened up new possibilities for parameter determination. It was Takayoshi who described a new identification technique utilizing injected negative sequence components. It is shown that the stator as well as rotor resistance and leakage inductance can be determined on line while the motor is driving the load. The theory is verified with a full-scale hybrid computer simulation of field-oriented controlled PWM inverter based induction motor drive. Here, only the rotor-flux-oriented type of control, also termed" Field-Oriented Control" (FOC), is considered. FOC can be implemented as indirect (feed forward) or direct (feedback) depending on the method used for rotor flux identification. The direct FOC determines the orientation of the air-gap flux by use of a hall-effect sensor, search coil or other measurement techniques. However, using sensors is expensive because special modifications of the motor are required for placing the flux sensors. Furthermore, it is not possible to directly sense the rotor flux. Calculating the rotor flux from a directly sensed signal may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop in the stator voltage equation and inaccuracies due to variations on flux level and temperature. In FOC, to perform the frame transformation, accurate rotor flux position is needed to be acquired.

3.5.2 Direct Vector Control

In direct FOC the rotor angle or control vector is obtained by the terminal voltages & currents directly by using flux estimators. The direct vector control is also known as feedback vector control scheme. Similar to Indirect Vector Control, various controllers have been implemented on direct vector controlled induction motor drives also to improve the performance of the drive. While the direct method is inherently the most desirable control scheme, it suffers from high cost and the unreliability of the flux measurement. Although the indirect method can approach the performance of the direct measurement scheme, the major weakness of this approach is centered upon the accuracy of the control gains which, in turn, depend heavily on the motor parameters assumed in the feed forward control algorithm.

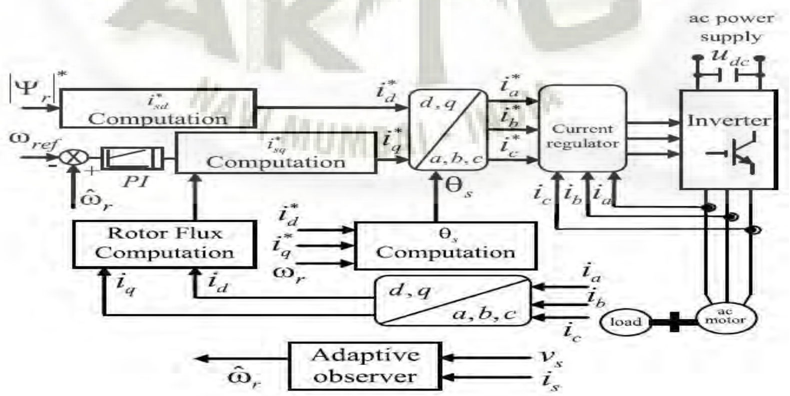


Figure 12: Basic FOC of Sensor Less Induction Motor

Because with inaccurate rotor flux position torque and flux components are not be completely decoupled, as a result of which dynamic response become poor. So, knowledge of rotor flux position is the core of the FOC. The measurement of the rotor flux position is different if we consider synchronous or induction motor. In synchronous machine the rotor speed and rotor flux speed are equal. Then rotor flux position is directly measured by position sensor or by integration of rotor speed. In the induction machine the rotor speed is not equal to the rotor flux speed, then it needs a particular method to calculate field angle.

3.5.3 Comparison with direct vector control

The major disadvantage of direct vector method is the need of so many sensors. Fixing so many sensors in a machine is a tedious work as well as costlier. Due to this the scheme is prevented from being used. Several other problems like drift because of temperature, poor flux sensing at lower speeds also persists. Due to these disadvantages and some more related ones, indirect vector control is used. In indirect vector control technique, the rotor position is calculated from the speed feedback signal of the motor. This technique eliminates most of the problems, which are associated with the flux sensors as they are absent.

3.5.4 Advantages of Indirect FOC

- The sensors are eliminated.
- The dynamic performance of the indirect
- vector control is better than the direct vector control
- The cost factor is decreased.
- There is no drift problem as in direct vector control.

3.5.5 Advantages of Field Oriented Control

- Improved torque response.
- Torque control at low frequencies and low speed.
- Dynamic speed accuracy and Reduction in size of motor, cost
- Four quadrant operation and Reduction in power consumption
- Short-term overload capability

3.6 Conclusion

Thanks to FOC it becomes possible to control, directly and separately, the torque and flux of AC machines. Field Orientated Controlled AC machines thus obtain every DC machine advantage: instantaneous control of the separate quantities allowing accurate transient and steady state management. In addition to this advantage, Field Orientated Controlled AC machines solve the mechanical commutation problems inherent with DC machines. TMS320F240, by providing high CPU power and highly versatile motor control dedicated peripherals, makes the use of DC machines obsolete in terms of power conversion efficiency and system reliability, when compared with FOC AC machines.

Chapter 4

The Space Vector PWM

4.1 Introduction

For a long period, carrier-based PWM methods were widely used in most applications. The earliest modulation signals for carrier-based PWM are sinusoidal. The use of an injected zero-sequence signal for a three-phase inverter initiated the research on non-sinusoidal carrier-based PWM. Different zero-sequence signals lead to different non sinusoidal PWM modulators. Compared with sinusoidal three-phase PWM, non-sinusoidal three-phase PWM can extend the linear modulation range for line-to-line voltages. Space-vector modulation has become one of the most important PWM methods for three-phase converters. There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for industrial applications .The most widely used PWM schemes for three-phase voltage source inverters are carrier based sinusoidal PWM and space vector PWM (SVPWM).The output voltage per phase for a sinusoidal PWM based three phase converter is limited to 0.5Vdc (peak value) and the line-to-line RMS voltage is 0.612Vdc.SVM is another direct digital PWM technique proposed in 1982 . It has become a basic power processing technique in three-phase converters. SVM based converter can have a high voltage output at 0.707Vdc (Line-to-line, RMS). The classic SVM strategy, first proposed by Holtz and Van der-Broeck Reviewing the literature it can be concluded that SVPWM has certain advantages over SPWM . They are:

- The output voltage is about 15% more in case of SVPWM as compared to SPWM.
- The current and torque harmonics produced are much less in case of SVPWM.

Thus SVPWM shows good utilization of the DC-link voltage low current ripple and is suitable for any high-voltage, high-power application.

4.2 Inverter

A device that converts dc power into ac power at desired output voltage and frequency is called an inverter. Some industrial applications of inverters are for adjustable speed ac drives, induction heating, stand by air-craft power supplies,

UPS (uninterruptible power supplies) for computers, HVDC transmission lines etc. The rectification is carried out by standard diodes or thyristor converter circuit. The inversion is performed by the methods. Inverter can be broadly classified into two type: voltage source inverters and current source inverters. A voltage-fed inverter (VFI), or voltage source inverter (VSI), is one in which the dc source has small or negligible impedance. In other words, a voltage source inverter has stiff dc voltage source at its input terminals.

4.3 PWM Principle:

An inverter contains electronic switches, it is possible to control the output voltage as well as optimize the harmonics by performing multiple switching within the inverter with the constant dc input voltage Vd. The PWM principle to control the output voltage is explained in figure 9. The fundamental voltage V1 has the maximum amplitude (4Vd / π) at square wave, but by creating two notches as shown, the magnitude can be reduced. If the notch widths are increased, the fundamental voltage will be reduced. Circuit model of a single-phase inverter with a center-taped grounded DC bus, and Fig 9 illustrates principle of pulse width modulation.

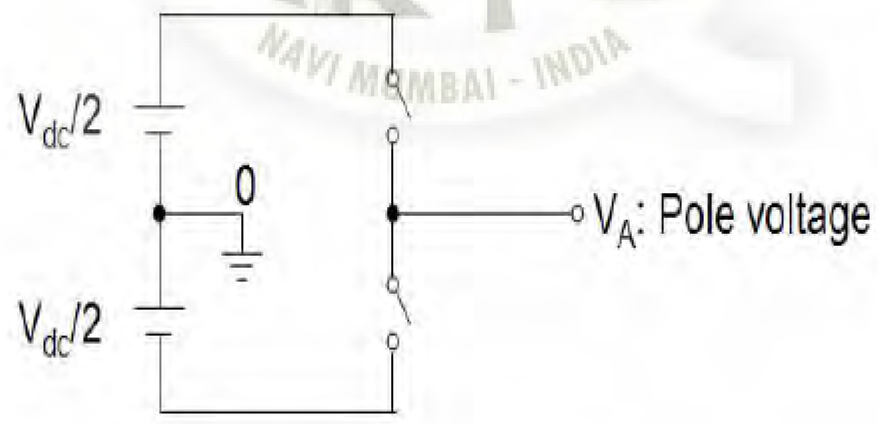


Figure 13: Circuit model of a single-phase inverter

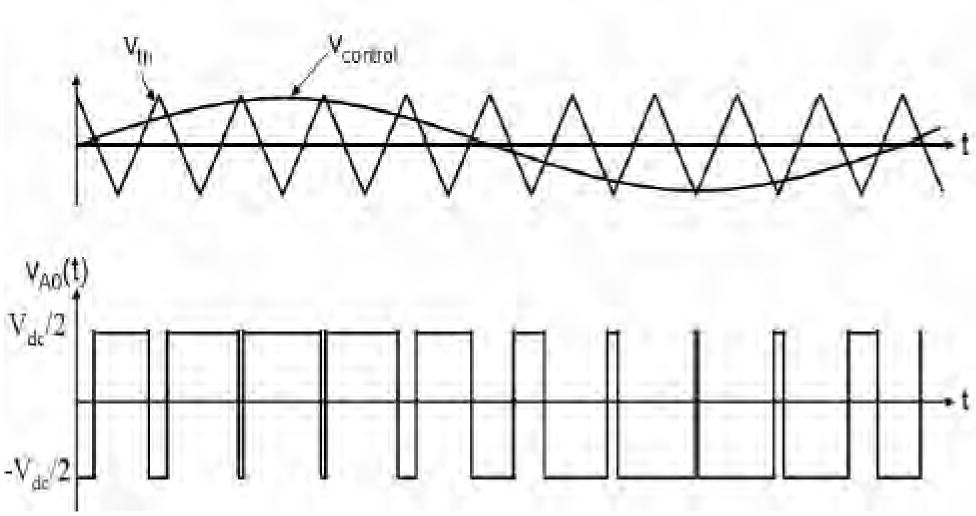


Figure 14: Pulse width modulation

The inverter output voltage is determined in the following:

When Vcontrol>Vtri, VA0 = Vdc/2 When Vcontrol<Vtri, VA0 = −Vdc/2

Also, the inverter output voltage has the following features:

- PWM frequency is the same as the frequency ofVtri
- Amplitude is controlled by the peak value of Vcontrol
- Fundamental frequency is controlled by the frequency of Vcontrol

Modulation index (m) is defined as:

m = Vcontrol / Vtri = peak of(VAo)1 / Vdc /2

Where, (VA0)1: fundamental frequecny component of VA0 The modulation method is an important part of the control structure. It should provide features like:

- Wide range of linear operation.
- Low content of higher harmonics in voltage and current.
- Low frequency harmonics.
- Operation in over modulation.
- Reduction of common mode voltage.
- The average value of voltage and current fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load is.
- The PWM switching frequency has to be much faster than what would affect the load, which is to say the device that uses the power. Typically switching have to be done

several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

- The term duty cycle describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on.
- The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero.

4.4 PWM Classification:

There are many possible PWM techniques proposed in the literature.
The classifications of PWM techniques can be given as follows:

- Sinusoidal PWM
- Selected harmonic elimination PWM
- Minimum ripple current PWM
- Space-vector PWM
- Hysteresis band current control PWM
- Delta modulation
- Random PWM
- Sigma-delta modulation
- Sinusoidal PWM with instantaneous current control

Often, PWM techniques are classified on the basis of voltage or current control, feed
forward and feedback method, carrier-or-non-based control, etc.

4.4.1 Space Vector PWM:

Another method for increasing the output voltage about that of the SPWM technique is the space vector (SVPWM) technique. The two methods have similar results but their methods of implementation are completely different. In the SVPWM technique, the duty cycles are computed rather than derived through comparison as in SPWM. The SVPWM technique can increase the fundamental component by up to 27.39% that of SPWM. The fundamental voltage can be increased up to a square wave mode where a modulation index of unity is reached. SVPWM is accomplished by rotating a reference vector around the state diagram, which is composed of six basic non-zero vectors forming a hexagon. A circle can be inscribed inside the state map and corresponds to sinusoidal operation. The area inside the inscribed circle is called the linear modulation region or under-modulation region. As seen in figure 11, the area between outside circle and inside the hexagon is called the nonlinear modulation region or over-modulation region. The concepts in the operation of linear and nonlinear modulation regions depend on the modulation index, which indirectly reflects on the inverter utilization capability.

4.4.2 Principle of Space vector PWM:

A three-phase mathematical system can be represented by a space vector. For example, given a set of three-phase voltages, a space vector can define by

V (t) = 3/2 [Va (t) ej0 + Vb (t) ej2π/3 + Vc (t) ej4π/3] …..(1)

Where Va (t), Vb (t), and Vc (t) are three sinusoidal voltages of the same amplitude and frequency but with $+120^0$ phase shifts.The space vector at any given time maintains its magnitude. As time increases, the angle of the space vector increases, causing the vector to rotate with a frequency equal to that of the sinusoidal waveforms.

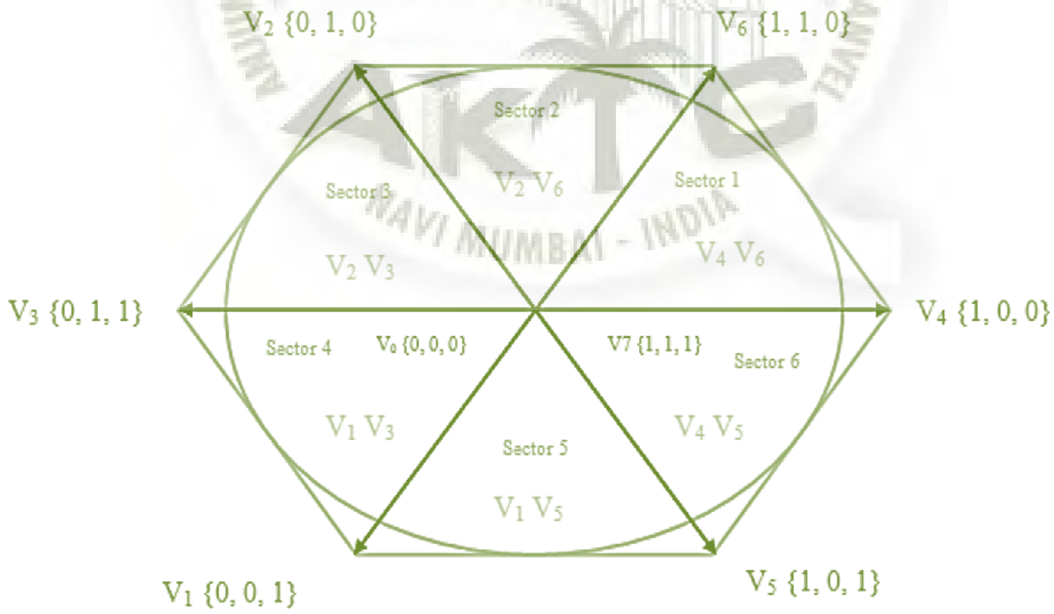


Figure 15: Space Vector diagram for level Inverter

When the output voltage of a three phase six-step inverter are converted to a space vector and plotted on the complex plane. The corresponding space vector takes on the one of six discrete angles as time increases .The central idea of SVPWM is to generate appropriate PWM signals so that a vector with any desired angle can be generated SVPWM is a form of PWM proposed in the mid-1980s that is more efficient compared to natural and regularly sampled PWM. In the space vector modulation, a three phase two level inverter can be driven to eights switching states where the inverter has six active states (1-6) and two zero states (0 &7).

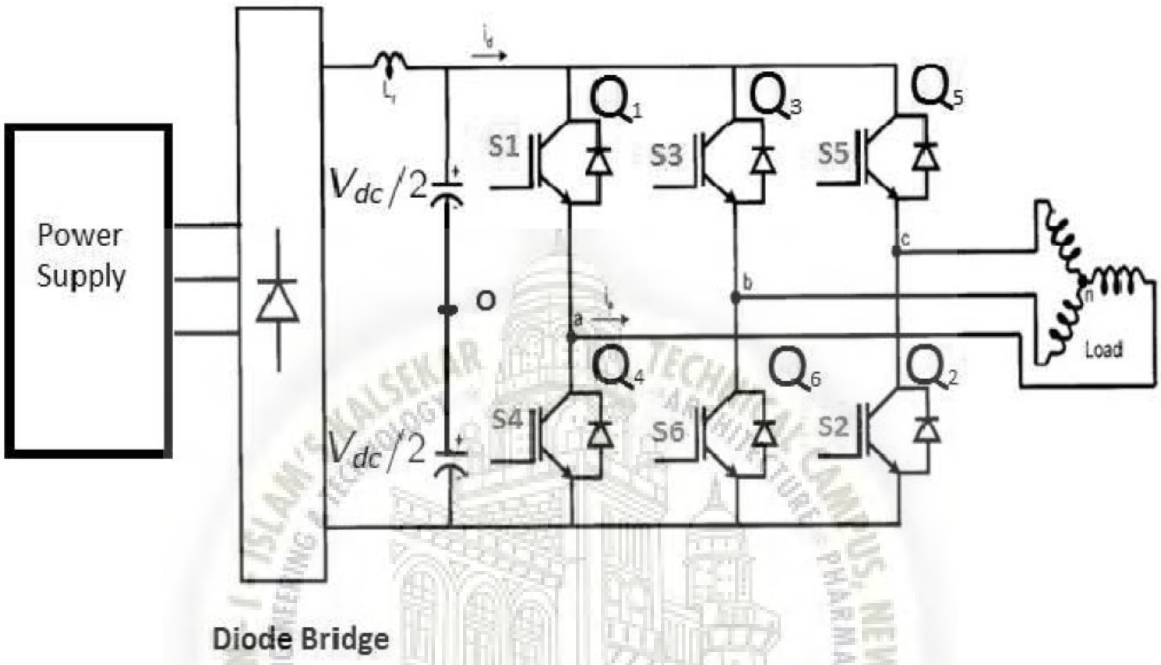


Figure 16: Circuit diagram for two-phase bridge inverter

A typical two-level inverter has 6 power switches (labeled S1 to S6) that generate three-phase voltage outputs. A detailed drawing of a three-phase bridge inverter is shown in figure 16. The circuit has a full-bridge topology with three inverter legs, each consisting of two power switches.

The circuit allows only positive power flow from the supply system to the load via a full-bridge diode rectifier. Negative power flow is not possible through the rectifier diode bridge. The six switching power devices can be constructed using power BJTs, GTOs, IGBTs, etc. the choice of switching devices is based on the desired operating power level, required switching frequency, and acceptable inverter power losses. When an upper transistor is switched on, the corresponding lower transistor is switched off. Therefore, the ON and OFF states of the upper transistors S1, S3, S5 can be used to determine the current output voltage. The ON and OFF states of the lower devices are complementary to the upper ones. Two switches on the same leg cannot be closed or opened at the same time. The basic principle of SVPWM is based on the eight switch combinations of a three phase inverter.

The switch combinations can be represented as binary codes that correspond to the top switches S1, S3, S5 of the inverter as shown in figure 17. Each switching circuit generates three independent pole voltage Vao, Vbo, and Vco, which are the inverter output voltages with respect to the mid-terminal of the DC source marked as 'O' on the same figure. These voltages are also called pole voltages. The pole voltages that can be produced are either Vdc/2 or –Vdc/2. For example, when switches S1, S6, S2 are closed, corresponding pole voltages are Vao = Vdc/2, Vbo = - Vdc/2, and Vco= - Vdc/2. This state is denoted as (1,0,0) and, according to equation (a), may be depicted as the space vector V(t) = 3/2 (Vdc ejo). Repeating the same procedure, we can find the remaining active non-active states shown in figure 17.

