Closed Loop Field Orientation Control of Three Phase Induction Motor

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CERTIFICATE

It is certified that the contents and form of thesis entitled **“Closed Loop Field Orientation Control of Three Phase Induction Motor”** submitted by *Samreen Siddique (08NUSTBEE-459), Abdul Mannan Akhtar (08NUSTBEE-299) & Waqas Maqsud (08NUSTBEE-432)* have been found satisfactory for the requirement of the degree.

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Co-Advisor: Mr. Abid Mushtaq

DEDICATION

To Allah the Almighty

&

To our Parents and Faculty

ACKNOWLEDGEMENTS

We are deeply thankful to our advisor and Co-Advisor, Dr.Habib-ur-Rehman, and Mr. Abid Mushtaq for helping us throughout this project. Their guidance, support and motivation enabled us in achieving the objectives of the project.

We are also indebted to our families who have been there in failure and in success. Without them we would not have been able to reach our goals.

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ABSTRACT

This final year project is focused on the design of “Closed Loop Scalar and Vector (Field Oriented) Control of Induction Motor”. Variable Speed Induction Motors have vast application in the industry. Induction Motor Drives are not manufactured locally in Pakistan but are employed in nearly every industry; therefore business potential in the area of development of locally made Induction Motor Drives is enormous.

In the project two prominent techniques of controlling the induction motor i.e. Scalar (Volts/Hertz) Control and Vector/Field Oriented Control are analyzed. Effects of various parameters (such as rotor resistance, voltage and electrical frequency) on the torque-speed characteristic curves were recorded using MATLAB. MATLAB/Simulink model for the Scalar Control of Induction machine has been developed. Performance of Scalar Control and Field Oriented Control has been compared in the simulation environment. The results show that Field Oriented Control has better speed tracking as compared to the Scalar Control because of decoupled control of flux and torque. Implementation of three phase inverter for motor control using MITSUBISHI Electronics PM30CSj060, Intelligent Power Module has been done.

Various deliverables of our project include understanding and Mathematical modeling of Induction Motor, Flux Estimator, Speed Regulator, Current Regulator, Inverter Design, Simulation of Scalar Control and Field Oriented Control in MATLAB and Hardware Implementation of Scalar Control.

Chapter 1- Introduction

Approximately fifty percent of the electrical energy being produced in industrialized countries is converted into mechanical energy utilizing electric motors Induction motors are still reigning the industry more or less. Approximately ninety percent of all industrial drive systems use induction motors. Most of them are uncontrolled, but the percentage of adjustable speed induction motor drives is steadily increasing, replacing dc drives. If all uncontrolled drives were replaced with controlled intelligent drives more than 50 billion dollars can be saved.

Industries require low cost, low maintenance and robust electrical motors, and this has resulted in the success and emergence of AC Induction motors. Induction motor applications occupy a vast range of industry from consumer to automotive according to their sizes and power ratings.

1.1 Comparison of DC and AC motor drives

Commutator and Brushes

The major weak points of DC armatures the mechanical commutator and brush assembly. Both these components do not exist on squirrel cage induction motors. The nonexistence of the mechanical commutator means greater speeds are conceivable with the equivalent induction motor. Higher armature voltages can be employed with an induction motor due to restrictions in the voltage that can be braced between neighboring commutator segments in a dc machine armature. The rate of rise of the current is set by the capability of the brush to complete the reversal of the current in the armature coil undergoing commutation; this rate of rise in the current limits the transient response. The full permitted rate of rise of current in modern solid frame dc motors is limited to 30 times rated current per second. In older motors this limit can be as low as 5 per unit per second. Although for contemporary laminated frame dc motors a rate of rise of 200 per unit per second is tolerable, even with this enhanced ability this feature can be the limiting factor affecting torque response in a dc motor. No such inherent constraint exists in an induction motor and the rates of current rise seen in such a motor is limited only by the leakage inductance of the machine and the value of voltage accessible to force the current from one value to another.

Power and Speed Range

The existence of commutator in a dc machine limits its speed. In general, for large motors it is not likely to obtain dc motors with a speed *power product larger than 2.6x10^6 (kW) (rpm). For example, it is difficult to locate a 1500 rpm, 1350 kW dc motor for purchase. Induction motors of this rating can be assembled for speeds reaching several times this rpm without great effort.

Efficiency

The efficacy of induction motors when used for variable speed operation is generally equivalent and frequently better than equivalent dc motor efficiency, although the presence of the rotor cage adds an surplus loss component not met in a dc machine. We do not need to design the induction motor cage to permit for a direct on line start when driven from a converter, the cage resistance can be chosen only to provide optimum running performance and minimum loss.

Power Factor

The dc converter of a dc drive operates with an input fundamental component power factor which ranges from 0 to 0.9 and increases roughly in ratio to the motor speed. Unity power factor cannot be obtained because the converter requires some voltage margin to allow for supply voltage dips, dynamic requirements and to prevent loss of commutation capability in the inversion mode. Although the induction motor always runs at lagging power factor, typically 0.95 at rated load for machines in the 300kW range, the reactive power necessities of the motor are supplied by the dc link filter capacitor and inverter. With modern pulse width modulated inverters acting as the machine side converter, the input fundamental component power factor is high, typically above 0.95, irrespective of the motor speed

Inertia

An ac machine of the same power rating and speed will have a lower inertia than its dc motor equivalent. In a dc machine, a parameter that affects commutation is the reactance voltage of the armature windings which relates to the commutating capability of the motor. The need to keep this factor within certain bounds, limits the length of the core and hence results in an increased diameter for a given power and speed. The lesser inertia of an induction motor means faster speed response for a machine with the same torque producing capability.

Protection

Monitoring and protection of a squirrel cage motor is simpler than for a dc motor. Without a direct on line starting capability and with the ability of the squirrel cage rotor to withstand much higher temperatures than the stator, stator temperature monitoring gives ample thermal protection for the entire machine. For high power applications it is usually necessary to use a dc circuit breaker to provide protection for large dc machines. These breakers are very expensive and require regular maintenance. However, DC circuit breakers need not be used for ac drive systems.

Motor maintenance

An essential part of any motor comparison is the cost of keeping spares as well as the frequency of maintenance. A supply of brushes and brushes holders are necessary stock items for dc motors. A dc motors must be regularly taken out of service to check or replace brushes and at less frequent intervals to resurface the commutator. Maintenance of these brushes is particularly burdensome in harsh environmental conditions. Except for the bearings, an induction motor is essentially maintenance free.

Ruggedness

Squirrel cage rotor is clearly far more robust than the dc machine. Progressive degradation of insulation due to electrical stressing, thermal cycling and creep is eliminated in a squirrel cage winding. Over the years, induction motors have been successfully used under conditions which could not be sustained by other electrical machine structures. If deterioration of the rotor does not occur, such as a broken bar or end ring, the machine is often capable of continued operation, perhaps at reduced power, until maintenance can be scheduled. Modern computer data acquisition and signal processing techniques have made possible the early detection of broken bars and the like.

Standstill Performance

A normal dc machine cannot develop high torque for extended periods at standstill since the armature current then flows through a particular group of armature coils and commutator segments under this condition. Although special mill duty motors can be purchased to provide rated torque over several seconds they are essentially oversized relative to the induction motor which has no such limitation.

Size and Weight

Mainly because of the commutator assembly, a dc machine of the same torque capacity is significantly larger than the equivalent induction machine. Table-1 shows a comparison of the two motors for three widely different sizes corresponding to 6MW, 75kW and 1.5kW. The data for the two smaller machines are for standard squirrel cage machines while the larger machine is special designed for variable speed application.

Table 1-Comparison of Induction and DC motors for three diverse sizes

Machine Size	Large		Medium		Small	
Machine type	Cage	DC	Cage	DC	Cage	DC
Rating (kW)	6000	6000	75	75	1.5	1.5
Speed (rpm)	60	60	1500	1500	1500	1500
Efficiency (%)	95.1	92	93.5	88	75	83
Inertia (kgm^2)	30000	60000	0.75	0.673	0.0039	0.0098
Length (cm)	1500	1500	86.3	102.2	32.25	41.6
Width (cm)	410	473	45	39	17	21
Weight (kg)	-	-	385	480	23	42.5

A DC motor has separate windings for stator and rotor. Due to decoupled components we have a better control of the deliverables of a dc motor. However in Induction machine there are no separate windings for the rotor and the voltage is induced through transformer action so the aim of establishing a control technique is to decouple the flux and torque and using these get the components of stator current vector. Field oriented control is based on decoupled components of current.

In contrast to Field vector control there were scalar methods of controlling induction machine i.e. by changing the number of poles, slip, supply frequency or supply voltage. By changing the stator voltage, we can change the slip but this method was sluggish and did not optimize the efficiency because losses in the rotor increase with an increase in slip. So for the wide range speed control adjusting the supply frequency using field oriented control constitutes the only practical solution up to date.

1.2 AC Machinery Basics

In AC machines under normal operating conditions, two magnetic fields are present:

- Rotor magnetic field existing in the rotor part of the machine
- Stator magnetic field existing in the stator part of the machine

The interaction of these two magnetic fields produces the torque in machine. [4]

AC machinery can be divided into two major types.

1. Synchronous Machines
2. Asynchronous Machines

Induction machines come under the category of Asynchronous machines.

1. Synchronous Machine - *whose magnetic field current is supplied by a separate dc power source*. [5]
2. Asynchronous Machine – *whose field current is supplied by magnetic induction (transformer action) into field windings.* [5]

In AC machines we have Motors and Generators.

1. Motors – *Rotor Field lags Stator Field.(Converts Electrical Energy to Mechanical)*
2. Generator – *Rotor Field leads Stator Field. (Converts Mechanical Energy to Electrical)*

1.3-Operating Principle of AC Motors

Synchronous Motors

A three phase voltage is applied to the stator of a synchronous motor, this produces a three phase current in the windings. This current then produces a rotating magnetic field *Bs*. The field current I_f of motor produces a steady-state magnetic fieldB_R. The rotating field tends to allign with the stator field. Because the stator magnetic field is rotating, the rotor magnetic field will tend to catch up with it. The larger the angle between two magnetic fields greater the torque on the rotor of machine. So the basic principle of Synchronous machine is that rotor chases the rotating stator magnetic field around the circle, never quite catching up with it. [6]

AC induction motor

Operation

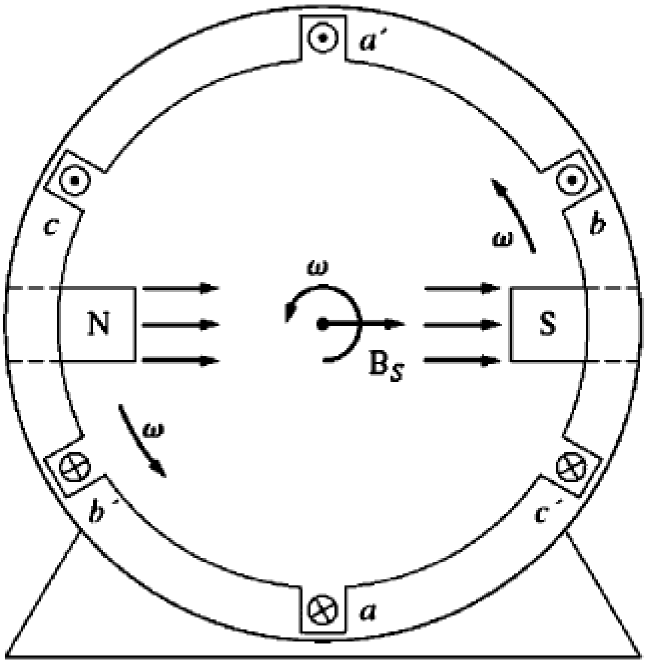
A 3-phase voltage is applied to the stator, as a result of which three phase current flows and produce a rotating magnetic field. This magnetic field induces current in the rotor windings. When current flows in the rotor a magnetic field is produced by the rotor, this magnetic field then interacts with the stator magnetic field to induce torque in the rotor. Stator winding of the induction motor is same as that of synchronous motor, three phase AC voltage is supplied directly whereas the rotor windings are electrically shorted and currents are induced by the transformer action from stator windings.

Construction

In an induction motor, stator consists of poles which carry the supply current to induce a magnetic field in the rotor. To enhance the dissemination of the magnetic field, the windings are distributed in slots around the stator, with the magnetic field having the same number of north and south poles. There are three types of rotor: squirrel cage rotors, slip ring rotors and solid core rotors.

- Squirrel cage rotors are made up of skewed bars of copper or aluminum along the length of the rotor to reduce noise
- Slip ring rotors have windings connected to slip rings instead of the bars in the squirrel cage
- Solid core rotors are made from mild steel.

Relationship between Electrical Frequency and Speed of Magnetic Field Rotation



A Simple Two Pole stator winding

In the figure above rotating magnetic field can be represented as North Pole (where the flux leaves the stator) and a South Pole (where the flux enters the stator). These magnetic poles complete one mechanical rotation around stator surface for each electrical cycle of the applied current. So, the mechanical speed of rotation of magnetic field in revolutions per second is equal to electrical frequency in hertz.

So, $\omega e = \omega m$ (TWO POLES)

Windings on the two pole stator occur in the following order (counter-clockwise)

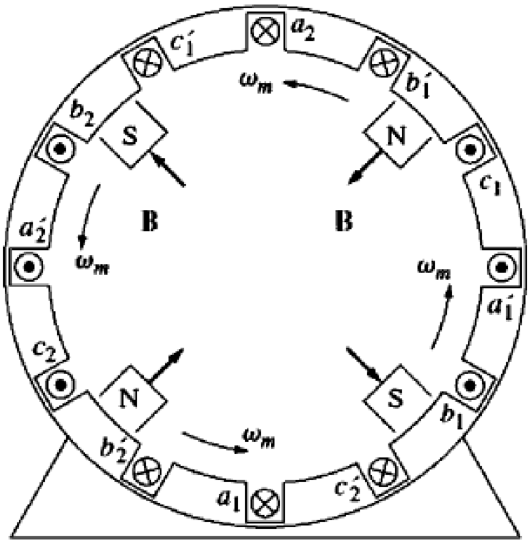
a-c’-b-a’-c-b’

If this pattern is repeated twice on the stator that is

a-c’-b-a’-c-b’- a-c’-b-a’-c-b’

Now if three-phase current is applied to the stator two North Poles and two South Poles will be produced in stator winding, In this winding a pole moves only halfway around the stator in one electrical cycle. Since one electrical cycle is 360^0 and mechanical motion is 180^0 , the relationship between electrical angle θe and mechanical angle θ_m in the stator is

$$\text{So } \theta_e = 2\theta_m$$



A simple Four Pole stator winding

Thus for the four pole winding the electrical frequency of the current is twice the mechanical frequency of rotation. So in general if the number of magnetic poles on an AC machine stator is P, then there are P/2 repetitions of the winding sequence a-c'-b-a'-c-b'. So the relation becomes

$$\omega_e = \frac{P}{2}\omega_m$$

And we know that $f_m = n_m/60$, it is possible to relate the electrical frequency in hertz to the resulting mechanical speed of the magnetic fields in revolution per minute. This relationship is [7]

$$n_{sync} = \frac{120 f_e}{P}$$

Chapter 2-Literature Review

2.1-Control techniques- An Overview

Open Loop Scalar Control Technique

One type of operation method in AC induction motors is open loop control with no velocity/ position feedback. For maximum torque in the operation range the Voltage/frequency ratio is kept. Advantages of this method are that it is relatively inexpensive and easy implementation.

