CLOSED LOOP CONTROL OF INDUCTION MOTOR DRIVE USING VECTOR CONTROL TECHNIQUE

A PROJECT REPORT

Submitted by

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BONAFIDE CERTIFICATE

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P E P S '08 *at Sethu Institute of Technology held on 18th April 2008.*

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ABSTRACT

The vector control of AC machine enables the dynamic control of AC motors, and induction motor in particular to a level comparable to that of DC machine. The vector control of currents and voltages results in the control of spatial orientation of the electromagnetic fields in the induction machine that led to the term field orientation. Field orientated control schemes provide a significant improvement to the dynamic response of induction motor. The usual method of induction motor position and torque control, which is becoming an industrial standard, uses the indirect field orientation principle in which the rotor speed is sensed and used to estimate the stator impressed frequency. This project proposes indirect vector control technique using space vector pulse width modulation for speed control applied to small induction motor. The closed loop control is achieved by sensing the machine terminal currents and angular velocity. The terminal currents are sensed and converted into direct axis and quadrature axis current by three phase to two phase transformation technique. The d axis current represents actual flux value and q axis current represents the actual torque value.

These actual flux and torque components are used in comparison with the torque and reference flux and reference speed to achieve the desired speed control. In the simulation study the induction machine is modeled using dynamic state space equations, with the modular system each equation is solved by individual subsystem. The space vector PWM together with the vector control block will be used to obtain the desired closed loop operation

Simulation study has carried out with the help of MATLAB software. The simulation study has been performed on space vector PWM inverter and induction motor using vector control technique. Finally the control logic for switching the inverter has been implemented in hardware using PIC microcontroller 16F877.

ஆய்வு சுருக்கம்

மோட்டார் சுழற்சி கட்டுப்பாடு தொழிற்சாலைகளில் இன்றியமையாதது இந்த நவீன பீல்டு ஒருங்கிணைப்பு கட்டுபாடு முறையானது மோட்டாரை வேறுப்பட்ட சுழற்சிகளுக்கு கொண்டு செல்லும் இடைப்பட்ட கால அளவை குறைக்கும் திறனுடையது. சுழற்சி கட்டுப்பாடு முடப்பட்ட சுற்றின் வழியாக இயக்கப்படுவதால் தேவையான சுழற்சி வேகத்தை மிகவும் விரைவாக அடைய உதவுகிறது. இக்கட்டுபாடு முறை மின் அழுத்தம் மற்றும் மின்னோட்டம் பீட்பேக் செய்யப்பட்டு தேவையான மின்னழுத்தம் மற்றும் மின்னோட்டத்துடன் ஒப்பிட்டு பார்த்து மேலும் தேவையான வேகத்தை அடைய உதவுகிறது.

மேட்லேப் மென் பொருள் வாயிலாக சுழற்சி கட்டுப்பாடு முறை ஆய்வு செய்யப்பட்டுள்ளது. மேலும் கட்டுபாடு சிக்னல்கள் வன்பொருள் வாயிலாக நிறைவேற்றப்பட்டுள்ளது.

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LIST OF SYMBOLS

Symbol	Abbreviation
V/f	Voltage/frequency control
Te	Electro mechanical Torque
Kt'	Torque constants
I_f	Field Current in Amps
Ia	Armature Current in Amps
d^e-q^e	Synchronously Rotating Frame
i_{ds}	Direct Axis Component of Current in Amps
i_{qs}	Quadrature Component of Current
θ_e	Electrical Angle Displacement
ζ	Dummy Variable for Integration
K_s	d-q Transformation Variable
K_s^{-1}	Inversion d-q Transformation
d^s-q^s	Stationary Reference Frame
$V_{ds}{}^S$	Direct Axis Component of Voltage in Stationary Frame
$V_{qs}{}^S$	QuadratureAxis Component of Voltage in Stationary Frame
V_{as}	a phase voltage in Stationary Axis
V_{bs}	b phase voltage in Stationary Axis
V_{bc}	c phase voltage in Stationary Axis
R_s	Stator Resistance in Ohms
R_r	Rotor Resistance in Ohms
$\psi_{ds}{}^s$	Direct axis Flux Component of stator in Webers
$\psi_{qs}{}^s$	Quadrature axis Flux Component of stator in Webers
ψ_{dr}	Direct axis Flux Component of Rotor in Webers
ψ_{qr}	Quadrature axis Flux Component of Rotor in Webers
Lls	Stator Leakage Inductance in Henry
Llr	Rotor Leakage Inductance in Henry
ω_e	Angular Velocity of Stator in radians/sec

ω_r	Angular Velocity of Rotor in radians/sec
L_m	Mutual Inductance between Stator and Rotor in Henry
S	Laplace Operator
F_{mq}	q Axis magnetizing flux in Webers
F_{md}	d Axis magnetizing flux in Webers
ω_b	Base angular Velocity in radians/sec
Vdc	Dc link Voltage
f	Frequency in Hz
T	Time Period in Secs
L_f	Filter Inductance in Micro Henry
C_f	Filter Capacitance in Micro Farads
L_{load}	Load Inductance in Henry
R_{load}	Load Resistance in Ohms