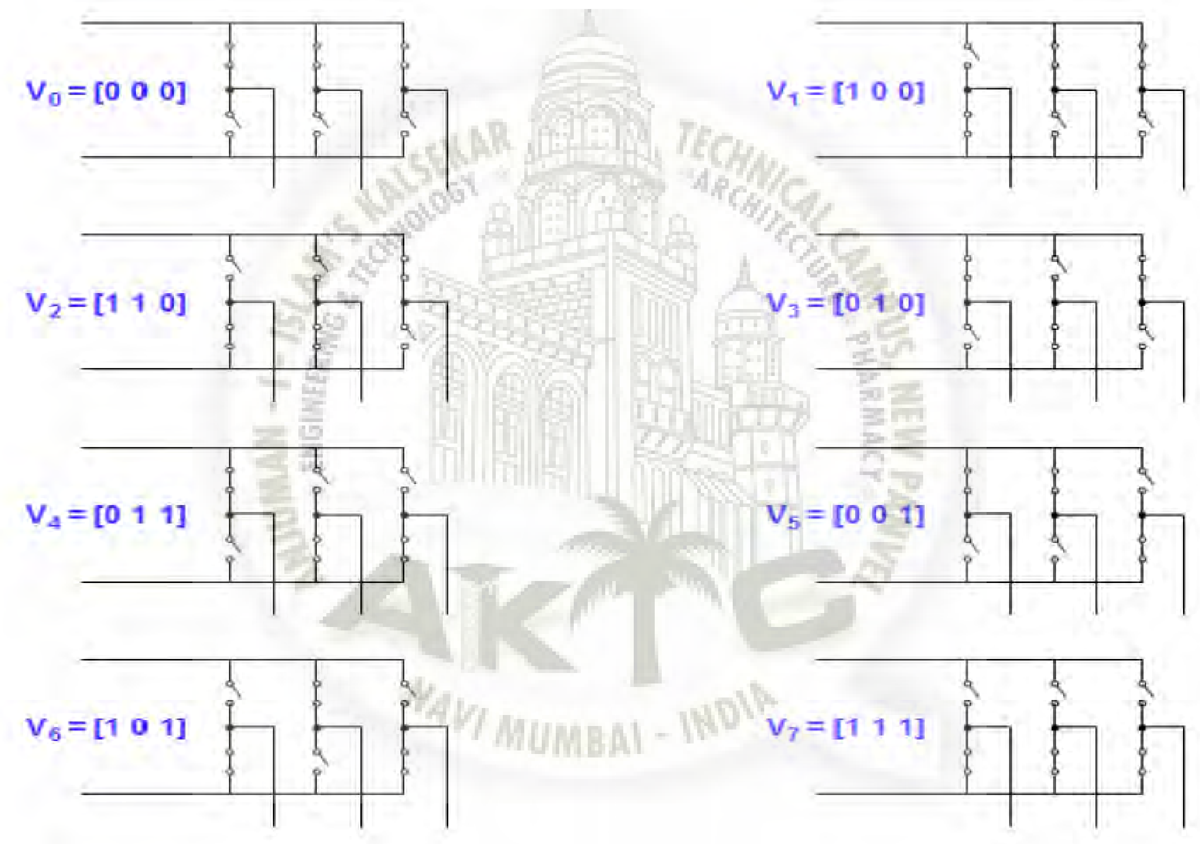


Figure 17: Eight switching configuration of three-phase inverter

The three-phase inverter is therefore controlled by six switches and eight inverter configurations. The eight inverter states can transform into eight corresponding space vectors. In each configuration, the vector identification uses a 'O' to represent the negative phase voltage level and a '1' to represent the positive phase voltage level. The relationship between the space vector and the corresponding switches states is given in Table 1 and figure 15. In addition, the switches in one inverter branch are in controlled in a complementary fashion (1 if the switch is on and 0 if it is off). Therefore,

S1 + S4 = 1

S3 + S6 = 1

S5 + S2 = 1

We use orthogonal coordinates to represent the three-phase two-level inverter in the phase diagram. There are eight possible inverter states that can generate eight space vectors. These are given by the complex vector expressions:

Vk = {2/3 Vdc ej(k-1) π/3 if k = 1,2,3,4,5,6

0 if k = 0,7.

The entire space is divided into six equal-size sectors of 60^0. Each sector is bounded by two active vectors. V0 and V7 are two voltage vectors with zero amplitude located at the origin of the hexagon. The eight active and non-active and state vectors are geometrically drawn in fig 18.

Table 1: Space Vectors, Switching States, and On-State Switches

Space vector		Switching states(three phase)	On state switch	Vector definition
Zero vector	V_0	[111]	S1, S3, S5	0
		[000]	S4, S6, S2	
Active vector	V_1	[100]	S1, S6, S2	$V_1 = \frac{2}{3} Vde^{j0}$
	V_2	[110]	S1, S3, S2	$V_1 = \frac{2}{3} Vde^{j\frac{\pi}{3}}$
	V_3	[010]	S4, S3, S2	$V_1 = \frac{2}{3} Vde^{j\frac{2\pi}{3}}$
	V_4	[011]	S4, S3, S5	$V_1 = \frac{2}{3} Vde^{j\frac{3\pi}{3}}$
	V_5	[001]	S4,S6, S5	$V_1 = \frac{2}{3} Vde^{j\frac{4\pi}{3}}$

	V_6	[101]	S1, S6, S5	$V_1 = \frac{2}{3}Vde^{j\frac{5\pi}{3}}$

The reference voltage vector Vref rotates in space at an angular velocity ω = 2πf, where f is the fundamental frequency of the inverter output voltage. When the reference voltage vector passes through each sector, different sets of switches in Table 1 will be turned on or off. As a result, when the reference voltage vector rotates through one revolution in space, the inverter output varies one electrical cycle over time.

The inverter output frequency coincides with the rotating speed of the reference voltage vector. The zero vectors (Vo and V7) and active vectors(V1 and V6) do not move in space. They are referred to as stationary vectors. Figure 14.shows the reference vector Vref in the first sector. The six active voltage space vectors are shown on the same graph with an equal magnitude of 2Vdc / 3 and a phase displacement of 600. The inverter cannot produce a desired reference voltage vector

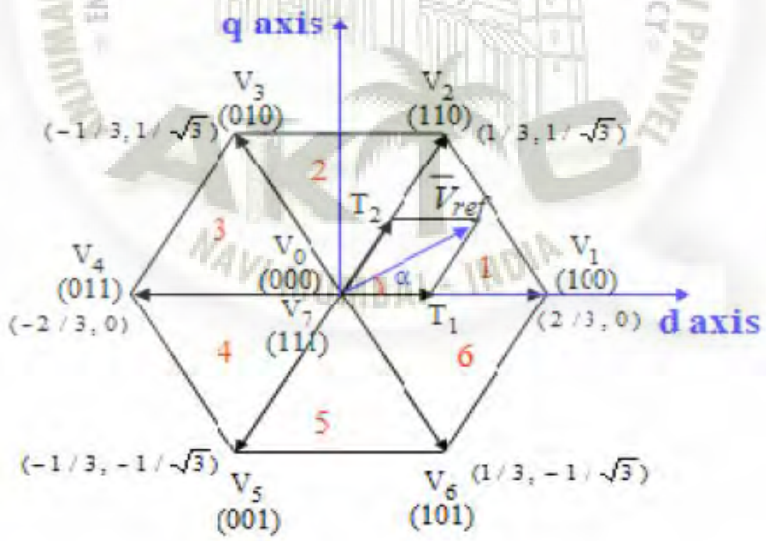


Figure 18: Basic switching vectors and sectors.

directly. It is possible to decompose the reference vector into vectors that lie on two adjacent active vectors and two zero vectors (which are located at the center of the hexagon).The relationship between the switching variable [S1, S3, S5] and the line-to-line voltage vector [Vab, Vbc, Vca] is shown in equation. when the upper or lower transistor of a phase is ON, the switching signal of that phase is ‘1’ or ‘-1’ and when an upper or lower transistor is OFF , then the switching signal is ‘0’.

4.4.3 Angle and Reference Voltage Vector:

In the Space Vector PWM, the three-phase output voltage vector is represented by a reference vector that rotates at an angular speed of w = 2pi f . The Space Vector PWM uses the combinations of switching states to approximate the reference vector Vref . A reference voltage vector Vref that rotates with angular speed in the ab plane represents three sinusoidal waveforms with angular frequency ‘w’ in the abc coordinate system. Each output voltage combination in Table 1 corresponds to a different voltage space vector.

Three sinusoidal and balanced voltages are given by the relations:

Va(t) = Vref*cos (wt)

Vb(t) = Vref*cos (wt -2π/3)

Vc(t) = Vref*cos (wt +2 π /3):

For any three-phase system with three wires and equal load impedances we have

Va(t)+Vb(t)+Vc(t) = 0

The space vector with magnitude Vref rotates in a circular direction at an angular velocity of w where the direction of rotation depends on the phase sequence of the voltages. If it has a positive phase sequence, then it rotates in the counterclockwise direction. Otherwise, it rotates in the clockwise direction with a negative phase sequence. The three-phase voltages could be described with only two components, a and b, in a two-dimensional plane. The magnitude of each active vector is 2Vdc/3. The active vectors are 60^0 apart and describe a hexagon boundary. The locus of the circle projected by the space reference vector Vref depends on V0 , V1 ,V2 , V3 , V4 , V5, V6, V7,

V re f = 2 / 3 [Va+aVb+a2Vc]

Where a = e j2π/3. The magnitude of the reference vector is:

$$| Vref | = \sqrt{V_\alpha^2 + V_\beta^2}$$

The phase angle is evaluated from

θ = tan -1 (V β / Vα)

4.4.4 Modulation Index of Linear Modulation:

In the linear region, the rotating reference vector always remains within the hexagon. The largest output voltage magnitude is the radius of the largest circle that can be inscribed within the hexagon. This means that the linear region ends when the reference voltage is equal to the circle inscribed within the hexagon. The fundamental component of the voltage waveform is shown in figure. From a Fourier analysis, the fundamental voltage magnitude is given by

Vmax-six step = 2 Vdc/π

The ratio between the reference vector Vref and the fundamental peak value of the square phase voltage wave (2 Vdc/π) is called the modulation index. The mode of operation is determined by the modulation index `(MI). in this linear region, the MI can be expressed as

MI = Vref / Vmax-six step

From the geometry of figure 14, the maximum modulation index is obtained when Vref equals the radius of the inscribed circle.

Vref(max) = 2/3 Vdc cos (π /6)

MImax = 2/3 Vdc cos (π /6) / 2 Vdc/π = 0.907.

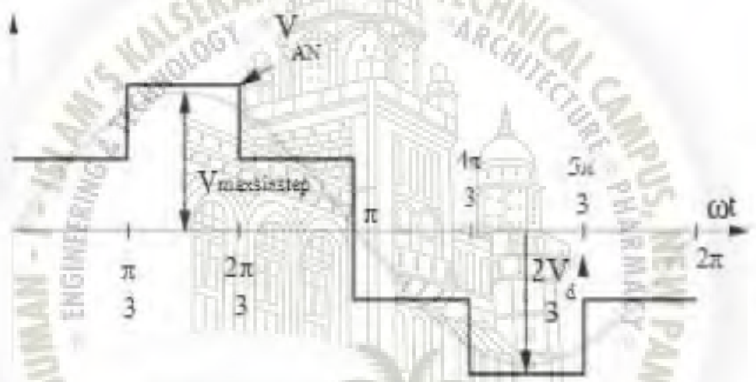


Figure 19: Fundamental of Voltage Waveform

4.4.5 Sector Determination:

It is necessary to know in which sector the reference output lies in order to determine the switching time and sequence. The identification of the sector where the reference vector is located is straightforward. The phase voltages correspond to eight switching states. Six non zero vectors and two zero vectors at the origin. Depending on the reference voltages Vα and

Vβ , the angle of the reference vector can be used to determine the sector as per Table 2.

Table 2: Sector Definition.

Sector	Degrees
1	$0 < \theta < 60^{o}$
2	$60 < \theta < 120^{o}$
3	$120 < \theta < 180^{o}$
4	$180 < \theta < 240^{o}$
5	$240 < \theta < 300^{o}$
6	$300 < \theta < 360^{o}$

4.4.6 Time Duration Ta, Tb, T0:

The duty cycle computation is done for each triangular sector formed by two state vectors. The magnitude of each switching state vector is 2Vdc/3 and the magnitude of a vector to the midpoint of the hexagon line from one vertex to another is Vdc / √3. In the under–modulation, the maximum possible modulation index is 0.907 as derived previously.

The reference space vector rotates and moves through different sector of the complex plane as time increases. In each PWM cycle, the reference vector Vref is sampled at a fixed input sampling frequency fs. During this time, the sector is determined and the modulation vector Vref is mapped onto two adjacent vectors. The non-zero vectors can represent by

Vk = 2/3 Vdcej(k-1)π/3

For k = 1, 2, 3, 4, 5, 6.

Therefore, the non-zero vectors for Vk and Vk+1 become

Vk = 2/3 Vdc[cos (k-1)π/3 + jsin(k-1) π/3]

Vk+1 = 2/3 Vdc*ejkπ/3 = 2/3 Vdc [cos kπ/3 + jsin kπ/3].

Since the sum of Ta and Tb should be less than or equal to Ts, the inverter has to stay in a zero state for the rest of the period. The duration of the null vectors is the remaining time in the switching period. Since

Ts = T0 + (Ta + Tb)

then the time interval for the zero voltage vectors is

T0 = Ts – (Ta + Tb)

The switching times are arranged symmetrical around the center of the switching period. The zero vector V7 (1,1,1) is placed at the center of the switching period, and the zero vector V0 (0,0,0) at the start and the end, and the total period for a zero vector is divided equally among the two zero vectors.

In the under-modulation region, as the modulation index increases, the reference voltage vector grows outward in magnitude. It reaches the inscribed circle of the hexagon and T0 will reduce to zero whenever the tip of the reference voltage vector is on the hexagon. If the modulation index increases further, then T0 becomes negative and meaningless. Therefore, the modulation index will reach a maximum of 0.907 in the linear under-modulation region.

The time durations of two adjacent nonzero vectors in each sector are calculated based on the magnitude and phase of the reference voltage. A zero state vector is applied followed with two adjacent active vectors in half of the switching period. The next half of the switching period is symmetrical to the first half. To generate the signals that produce the rotating vector, an equation is required to determine the time intervals for each sector. Fig 20 shows the pulse patterns generated by space vector PWM in sector 1.

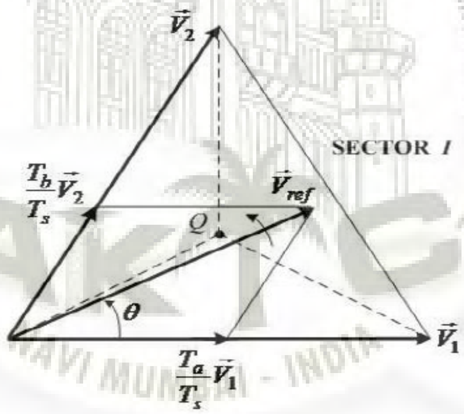


Figure 20: Vref Falls into Sector 1

4.4.7 Determination of the Switching Times for Each Transistor Switches:

It is necessary to be arrange the switching sequence so that the switching frequency of each inverter leg is minimized. There are many switching patterns that can be used to implement SVPWM. To minimize the switching losses, only two adjacent active vectors and two zero vectors are used in a sector. To meet this optimal condition, each switching period starts with one zero vectors and end with another zero vector during the sampling time Ts. This rule applies normally to three-phase inverters as a switching sequence. Therefore, the switching cycle of the output voltage is double the sampling time, and the two output voltage waveforms become symmetrical during Ts. Table 3 presents a symmetric switching sequence. Reference to this table, the binary representations of two adjacent basic vectors differ in only one bit, so that only one of the upper transistors switches is closed when the switching pattern moves from one vector to an adjacent one. The two vectors are time weighted in a sample period Ts to produce the desired output voltage.

Table 3: seven-segments switching sequence for all sector

	Switching Segments						
Sector	1	2	3	4	5	6	7
1	V_0 000	V_1 100	V_2 110	V_7 111	V_2 110	V_1 100	V_0 000
2	V_0 000	V_3 010	V_2 110	V_7 111	V_2 110	V_3 010	V_0 000
3	V_0 000	V_3 010	V_4 011	V_7 111	V_4 011	V_3 010	V_0 000
4	V_0 000	V_5 001	V_4 011	V_7 111	V_4 011	V_5 001	V_0 000
5	V_0 000	V_5 001	V_6 101	V_7 111	V_4 101	V_6 001	V_0 000
6	V_0 000	V_1 100	V_6 101	V_7 111	V_6 101	V_1 100	V_0 000

4.4.8 Types of Different Schemes:

There are two modes of operation available for the PWM waveform: symmetric and asymmetric PWM. The pulse of an asymmetric edge aligned signal always has the same side aligned with one end of each PWM period. On the other hand, the pulse of symmetric signals is always symmetric with respect to the center of each PWM period. The symmetrical PWM signal is often preferred because it has been shown to have the lowest total harmonic distortion (THD), and has been implemented. Output patterns for each sector are based on a symmetrical sequence. There are different schemes in space vector PWM and they are based on their repeating duty distribution.

Based on the equations for Ta, Tb, T0, T7, and according to the principle of symmetrical PWM, the switching sequence in table 4 is shown for the upper and lower switches.

Table 4: Switching Pulse pattern for the three phase for each sector.

Sector	Upper switches (S1,S3,S5)	Lower Switches (S4,S6,S2)
I	S1=T1+T2+T0/2 S3=T2+T0/2 S5=T0/2	S4=T0/2 S6=T1+T0/2 S2=T1+T2+T0/2
II	S1=T1+T0/2 S3=T1+T2+T0/2 S5=T0/2	S4=T2+T0/2 S6=T0/2 S2=T1+T2+T0/2
III	S1=T0/2 S3=T1+T2+T0/2 S5=T2+T0/2	T1+T2+T0/2 S6=T0/2 S2=T1+T0/2
IV	S1=T0/2 S3=T1+T0/2 S5=T1+T2+T0/2	S4=T1+T2+T0/2 S6=T2+T0/2 S2=T0/2
V	S1=T2+T0/2 S3=T0/2 S5=T1+T2+T0/2	S4=T1+T0/2 S6=T1+T2+T0/2 S2=T0/2

VI	S1=T1+T2+T0/2 S3=T0/2 S5=T1+T0/2	S4=T0/2 S6=T1+T2+T0/2 S2=T2+T0/2

Fig.21 shows the switching patterns of all six sectors in the circle. As shown in the same figure, the space vector for a three-phase voltage source inverter is divided into six sectors based on six fundamental vectors. Any voltage vector in this vector space can be synthesized using two adjacent vectors. One switching period is depicted in the same figure. In sector 1, for example, switching is achieved by applying a zero state vector followed by two adjacent active state vectors in a half switching period. The next half of the switching period is the mirror image of the first half.