Three phase AC currents are applied to the three stator windings of same amplitude and frequency and a phase difference of 120 degrees. This current produces a rotating magnetic field. This rotating field induces EMF (electromotive force) in the rotor, which then creates a magnetic field in the rotor. The magnetic field of the rotor tends to line up with the rotating magnetic field in the stator. This causes the rotor to rotate. There are two main principles that govern the operation of an AC Induction motor:

1. Base speed is directly proportional to:

- Frequency of the supply current
- The number of poles of the motor.

2. Torque is directly proportional to the ratio Voltage/frequency of the supply current

Hence if the input frequency of the AC supply current is varied, speed can be controlled. Now to maintain constant torque amplitude of the input voltage is varied in proportion to the frequency speed. This results in the varying of the ratio V/f to control the speed of the induction motor. This is the aim of this technique. [2]

Scalar Control technique with Current Feedback

A disadvantage of open-loop V/f control discussed above is that the motor can stall (come to a standstill) if the speed increase is very abrupt or if the load is changed abruptly. To check whether the motor is working according to the input given or if it has stalled a feedback is required. Feedback should be such a parameter that changes considerably in normal and abnormal state to help differentiate between the two. In case of a stall, motor produces very high currents which result in a decrease in torque. If current is monitored, stall condition and excessive slip can be detected and frequency may then be adjusted accordingly. Malfunction of the inverter bridge may also cause a high current condition though. If the high current state exists, motor may be over heated if the drive is not turned off. The speed reference in this method is given by the user. [2]

Scalar Control technique with Velocity Feedback

In the previously discussed technique, open-loop V/f control, the rotor is anticipated to follow the rotating flux of the stator, with a little slip present according to the load. According to different application, the load may vary and hence the speed of the motor. Speed feedback is added in the velocity feedback technique to enhance the speed control. The reference speed and the actual speed (done by a speed measurement method) are compared to generate an error signal. This error signal is the input to the PI controller which determines and outputs the adjusted drive frequency. Amplitude of the drive waveform is then calculated by the standard V/f process. [2]

Field Oriented Control

Field oriented control also known as vector control is a relatively new method which controls three parameters of the motor:

- Electrical frequency
- Amplitude of the motor drive voltage
- Phase of the motor drive voltage

Whereas the scalar methods described before control the frequency and amplitude only.

A 3-phase voltage is generated as a phasor to control the 3-phase stator current phasor which then controls the rotor current phasor and rotor flux vector. Field Oriented Control is used in high performance drive systems because it aims instantaneous control.

In this method the torque developed in the motor is included in the control variables. Instantaneous values of the three phase variables are represented by vectors. For example, three phase currents can be determined by the current vector and vice versa. Space vectors of three-phase motor variables are operated according to the control algorithm.

Speed control is necessary because it can result is significant energy saving. For instance consider a constant-speed blower; its output is controlled by blocking the air flow in a valve. That valve may be kept fully open or not needed at all if the blower was attached to an adjustable-speed drive system. At a low air output, the motor would consume less power if attached to an ASD rather than without it. For better drivability, high-performance adjustable-speed drives are also increasingly used in electrical traction and other electric vehicles.

Requirement of sensors is considerable in vector control such as voltage and current sensors. For high performance applications of the adjustable speed rives speed and position sensors may be required too. Now, all control methods and systems for adjustable system drives are based on microprocessors, microcontrollers or digital signal processors. Now an ASD (adjustable system drive) symbolizes an intricate and costly choice as compared to an uncontrolled motor. With the progress the motion-control industry is making these days in the development of reliable, efficient and user friendly systems, adjustable speed rives will undoubtedly achieve their deserved share in industry applications. [3]

Chapter 3- Design and Implementation of Scalar Control

3.1-Models of an Induction Machine

3.1.1-Transformer Model

Operation in an induction motor depends on induced voltages and currents in its rotor from the stator circuit; because of this transformer action the equivalent circuit of the induction motor is similar to that of the equivalent circuit of transformer.

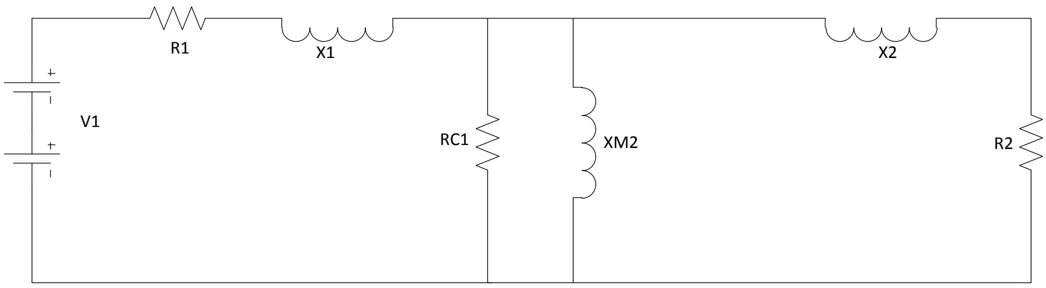


Figure 1- Per phase equivalent circuit of an induction motor

Parameters of induction motor used for simulation:

n_{sync}=synchronous speed (r/min)=1800

R_1= Stator resistance= 0.641 ohms

X_1= Stator leakage reactance= 1.106 ohms

E_1= Applied voltage= 460 V

X_m=magnetizing reactance = 26.3 ohms

a_{eff}=effective turns ratio;

E_r= rotor voltage coupled with primary E1 by an effective turns ration aeff;

R_r And jX_r= Rotor impedances= 0.332 +0.464j

3.1.2-Rotor Circuit Model

Magnitude of induced rotor voltage at locked-rotor condition =Er_0

The magnitude of induced voltage at any slip will be given by the equation. E_r= s Er_0

And frequency is given by, $f_r = s\ f_e$

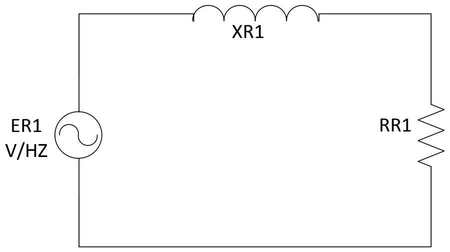


Figure 2-Rotor circuit model of an induction motor

With rotor inductance of L_r the rotor reactance is given by $X_R = \omega_r L_R$

And,

$$X_R = 2\pi s f_e L_R$$

$$= s(2\pi f_e L_R)$$

$$= sX_{R0}$$

X_{RO} is blocked-rotor rotor reactance.

So from Figure-2, the rotor current can be found as,

$$I_R = \frac{E_R}{R_R + jX_R}$$

$$I_R = \frac{E_R}{R_R + jsX_{R0}}$$

So the Rotor equivalent impedance is

$$Z_{R.eq} = R_R/s + jX_{R0}$$

3.1.3-Equivalent Circuit Model

For the final equivalent circuit we refer the rotor part of the model to the stator part. If effective turn's ratio is a$_{eff}$ then transformed rotor voltage will become $E_1 = E_R' = a_{eff}E_{R0}$

The rotor current becomes,

$$I_2 = \frac{I_R}{a_{eff}}$$

The rotor impedance becomes

$$Z_2 = a_{eff}^2(\frac{R_R}{s} + jX_{R0})$$

Separating the real and imaginary part we get;

$$R_2 = a_{eff}^2 R_R$$

$$X_2 = a_{eff}^2 X_{R0}$$

The final equivalent circuit as shown in Figure-3

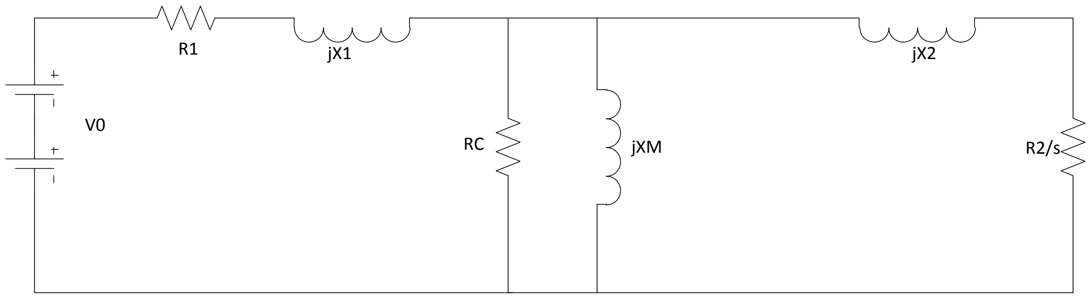


Figure 3-Per phase equivalent circuit of an induction motor

3.2-Torque/Speed characteristic curves

3.2.1-Effect of rotor resistance variation

Firstly we analyze the equations and see the relation of induced torque τ_{ind} with rotor resistanceR_2:

$$\tau_{ind} = \frac{3{V_{th}}^2 \frac{R_2}{s}}{\omega_{sync}\left[(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2\right]}$$

Pull out torque is given by the equation:

$$\tau_{max} = \frac{3{V_{th}}^2}{2\omega_{sync}\left[R_{th} + \sqrt{{R_{th}}^2 + (X_{th} + X_2)^{\ 2}}\right]}$$

- Pullout torque is not dependent on R_2; therefore magnitude of pull out torque should remain constant upon variation of R_2

Starting torque is given by the equation:

$$\tau_{start} = \frac{3{V_{th}}^2 R_2}{\omega_{sync}[(R_{th} + R_2)^2 + (X_{th} + X_2)^2]}$$

- Starting torque increases by increasing the rotor resistance

$$s_{max} = \frac{R_2}{\sqrt{{R_{th}}^2} + (X_{th} + X_m)^2}$$

- Doubling rotor resistance R_2 doubles the slip and thus decreases the mechanical speed of the motor.

In view of all the above equations, the resulting torque-speed characteristic curves on increasing the rotor resistance can be seen on Figure-4

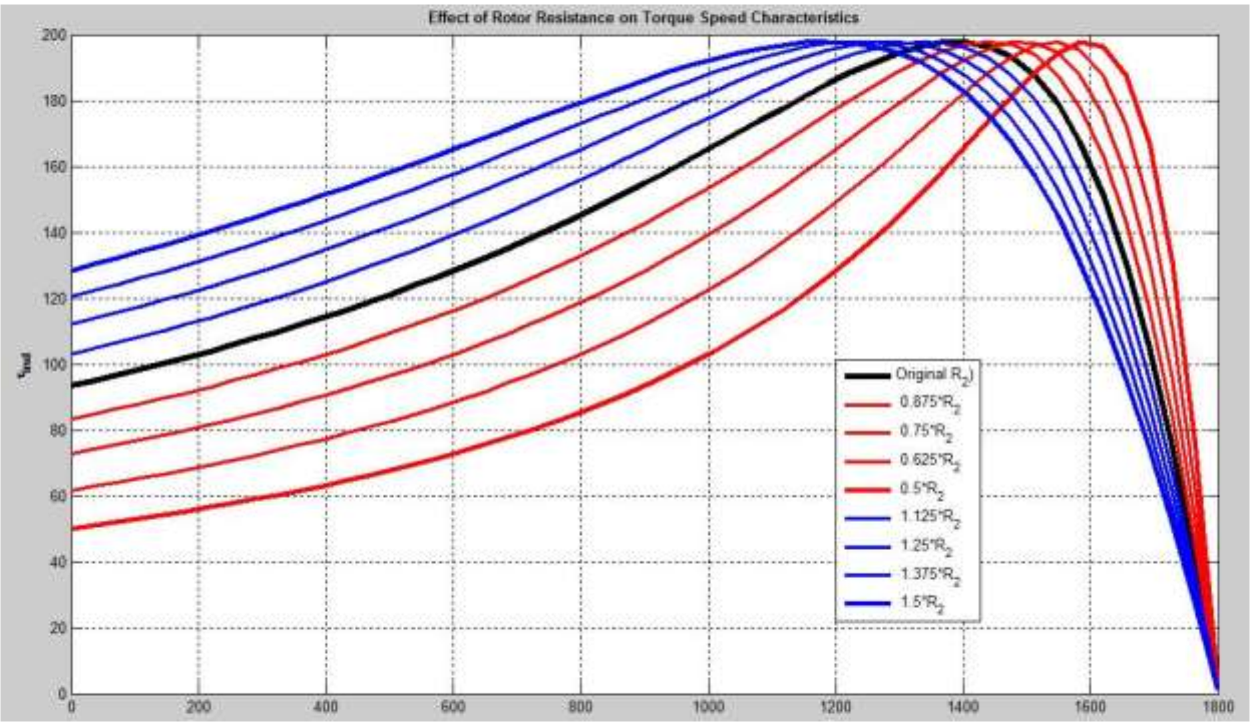


Figure 4- Effect of rotor resistance on torque-speed characteristics

We see from the Figure-4 that:

- Starting torque increases by increasing rotor resistance
- Pull out speed decreases by increasing rotor resistance
- Pull out torque remains constant
- Increasing the rotor resistance decreases the efficiency of the motor

3.2.2-Effect of Phase Voltage Variation and Constant Frequency on Torque/Speed characteristics

Since all the known equations of torque employ V_{th} instead of V_φ, we first analyze the relation between these two.

$$V_{th} = \frac{V_\varphi X_m}{\sqrt{{R_1}^2 + (X_1 + X_m)^2}}$$

For a particular motor, all resistances and reactance's are equal, V_{th} is directly proportional to V_{φ} . This means that the relationship of torque with V_{φ} is the same as that with V_{th}.