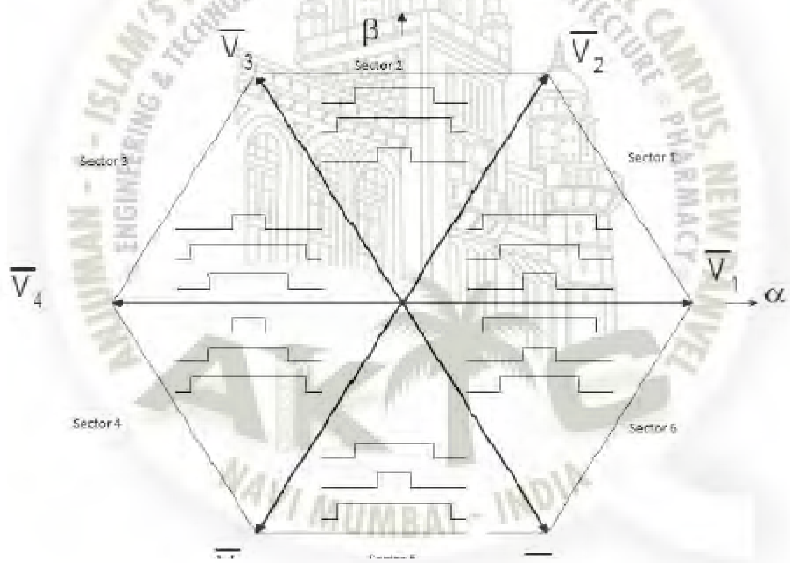


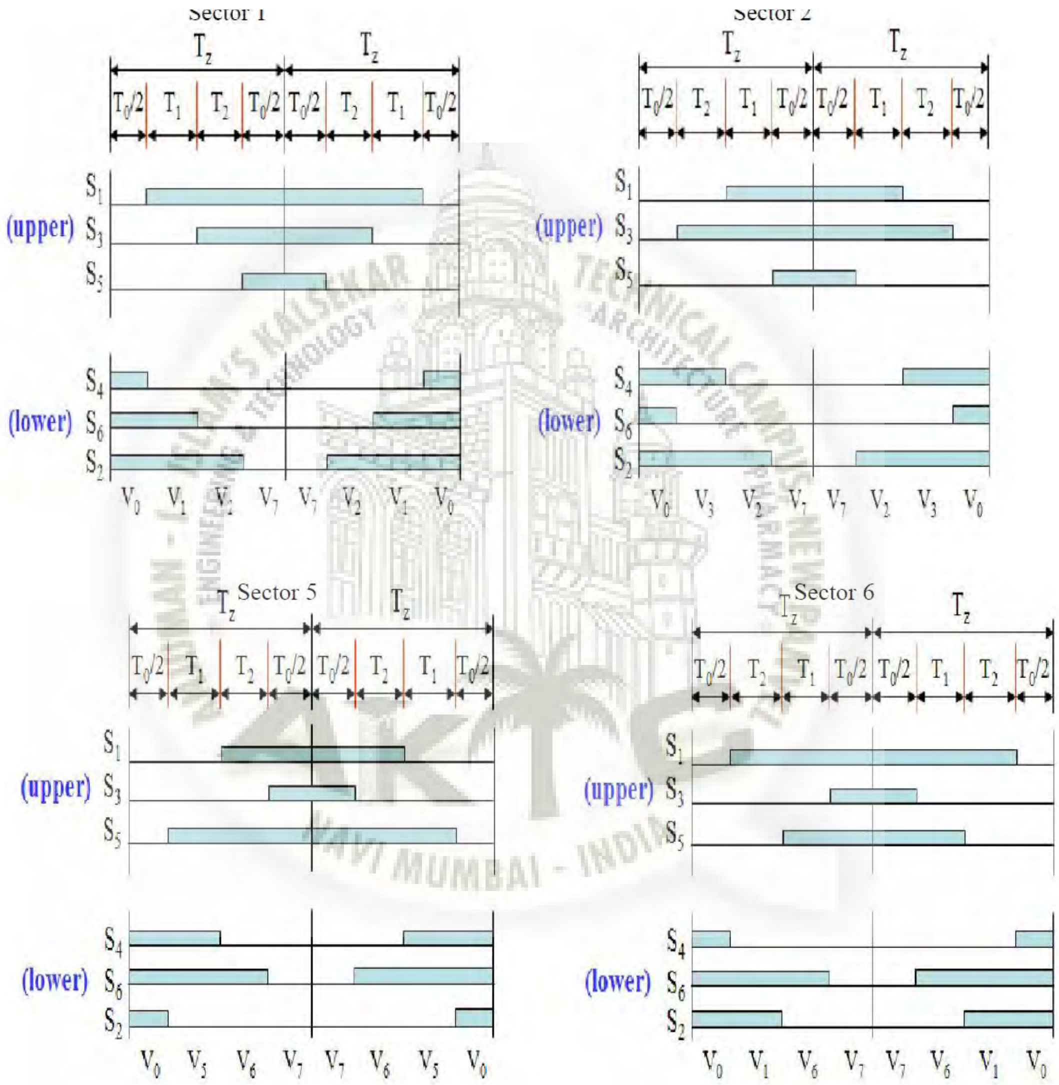
Figure 21: Switching patterns of six sectors in circle

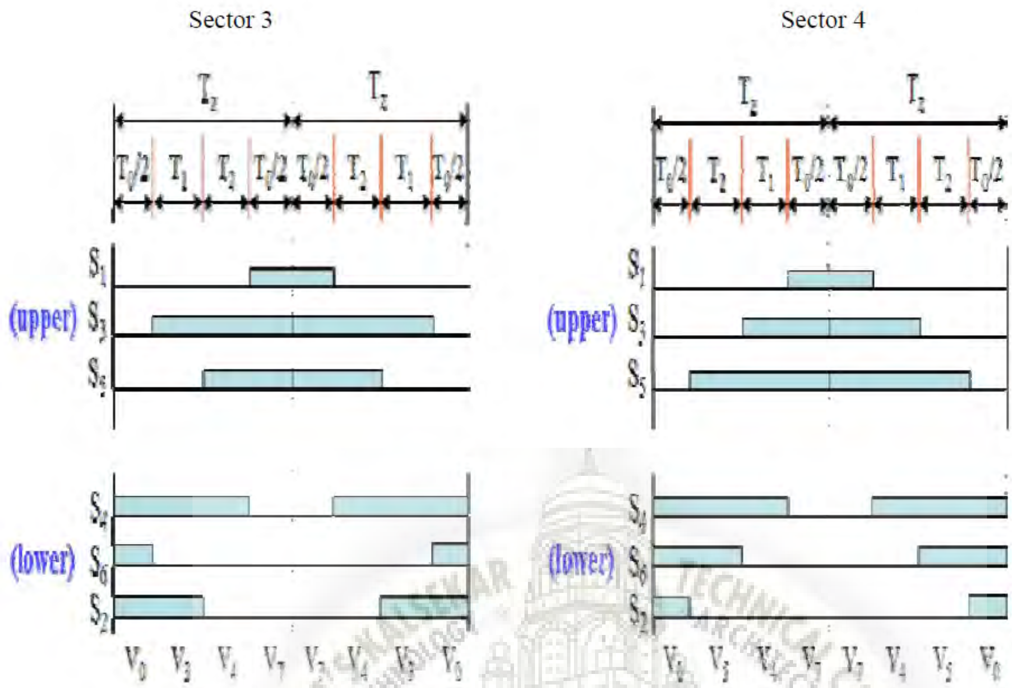
In order to reduce the switching loss of the power components of the inverter, it is required that at each time only one bridge arm is switched. After re-organizing the switching sequences, a scheme with center-aligned pulses is obtained as shown in figure 22.
The switching pulse patterns of six different sectors in figure 4.11 are shown for the upper and lower switches of a three-phase inverter. It is obvious that in the odd sector the active state sequence is in ascending-descending order; whereas, it is in a descending ascending order in an even sector. For example:

- In an odd sector 1, the state sequence of space vectors is in the order V0, V1, V2, V7, V7, V2,V1, V0.
- In an even sector 2, the state sequence of space vectors is: V0, V3, V2, V7, V7, V2, V3, V0.

Following the same procedure, we have the switching sequence summarized in table 4.5 for all six sectors.

Figure 22: Switching sequence of all six sectors.





4.5 Conclusion

In This work, sinusoidal and SVPWM Techniques has been described and applied twolevel3-phase inverted fed vector controlled induction motor. SVPWM uses the dc bus voltage than SPWM. In this proposed work, SPWM and SVPWM techniques are used and the results are compared. From that comparison, we can observed that Total harmonic distortion (THD) has been reduced fundamental component of voltage is increased in SVPWM technique near 25%compared to sinusoidal PWM.

Chapter 5

Implementation of Space Vector PWM Using Simulink

5.1 Introduction:

The purpose of Implementing SVPWM is to represent SVPWM techniques and then to simplify how it can be implemented on MATLAB Simulink Software. The Space Vector PWM (PVM) method is advanced, computation intensive PWM method & is possibly the best among all the PWM techniques for variable frequency drive applications.

The space vector approach in real time pulse width modulation offers variety of switching patterns for effective control of induction motor drives. The Simulink model of Space Vector Modulation is shown in below Figure [23];

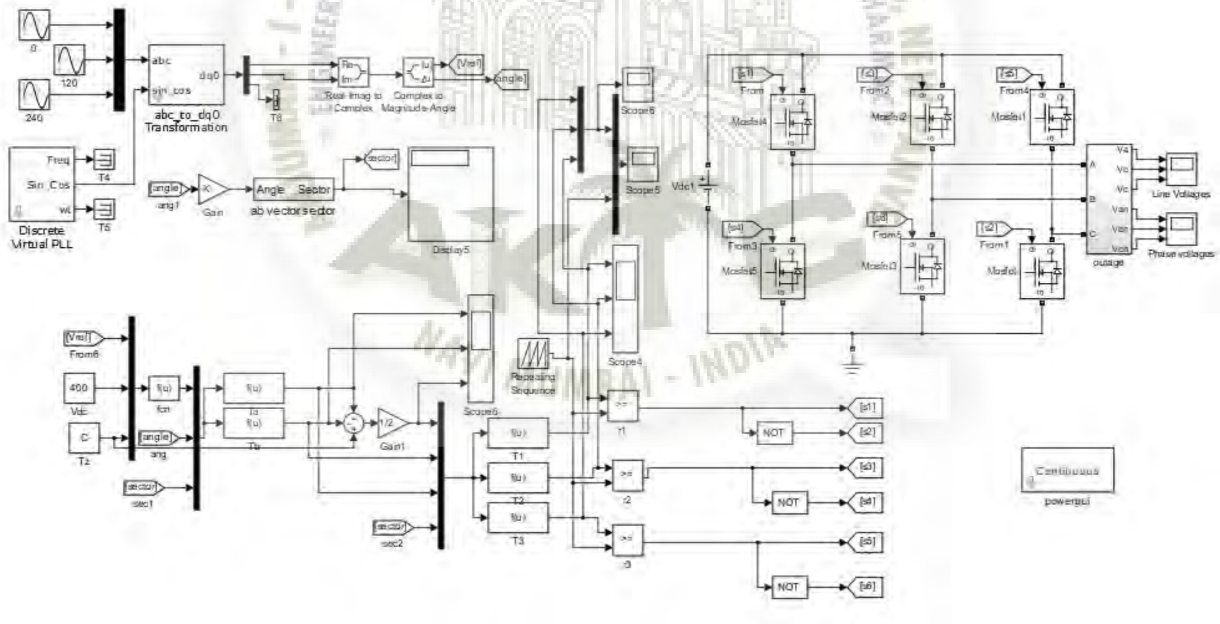


Figure 23: SIMULINK Model of Two level SVPWM

5.2 Transformationfromabc-Componentstodq0-Components :

It performs a Park transformation from three-phase (abc) reference frame to the dq0 reference frame. The Simulink component which used for transformation from adc to dq0 is shown in figure [24];

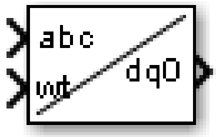


Figure 24: abc to dq0

The block supports the two conventions used in the literature for Park transformation:

- Rotating frame aligned with a-axis at t = 0. This type of Park transformation is also known as the cosinus-based Park transformation.
- Rotating frame aligned 90 degrees behind A axis. This type of Park transformation is also known as the sinus-based Park transformation. Use it in Simi Power Systems models of three-phase synchronous and asynchronous machines.

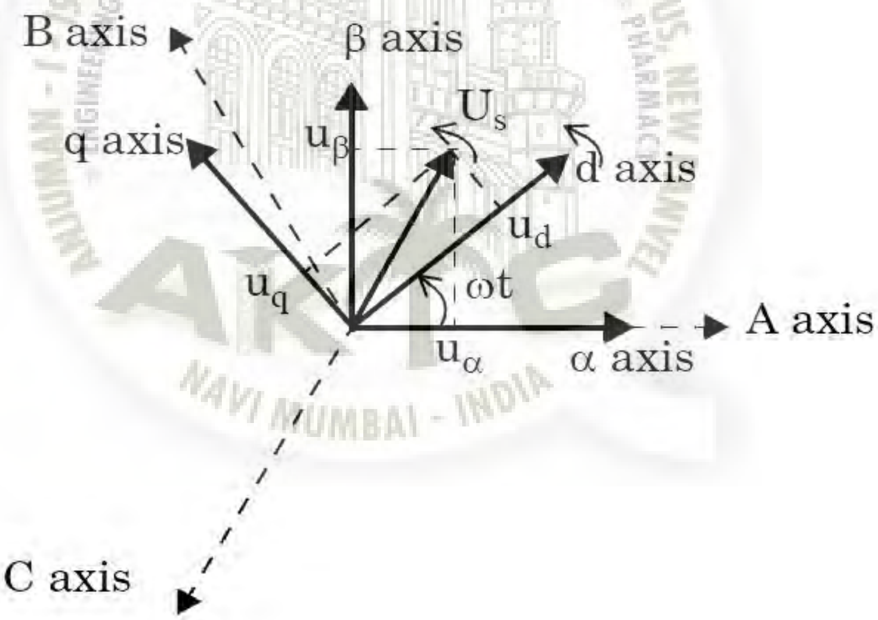


Figure 25: Phasor diagram of abc to dq0 transformation

Figure [25] represent the three axis transformation to two axis transformation by drawing a phasor.
At the input of abc to dq0 transformation block we are given two inputs, one of them is three phase supply and another is taken sin_cos trigonometric functions from other subsystem which is called as Discrete Virtual PLL as shown in Figure [26].

5.2.1 Discrete Virtual PLL (Phase Lock Loop)

The PLL block models a phase lock loop closed loop control system, which tracks the frequency and phase of a sinusoidal three-phase signal by using an internal frequency oscillator. The control system adjusts the internal oscillator frequency to keep the phases difference to 0. The figure [25] shows the internal diagram of PLL;

It generates sin_cos waves by using frequency with constant value, Digital clock with constant time and 2*pi of constant value. By multiplying all of these values we get,

$fcn1 = 2\pi ft$

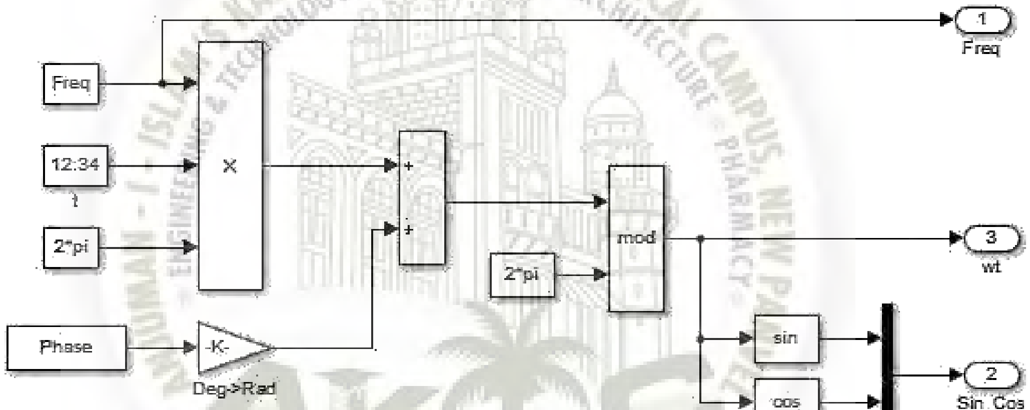


Figure 26: Internal diagram of PLL

Assume it is $fcn1$, after this we Convert Phase into radian by give a gain of $\frac{\pi}{180}$, then adding to $fcn1$then we obtained,

$$2\omega t + (\theta * \frac{\pi}{180})$$

Then we give it to *mod* operator with 2π multiplication to above equation. Finally we get three outputs of PLL model, they are frequency, ωt and sin_cos waveform. Here we terminated frequency and ωt. Sin_cos waveform gives to abc to dq0 transformation.

5.2.2 dq0 transformation:

After obtaining supply and sin_cos then it works internally for obtaining the below dq0-tranformation expressions,

$$Vd = \frac{2}{3}(Va * \sin\omega t + Vb * \sin\left(\omega t - \frac{2\pi}{3}\right) + Vc * \sin(\omega t + \frac{2\pi}{3}));$$

$$Vq = \frac{2}{3}(Va * cos\omega t + Vb * \cos\left(\omega t - \frac{2\pi}{3}\right) + Vc * \cos\left(\omega t + \frac{2\pi}{3}\right)));$$

$$Vo = \frac{1}{3}(Va + Vb + Vc)$$

The internal operation of dq0-tranformation model represented below in Figure [27];

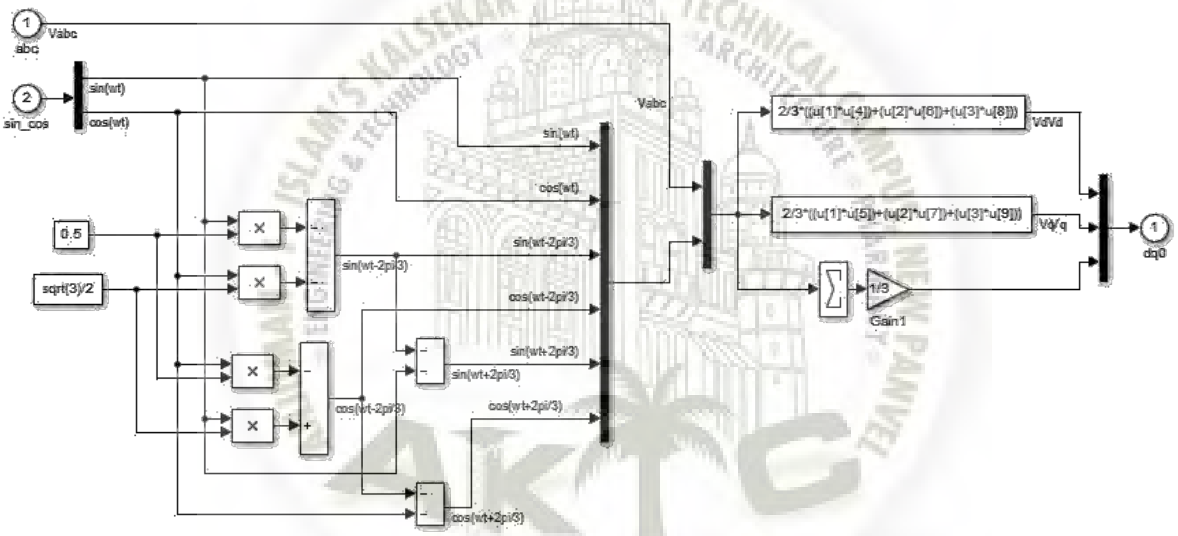


Figure 27: dq0-transformation Model

It has two inputs i.e. supply and sin_cos waveform. The sin_cos waveform connected to *demux*. $\sin\omega t$andcos ωt function given to *mux* which having 6 inputs there is two inputs are simple sin and cos and remaining are obtained which as shown in the Figure [27]. In the above figure [27], Inputs of *mux* are obtained by following stepwise expressions

$u1 = Va, u2 = Vb$ & $u3 = Vc$;

$u4 = \sin\omega t$;

$u5 = \cos\omega t$;

u6=$-\frac{1}{2}\sin\omega t-\frac{\sqrt{3}}{2}\cos\omega t$

then

u6

$$=-\left\{\sin(\omega t)\cos\left(\frac{2\pi}{3}\right)+\cos(\omega t)\sin(\frac{2\pi}{3})\right\}$$

$$u6=\sin\left(\omega t-\frac{2\pi}{3}\right);$$

$$u7=-\left[\frac{1}{2}\cos(\omega t)-\frac{\sqrt{3}}{2}\sin\omega t\right]$$

$$u7=\cos\left(\omega t-\frac{2\pi}{3}\right);$$

$$u8=-u4-u6$$

$$u8=-\sin(\omega t)-\sin\left(\omega t-\frac{2\pi}{3}\right);$$

$$u8=\sin\left(\omega t+\frac{2\pi}{3}\right);$$

$$u9=-u5-u7$$

$$u9=-\cos(\omega t)-\cos\left(\omega t-\frac{2\pi}{3}\right);$$

$$u9=\cos(\omega t)-\frac{1}{2}\cos(\omega t)+\frac{\sqrt{3}}{2}\sin(\omega t);$$

$$u9=\cos\left(\omega t+\frac{2\pi}{3}\right);$$

Then after obtained all above equations we combining them for obtaining Equations of Vd,Vq& Vo combined them as

$$Vd=\frac{2}{3}(u1*u4+u2*u6+u3*u8);$$

$$Vq=\frac{2}{3}(u1*u5+u2*u7+u3*u9);$$

$$Vo = \frac{1}{3}(u1 + u2 + u3)$$

We have obtained the real and imaginary components from Vd, Vq and Vo then by using simulink model of complex to magnitude-angle we get Magnitude and Angle which are Vref & Angle respectively. Angle we convert from Radian into degree by

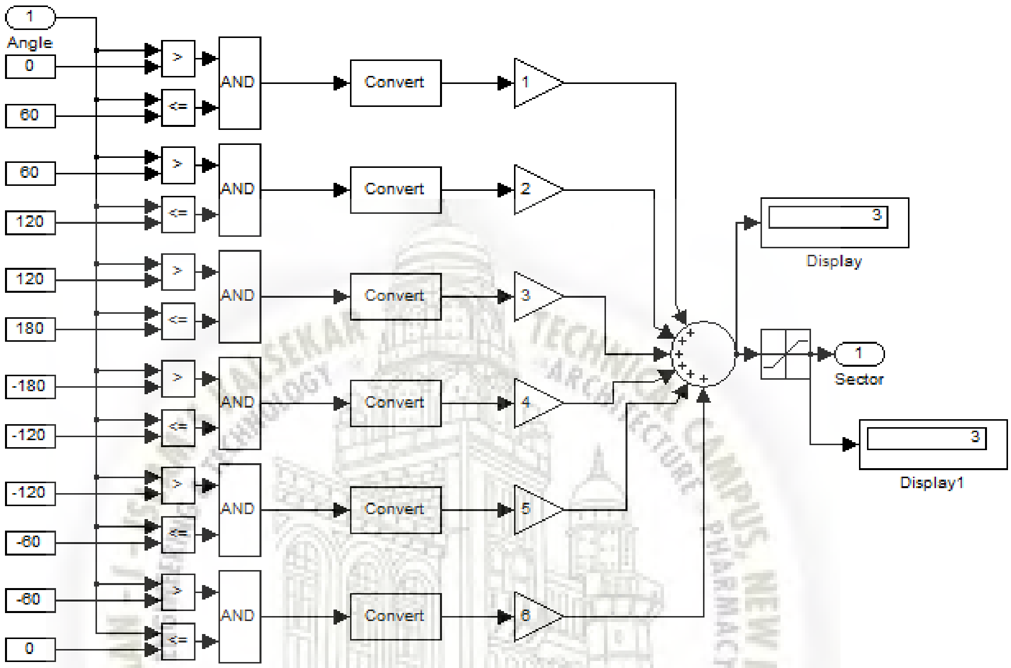


Figure 28: Sector Selection

give gain of $\frac{180}{\pi}$.