Induced torque is given by:

$$\tau_{ind} = \frac{3{V_{th}}^{2}\frac{R_2}{s}}{\omega_{sync}\left[(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2\right]}$$

- Induced torque varies with the square of V_{th}

$$\tau_{start} = \frac{3{V_{th}}^{2}R_2}{\omega_{sync}[(R_{th} + R_2)^2 + (X_{th} + X_2)^2]}$$

- Starting torque varies with the square of V_{th}

$$\tau_{max} = \frac{3{V_{th}}^{2}}{2\omega_{sync}\left[R_{th} + \sqrt{{R_{th}}^{2} + (X_{th} + X_2)^{\ 2}}\right]}$$

- Pull out torque varies with the square of V_{th}

$$s_{max} = \frac{R_2}{\sqrt{{R_{th}}^{2}} + (X_{th} + X_m)^2}$$

- Pull out speed is not affected by change in V_{th} since the relation of maximum slip is independent of V_{th}

In view of all the above equations, we see the following plot upon varying the phase voltage.

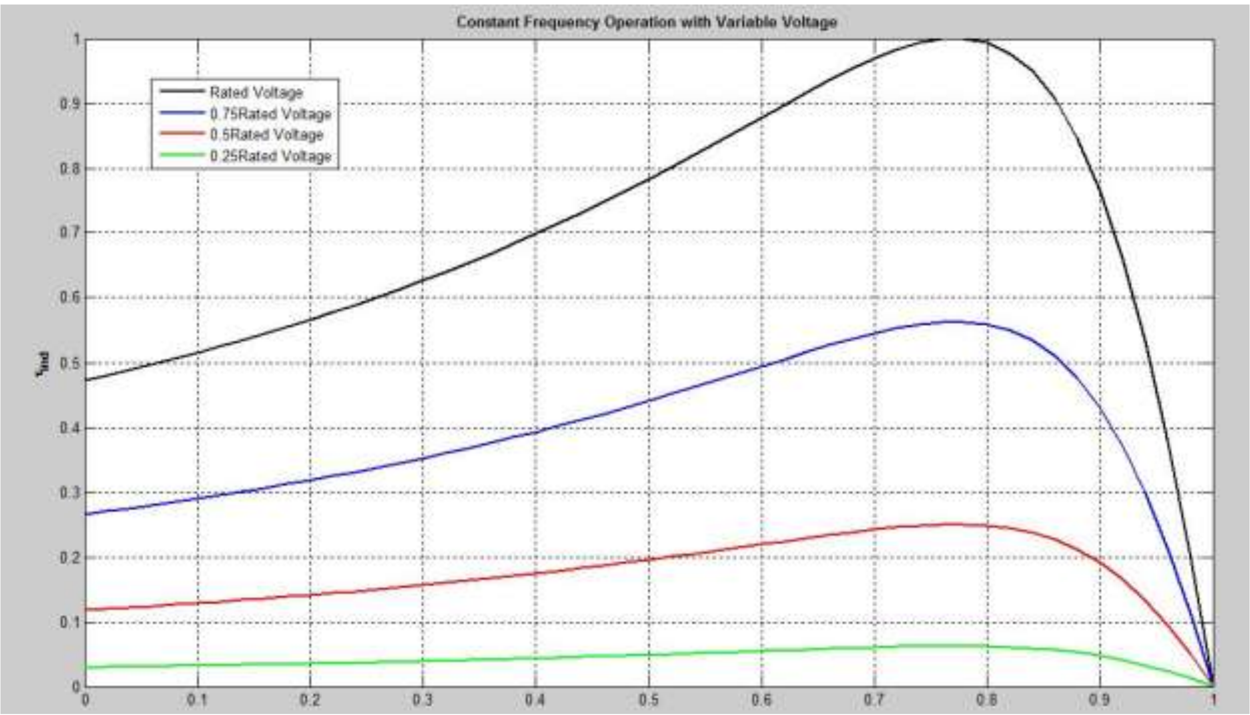


Figure 5- Effect of voltage on torque-speed characteristics

From the above plot, we deduce the following facts:

- Starting torque varies in proportional with the V_{th}
- Pull torque increases with the increase in V_{th} and decreases with the decrease in V_{th}
- Pull out speed remains constant upon changing V_{th}

3.2.3-Effect of frequency variation

We know:

$$n_{sync} = \frac{120f_e}{P}$$

Where,

n_{sync} is the synchronous speed

f_e is the line frequency

P is the number of poles

And,

$$\omega_{sync} = \frac{2\pi n_{sync}}{60}$$

This means that changing the line frequency in effect changes the ω_{sync} in the τ_{ind}equation:

$$\tau_{ind} = \frac{3{V_{th}}^2 \frac{R_2}{s}}{\omega_{sync}\left[(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2\right]}$$

$$\tau_{max} = \frac{3{V_{th}}^2}{2\omega_{sync}\left[R_{th} + \sqrt{{R_{th}}^2 + (X_{th} + X_2)^{\,2}}\right]}$$

From the above equation we see that

- Magnitude of pull out torque decrease with the increase in frequency.

$$\tau_{start} = \frac{3{V_{th}}^2 R_2}{\omega_{sync}[(R_{th} + R_2)^2 + (X_{th} + X_2)^2]}$$

- Starting torque should decrease with the increase in frequency

In view of the above equations, the resulting torque-speed characteristic curves are as follows:

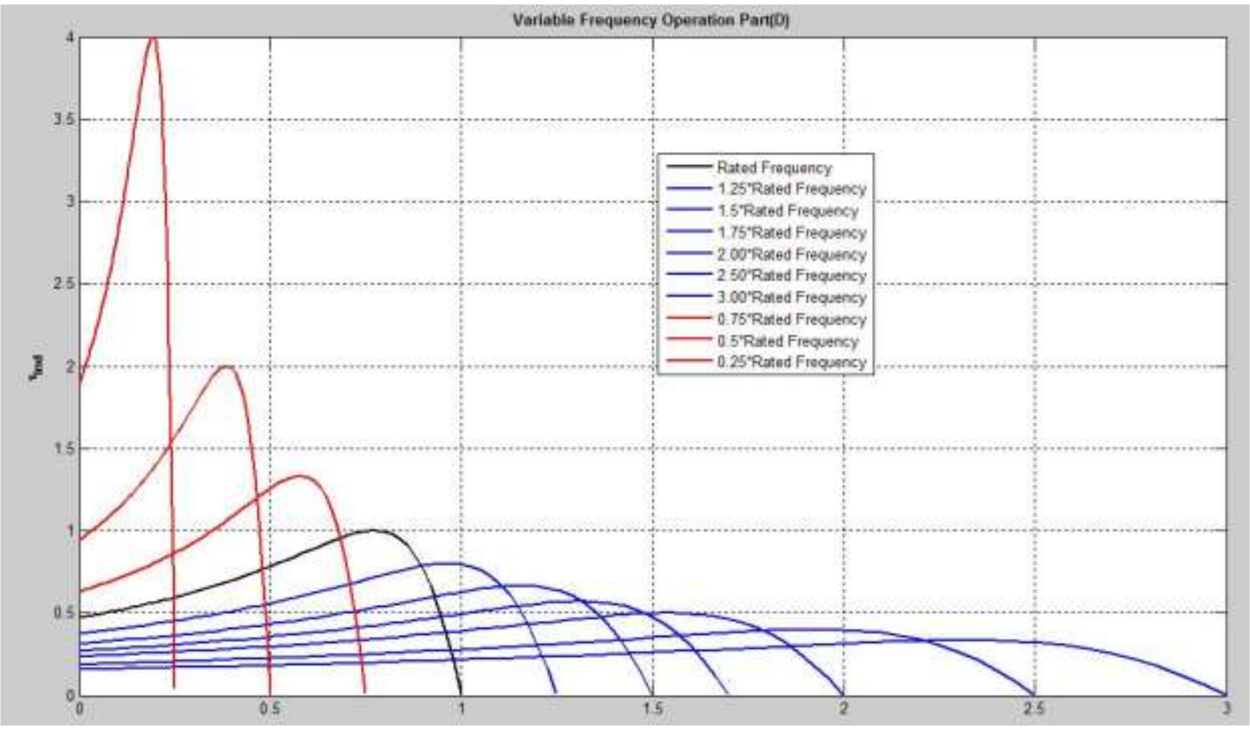


Figure 6-Effect of line frequency variation on torque-speed characteristics

We deduce the following facts from the above plot:

- The magnitude of the pullout torque decreases with the increase in frequency
- Pullout speed increases with the increase in frequency
- Starting torque decreases with the increase in frequency

3.2.4-Effect of variation in both, Voltage and Line Frequency

Next we plot the graph from 50% of frequency and voltage to their rated values and then onwards we increase only frequency in steps of 10% , up to 150% of the rated value)

$$\tau_{ind} = \frac{3{V_{th}}^2 \frac{R_2}{s}}{\omega_{sync}\left[(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2\right]}$$

$$\tau_{max} = \frac{3{V_{th}}^2}{2\omega_{sync}\left[R_{th} + \sqrt{{R_{th}}^2 + (X_{th} + X_2)^{\ 2}}\right]}$$

$$\tau_{start} = \frac{3{V_{th}}^2 R_2}{\omega_{sync}[(R_{th} + R_2)^2 + (X_{th} + X_2)^2]}$$

From the above equations we see,

Torque is directly proportional to the square of V_{th} and inversely proportional to the frequency. Therefore the effect of voltage is greater on torque than the effect of frequency. Overall, the torque induced, pull out torque and starting torque should increase by increasing both V_{th} and frequency.

3.3-Analyzing Closed Loop Constant Volts per Hertz Control in Simulink

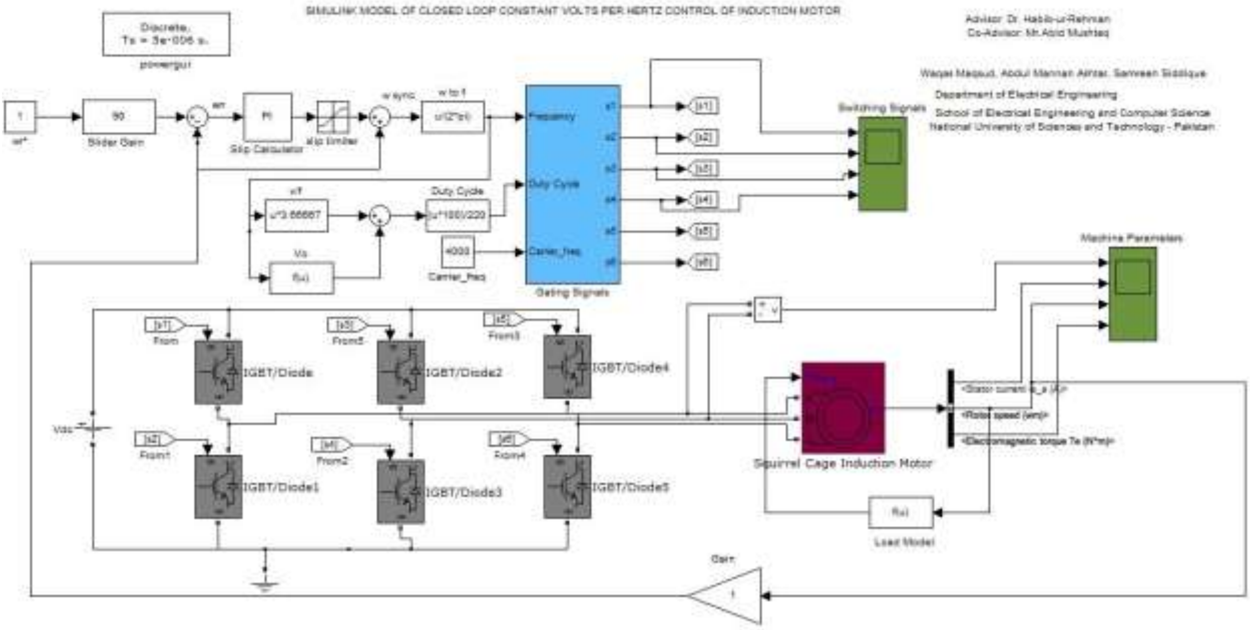


Figure 7-Simulink Model of open loop constant volts per hertz control

Electronic switches like IGBTs, MOSFETs and GTOs are employed in variable speed control of AC machines. Today, DC motors and thyristor bridges are being phased out by asynchronous machines with pulse width modulation-voltage source converters. If pulse width modulation technique is merged with latest control techniques like FOC (field oriented control) or DTC (direct torque control), speed and torque control like that of DC machines may be achieved.

In the Simulink model of Figure-7 we have used Asynchronous machine from simpowersystems library of Simulink with the following machine parameters:

Rated Power	2238Watts
Line to line voltage	220Volts
Electrical frequency	60Hertz
Stator resistance	1.115ohms
Stator inductance	0.005974H
Rotor resistance	1.083ohms
Rotor inductance	0.005974H
Mutual inductance	0.2037H
Inertia constant	0.02
Friction factor	0.005752
Pole pairs	2

.

For simulation purposes, it has been assumed that the load with the system is a fan or a pump with a quadratic torque speed relation.

$$T = k \times \omega^2$$

The nominal value of torque is,

$$T_n = \frac{2238Watts}{188.}$$

Therefore, the constant *k* should be

$$k = \frac{T_n}{\omega^2}$$

$$= \frac{11.87}{188.5} = 3.34 \times 10^{-4}$$

So we have taken the feedback of ω_m and using the above relation fed the torque to the motor.

3.4-Results of Scalar Control in simulation environment

- The steady state speed (181 rad/sec) is achieved after 0.5 seconds as in Figure-7 below.
- The starting current is 90 Amperes with 60 hertz frequency and 64 Amperes rms value and at steady state the current's value is 10.5 Amperes. As expected, the magnitude of the 60 Hz voltage contained in the chopped wave stays at

$$220 \times \sqrt{2} = 311\ V$$

- The mean value of the torque of the motor is 11.9 Nm although it is a very noisy signal, corresponding to the load torque at nominal speed.
- Current Harmonics are filtered by inductance of stator and the dominant harmonic is 60Hz.