5.3 Selection of Sector :

As we have obtained Vref and angle as explained above, further to obtained the sector acquired by Vref we need some algorithm which has been illustrated through follsimulink model.

5.3.1 Determine switching times:

Space vector PWM entire space is split into six sectors and each sector is created by two active vectors and two zero vectors. Space vector PWM is the time arranging of these four vectors in a sector to create the resultant same as reference vector. The reference vector is rotating in the space vector hexagon about the central point with angular speed same as synchronous speed. In the below Simulink Model Figure [29], we determined the Vector switching times for First vector, second vector & zero vector.

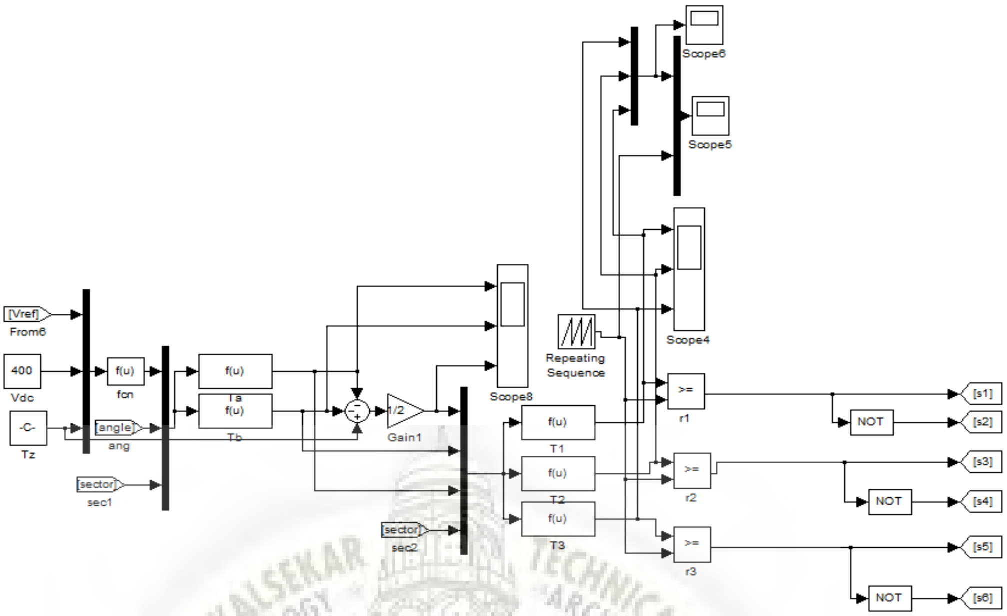


Figure 29: Model of determining Switching States

After obtaining vector switching times we determining switching state by using some Mathematical models which are mentioning in below;

$$fcn = \frac{\sqrt{3} * u3 * u1}{u2}$$

This relate to Modulation Index= $\frac{\sqrt{3} * Ts * Vref}{Vdc}$;

In the Figure [G], we seen that Ta is a time function which written in Simulink as,

$$Ta = u1 * \left\{ \sin\left[\frac{u3 * \pi}{3}\right] * \cos(u2) - \cos\left[\frac{u3 * \pi}{3}\right] * \sin(u2) \right\}$$

Then, $Ta = u1 * \sin\left[\frac{u3 * \pi}{3} - u2\right];$

Also for $Tb = u1 * \left\{ \sin(u2) * \cos\left[\frac{(u3-1) * \pi}{3}\right] - \cos(u2) * \sin\left[\frac{(u3-1) * \pi}{3}\right] \right\}$

Then, $Tb = u1 * \sin\left[\frac{(u3-1) * \pi}{3} - u2\right];$

If we observe Simulink model then we get, $u1 = a = \frac{\sqrt{3} * Ts * Vref}{Vdc} = fcn$=Modulation Index and $u2 = angle = \alpha$ which is obtained from dq0-transformation and also $3 = sector\ Number$.

Formula for determining T0 is, $T0 = Tz - (Ta + Tb)$

In Simulink for obtaining of T0 we connect summation which adding Ta & Tb then subtract with Tz.

For easily understanding of above explanation we can refer Table [5] which given below as,

Table 5: Times T1, T2 & T0 for all Sectors

Sector	Ta	Tb	T0
I	$a * \sin\left[\frac{\pi}{3} - \alpha\right]$	$a * \sin[\alpha]$	$Tz - Ta - Tb$
II	$a * \sin\left[\frac{2\pi}{3} - \alpha\right]$	$a * \sin\left[\frac{\pi}{3} - \alpha\right]$	$Tz - Ta - Tb$
III	$a * \sin[\pi - \alpha]$	$a * \sin\left[\frac{2\pi}{3} - \alpha\right]$	$Tz - Ta - Tb$
IV	$a * \sin\left[\frac{4\pi}{3} - \alpha\right]$	$a * \sin[\pi - \alpha]$	$Tz - Ta - Tb$
V	$a * \sin\left[\frac{5\pi}{3} - \alpha\right]$	$a * \sin\left[\frac{4\pi}{3} - \alpha\right]$	$Tz - Ta - Tb$
VI	$a * \sin[2\pi - \alpha]$	$a * \sin\left[\frac{5\pi}{3} - \alpha\right]$	$Tz - Ta - Tb$

5.3.2 Determination Switching time of each power electronic Switch:

In the Simulink model we determine switching time of each switch by using below model as shown in Figure [30];

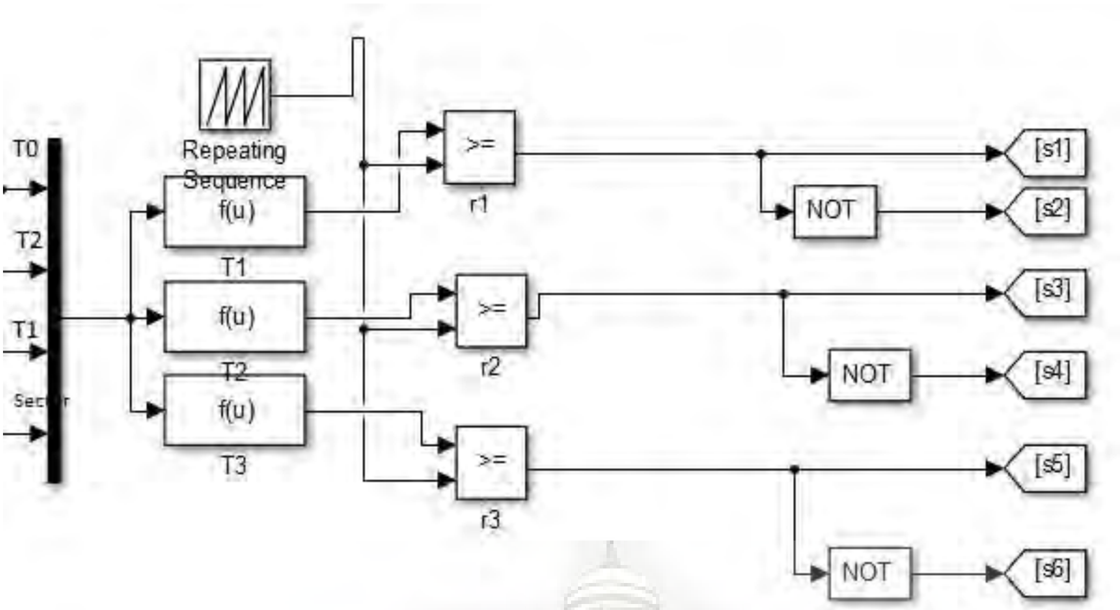


Figure 30: Conditional Operation of switching

In above model T1, T2 and T3 are:

T1 having following Conditional equation which determine switches ON\OFF operation.

$$(u[4] == 1) * (u[1] + u[2] + u[3]) + (u[4] == 6) * (u[1] + u[2] + u[3]) + (u[4] == 2) * (u[1] + u[3]) + (u[4] == 3) * (u[1]) + (u[4] == 4) * (u[1]) + (u[4] == 5) * (u[1] + u[2])$$

Also T2 having following Conditional equation which determine switches ON\OFF operation

$$(u[4] == 6) * (u[1]) + (u[4] == 1) * (u[1] + u[2]) + (u[4] == 2) * (u[1] + u[2] + u[3]) + (u[4] == 3) * (u[1] + u[2] + u[3]) + (u[4] == 4) * (u[1] + u[3]) + (u[4] == 5) * (u[1])$$

And finally for T3 which have following Conditional equation which determines switches ON\OFF operation.

$$(u[4] == 6) * (u[1] + u[3]) + (u[4] == 1) * (u[1]) + (u[4] == 2) * (u[1]) + (u[4] == 3) * (u[1] + u[2]) + (u[4] == 4) * (u[1] + u[2] + u[3]) + (u[4] == 5) * (u[1] + u[2] + u[3])$$

Where u (1) =T0, u (2) =Tb=T2, u (3) =Ta=T1 and u (4) =sector Number

For better understanding of above three equations we illustrate it in Table 4, which describe the Switches ON/OFF in each of leg of inverter.

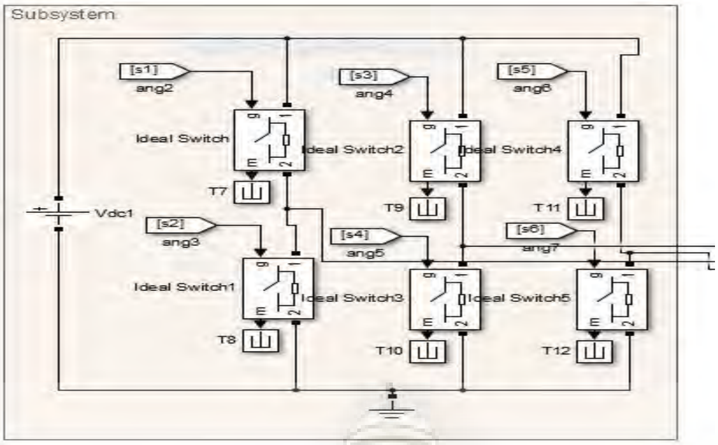


Figure 31Two-level Inverter

There are eight possible combination of switching states in the Two-level Inverter, in this combination zero and eight states have not sector but they are present at the starting and ending point which are zero vector so not take in calculation consideration. The Inverter connection with Ideal switches and gives it S1, S2, S3, S4, S5 & S6 to gate terminal as shown in Figure [31];

As each switching period which have sampling time half, there is Tz starts & ends with zero as explained earlier i.e. there will be two zero vectors per Tz or four null vectors per Tz, duration of each null vector is Tz/4 which are illustrates in Figures [30] & [31] which are gives the switching patterns of all sectors. After that we take output of Inverter as three phase Supply gives to Electrical Equipment.

Chapter 6

Dynamic Modeling of Induction Machine and Implementation Using Simulink

6.1 Introduction:

The dynamic simulation is one of the key steps in the validation of the design process of the motor-drive system, which eliminates the designing mistakes and the resulting errors in the prototype construction and testing. The dynamic model of the induction motor in direct, quadrature, and zero-sequence axes can be derived from fundamental equations of transformation. The dynamic analysis of the symmetrical induction machines in the arbitrary reference frame has been intensively used as a standard simulation approach from which any particular mode of operation may then be developed. Matlab/Simulink has an advantage over other machine simulators in modelling the induction machine using dq0 axis transformation. Generally modelling of these equations is considered difficult so that in this paper they are presented in their simplified form. The transformations used at various steps are based on simple trigonometric relationship obtained as projections on a set of axes. The dynamic model is used to obtain transient responses, small signal equations, and a transfer function of induction motor. Dynamic models (mathematical models) are employed in to better understand the behaviour of induction motor in both transient and steady state. The dynamic modelling sets all the mechanical equations for the inertia, torque and speed versus time. It also models all the differential voltage, currents and flux linkages between the stationary stator as well as the moving rotor. This mathematical model has been done by using MATLAB /Simulink which will represent the three phase induction motor including a three phase to d-q axis transformations. The main benefit with MATLAB Simulink is that in the electromechanical dynamic model can be accomplished in a simple way and it can be simulated faster using function blocks.

A generalized dynamic model of the induction motor consists of an electrical sub-model to implement the three-phase to two-axis (3/2) transformation of stator voltage and current calculation, a torque sub-model to calculate the developed electromagnetic torque, and a mechanical sub-model to yield the rotor speed. In addition, a stator current output sub-model is needed for calculating the voltage drop across the supply cables.

6.2 Assumptions:

There are few assumptions are to be made while deriving mathematical model of a 3-phase Induction Motor. They are listed below.

1. Uniform air gap.
2. Squirrel cage type construction.
3. Balanced stator and rotor windings, with sinusoidal distributed winding.
4. Saturation and parameter change are neglected.

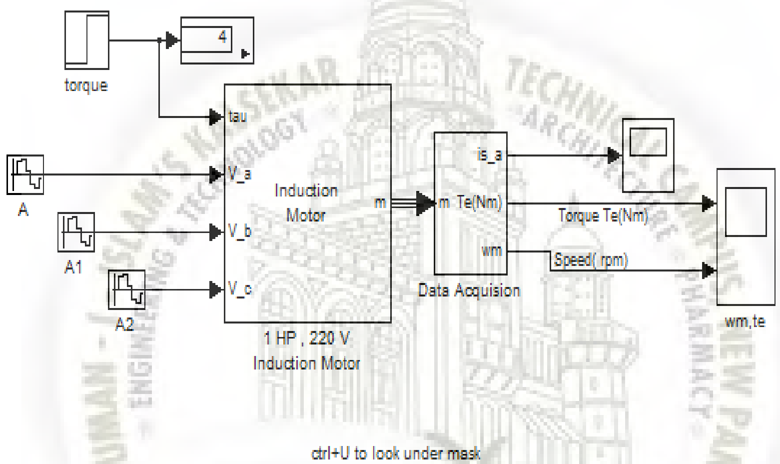


Figure 32: Dynamic Model of IM

The steady state model and equivalent circuit of the Induction Motor is useful for studying the performance of the machine in steady state. This implies that all electrical transients are neglected during load changes or stator frequency variations. Such variations arise in application involving variable-speed drives. The variable-speed drives are converter fed from finite sources, unlike the utility sources, due to limitations of the switch ratings and filter sizes. This results in their incapability to supply large transient power. Hence, we need to evaluate the dynamics of converter-fed variable-speed drives to assess the adequacy of the converter switches and the converters for a given number of motor and their interaction to determine the excursions of currents & torque in the converter and motor.

6.3 Equivalent Circuit of an Induction Motor

The voltage and torque equations that describe the dynamic behaviour of an induction motor are time-varying. It is successfully used to solve such differential equations and it may involve some complexity. A change of variables can be used to reduce the complexity of these equations by eliminating all time-varying inductances, due to electric circuits in relative motion, from the voltage equations of the machine.

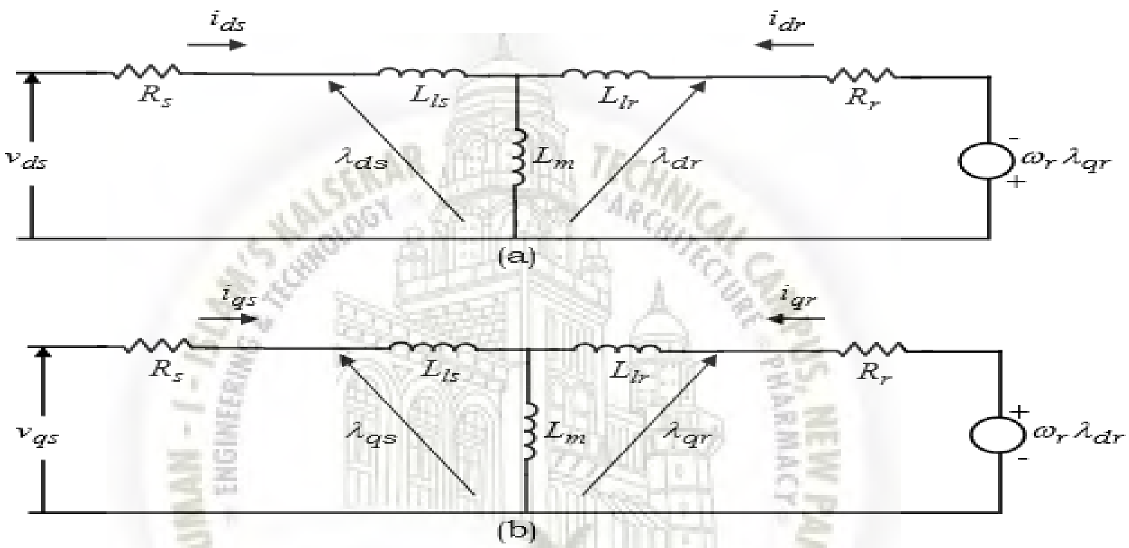


Figure 33: Equivalent Circuit of IM

Fig. 33 A dq0 equivalent circuit of an Induction Motor The above figure shows a dq0 equivalent circuit of an Induction motor. The circuit comprise of various time varying inductances which are to be simulated to analyse the dynamic performance of the 3-phase Induction motor.

6.4 Electrical Sub-model of the Induction Motor:

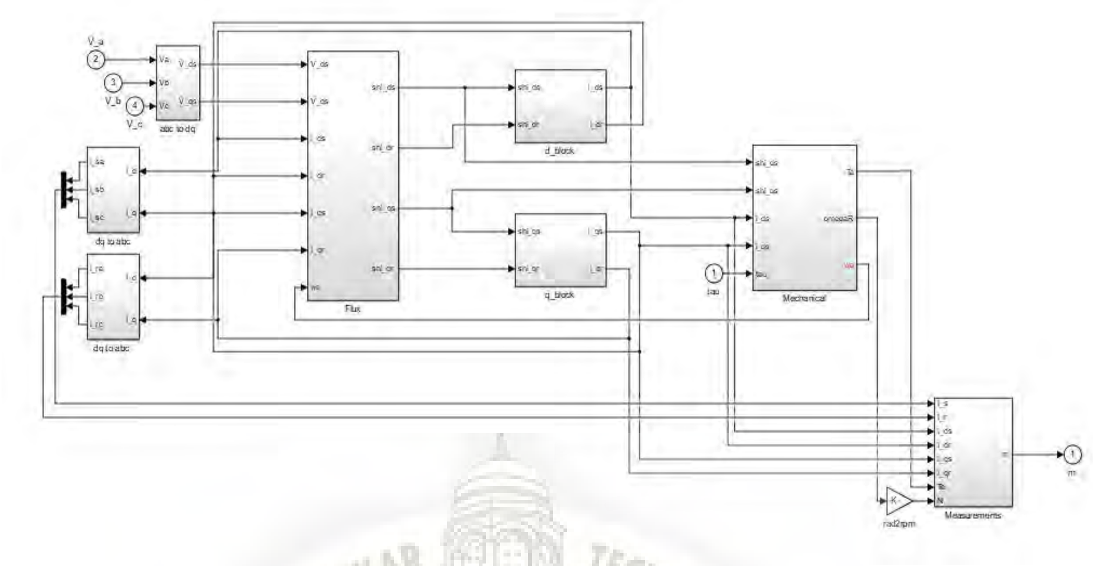


Figure 34: Subsystem of IM

The sub-model of Induction Motor is represented in Simulink Model as shown below:

The three-phase to two-axis voltage transformation is achieved using the following equation,

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_0 \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 1 & 1 & 1 \end{bmatrix} * \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

This is as shown below in Simulink Model,

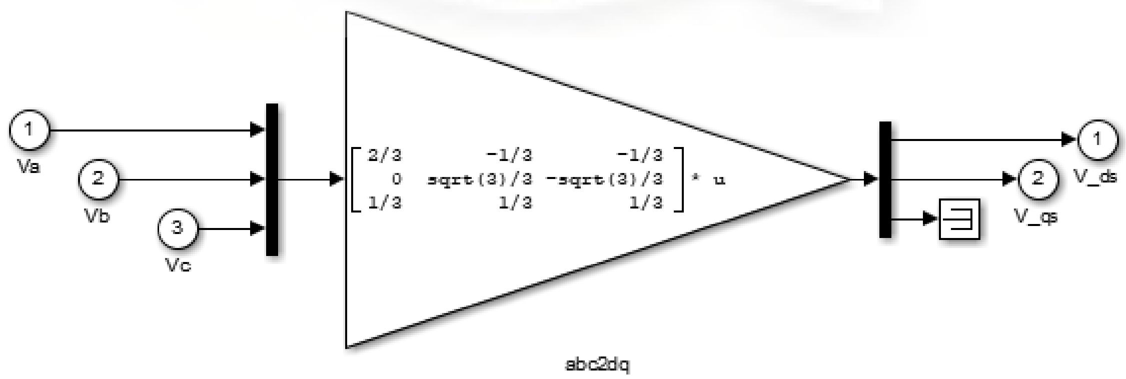


Figure 35abc to dq0 transformation

6.4.1 Sub-Model for Flux generation:

The stationary frame-dynamic model (Stanley equation) equations are given as,

$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs}$ --- (1)

$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds}$ --- (2)

$V_{qr} = R_r i_{dr} + \frac{d}{dt}\varphi_{qr} - \omega_e \varphi_{dr} = 0$ --- (3)

$V_{dr} = R_r i_{qr} + \frac{d}{dt}\varphi_{dr} - \omega_e \varphi_{qr} = 0$ --- (4)

From (1) we can obtain,

$$\varphi_{qs} = \int (-i_{qs} R_s + V_{qs}) ds$$

From (2) we can obtain,

$$\varphi_{ds} = \int (-i_{ds} R_s + V_{ds}) ds$$

From (3) we can obtain,

$$\varphi_{qr} = \int (\omega_e \varphi_{dr} - i_{dr} R_r) ds$$

From (4) we can obtain,

$$\varphi_{dr} = \int (-\omega_e \varphi_{qr} - i_{qr} R_r) ds$$

All above equations we modelled into the Simulink Model as shown in Figure [34].

6.4.2 Sub-Models for determination of d and q components of Stator & Rotor Currents:

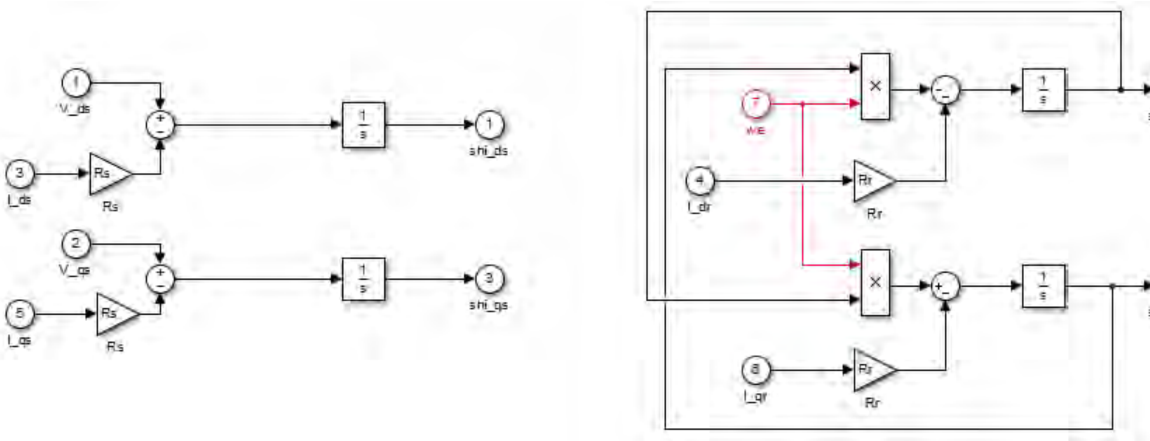


Figure 36: Sub model of flux generation

The dynamic model of induction motor and the function of this block is use to convert the φ_{ds} and φ_{dr} to current i_{ds} andi_{dr}. Also this block has equation to convert to flux into current reference.
Below equations are expressed in SIMULINK Model given as,

$$i_{ds} = \frac{[L_r\varphi_{ds} - L_m\varphi_{dr}]}{(L_rL_s - L_m^2)}$$

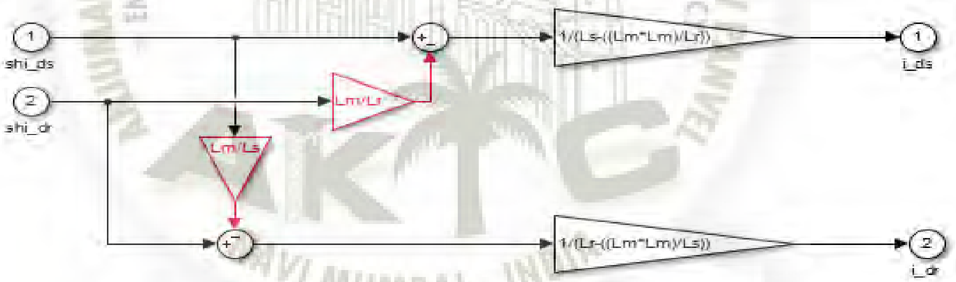


Figure 37: Current of d-component

$$i_{dr} = \frac{[L_m\varphi_{ds} - L_s\varphi_{dr}]}{(L_m^2 - L_rL_s)}$$

Both above and below block has the same function only the difference is above block convert d-axis of flux and below convert q-axis of flux into their respective currents. In the below model we use following expressions;

$$i_{qs} = \frac{[L_r\varphi_{qs} - L_m\varphi_{qr}]}{(L_rL_s - L_m^2)}$$

$$i_{qr} = \frac{[L_m\varphi_{qs} - L_s\varphi_{qr}]}{(L_m^2 - L_rL_s)}$$

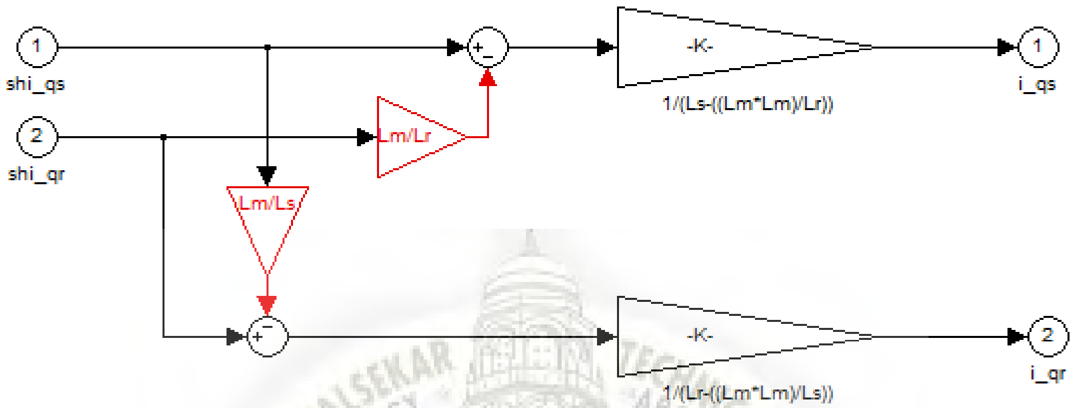


Figure 38: Currents of q-components

6.4.3 Sub-Model of Inverse Transformation from dq0 to abc-components:

In this subsystem we convert two components in to three components which is required for the induction machine. For the conversion of this we will using following Matrix equation in the SIMULINK Model which is shown in above Figure,

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}$$

The above matrix shows stator currents of dq0 components.

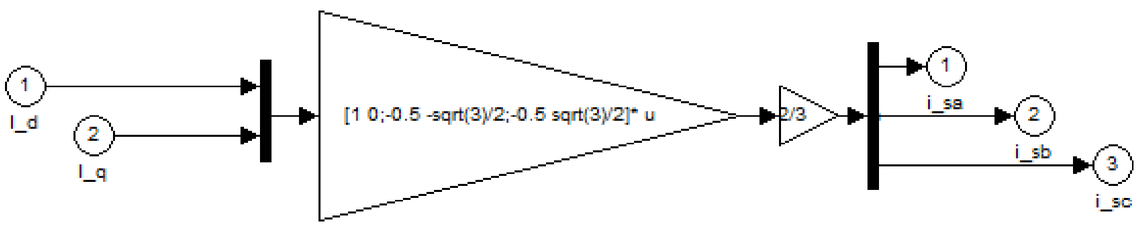


Figure 39: dq0 to abc conversion of Stator current

For Rotor currents we use below matrix equation as given below,

$$\begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix}$$

Which expressed in below Model as shown in Figure [40].

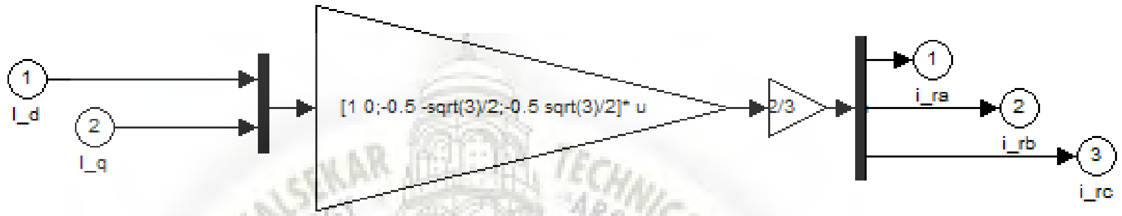


Figure 40: dq0 to abc conversion of Rotor current

6.4.4 Sub-Model of Mechanical Output:

Based on the flux and currents of dq0 components of stator, the Electromagnetic torque and rotor speed can be determined as follows,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_e}(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds})$$

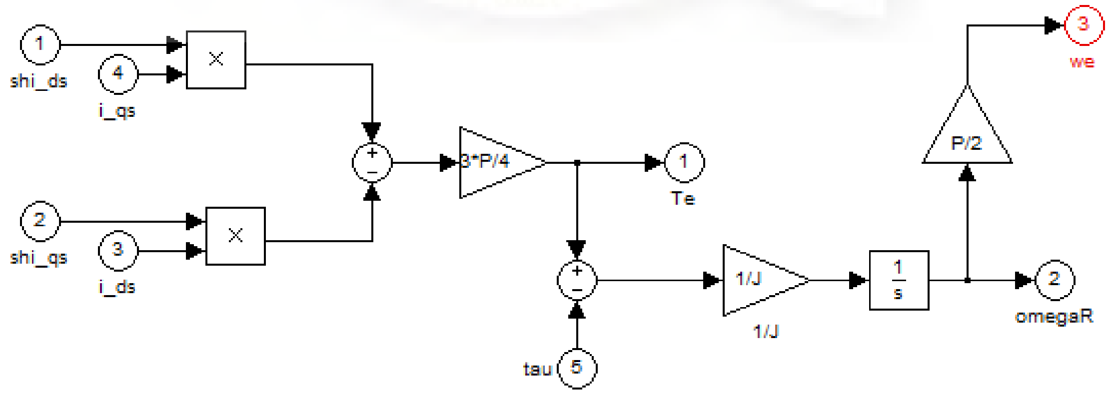


Figure 41: Mechanical Model of IM

$$\omega_e = \int \left(\frac{P}{2J}\right)(T_e - T_l)\, ds$$

Above model determined by following expression,

$$[(\varphi_{ds} * i_{qs}) - (\varphi_{qs} * i_{ds})] * \frac{3P}{4} = T_e$$

And for rotor speed $(T_e - \tau)$

With τ is reference torque

Then $(T_e - \tau) * (1/J)$ which is Integrate and Multiplied by P/2 as,

$$\int \left[\frac{P(T_e - \tau)}{2J}\right] ds$$

6.5 Measurements:

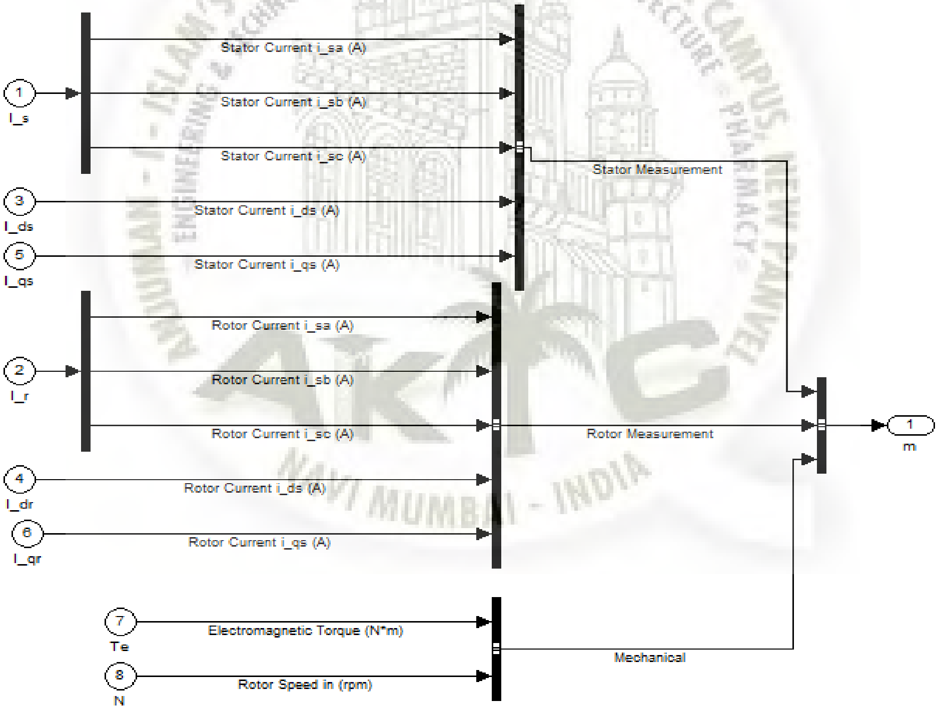
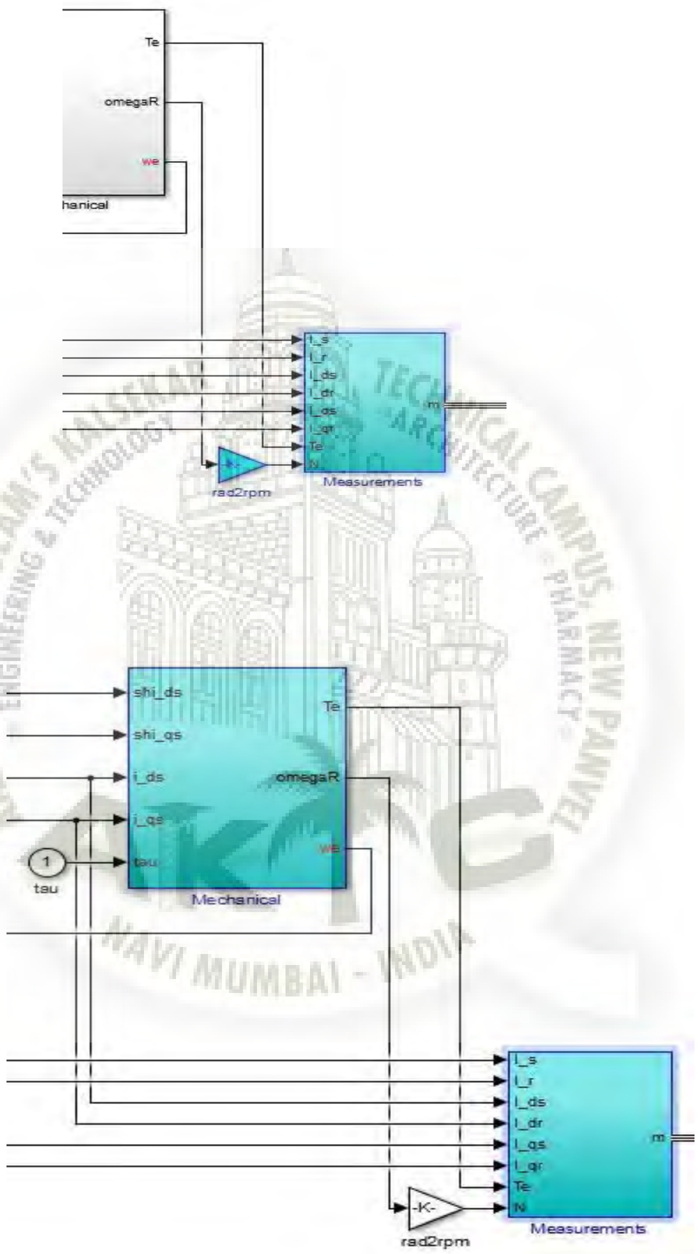


Figure 42: Measurements of IM Parameters

For measurements of Currents, Torque and rotor we modelled a SIMULINK model as shown in figure. Measurements of Currents are split into two components first stator Measurements and second rotor measurement. These are obtained by using Bus-selector which functioning to select the proper component of current which derive from previous Models.

And at the last we measured Electromagnetic Torque (N-m) and Rotor Speed (rpm), Torque is determined as shown in figure , obtained T_e we give to the measurement Model.



For Rotor speed calculation we used following model which is shown below:
In the above figure we illustrated that, After obtained the equation of T_e i.e. Electrical Torque which is actual motor running torque. Another torque which is desirable i.e.T_l for the application purpose. By using T_e&T_l and Reciprocal of Rotor Inertia then, integrate them for obtaining the rotor speed.

In the Model we use block of conversion which converted Radian to RPM.

By using above SIMULINK Model we determined the T_e which is obtained into the Mechanical subsystem which follows below equation for obtaining actual torque of motor.

6.6 Sub-model of Data Acquisition:

The sub-model of data acquisition is as shown in below figure, in which we will use low pass filter for determination of Electromagnetic Torque in N-m.

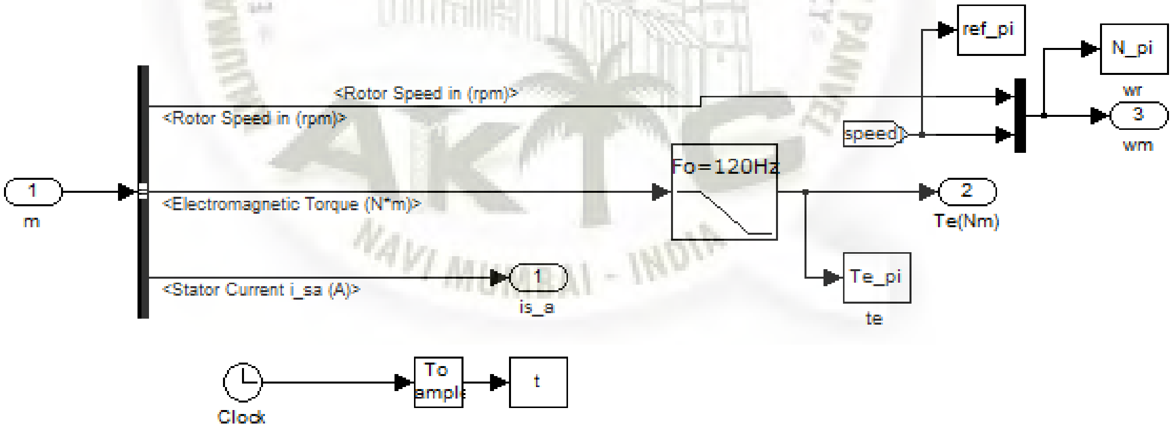


Figure 45: Sub-model of Data Acquisition

Finally, we obtained the Speed torque characteristic, which shows at constant speed motor runs at desirable torque.