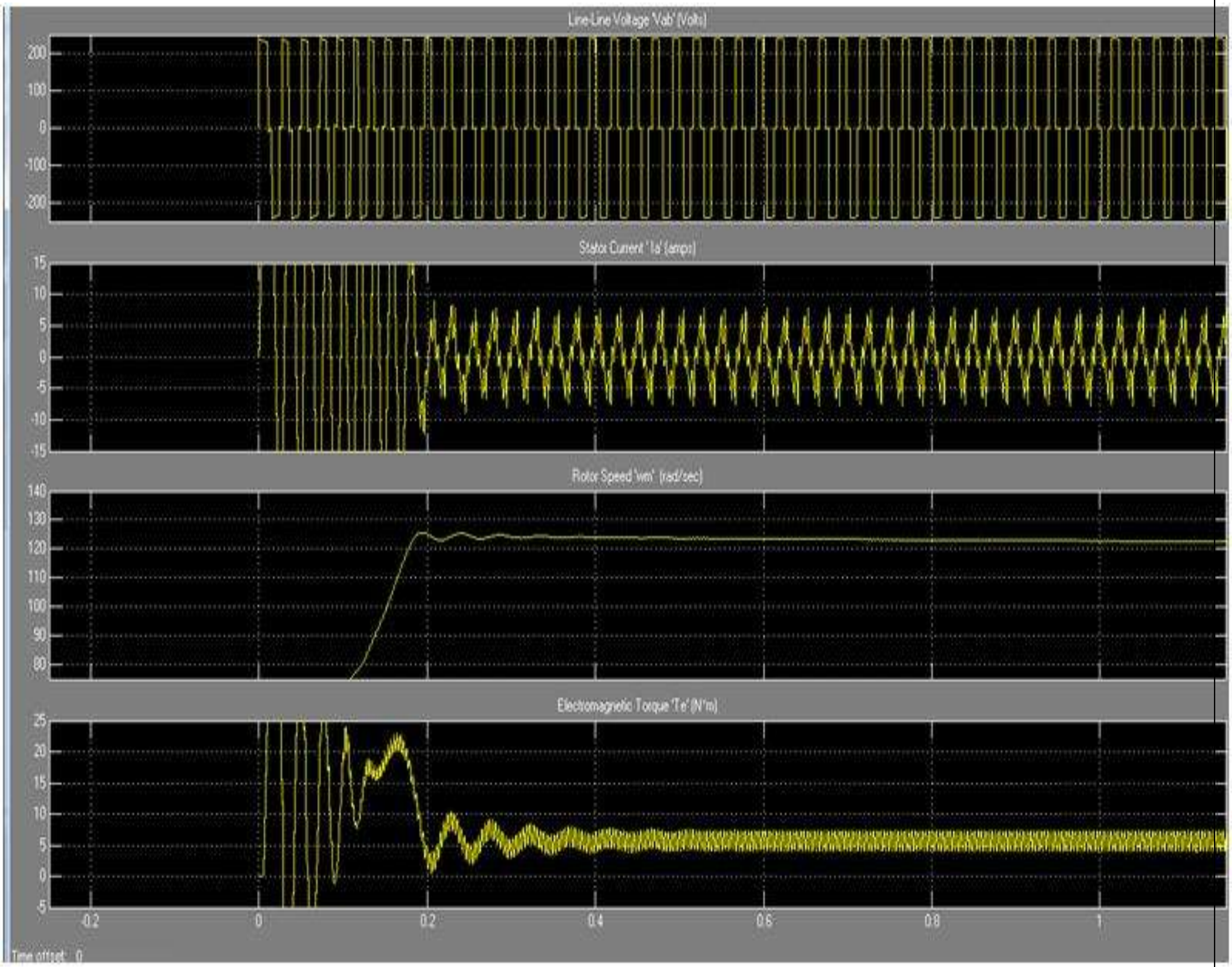


Figure 8-Voltage, stator current, rotor speed and torque obtained as a result of scalar control in simulation environment

3.5-Implementation of Scalar Control using IPM PM30CSJ060 of MITSUBISHI Electronics

Scalar Control of 3 Phase Induction Motor of 0.5 H.P has been developed using PM30CSJ060, intelligent power module of MITSUBISHI electronics. AVR Atmega16L microcontroller has been used in the project. HCPL 4506 and PC817 opto couplers have been used for isolating microcontroller side from inverter side. Detailed description of hardware is as under:

3.5.1-Optocouplers

In applications which require the signal and data transfer between subsystems without making the physical connection, in order to protect the device at lower potential from overvoltage damage optocouplers are used. For example a microprocessor working at 5 V_{DC} being used to control the inverter of three phase 0.5 H.P induction motor.

Optocouplers are small in size as compare to relays. Relays work on lower speeds; optocouplers relatively are smaller in size, faster in speed and more reliable. There is no ohmic connection between the two sides in optocoupler and isolation is achieved by transmitting data using a beam of light across electrical barrier.

Optocouplers consist of optical transmitter and receiver. At the transmitter side Gallium Arsenide LED is used receiver end consist of phototransistor. Transmitter and receiver side are electrically isolated but allows the light to pass. Optocouplers can with stand very high voltages between 500 V to 7500 V. They are best for transferring the digital data (ON/OFF) but analog data can also be transferred by frequency or pulse width modulation.

Optocouplers have been used in our hardware for control inputs as well as fault outputs. Control inputs should be transferred using high speed opto coupled transistors. Hewlett Packard HCNW-4506 optocouplers have been used for control input signals in the project as they have high common mode transient immunity of 15 kV/us. Sharp PC817 low speed optocouplers for the transfer of fault signals to microcontroller have been used, they have advantage of low cost and high current transfer ratio. PC817 however do not have internal shielding so some noise may be coupled through optocoupler, thus an RC filter with time constant of 10ms can be added to remove this noise.

HCNW-4506 are designed for IPMs, Isolated IGBT gate drives, Motor drives and Industrial inverters. It has AlGaAs LED at transmitter side which is optically coupled with photo detector with high gain. There is on chip 20kΩ resistor which eliminates the need of external pull-up resistor. A 0.1uF capacitor has been connected between the pin 5 and pin 8 of optocoupler which filters the noise in power supply lines. Anode is connected to the V_{cc} and Cathode is connected to the microcontroller signal via resistor of value 330 Ω.

Propagation delay was observed on the oscilloscope between the transmitter and receiver ends of HCNW-4506, it was found to be approximately 200 ns. Channel 1 in yellow color is the output of optocoupler and Channel 2 in blue is input to the optocoupler.

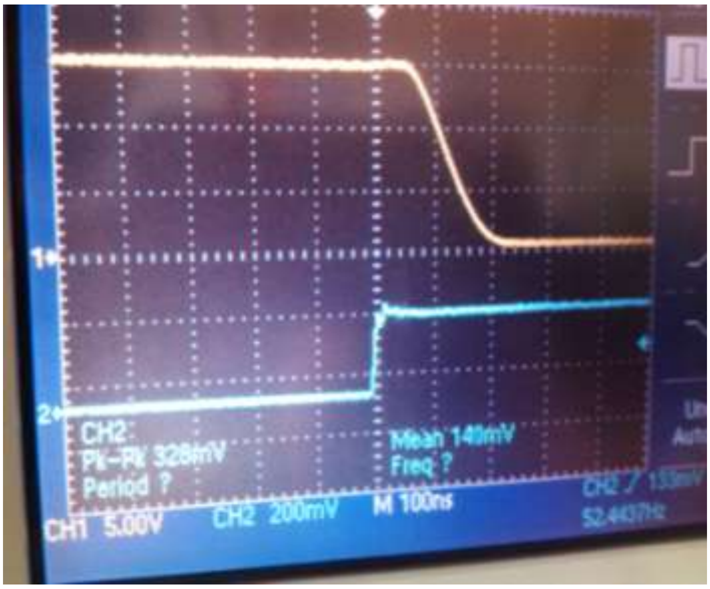


Figure 9-Propagation delay of 200ns in HCNW-4506

Pin Package of HCNW-4506 was not available in the Proteus ARES library; therefore pin package was made in the Proteus.

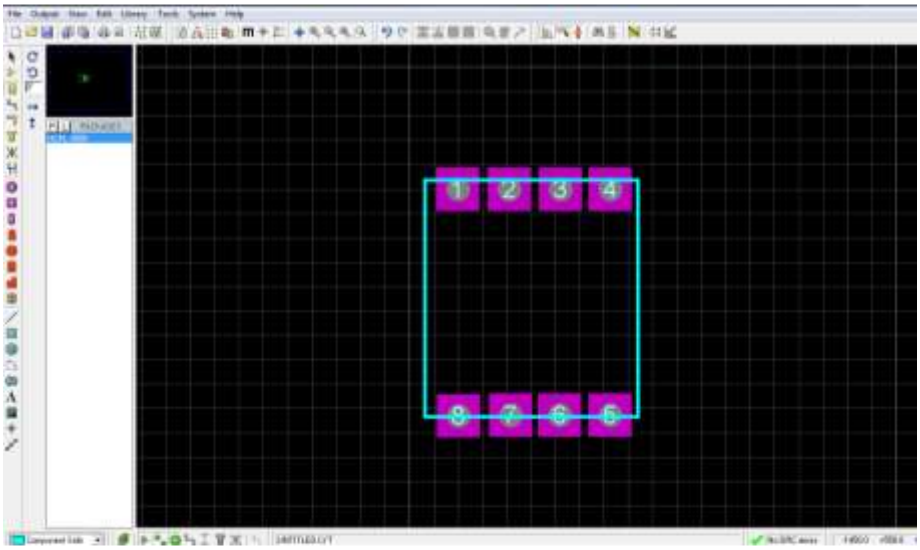


Figure 10-Pin package of HCNW-4506 Optocoupler

Functional Diagram of HCNW-4506 is as follows

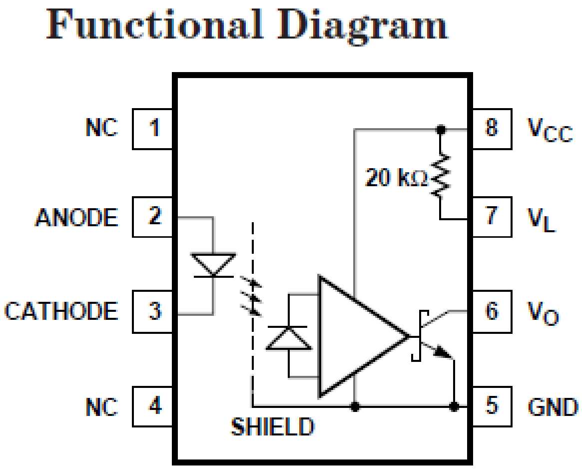


Figure 11- Functional diagram of HCNW-4506

PC 817 is contains a LED and a phototransistor which are coupled optically. The isolation voltage between two sides is about 5000 V_{rms} with response time of 4 us and minimum CTR of 50% at input current of 5mA. This optocoupler is designed for I/O interfaces of computer and feedback circuits.

Pin Package of PC817 was not available in the Proteus ARES library; therefore pin package was made in the Proteus.

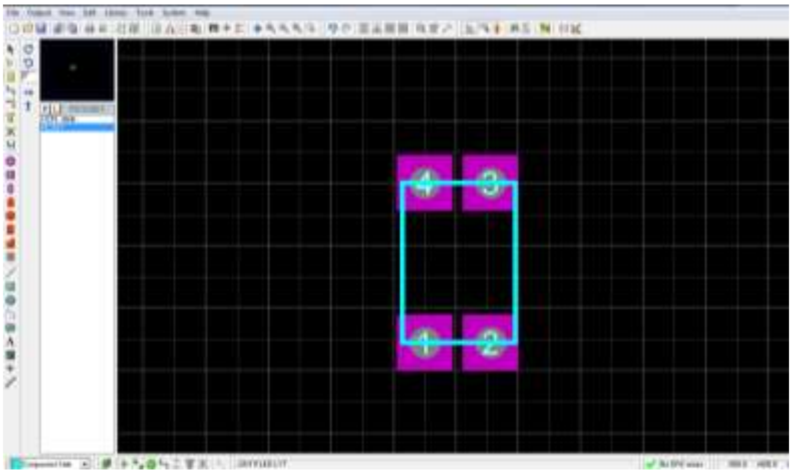


Figure 12-Pin package of PC 817 Optocoupler

Functional Diagram of PC 817 is as follows

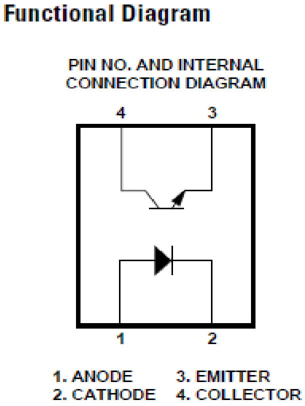


Figure 13-Functional Diagram of PC817 Optocoupler

Interface circuits between microcontroller and intelligent power module were designed on Proteus. The PCB Layout of these interface circuits are shown below.