Chapter 7

Results and Conclusion

7.1 Results in MATLAB Simulink Model

(two level vector control) Space vector PWM

Vector Control

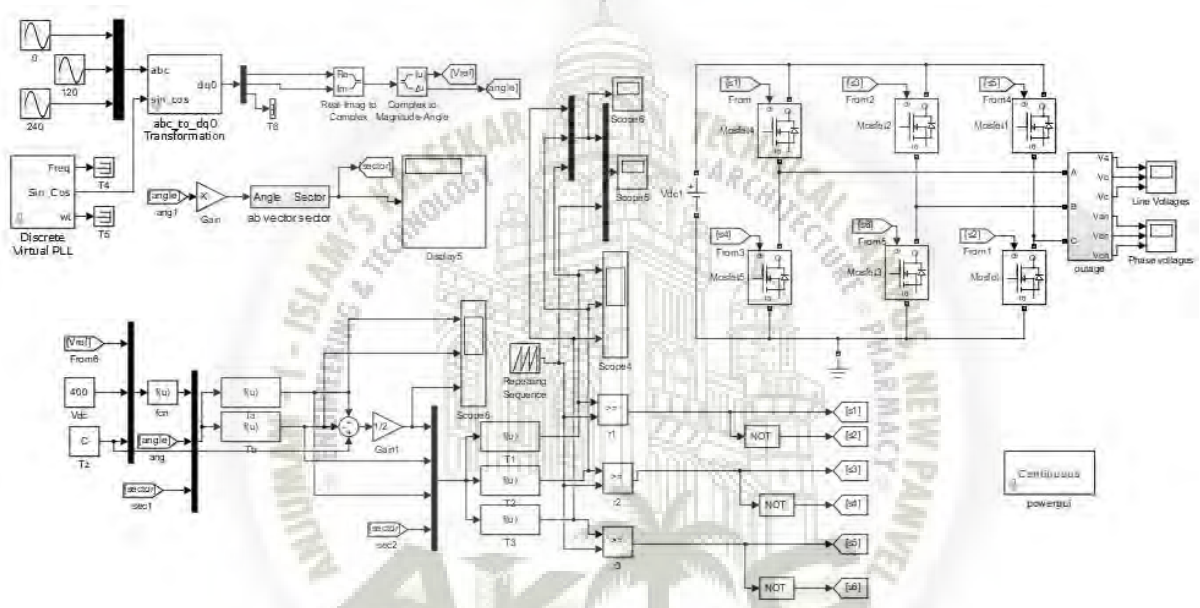


Figure 46: Simulink Model of Two Level (SVPWM)

The SIMULINK Models has been developed for SVPWM in MATLAB SIMULINK.

The Block Diagram of Space Vector Pulse width modulated inverter fed Induction Motor is shown in Figure

The simulation parameters used are:

Fundamental frequency =50 Hz

Switching frequency =6kHz

DC voltage =400Volt

Modulation Index (MI) = $\frac{\sqrt{3}V_{ref}T_z}{V_{dc}}$

Asynchronous Machine = 1HP, 220V, 50Hz

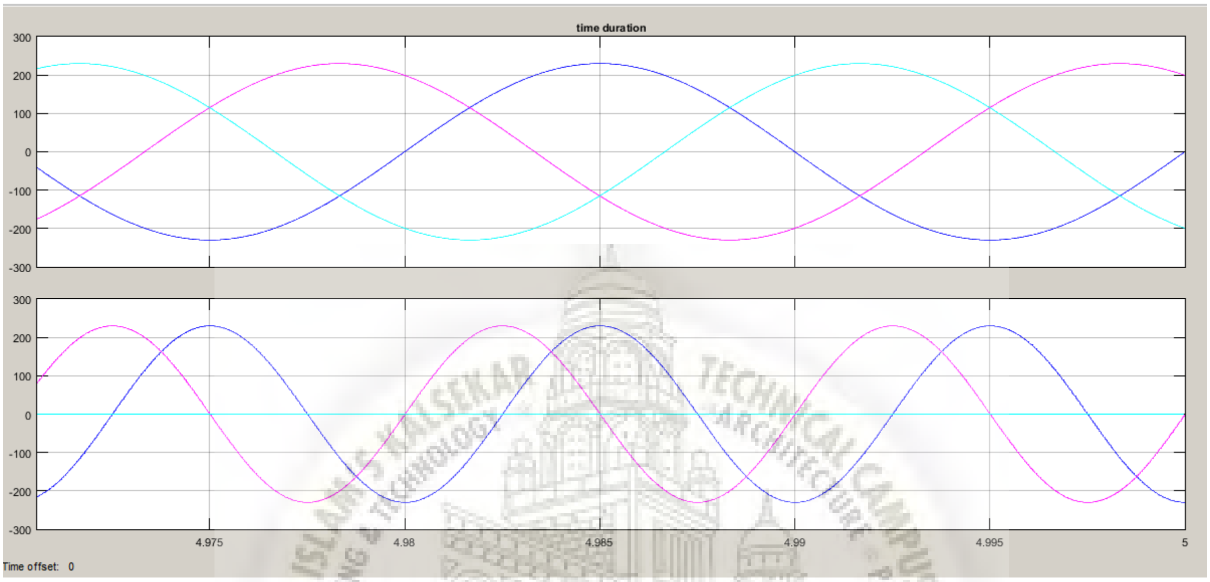


Figure 47: abc to dq0

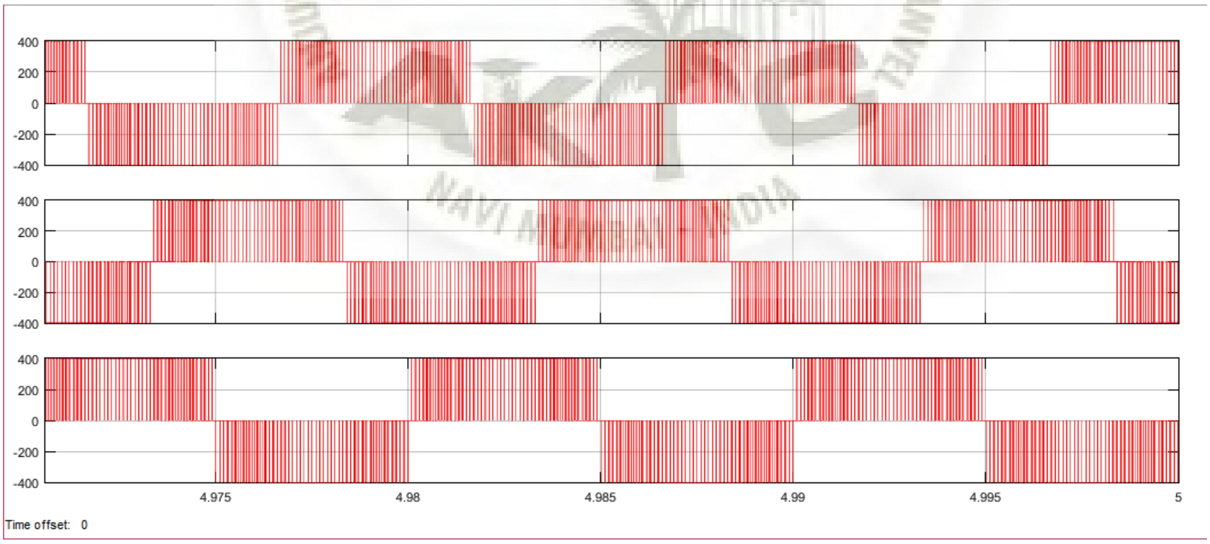


Figure 48: Line voltages Van, Vbn, Vcn

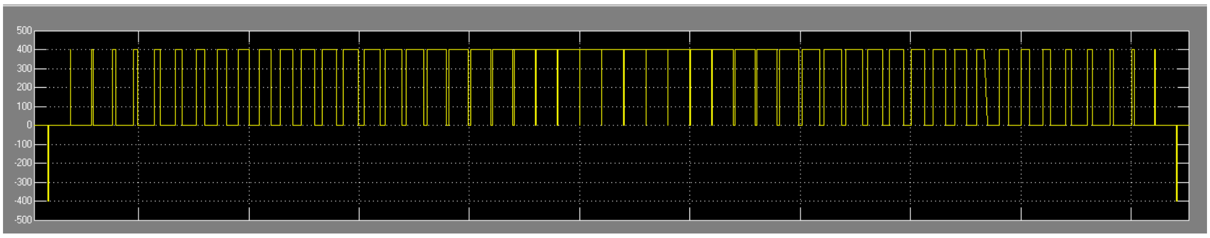


Figure 49: line voltage of half cycle of Va

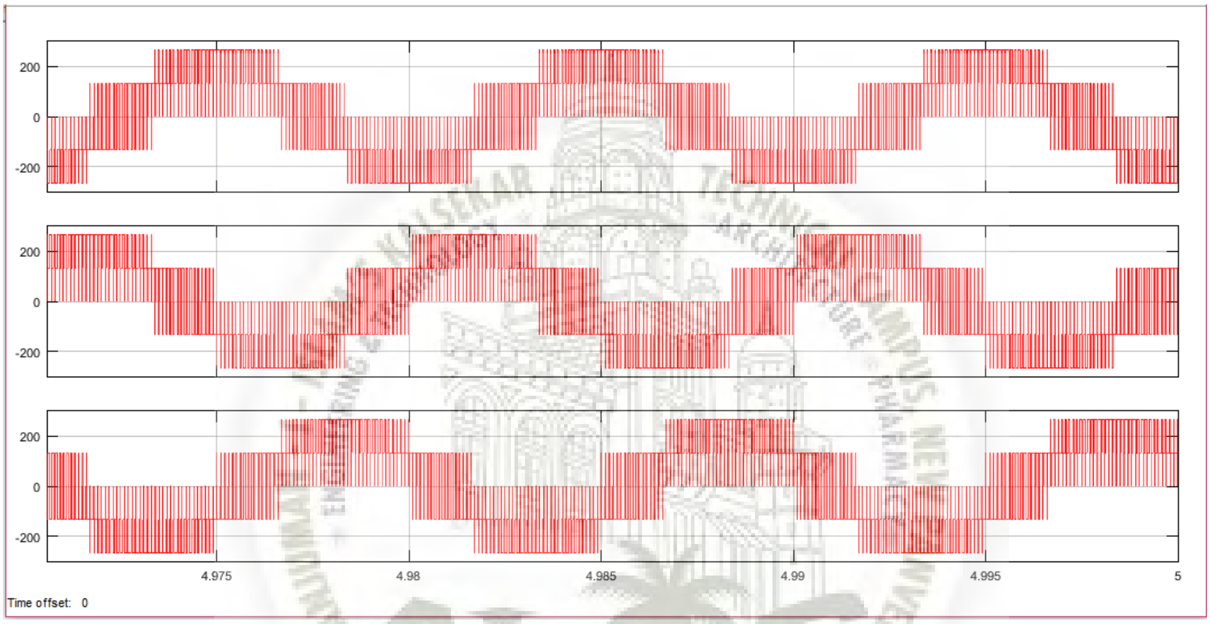


Figure 50: Phase voltages Van, Vbn, Vcn

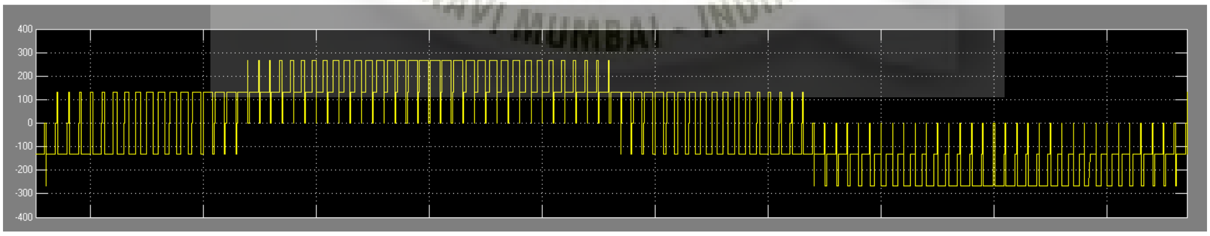


Figure 51: Phase voltage of one cycle of Van

Induction motor parameters:

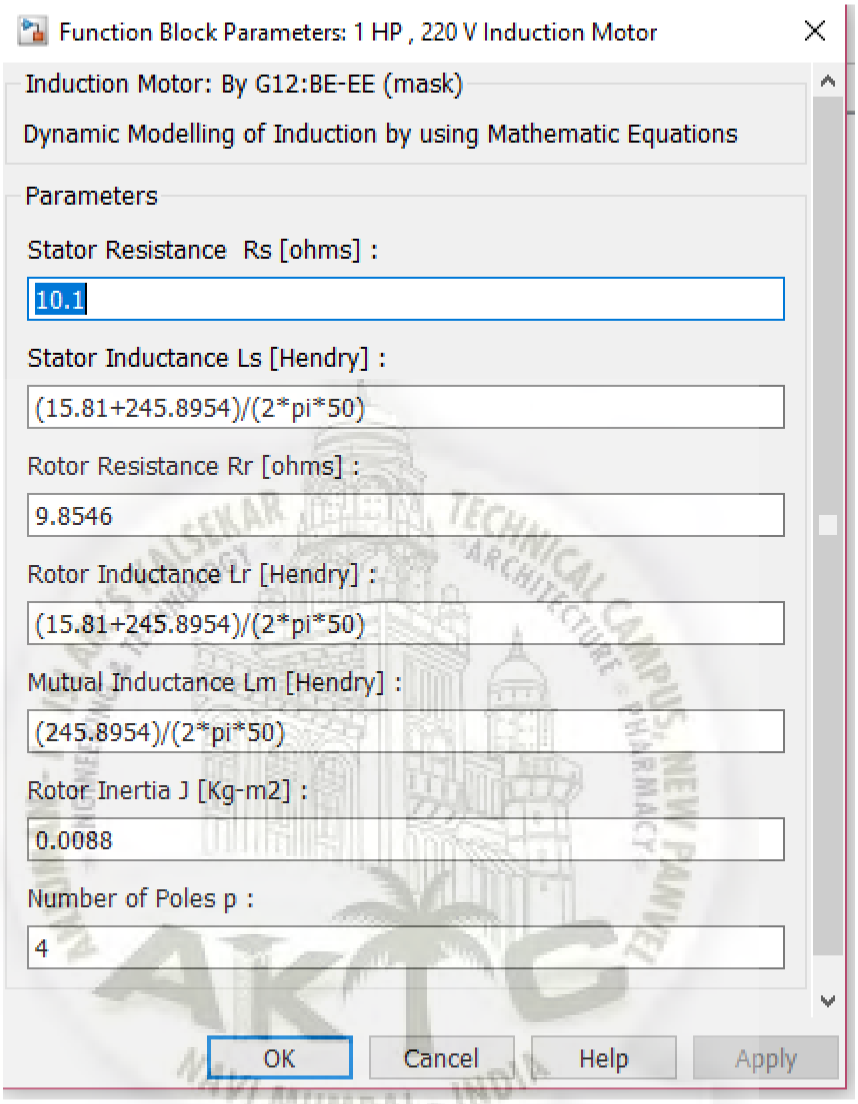


Figure 52: Three-phase Induction motor parameters

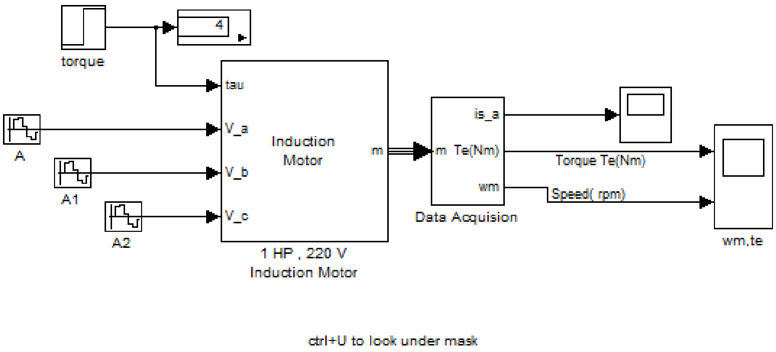


Figure 53: Dynamic modelling of induction motor

Speed torque characteristics of the three phase induction motor:

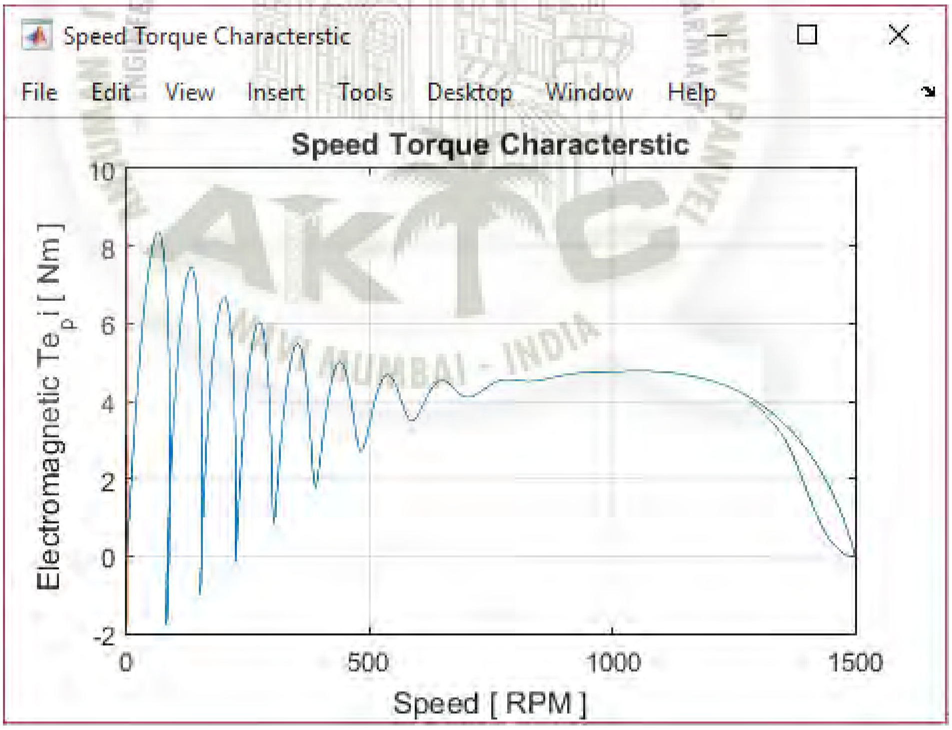
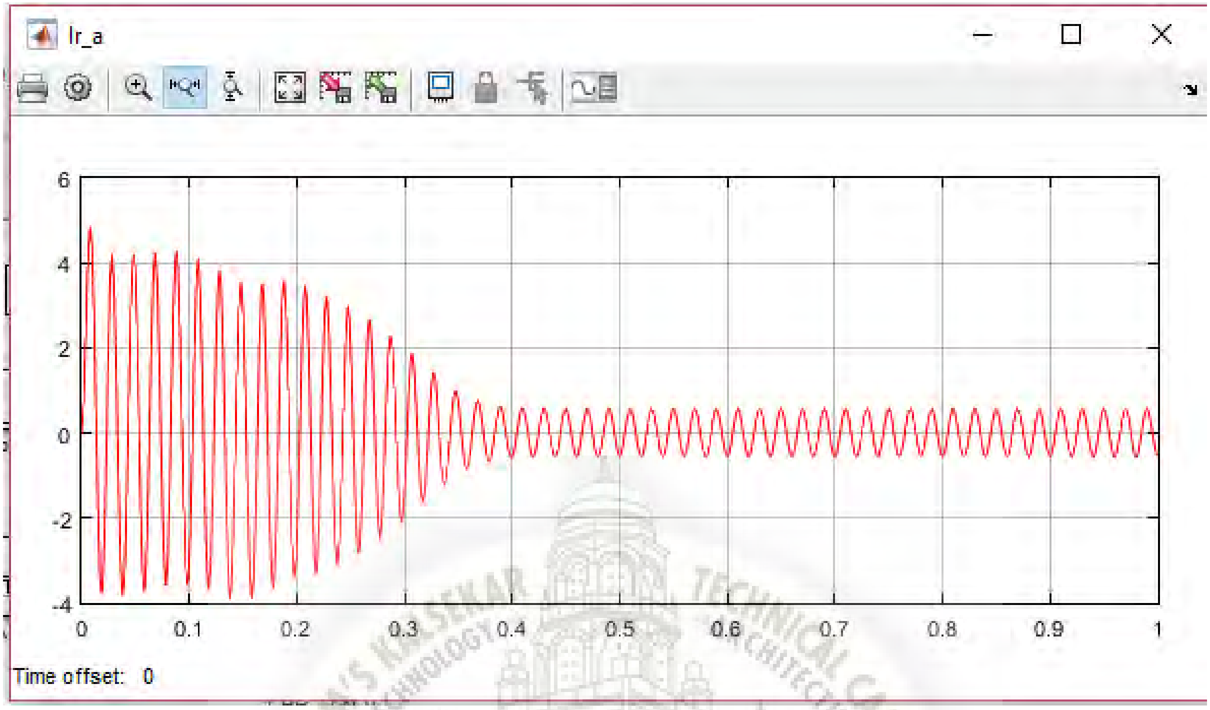