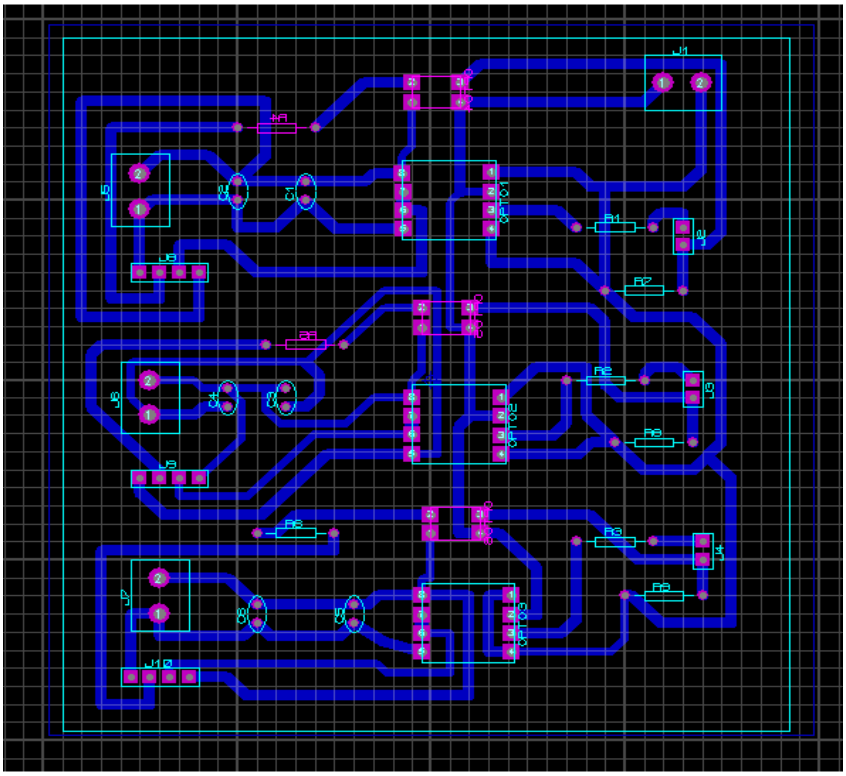


Figure 14-Interface circuit for the upper side IGBTs

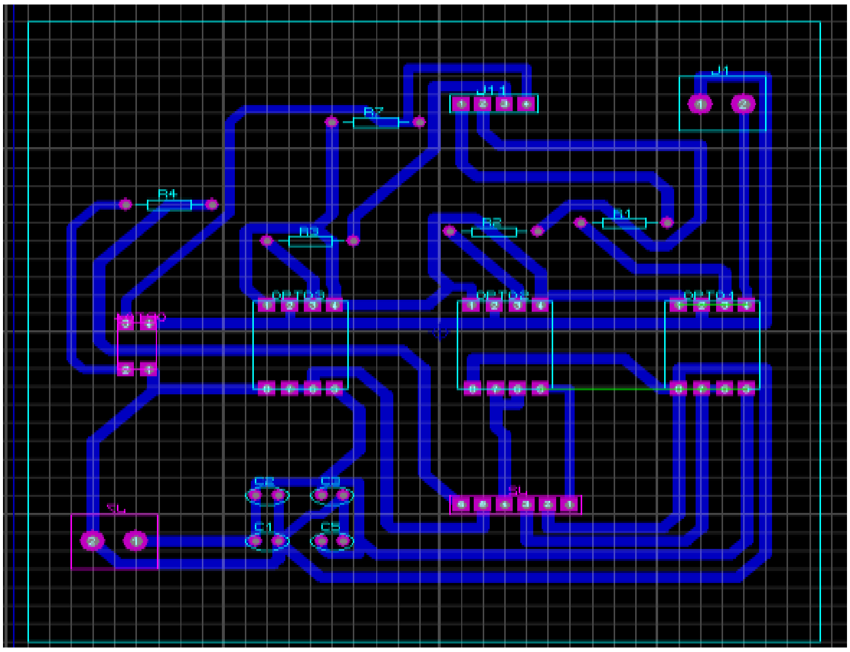


Figure 15-Interface Circuit of the lower side IGBTs

Inverters

Inverter is a device which converts the direct current (DC) to alternating current (AC). This conversion is done by making use of a Hex-Bridge of electronic switches that can be MOSFETs or IGBTs and its control circuit that can be any microprocessor. The output voltage level and frequency of AC can be adjusted according to requirement by programming the microprocessors. Inverters are commonly employed with DC sources such as batteries; solar panels etc to supply AC.

Many electronic devices run on alternating current source and many other run on direct current source. Thus inverters and converters have much importance and applications in the electronics industry which convert one form of energy into another. Constant research is being done to make efficient power converters without which the human life will be restricted with the only source available to them.

Modified sine wave and pure sine wave inverters are available in market nowadays. Modified sine wave inverters are square wave which allows DC bus voltage for a specific duty cycle making the rms value same as if it were a pure sine wave. These inverters are commonly available, cheaper and usable for less sensitive electronic equipment. However Printers, Laptops and sensitive medical equipment can be only powered with pure sine wave inverter. Pure sine wave inverters reduce audible noise and run the inductive loads such as induction motors without producing noise and faster due to lower content of harmonic distortion. Modified sine wave inverters destroy the gradually insulation of motor and produce annoying noise.

Applications of Inverter

1. DC Power Source Utilization

An inverter converts the DC electricity from sources such as batteries, solar panels, or fuel cells to AC electricity. The electricity can be at any required voltage; in particular it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage.

Micro-inverters convert direct current from individual solar panels into alternating current for the electric grid. They are grid tie designs by default. [11]

2. Uninterruptible Power Supplies

An uninterruptible power supply (UPS) uses batteries and an inverter to supply AC power when main power is not available. When main power is restored, a rectifier supplies DC power to recharge the batteries.

3. Induction Heating

Inverters convert low frequency main AC power to higher frequency for use in induction heating. To do this, AC power is first rectified to provide DC power. The inverter then changes the DC power to high frequency AC power.

4. HVDC Power Transmission

With HVDC power transmission, AC power is rectified and high voltage DC power is transmitted to another location. At the receiving location, an inverter in a static inverter plant converts the power back to AC.

5. Variable-frequency Drives

A variable-frequency drive controls the operating speed of an AC motor by controlling the frequency and voltage of the power supplied to the motor. An inverter provides the controlled power. In most cases, the variable-frequency drive includes a rectifier so that DC power for the inverter can be provided from main AC power. Since an inverter is the key component, variable-frequency drives are sometimes called inverter drives or just inverters.

6. Electric Vehicle Drives

Adjustable speed motor control inverters are currently used to power the traction motors in some electric and diesel-electric rail vehicles as well as some battery electric vehicles and hybrid electric highway vehicles such as the Toyota Prius and Fisker Karma. Various improvements in inverter technology are being developed specifically for electric vehicle applications. In vehicles with regenerative braking, the inverter also takes power from the motor (now acting as a generator) and stores it in the batteries.

7. Air conditioning

An air conditioner bearing the inverter tag uses a variable-frequency drive to control the speed of the motor and thus the compressor.

8. The General Case

A transformer allows AC power to be converted to any desired voltage, but at the same frequency. Inverters, plus rectifiers for DC, can be designed to convert from any voltage, AC or DC, to any other voltage, also AC or DC, at any desired frequency. The output power can never exceed the input power, but efficiencies can be high, with a small proportion of the power dissipated as waste heat.[11]

PM30CSJ060 (Intelligent Power Module)

Module PM30CSJ060 used in the project is a module for applications involving switching that can operate up to the frequency of 20 kHz. This module has built in gate drive circuit, protection circuits for Short Circuit, Over Current, Over Temperature and Under Voltage and freewheeling diodes. This module can be used for numerous applications that are UPS, Inverters and Motor Control etc.

This 60 grams module can operate at 600 V and 30 A. The control circuit of module operates at 15 V, dedicated 15 V power supplies are provided to the upper side IGBTs in the module, where as the lower side IGBTs are provided with one common supply of 15 V.

If a module experience Short Circuit, Over Current, Over Temperature or Under Voltage situation, it turn off the control sector of module and generate fault signal on the respective pin ($U_{FO,}$ V_{FO}, W_{FO} or F_O). Fault output supply voltage is 15 V and current of 20mA. Module is not suitable for operation in the linear region but in cut off and saturation states, under voltage lock out prevents any possibility of operation in active region.

Recommended conditions for the use of module are: DC bus Voltage from 0-400 V, Control Voltage 15 (+/-) 1.5 V, Input PWM frequency between 5 – 20 kHz and minimum dead time of 2.5 us.

Advantage of using integrated power module over discrete IGBTs hex bridge is reduction of design, development and manufacturing costs. Self protection features of the module have reduced the chances of destruction of module during development and after development in the field under harsh conditions. Module has lower on state and switching losses.

Pin Package of PM30CSJ060 was not available in the Proteus ARES library; therefore pin package was made in the Proteus.

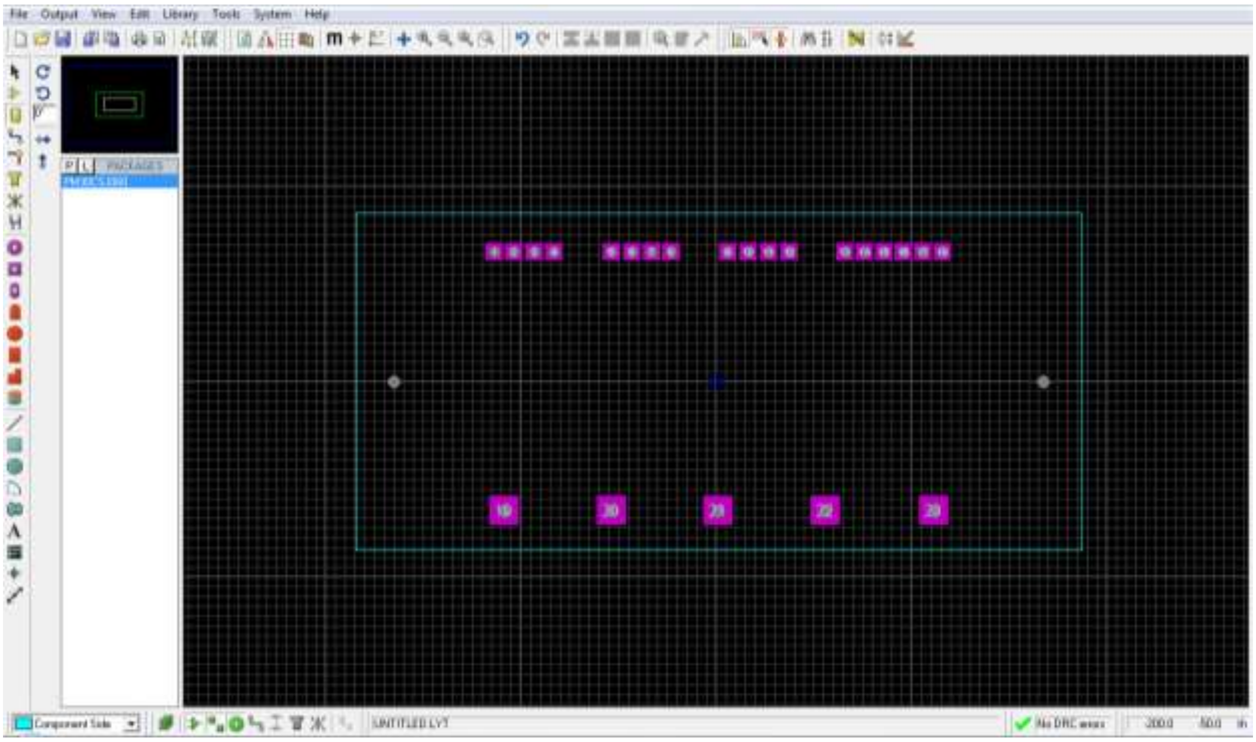


Figure 16-Pin package of IPM PM30CSJ060

Interface circuits between optocouplers and intelligent power module were designed on Proteus. The PCB Layout of the circuit is shown below:

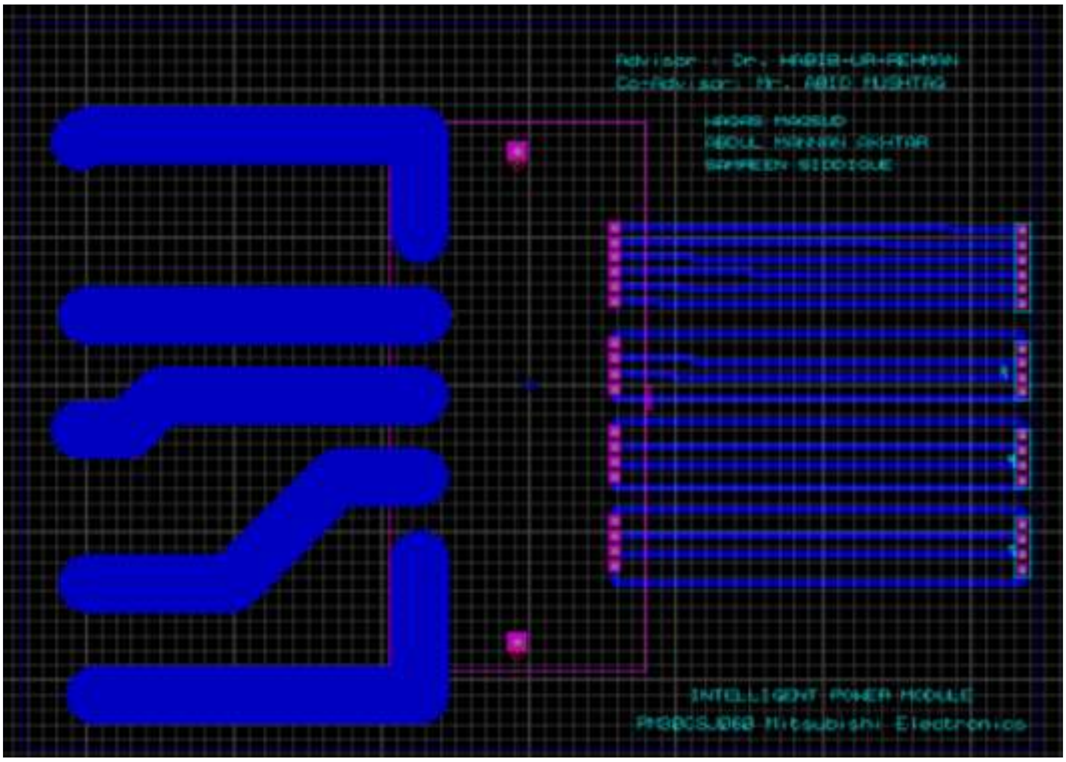


Figure 17-PCB layout of PM30CSJ060 circuit board

Microcontroller (AVR Atmega16L)

AVR Atmega16L microcontroller has been used in the project. Coding was done in C language in AVR Studio environment.

Code of Square Wave Inverter

```
#include <avr/io.h>

#include<util/delay.h>

int main(void)

{

        DDRB=255;

        DDRC=0;
```

```
        int f=50;                    //required output frequency in Hz

        int delay;

        int dt=50;                  // dead time in micro seconds


        delay=(1000/(6*f));  // calculates delay in milliseconds

        while(1)

        {



                              // 0 0 A A' B B' C C' Phase sequence on port b
PORTB=0b11011001 ;         // step 1

_delay_ms(delay);

PORTB=0b11011011;         //leg 3 zero state

_delay_us(dt);


PORTB=0b11011010;       //step 2

_delay_ms(delay);

PORTB=0b11011110;      //leg 2 zero state

_delay_us(dt);


PORTB=0b11010110;      //step 3

_delay_ms(delay);
```

```
PORTB=0b11110110;     //leg 1 zero state

_delay_us(dt);



PORTB=0b11100110;     // step 4

_delay_ms(delay);

PORTB=0b11100111;      //leg 3 zero state

_delay_us(dt);



PORTB=0b11100101;     // step 5

_delay_ms(delay);

PORTB=0b11101101;     //leg 2 zero state

_delay_us(dt);



PORTB=0b11101001;     // step 6

_delay_ms(delay);

PORTB=0b11111001;    //leg 1 zero state

_delay_us(dt);





               }

             }
```

Chapter 4- Design and Implementation of Field Oriented Control

4.1-Generalized Model of Induction Machines

The generalized model of induction machines in the stationary frame of reference can be represented by the 5th order, nonlinear, differential equations:

$$
\begin{aligned}
V_{\alpha s} &= R_S I_{\alpha s} + p\lambda_{\alpha s} \\
V_{\beta s} &= R_s I_{\beta s} + p\lambda_{\beta s} \\
0 = V_{\alpha r} &= R_r I_{\alpha r} + p\lambda_{\alpha r} - \omega_r \lambda_{\beta r} \\
0 = V_{\beta r} &= R_r I_{\beta r} + p\lambda_{\beta r} + \omega_r \lambda_{\alpha r} \\
T_e &= Jp\omega_r + B_m \omega_r + T_L
\end{aligned}
$$

Where the stator and rotor fluxes and the torque are given by:

$$
\begin{aligned}
\lambda_{\alpha s} &= L_s I_{\alpha s} + L_m I_{\alpha r} \\
\lambda_{\beta s} &= L_s I_{\beta s} + L_m I_{\beta r} \\
\lambda_{\alpha r} &= L_m I_{\alpha s} + L_r I_{\alpha r} \\
\lambda_{\beta r} &= L_m I_{\beta s} + L_r I_{\beta r} \\
T_e &= 3\frac{P}{2}\frac{L_m}{L_r}(\lambda_{\alpha r} I_{\beta s} - \lambda_{\beta r} I_{\alpha s})
\end{aligned}
$$

$$
\begin{aligned}
\lambda_r &= \sqrt{\lambda_{\alpha r}^2 + \lambda_{\beta r}^2} \\
\lambda_{dr} &= \lambda_r \text{ and } \lambda_{qr} = 0, \\
T_e &= \frac{3P}{2}\frac{L_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) \\
&= \frac{3P}{2}\frac{L_m}{L_r}\lambda_{dr} i_{qs}
\end{aligned}
$$

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

$$\alpha = e^{j\frac{2}{3}\pi}$$

Where (a, b, c) are the three phase system axes. This current space vector depicts the three phase sinusoidal system. It still needs to be transformed into a two time invariant co-ordinate system. This transformation can be split into two steps:

- (a, b, c)→ (α, β) (the Clarke transformation) which outputs a two co-ordinate time variant system
- (α, β) → (d, q) (the Park transformation) which outputs a two co-ordinate time invariant system

4.2-The (a, b, c) -> (a, b) projection (Clarke Transformation)

The space vector can be reported in another reference frame with only two orthogonal axis called (a, b).

The projection that modifies the three phase system into the (a, b) two dimension orthogonal system is presented below.

$$i_{S\alpha} = i_a$$

$$i_{S\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b$$

We obtain a two co-ordinate system $\begin{pmatrix} i_{S\alpha} \\ i_{S\beta} \end{pmatrix}$ that still depends on time and speed.

The (a,b)→ (d, q) projection (Park transformation)

This is the most important transformation in the FOC. In fact, this projection modifies a two phase orthogonal system (a,b)in the d, q rotating reference frame. If we consider the d axis aligned with the rotor flux, the next diagram shows, for the current vector, the relationship from the two reference frame:

(vector diagram)

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 (a,b) 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 system $\begin{pmatrix} i_{Sd} \\ i_{Sq} \end{pmatrix}$ 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.

4.3-The (d, q) -> (a, b) 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_r which is the voltage space vector to be applied to the motor phases.

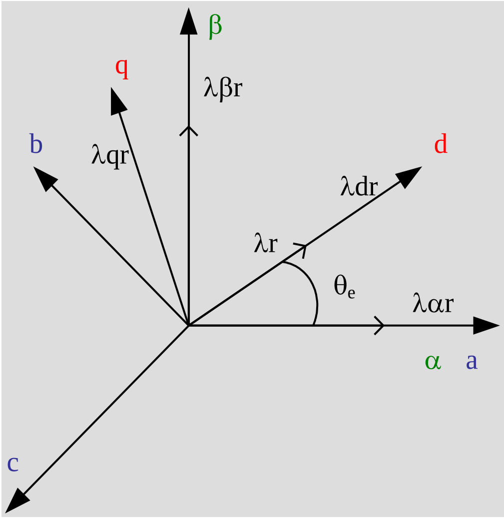
Resultant flux vector

$$\lambda_r = \sqrt{\lambda_{\alpha r}^2 + \lambda_{\beta r}^2}$$

$$\lambda_{dr} = \lambda_r \text{ and } \lambda_{qr} = 0,$$

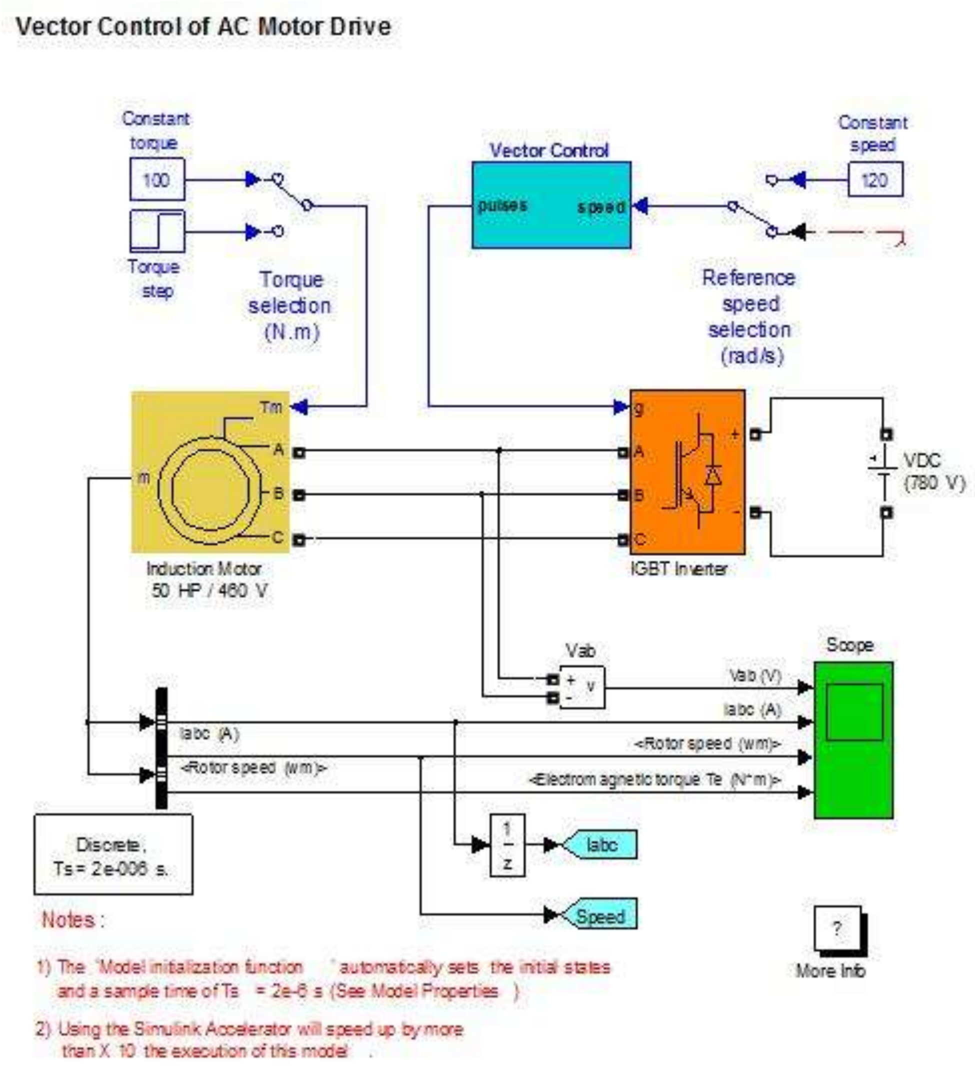
$$T_e = \frac{3P}{2}\frac{L_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds})$$

$$= \frac{3P}{2}\frac{L_m}{L_r}\lambda_{dr} i_{qs}$$



The resultant flux vector is aligned with the d-axis; therefore, the flux with q-axis will be zero.

4.4-The Basic Scheme for FOC


Vector Control of AC Motor Drive

Notes :

1) The 'Model initialization function' automatically sets the initial states and a sample time of Ts = 2e-6 s (See Model Properties)

2) Using the Simulink Accelerator will speed up by more than X 10 the execution of this model.

Figure 9-Vector Control in an AC drive

The above figure describes the concept of FOC. A reference speed or torque signal is set by the user according to which the vector control block determines the signals that will then drive the inverter of the induction motor.

Principles of field orientation along a selected flux vector can be summarized as follows.

1. Given the reference values, T_{Mref} and λ_{fref} of the developed torque and selected flux, find the corresponding reference components, of the stator current vector in the revolving reference frame.

2. Determine the angular position of the flux vector in question to be used in the D, Q → d, q transformation.

3. Given the reference components of the stator vector in the stator reference frame, use the dq→abc transformation to obtain reference stator currents for a current controlled inverter feeding the motor.

$$i_{Dr} = \frac{1}{R_r}\left(\omega\lambda_{qr} - \frac{d\lambda_{dr}}{dt}\right)$$

Under the field orientation condition, λ_{qr} 0 and, with λ_{dr} constant,. Hence, i_{Dr} = 0 and $i_r = i_{qr}$

$As, \lambda_r = \lambda_{dr}$ This indicates orthogonality of the rotor current and flux vectors. This is the condition of optimal torque production, that is, the maximum torque per ampere ratio, typical for the dc motor. Thus, the field orientation makes operating characteristics of the induction motor similar to those of that machine.

Vector Control techniques

- Indirect FOC
- Direct FOC
- Direct Torque Control

In our project we'll discuss the first two techniques of vector control.

4.5-Indirect FOC

In the indirect field orientation (IFO), the angular position, r, of the rotor flux vector is determined indirectly as $\theta_r = \int_0^t \omega_r dt + P_p\theta_m$

Where ω_r denotes the rotor frequency required for field orientation and $\theta_m$is the angular displacement of the rotor, measured by a shaft position sensor, typically a digital encoder. The required rotor frequency can be computed directly from motor equations under the field orientation condition.

$$\lambda_r = \lambda_{dr}$$

$$i_r = \frac{1}{L_r}(\lambda_{dr} - L_m i_s)$$

$$\omega_r = \frac{1}{\tau_r}\frac{i_{qs}}{i_{ds}}$$

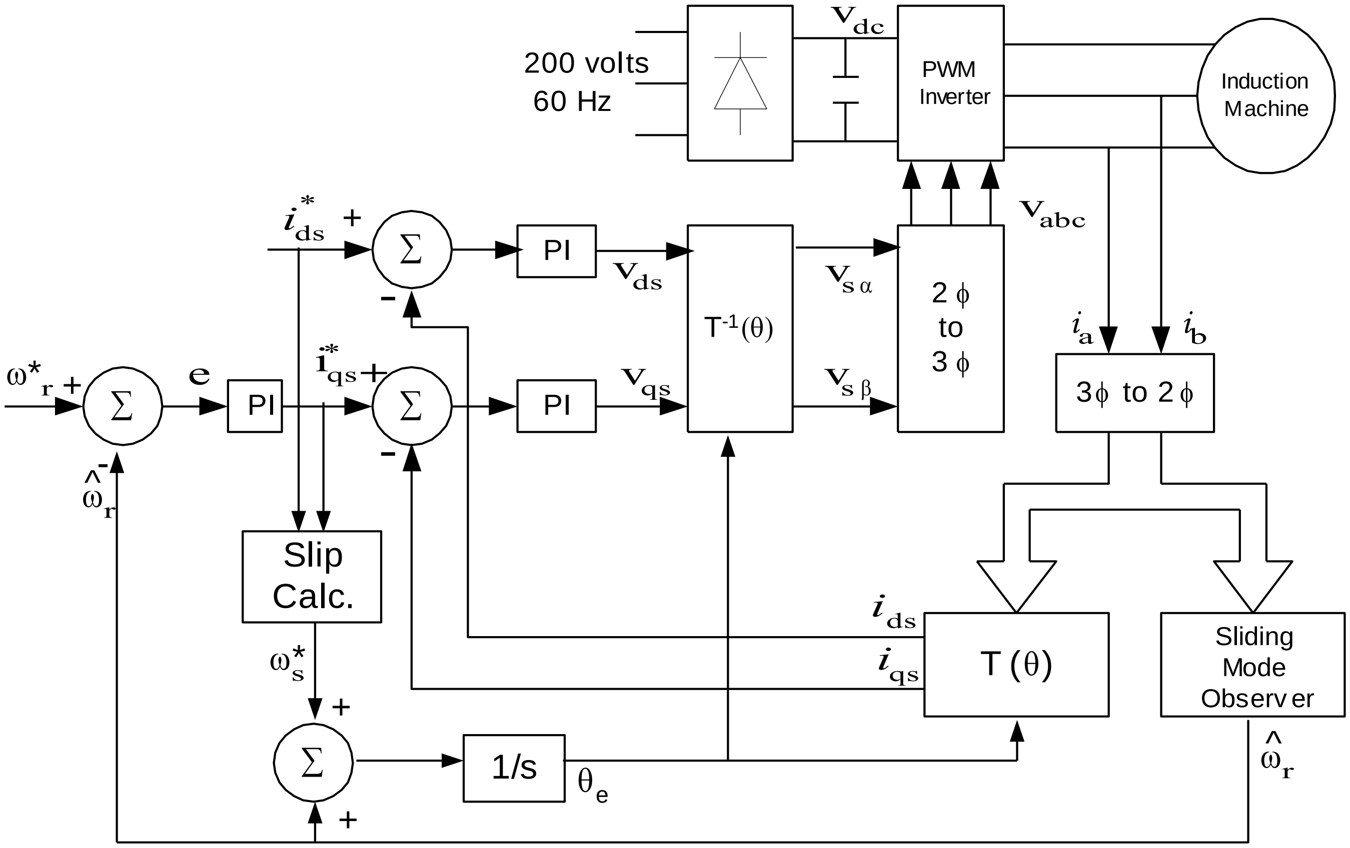
Variables i_{ds} and i_{qs}represent the required flux-producing and torque producing components of the stator current vector.