Figure 54: Speed-Torque Characteristic

Current



igure 55: rotor current

Speed:

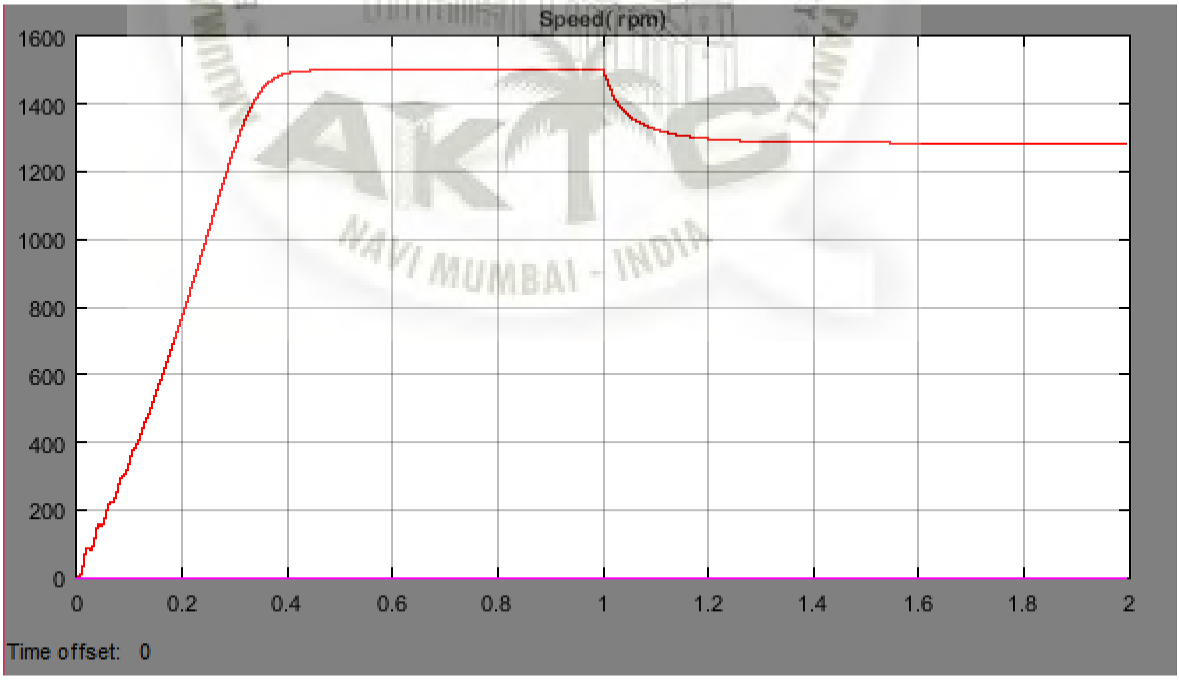


Figure 56: Speed of Rotor

Torque:

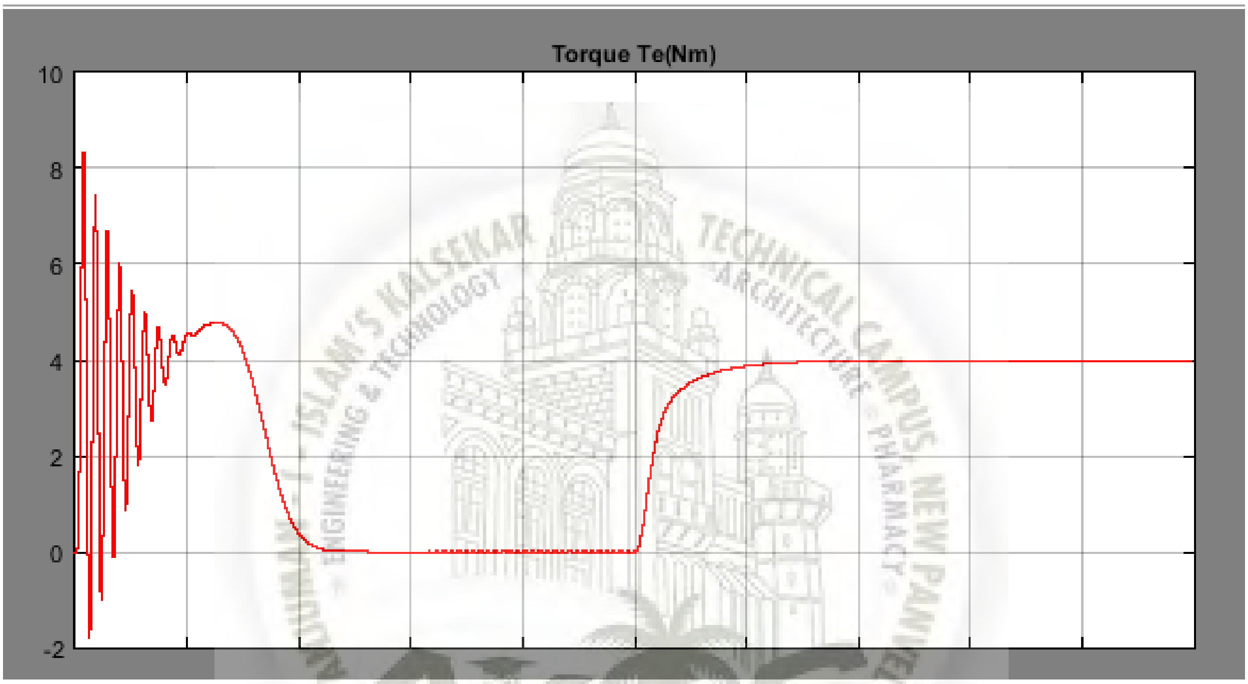


Figure 57: Electromagnetic torque developed

Open loop integration of two level vector control SVPWM and three phase induction machine:

In such a developing era there are large numbers of variable speed three phase induction motor drives. These drives are used to serve the various industrial expectations esaly, efficiently and economically. There is various methods of speed control of induction motor but in this paper we have used constant V/f method. If only frequency is changed and stator voltage kept constant, the stator flux will not be at its rated value. The operation with flux above or below the rated value is not desirable. For constant flux operation it is necessary that the induced emf increases or decreases linearly with applied frequency. At higher voltage and higher frequency operation stator drops are very small and thus constant flux operation obtained by keeping V/f ratio constant. The relation between voltage and frequency is shown in fallowing fig.

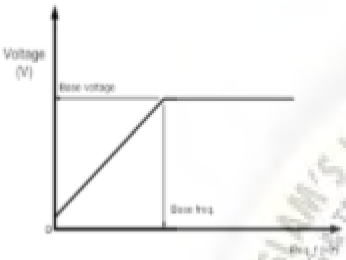


Figure 58: voltage and frequency variation

The variable voltage and variable frequency can be obtained from pulse width modulation method. In this paper we have discussed about the SVPWM method.

Space vector PWM refers to a special switching scheme of the six power semiconductor switches of a three phase power converter. Space vector PWM (SVPWM) has become a popular PWM technique for three-phase voltage-source inverters in applications such as control of induction and permanent magnet synchronous motors. The mentioned drawbacks of the sinusoidal PWM and hysteresis-band current control are reduced using this technique. Instead of using a separate modulator for each of the three phases (as in the previous techniques), the complex reference voltage vector s processed as a whole. Therefore, the interaction between the three motor phases is considered. It has been shown, that SVPWM generates less harmonic distortion in both output voltage and current applied to the phases of an ac motor and provides a more efficient use of the supply voltage in comparison with sinusoidal modulation techniques.

SVPWM provides a constant switching frequency and therefore the switching frequency can be adjusted easily. Although SVPWM is more complicated than sinusoidal PWM and hysterisis band current control, it may be implemented easily with modern DSP-based control systems.

The principle of space vector modulation is briefly explained in chapter 4.

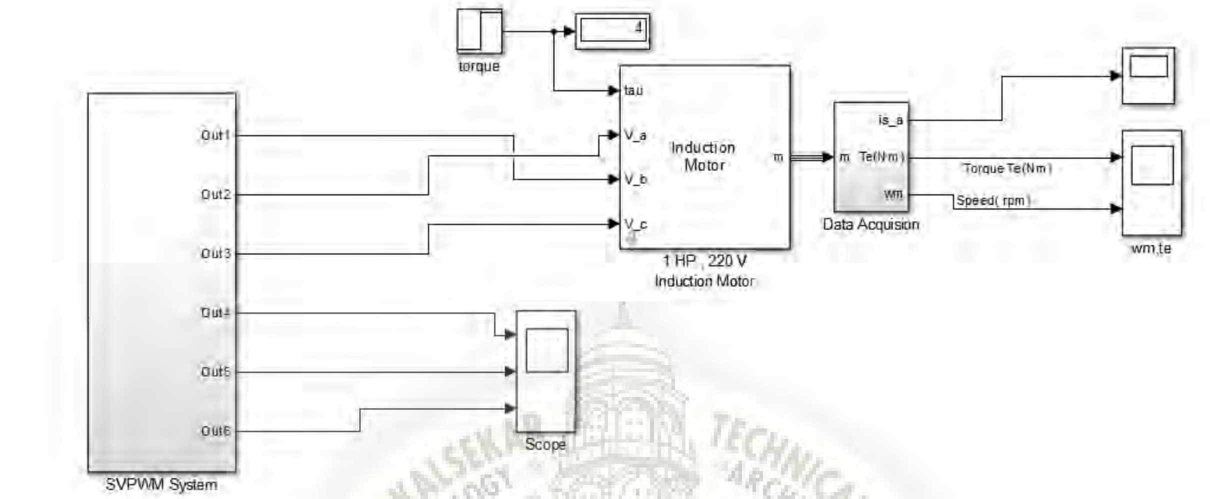


Figure 59: SVPWM Fed Three Phase Induction Motor

speed torque characteristics of SVPWM fed induction motor:

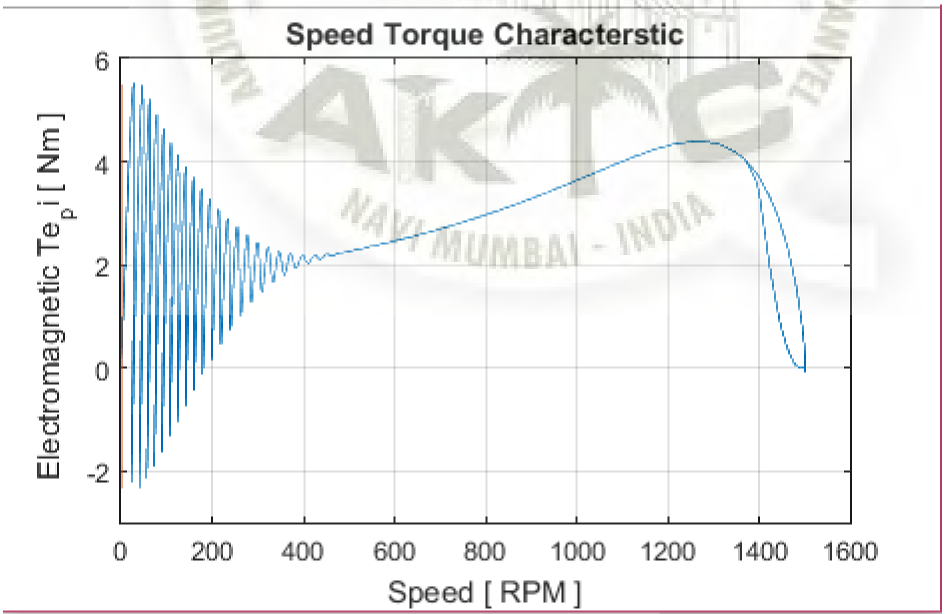


Figure 60: Speed torque characteristics of SVPWM fed induction motor

Current

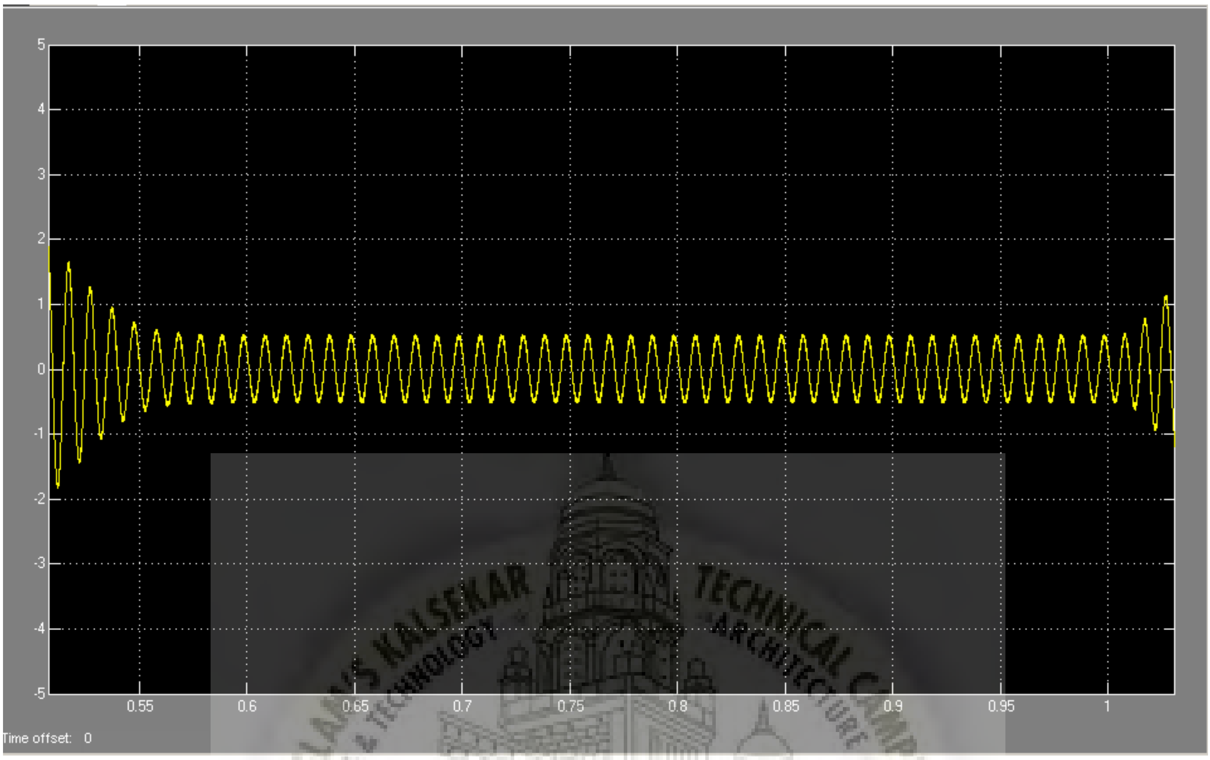


Figure 61: Rotor Current

Obtained graph of torque and speed respectively:

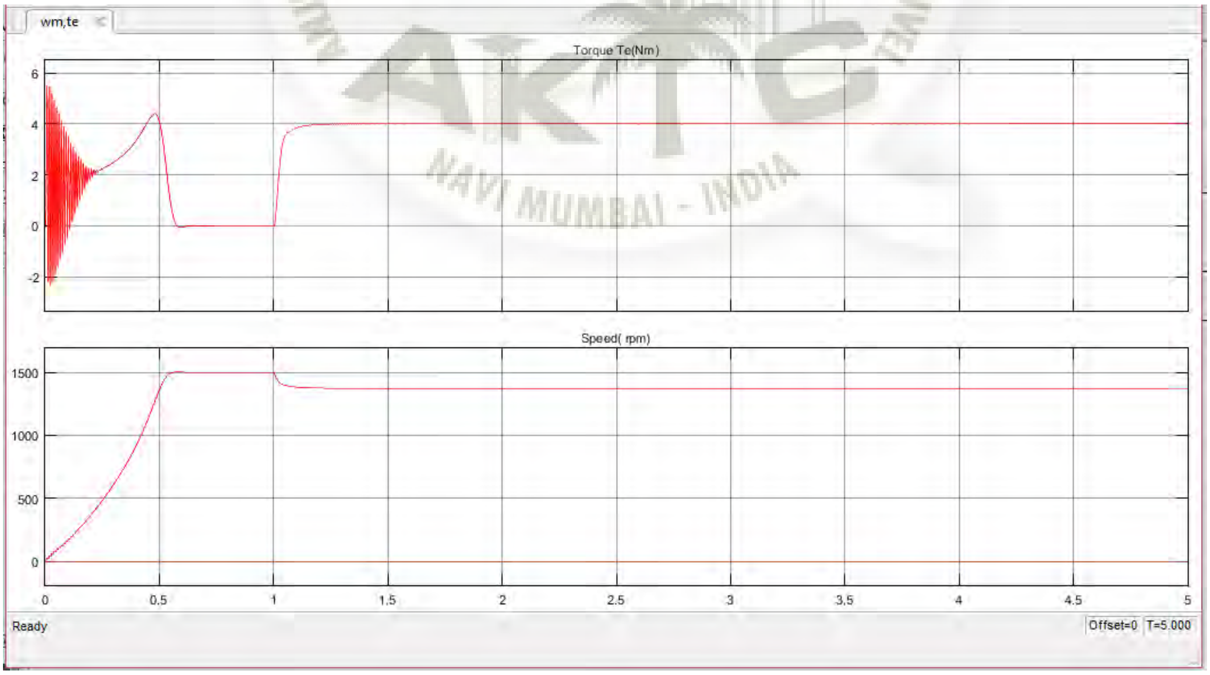


Figure 62: Elecromagnetic Torque developed & Speed of Rotor

Stator current

Rotor current

Ids(stator current in direct axis)

Iqs(stator current in quadrature axis)

Idr(rotor current in direct axis)

Iqr (rotor current in quadrature axis)