The reference current i_{ds}corresponding to a given reference flux, can be found from,

$$i_{ds} = \frac{1}{L_m}\left(\tau_r \frac{d\lambda_r}{dt} + \lambda_r\right)$$

While the other reference current,i_{qs}, for a given reference torque, T_M, can be obtained from the torque equation of a field-oriented motor as:

$$i_{qs} = \frac{1}{k_T}\frac{T_M}{\lambda_r}$$



The above figure demonstrates the modules in in IFO system.

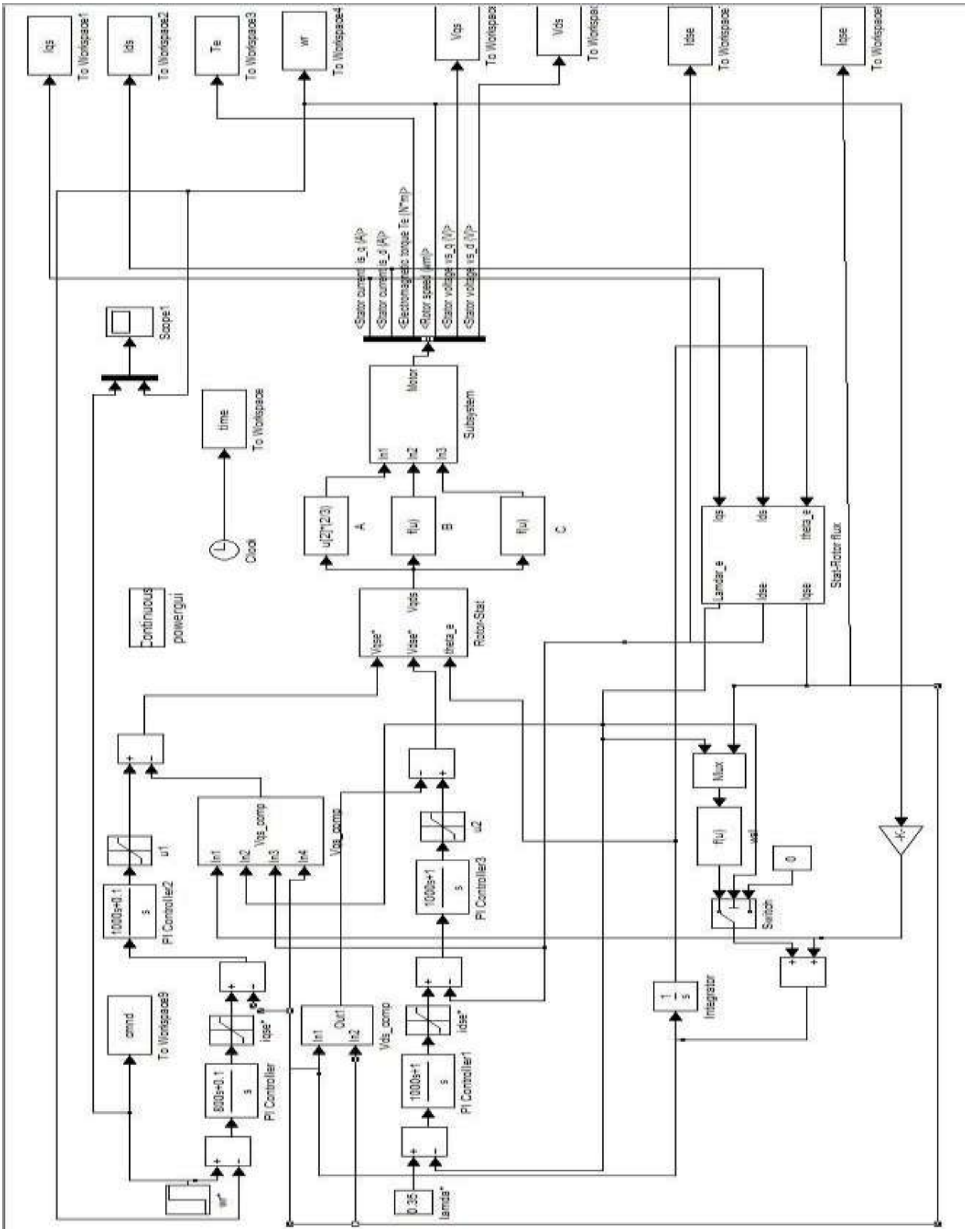


Figure 10-Simulink model of IFO

Simulation in MATLAB

Program code:

```
% Electrical system equivalent circuit parameters in air gap flux circuit
rs=.6;                                  % stator resistance
rr=.412;                                        % rotor resistance
Lls=.732/377;                           % leakage inductance on stator side
Llr=.732/377;                           % leakage inductance on rotor side
Lm=15.645/377;                          % magnetizing inductance
p=4;                                    % number of magnetic poles

% Define new parameters for the rotor flux equivalent circuit
r1=rs;                                  % Stator resistance
Lr=Lm+Llr;                              % Total rotor inductance
Ls=Lm+Lls;              % Total stator inductance
l=(Lm+Lls)-(Lm^2/Lr);                   % Total leakage inductance
M=Lm^2/Lr;                              % Magnetizing inductance
r2=(Lm^2/(Lr^2))*rr;                    % Rotor resistance
T2=M/r2;                                % Rotor time constant
Tr=T2;                                        % Rotor time constant
Tc=T2;

%Define L Matrix
L=[                                     % L matrix of machine model
(l+M) 0 M 0                             % Rotor flux equivalent circuit
0 (l+M) 0 M
M 0 M 0
0 M 0 M];

% Mechanical system parameters
Bm=.008;                            % damping coefficient(0.008)
J=.08;                                  % moment of inertia(0.08)
Tl=0;                                   % load torque
Te=0;                                   % initial electromagnetic torque

% Trapezoidal integration algorithm parameters
k=80;                                   % integration parameter
alpha=.3;                               % integration parameter
yy=0;

% Initial conditions for the machine
time=0;                                 % total initial time (used for
plotting)
sst=0;                                  % total initial time
x=[0;0;0;0];                            % initial machine currents in d-q
frame
wr=0;                                   % initial electrical speed of rotor
iqs=0;                                  % initial current in qs
ids=0;                                  % initial current in ds
iqr=0;                                  % initial current in qr
idr=0;                                  % initial current in dr
lambdadr=0;                             % initial dr flux
lambdadre=0;                            % initial dr flux
```

```
% Rotor speed conversion factor
confac=60/(2*pi);                         % from rad/sec to rpm

% PWM parameters
vdc=500;                                  % stiff dc voltage of the inverter
hb=2.0;                                   % width of hysteresis band
iafbk=0;                                  % initial phase a feedback current
ibfbk=0;                                  % initial phase b feedback current
icfbk=0;                                  % initial phase c feedback current
%va=300;vb=300;vc=300;

clear;clf;clc % Clear previous output, clear graphics, clear matlab window

tic;
begin

Tc1=Tc;
R2=r2;

% Input the total number of iterations
z=500000; %input('Number of iterations in Trapezoidal Integration Loop??');

% Zero the arraies which will be used to save the simulation result
zj=1:z/20;
zero=zeros(size(zj));
torq=zero;                                % The ElectroMagnetic Torque
speedcom=zero;                            % Rotor speed command
speed=zero;                               % Rotor speed
Error=zero;
Idseact=zero;
Iqsact=zero;                              % Iqs actual - sync. frame
Iqscom=zero;                              % Iqs command
time=zero;                                % Plotting time
Ia=zero;
Ws=zero;
Ib=0;
Ic=0;
Fluxd=0;
FLuxq=0;
Fluxa=0;
Fluxb=0;
Fluxc=0;


% Give the flux command (these signals are in syncrhonous frame)
idscom=3;                                 % Flux current command in sync
frame

% Slip calculator initial conditions
Do=0;                                     % Initial value of Denominator
theta=0;                                  % Initial theta angle
dt=.00001;                                % Initial time increment for
tranfer function
t=0.0;
% Output counters
j=0;i=0;                                  % For plotting every 10th iteration
```

```
% Speed controller parameters
erroro=0;wrmact=0;wrmcom=0;Tspeed=0.005;Iqsmax=50;Iqsmin=-50;speedest2=0;

Ki=15;Kp=.05;


% Begin Loop Select the command speed
IFO=1;
DFO=0;
trap=0;
traplow=0;
step=0;
steplow=0;
constant=1;

for nn=1:z;

% Tap Speed Command
if constant
    if sst<7.0
        wrmcom=150;
    end
end

if trap

Ki=15;Kp=.05;
if sst<.8;                              % First Quadrant Operation
wrmcom=(1000/0.8)*sst;
end;
if sst>=.8 & sst<1.2                     % Constant Speed Regulation
wrmcom=1000;
end;

if sst>=1.2 & sst<2.8                     % Second Quadrant Operation
wrmcom=1000-(1000/0.8)*(sst-1.2);
end;

if sst>=2.8 & sst<3.2
wrmcom=-1000;
end

if sst>=3.2 & sst<4.8
wrmcom=-1000+(1000/0.8)*(sst-3.2);
end

if sst>=4.8 & sst<5.2
wrmcom=1000;
end

if sst>=5.2 & sst<6.8
wrmcom=1000-(1000/0.8)*(sst-5.2);
end

if sst>=6.8 & sst<7.0
wrmcom=-1000;
end
end;
```

```
%low speed trap command

if traplow
Ki=15;Kp=.05;

if sst<.8;                                % First Quadrant Operation
wrmcom=(20/0.8)*sst;
end;
if sst>=.8 & sst<1.2                       % Constant Speed Regulation
wrmcom=20;
end;
if sst>=1.2 & sst<2.8                       % Second Quadrant Operation

wrmcom=20-(20/0.8)*(sst-1.2);
end;
if sst>=2.8 & sst<3.2
wrmcom=-20;
end

if sst>=3.2 & sst<4.8
wrmcom=-20+(20/0.8)*(sst-3.2);
end

if sst>=4.8 & sst<5.2
wrmcom=20;
end
end;


%Step Command

if step
if sst<1.0;                                % First Quadrant Operation
wrmcom=150;
end;
if sst>=1.0 & sst<2.0                       % Constant Speed Regulation
wrmcom=-150;
end;

if sst>=2.0 & sst<3.0                       % Second Quadrant Operation
wrmcom=150;
end;

if sst>=3.0 & sst<4.0
wrmcom=-150;
end

end;


%low speed Step command
if steplow

if sst<0.5
wrmcom=20;
end;
```

```
if sst>=0.5 & sst<1.0                     % Second Quadrant Operation
wrmcom=-20;
end;

if sst>=1.0 & sst<1.5                     % Second Quadrant Operation
wrmcom=20;
end;

if sst>=1.5 & sst<2.0                    % Second Quadrant Operation
wrmcom=-20;
end;

if sst>=2.0 & sst<2.5                     % Second Quadrant Operation
wrmcom=20;
end;

if sst>=2.5 & sst<3.0                    % Second Quadrant Operation
wrmcom=-20;
end;
end;


% Generate Iqs command from speed error
error=wrmcom-wrmact;                   % error in speed command(wrmact)
integralerror=erroro+error*dt;            % integrate the error
erroro=error;                             % update initial value of error
iqscom=Kp*error+Ki*integralerror;         % PI control to get Iqscom
if iqscom>Iqsmax                          % current limit ckt.
    iqscom=Iqsmax;
elseif iqscom<Iqsmin
    iqscom=Iqsmin;
end


if IFO
% Slip calcuator
%Dn=(Tr*Do+idscom*dt)/(dt+Tr);            % New value of denominator
%Do=Dn;                                   % Update value of denominator
Dn=idscom;                                % Neglect the dynamics of the slip
speed
Nn=iqscom/Tr;                             % Numerator
swe=Nn/Dn;                                % Transfer function for slip

% Calculate the new value of synchronous speed and theta angle
omega=wr+swe;                             % synchronous speed(wr)
theta=theta+omega*dt;                     % angle between synchronous &
stationary
end;

if DFO




end;


% Synchronous to stationary transform
iqss=(cos(theta)*iqscom+sin(theta)*idscom);    % iqs in stationary frame
```

```
idss=(-sin(theta)*iqscom+cos(theta)*idscom);   % ids in stationary frame

% Convert iqs and ids to 3 phase current commands for inverter
iacom=iqss;                               % a phase current command
ibcom=-.5*iqss+.866*idss;                 % b phase current command
iccom=-.5*iqss-.866*idss;                 % c phase current command

% Generate hysteresis bands for a width of 2 amps
ial=.95*iacom;                            % lower band for phase a
iah=1.05*iacom;                           % upper band for phase a
ibl=.95*ibcom;                            % lower band for phase b
ibh=1.05*ibcom;                           % upper band for phase b
icl=.95*iccom;                            % lower band for phase c
ich=1.05*iccom;                           % upper band for phase c

% Switching algorithm for the pwm inverter
if iafbk>iah;                             % compare with upper limit
    va=0;
else   iafbk<ial;                         % compare with lower limit
    va=vdc;
end
if ibfbk>ibh;                             % compare with upper limit
    vb=0;
else  ibfbk<ibl;                          % compare with lower limit
    vb=vdc;
end
if icfbk>ich;                             % compare with upper limit
    vc=0;
else   icfbk<icl;                         % compare with lower limit
    vc=vdc;
end

% Calculate the voltages that actually go across the machine
vn=(1/3)*(va+vb+vc);
van=(va-vn);                              % acutal a phase voltage
vbn=(vb-vn);                              % actual b phase voltage
vcn=(vc-vn);                              % actual c phase voltage

%Convert 3-Phase Voltages into Vqs & Vds
vqs=van;                % vqs
vds=0.867*vbn-0.867*vcn;                          % vds

% Define R Matrix
R=[                                       % R matrix of machine model
-r1  0  0  0                              % Rotor flux equivalent circuit
0 -r1  0  0
0 wr*M -R2 wr*M
-wr*M 0 -wr*M -R2];

% Calculate the A&B Matrices - Also define the input matrix
u=[vqs;vds;0;0];                          % input matrix
A=inv(L)*R;                               % A matrix
B=inv(L);                                 % B matrix

%Calculate settling time and time interval
%t=1/(k*max(abs(real(eig(A)))));           % time step

dt=0.00001;
t=dt;                                    % time step
```

```
sst=sst+t;
% Calculation of Currents
xdot=A*x+B*u;                             % Ax+Bu
xhat=x+t*xdot;                            % Predictor
xdothat=A*xhat+B*u;                       % Corrector
x=x+(t/2)*((1+alpha)*xdothat+(1-alpha)*xdot);   % Trapezoidal Integration

% Define individual currents from current matrix 'x'
iqs=x(1);ids=x(2);iqr=x(3);idr=x(4);     % iqs,ids,iqr,and idr
iqseact=iqs*cos(theta)-ids*sin(theta);
idseact=iqs*sin(theta)+ids*cos(theta);

% Convert iqs and ids to 3 phase current for comparison at beginning of
loop
iafbk=iqs;                                % actual a phase current 'IAfbk'
ibfbk=-.5*iqs+.866*ids;                   % actual b phase current 'IBfbk'
icfbk=-.5*iqs-.866*ids;                   % acutal c phase current 'ICfbk'

% Calculate the flux linkages and Torque in stationary frame
lambdadr=M*(ids+idr);                     % flux linkage of ds
lambdaqr=M*(iqs+iqr);;                    % flux linkage of qs
lambdaa=lambdaqr;
lambdab=-.5*lambdaqr+.866*lambdadr;
lambdac=-.5*lambdaqr-.866*lambdadr;
realflux=sqrt(lambdadr^2+lambdaqr^2);    % actual flux in machine

Te=(3/2)*(p/2)*(lambdadr*iqs-lambdaqr*ids);     % EM Torque calculation

% Define State Space for Speed; Calculate the speed
u1=Te-Tl;                                 % u matrix
A1=(-Bm/J);                               % A matrix
B1=(p/(2*J));                             % B matrix
xdot1=A1*wr+B1*u1;                        % Ax+Bu
xhat1=wr+t*xdot1;                         % Predictor
xdothat1= A1*xhat1+B1*u1;                 % Corrector
wr=wr+(t/2)*((1+alpha)*xdothat1+(1-alpha)*xdot1);       % Trapezoidal
Integration

% Calculate the mechanical speed, which is the rotor velocity
wrm=(2/p)*wr;                             % Calculating mechanical speed of
rotor
wrmact=wrm*confac;                        % Convert from rad/sec to rpm

% Define Output Variables
j=j+1;                                    % Increment j
if j==10                                  % Is j=10? if so,
i=i+1;                                    % increment i
Error(i)=error;
Idsact(i)=idseact;
Idscom(i)=idscom;
Iqsact(i)=iqseact;                        % Iqs actual - sync. frame
Iqscom(i)=iqscom;



                                           % Iqs estimated - sync. frame
torq(i)=Te;                               % The ElectroMagnetic Torque
speed(i)=wrmact;                          % Rotor speed
speedcom(i)=wrmcom;                       % Rotor speed command
Ws(i)=swe;
```

```
time(i)=sst;                              % Plotting time
Ia(i)=iafbk;                              %actual currents
Ib(i)=ibfbk;
Ic(i)=icfbk;
Fluxa(i)=lambdaa;
Fluxb(i)=lambdab;
Fluxc(i)=lambdac;

j=0;                                      % Reset j

end;                                      % End output routine
end;                                      % End the main loop

subplot(7,2,1)
plot(time,speed, time,speedcom);
ylabel('rpm');
grid;

subplot(7,2,2)
plot(time,torq);
ylabel('te');
grid;

subplot(7,2,3)
plot(time, Idscom);
ylabel('Id');
grid;

subplot(7,2,4)
plot(time,Iqsact,time,Iqscom);
ylabel('Iq');
grid;

subplot(7,2,5)
plot(time,Ws);
ylabel('slip');
grid;



subplot(7,2,6)
plot(time,Ia);
ylabel('ia-act');
grid;

subplot(7,2,7)
plot(time,Ib);
ylabel('ib-act');
grid;

subplot(7,2,8)
plot(time,Ic);
ylabel('ic-act');
grid;

subplot(7,2,9)
```

```
plot(time,lambdadr);
ylabel('flux-d');
grid;

subplot(7,2,10)
plot(time,lambdaqr);
ylabel('flux-q');
grid;

subplot(7,2,11)
plot(time,Fluxa);
ylabel('flux-a');
grid;


subplot(7,2,12)
plot(time,Fluxb);
ylabel('flux-b');
grid;

subplot(7,2,13)
plot(time,Fluxc);
ylabel('flux-c');
grid;
```

Results

For trapezoidal speed command

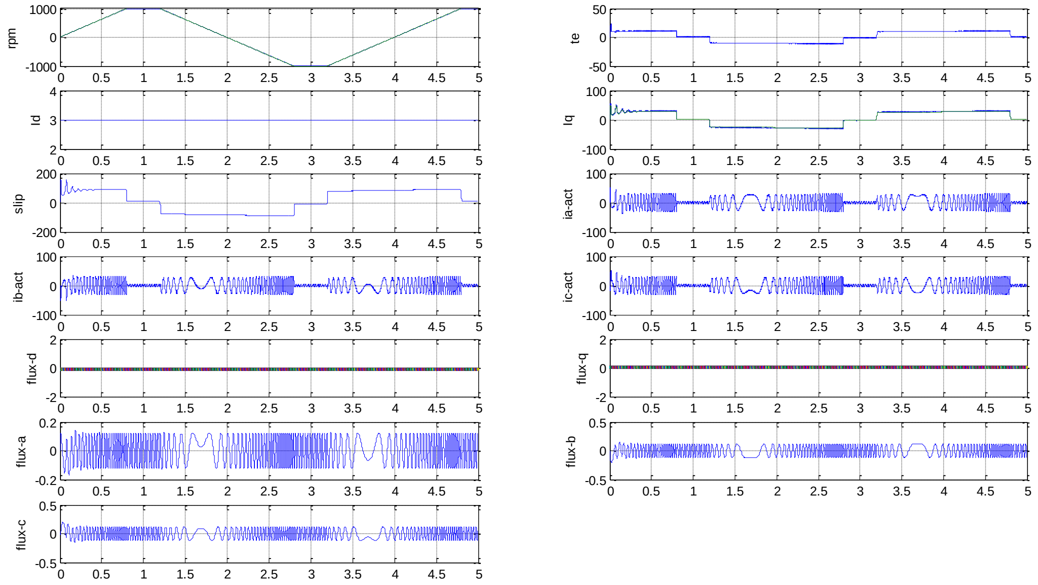


Figure 18-Results of FOC for trapezoidal speed command

For step speed command

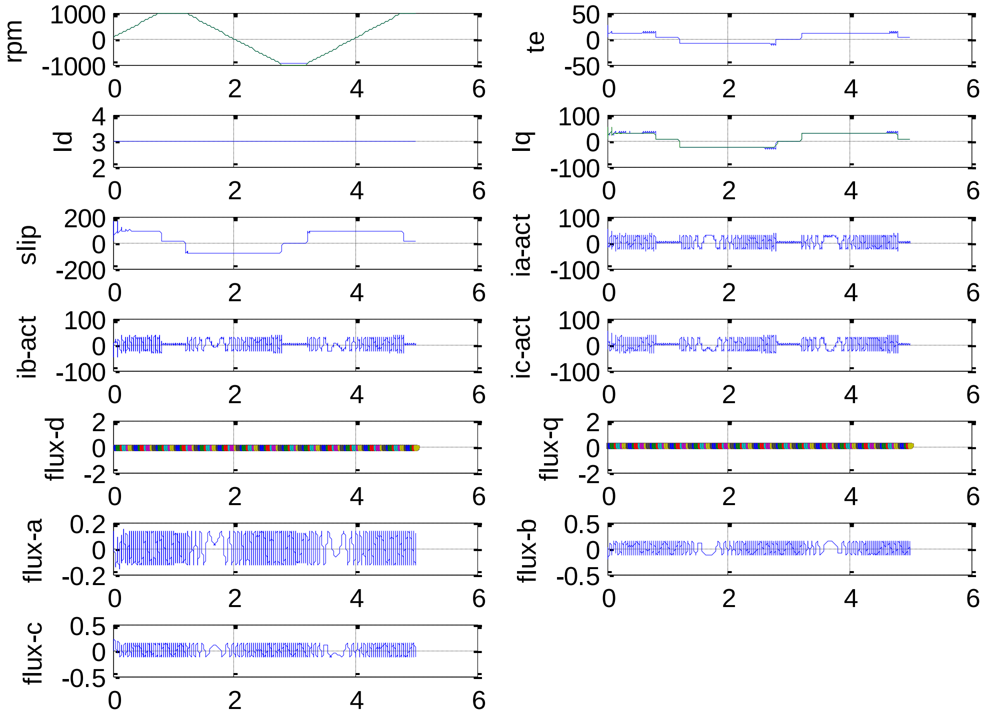


Figure 19-Results of FOC for step speed command

For constant speed command

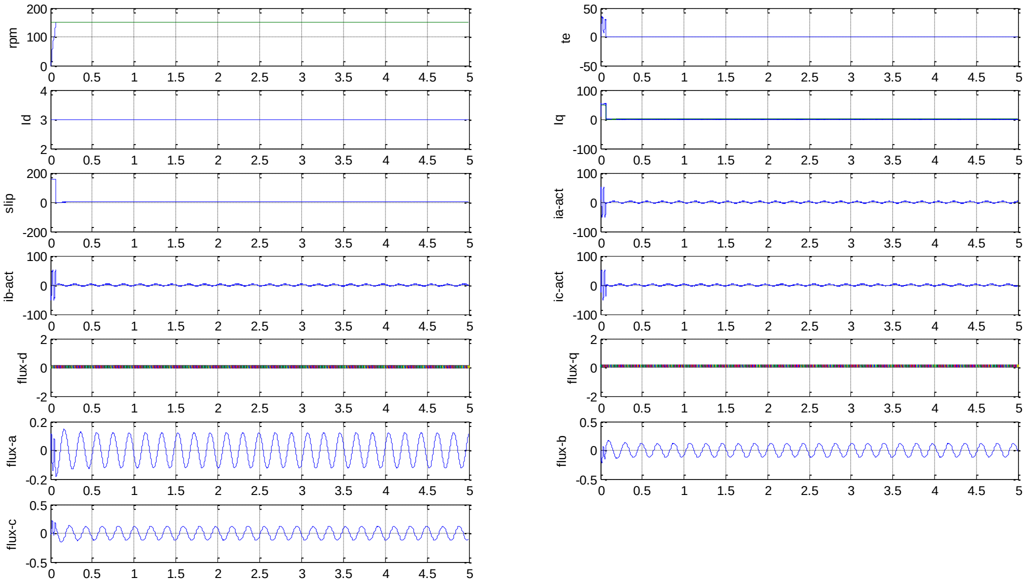


Figure 20-Results of FOC for constant speed command

4.6-Direct FOC

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

Sensors of the air-gap flux are inconvenient, and they spoil the ruggedness of the induction motor. Therefore, in practice, the rotor flux vector (or another flux vector used for the field orientation) is usually computed from the stator voltage and current. For best performance, the torque and flux in induction motors with direct field orientation are closed-loop controlled. The torque, which is difficult to measure directly, can be calculated using an appropriate equation.

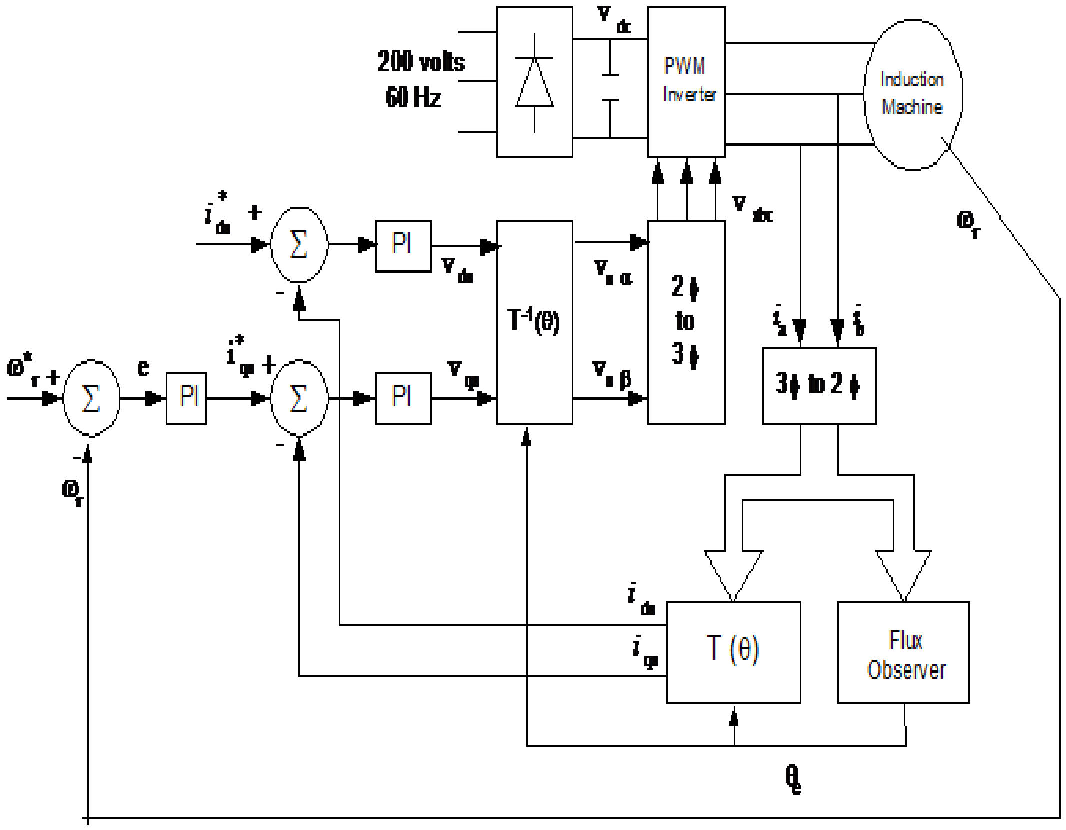


Figure 21-Model of Direct Field Oriented Controlled System

Chapter 5- Conclusions and Future Recommendations

5.1-Summary of FOC

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

The whole procedure of Field Oriented Control can be summarized:

- 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).
- 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.
- 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 control method we choose as discussed separately in the DFO and IFO systems.

5.2-Conclusion

It is concluded that field oriented control makes the direct and separate control of torque and flux in AC machines possible.AC machines that are controlled by this method have all the advantages of Dc machine- that are, precise transient and steady state management as a result of instantaneous control of the separate quantities, and they are still preferable over DC machines because of the mechanical commutation and maintenance problems (slip rings and brushes) in DC machines are not present in Field Oriented Controlled AC machines.

5.3-Future Recommendations

- Realization of DFO in simulation environment
- Hardware Implementation of IFO
- Implementation of control technique that replaces PI controller and does not require tedious tuning.

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