Above al parameters are shown in below waveforms respectively

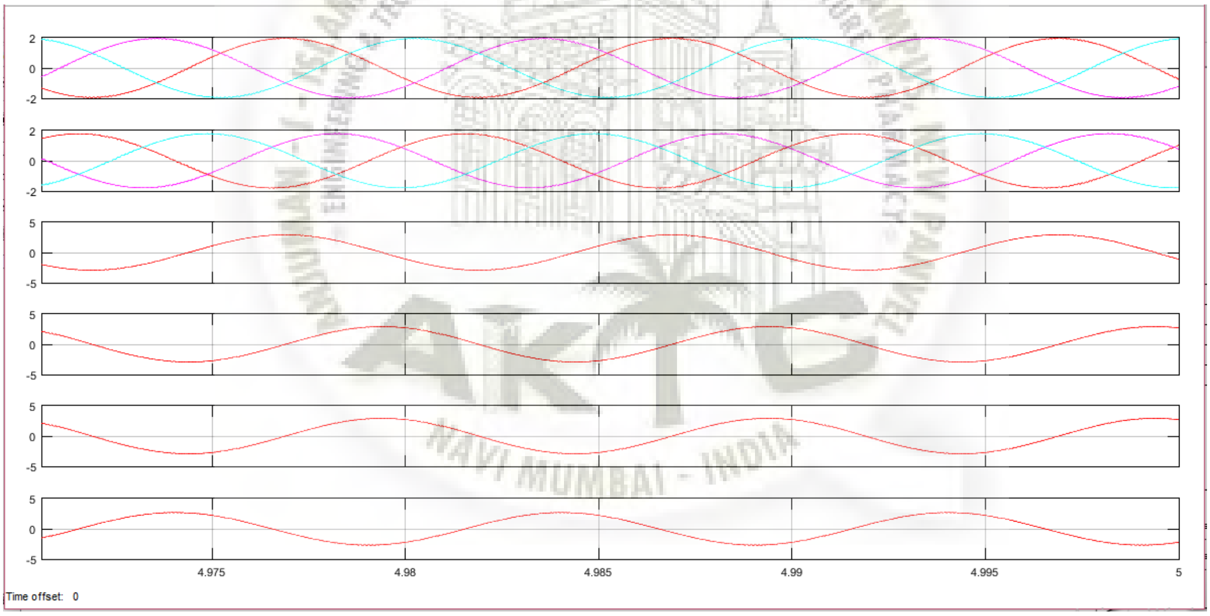


Figure 63: currents components of stator and Rotor

7.2 Conclusion:

Mechanical energy is needed in the daily life use as well as in the industry. Induction motors play a very important role in both worlds, because of low cost, reliable operation, robust operation and low maintenance. To derive the mathematical model of a 3 phase Induction motor, the theory of reference frames has been effectively used as an efficient approach. Dynamic models (mathematical models) are employed in to better understand the behavior of induction motor in both transient and steady state. The dynamic modeling sets all the mechanical equations for the inertia, torque and speed versus time. It also models all the differential voltage, currents and flux linkages between the stationary stator as well as the moving rotor. This paper presents a step by step Matlab/Simulink implementation of an induction machine using dq0 axis transformations of the stator and rotor variables in the Stationary reference frame [1]. In this Chapter, an implementation and dynamic modeling of a three-phase induction motor using Matlab/Simulink is presented in a step-by-step manner. The model was simulated by 3 hp induction motor. The simulated machine has given a satisfactory response in terms of the torque and speed characteristics. This concludes that the Matlab/Simulink is a reliable and sophisticated way to analyze and predict the behavior of induction motors using the theory of reference frames

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Achievements

1. **Publications**

Title : *Study of Speed Control of ACIM Using Indirect Field Oriented Control*
Authors : shabbir siddiqui , Hussain Khan I. Pathan, Tahir Shaikh, Mahfuz alam

(https://www.erpublication.org/page/view_issue/Volume-9-Issue-3)

Paper id- ijetr2729

2. **Training and project work**:

This project is conducted at **BHABHA ATOMIC RESEARCH CENTER**

All members of this project group was a project trainee in BARC from **29th August 2018** to **6th April 2019**.

ISSN : 2321-0869 (O) 2454-4698 (P)

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Study of Speed Control of ACIM Using Indirect Field Oriented Control

Shabbir Siddiqui, Hussain Khan I. Pathan, Mahfuz alam, Tahir Shaikh, Shraddha Hule

Abstract— **This study has been undertaken to investigate the speed control ACIM using field oriented control. The principle of vector control of electric drives is based on the control of both the magnitude and the phase of each phase current and voltage. for this purpose, the study of available conventional and non-conventional approaches has been presented. This paper also presents a clear study which illustrates introduction of efficient vector control of ACIM.**

Index Terms— **ACIM-ac induction motors, vector control**

I. INTRODUCTION

Induction motor or asynchronous motor is the most extensively used in the industrial, commercial, residential settings as these motors are simple and robust in construction having low cost and minimum maintenance, high dependability and sufficiently high proficiency due to these conveniences ACIM are most widely used in industrial applications. However, control of ACIM is more difficult than the control of DC machines, with the help of scalar methods speed can be control as it is simple to implement but it has the coupling effect thus it is responsible for slow response which leads to oscillations due to higher order effect. But in many operations and machinery in industries sensitive revolutions and torque adjustment have to be peripheral with high accuracy, so dc motor drives were generally used variable speed drives because of the simplicity of control due to decoupling between armature current and the field current.

The control and estimation of ac drives in general is considered more complex than these of dc drives and this complexity increases substantially if performance are demanded. Also to control the ACIM there are different types of conventional methods are available such as followings:

- Conventional approach-
  1. Variable supply voltage control
  2. Variable rotor resistance control
  3. Constant volts/hertz control (scalar control)
- Non-conventional approach-
  1. Direct torque control(DTC)
  2. Vector control

First three speed control methods stated above have many drawbacks including saturation of core due to variation in flux. In the scalar control method, the steady state model of the motor is used and speed control is carried out with the fixed ratio of v/f. The scalar speed control method for ACIM is the most commonly known and used due to convenience of easy implementation. The fundamental property of this method is to keep ratio of the voltage which is supplied to the stator at speed between initial and final or rated value to the frequency (v/f) and therefore the air gap flux and induced torque is fixed. Speed control may be carried out keeping the voltage fixed and increasing the frequency at speed greater than rated speed thus weakening the air gap flux. The biggest downside of scalar method is that the rated torque is reduced as a result of the relative effect of the voltage which decreases with the stator resistance at low voltage of 3-5 HZ on the phase voltage.

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II. NON-CONVENTIONAL APPROACH

- Direct torque control(DTC)
- Vector control

The name direct torque control is derived by the fact that on the basis of errors between the reference and the estimated values of the torque and flux it is possible to directly control. DTC allows good torque control in steady state and transient operating conditioned as well to be obtained, it is well known that DTC having some downside that can be summarized in the following points:

1. Inconvenient to control torque and flux at very low speed
2. High current and torque ripple
3. Variable switching frequency behavior
4. High noise level at low speed
5. paucity of direct current control

these downsides can be overcome with the help of vector or field oriented control. With the help of this method ACIM can be control similar to the separately excited dc motor, the mmf produced by the armature current are spatially quadrature. Therefore, there is no magnetic coupling between field circuit and armature circuit thus the armature current can be changed independently and torque can be control swiftly keeping field flux constant.

In ac machines also the torque is produced by the interaction of flux and current but in induction motor (ACIM) the power is fed to the stator, only the current is responsible for production of torque and flux. This is obtained by controlling the magnitude frequency and phase of stator current by mathematical transformation and inverter control. So the control of the motor is obtained by controlling both magnitude and phase angle of the current. This kind of approach towards speed control method is called vector or field oriented control.

III. FIELD ORIENTED CONTROL

Vector or field oriented control in ACIM is executed by independently controlling torque component and field component of the stator current through a coordinated change in supply voltage amplitudes, phase and frequency with this method ACIM can give performance comparable to dc machines. In field orientation control current which is supplied to the motor is split into two components i.e. flux component and torque component, in which flux component is direct in phase with the rotor flux and torque component is directed in quadrature. It behaves like dc quantities in steady state. The torque component in space phasor can be written as [1]

$$T_e = KI_{ds}I_{qs} \text{ or } T_e = KI_{dr}I_{qr} \quad (1)$$

n ACIM stator current phasor I_s produces the rotor flux and the torque component of stator current producing the flux is in phase with rotor flux of I_{ds} of the stator current is similar to field current of dc machine. The current I_{qs} is responsible for production of total flux and aligned to the direction of the flux vector. In an ACIM there are three distinct flux space phasors i.e. Air gap flux, stator flux and rotor flux. [1] The simple scheme is shown in fig.2

Vector control can be performed with respect to any of these flux phasor by attaching d axis of the reference, the respective flux space or direction. Rotating reference frame rotating with the total flux linkage space vector of the rotor as reference frame is the field frame. So this method is known as field oriented control method.

If instantaneous current i_a, i_b, i_cin the stator phases then the stator phases then the stator current vector is defined as follow:

$$i_s = i_a + i_b e^{j2\pi/3} + i_c e^{j2\pi/3} \quad (2)$$

these current space vector shows the three phase sinusoidal system. But this three phase sinusoidal system needs to be transformed into time invariant coordinate system. This transformation can be split into two steps with two time with two transformation method.

- $(abc) \rightarrow (\alpha\beta)$ (The Clark transformation) which gives a two coordinated time variant system.
- $(\alpha\beta) \rightarrow (dq)$ (Park transformation) which gives a two coordinated time invariant system.

In this process d-q component in stator reference frame. There are then transformed into field reference frame is at an angle of θf with respect to stator reference frame shown in fig.1 below. θf is field angle θsl is the slip angle and θr is the angle between stator current space vector and the reference field frame than

$$\theta f = \theta r + \theta s \quad (3)$$

In terms of speed

$$\theta f = \int (\omega r + \omega sl)dt = \int \omega s \, dt \quad (4)$$

These current which is transferred are compared with i_{ds}* and i_{qs}*. The obtained error signals are amplified and used to control flux and torque. Then these are transformed from field frame to stator frame using inverse transformation. By 2/3 transformation once d-q components are known these can be converted into abc components. These currents are compared with the actual motor current and used to control the switching of inverter current regulated three phase inverter used switching control is also used to regulates the values of these current. Due to decoupled of these current dynamic response can be achieved as that of DC motor. Current I_s can orient

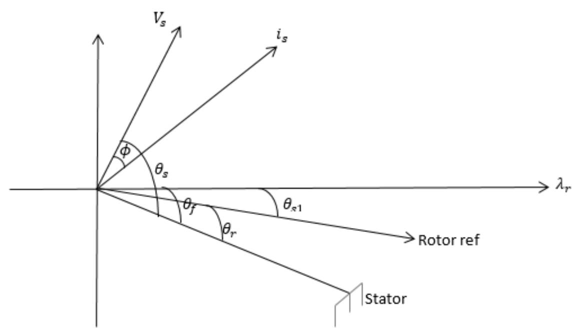

figure 1

with rotor flux axis or stator flux axis or with air gap flux axis for vector control but rotor flux orientation gives natural decoupling control whereas the air gap flux or stator flux orientation required compensation.

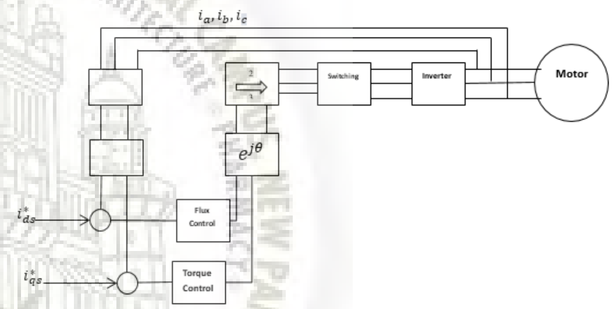

figure 2 Basic scheme of field oriented control

IV. DIRECT VECTOR CONTROL

In this method of field oriented control vector is obtained by the terminal voltage and current or flux linkage signal is achieved directly by flux evaluator or sensors requires specially assigned motor equipped with hall effect technology. In this it will be assured

that the position of rotor flux linkage vector d_r is known and it is at an angle of θf from stationary reference frame as illustrated in figure. The stator current Is, makes an angle θs with stator reference frame and an angle of θi with rotor flux linkage axis.

The component of current producing the rotor flux has to be in phase with dr. Thus I_f is resolved into d axis and q axis component in rotor flux linkage frame $Is \cos\theta = If$ is the field producing component and the component along q axis $It = Is \sin\theta t$ is the torque producing component since Is phasor rotates at synchronous speed and the rotor flux linkage space and slip speed. The relative speed between I_f and rotor field is zero. Thus current $I_t$and I_f are dc quantities and can be ideally used as control variables.[2]A block diagram of direct vector control is illustrated in fig.3.

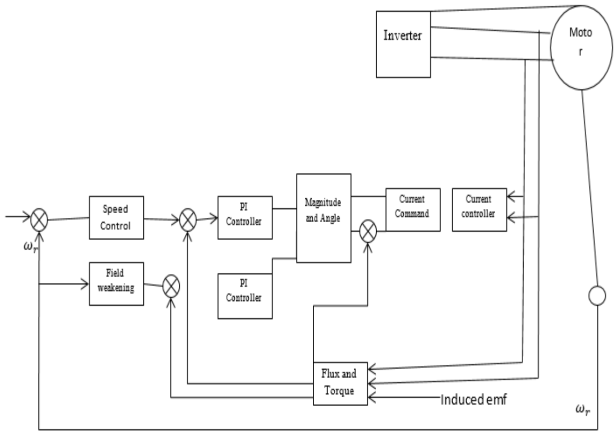

figure 3 Direct vector control scheme

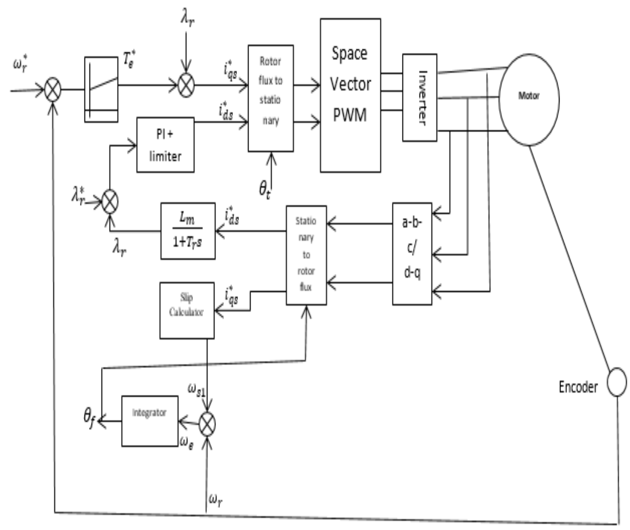

figure 4 Block diagram of indirect Vector control

However, use of sensors is very expensive because unique modification of the motor is required for placing the sensors which sense the flux. There may be inaccuracies by calculating rotor flux directly from directly sensed signal because at low speed due to stator resistance voltage drop in the stator voltage equation and inaccuracies due to variation on flux level and temperature. With this inaccuracy of motor, the rotor flux position, torque and flux components are not completely decoupled as result dynamic response becomes deficient. This method has so many downsides as it requires number of sensors and to fulfill this requirement special modification of motor is needed which further becomes a tedious task as well as devastating due to increase in cost. Thus this scheme is not favored.

V. INDIRECT VECTOR CONTROL

In indirect field oriented control method, the relative speed of the rotor flux linkage space vector is determined and integrated to obtain angle of movement of the field with respect to the rotor. This angle is added to the measured angle moved by rotor to obtain θr. Indirect vector has lot of dominance over direct FOC due to following reasons: [2][3][1]

1. The sensors are not required.
2. The dynamic performance of Indirect FOC is much better than direct vector control due to various precedence
3. Cost is reduced due to absence of sensor as that of direct FOC
4. Drift problems are eliminated
5. Torque response is improved
6. It is possible to control the torque at low frequencies and low speed
7. Accurate four quadrant operations possible
8. No need to do special modification in motor.
9. Requires less power hence overall performance is improved

So indirect vector control is very popular in industrial applications. With the help of phasor diagram it is possible to understand the principle of indirect FOC as shown: [1]

The angle θf will be varying with time as the rotor flux linkage space vector dr rotates and is referred as field angle where rotor speed ωr and rotor field speed is ωsl. Stator current can be directly controlled as motor is supplied through current the rotor equation with subscript e to indicate synchronous reference frame [1]

$$\frac{d\lambda_{dr}^e}{dt} = R_r i_{dr}^e - \omega_{s1}\lambda_{qr}^e \quad (5)$$

$$\frac{d\lambda_{qr}}{dt} + R_r i_{qr} - \omega_{s1}\lambda_{dr} = 0$$ (here the subscript e is ignored) (6)

Where

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (7)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (8)$$

From above equations the rotor current can be obtained in terms of stator currents as

$$i_{dr} = \frac{\lambda_{dr} - L_m i_{ds}}{L_r} \quad (9)$$

$$i_{qr} = \frac{\lambda_{qr} - L_m i_{qs}}{L_r} \quad (10)$$

Substituting these values of rotor currents in equations for flux linkages

$$\frac{d\lambda_{dr}}{dt} + \frac{R_r}{L_r}\lambda_{dr} - \frac{L_m}{L_r}R i_{ds} - \omega_{sl}\lambda_{qr} = 0 \quad (11)$$

$$\frac{d\lambda_{qr}}{dt} + \frac{R_r}{L_r}\lambda_{qr} - \frac{L_m}{L_r}R i_{qs} - \omega_{sl}\lambda_{dr} = 0 \quad (12)$$

The rotor flux linkage can be assumed to be assumed to be aligned with d^e axis, such that

$\lambda_{qr} = 0$ and $\frac{d\lambda_{dr}}{dt} = 0$ and total rotor flux $\lambda_r = \lambda_{dr}$.

Substituting these values in above equations,

The field producing component of the stator current can be obtained i.e.

$$i_f = i_{ds} = \frac{1}{L_m}\left(\lambda_r + \frac{L_r d\lambda_r}{R_r\, dt}\right) \quad (13)$$

And the torque producing component of stator current

$$i_T = i_{qs} = \omega_{sl}\frac{L_r\lambda_r}{L_m R_r} \quad (14)$$

And the torque is given by

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_r i_{qs} = K_T\lambda_r i_T \quad (15)$$

From the torque and flux producing components of stator current and rotor field angle θ_f, the reference d q axis currents are obtained as:

$$\begin{bmatrix} i_{qs}^* \\ i_{ds}^* \end{bmatrix} = \begin{bmatrix} \cos\theta_f & \sin\theta_f \\ -\sin\theta_f & \cos\theta_f \end{bmatrix}\begin{bmatrix} i_T^* \\ i_f^* \end{bmatrix} \quad (16)$$

From d-q component of stator current the line current can be obtained as

$$\begin{bmatrix} i_{as}^* \\ i_{bs}^* \\ i_{cs}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} & 1 \end{bmatrix}\begin{bmatrix} i_{qs}^* \\ i_{ds}^* \\ 0 \end{bmatrix} \quad (17)$$

Selecting the q axis along the „a" axis of the stator current in the line currents can be written as

$$i_{as}^* = i_{qs}^* = |i_s^*|\sin\theta_s \quad (18)$$

$$i_{bs}^* = i_{qs}^* = |i_s^*|\sin(\theta_s - \frac{2\pi}{3}) \quad (19)$$

$$i_{cs}^* = i_{qs}^* = |i_s^*|\sin(\theta_s + \frac{2\pi}{3}) \quad (20)$$

These three phase stator current commands are generated as derived in equation and can be implemented as shown in flow chart in figure 5

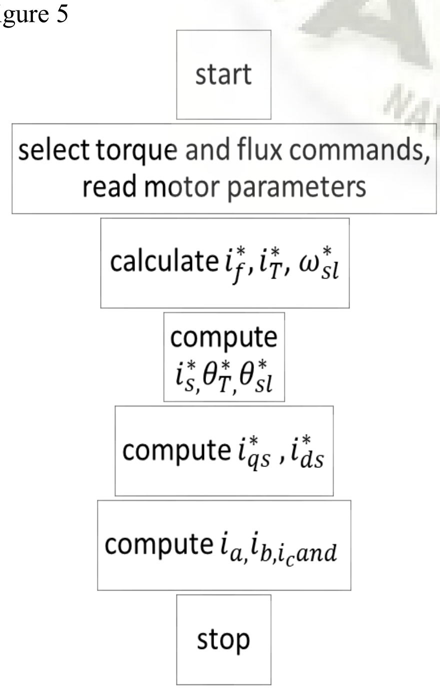

figure 5 flow chart for direct vector control

VI. CONCLUSION

This paper dealt with the study of speed control of ACIM-ac induction machine. following a description of common downsides of classic control structures it has been shown how the indirect field oriented control overcomes these downsides and what kind of benefits indirect field oriented controlled ac drive can bring. This paper has also presented a clear study which illustrates introduction of efficient vector control of ACIM. Also as far as scalar methods are concern it has been studied that although they are cheap but cannot achieve the performance of a direct current motor. Therefore, vector control applications are required for high-performance drives close to the performance of a direct current motors. The performance of indirect vector controlled induction motor in steady state and transient conditions are comparatively good.

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