CHAPTER 1

INTRODUCTION

1.1 Vector control or field – oriented control

Modern Industrial processes place stringent requirements on industrial drives by the way of efficiency, dynamic performance, flexible operating characteristics, ease of diagnostics. These coupled with the developments in micro-electronics and power devices have led to firm trend towards digital control drives. There is a wide variety of applications such as machine tools, elevators, mill drives robots, etc., and where the quick control of torque and position of the motor is essential. Such applications are dominated by DC drives and cannot be satisfactorily operated by volt/hertz (v/f) scheme. Over the last decades the principle of vector control of AC machines has evolved, by means of which AC motors and induction motors in particular, can be controlled to give dynamic performance drives These controllers are called vector controllers because they control both amplitude and phase of the ac excitation, the vector control of currents and voltages results in control of spatial orientation of the electromagnetic fields in the machine led to the term field orientation. Usually this term is reserved for controllers which maintain a 90° orientation between critical field components and hence the term field angle control was adopted. Indirect field orientation makes use of the slip relation necessary to produce the field orientation.

1.2. Objective

The aim of the project is to enhance dynamic performance of induction motor drive.

Vector control technique shall be used to obtain dynamic performance induction motor drive. Space vector PWM technique shall be used in the inverter side of the motor.

A simulation study will be done for induction motor drive and space PWM inverter.
It is intended to achieve the speed control by varying the frequency of the supply voltage.

The hardware control logic shall be developed for PWM technique.

1.3. Organization of the project

APPENDIX :

1.4 DC drive analogy

Scalar control is somewhat simple to implement but due to the inherent coupling effect of both torque and flux are the functions of voltage or current and frequency gives sluggish response and the system is prone to instability. This can be overcome with help of vector control. Vector control is also known as decoupling, orthogonal or transvector control.

Ideally a vector control induction motor drive operates like a separately excited motor, in a dc machine, neglecting the armature reaction effect and the field saturation, the developed torque is given by $T_e = K_t' I_a I_f$ .where I_a = the armature current and I_f = the field current. The construction of the DC machine is such that the field flux ψ_f produced by the current I_f is perpendicular to the armature flux ψ_a, which is produced by I_a . These space vectors, which are stationary in space, are orthogonal or decoupled in nature. This means that the torque is controlled by controlling the current I_a , the flux ψ_f

is not affected and we get the fast transient response and high torque/ampere ratio with the rated field flux ψ_f .Because of the decoupling nature the torque is controlled with out affecting the rated flux. Due to inherent coupling effect the induction motor gives sluggish response. This can be over come if the induction machine is considered operating in synchronously rotating frame $(d^e - q^e)$, where the sinusoidal variables appear as dc quantities in steady state. The induction motor with inverter and vector control the two control input currents i_{ds}^* and i_{qs}^* are used to achieve the desired operation. These currents are the direct and quadrature axis components of stator currents respectively. Therefore the torque can be expressed as $T_e = K_t' I_{ds} I_{qs}$. The DC machine like performance is only possible if i_{ds} is oriented in the direction of ψ_r and i_{qs} is perpendicular to it.

1.5 DQ Transformation Techniques

A change of variable which formulates a transformation of the 3 phase variables of stationary circuit elements to the arbitrary reference frame may be expressed as

$$f_{qd0s} = K_s f_{abcs} \tag{1.1}$$

$$(f_{qdos})^T = [f_{qs}\ f_{ds}\ f_{0s}] \tag{1.2}$$

$$(f_{abcs})^T = [f_{as}\ f_{bs}\ f_{cs}] \tag{1.3}$$

$$Ks = \frac{2}{3}\begin{bmatrix} \cos\theta e & \cos\left(\theta - \frac{2\Pi}{3}\right) & \cos\left(\theta + \frac{2\Pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta + \frac{2\Pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{1.4}$$

$\theta_e = \int_0^t \omega(\xi) + \theta(0)$ Where the dummy variable for integration similarly the inverse transformation is is given by

$$^{-1} = \begin{bmatrix} \cos\theta e & \sin\theta e & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \end{bmatrix} \qquad (1.5)$$

In the above equations f can represent either a voltage, current, flux linkage or electrical charge. The superscript T denotes transpose of matrix. The s subscript denotes the variables and parameters are associated with the stationary circuits. The angular displacement θ must be continuous; the angular velocity may take a value depending upon the frame of reference whether it is a stationary reference frame or any arbitrary velocity.

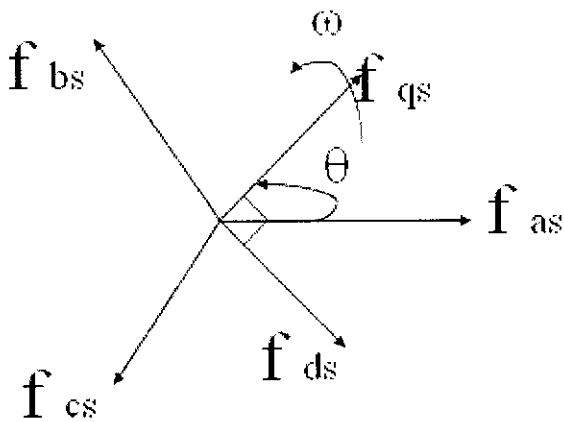

Figure1.1 Transformation of stationary circuit in to d-q plane

1.6 Dynamic d-q model

The dynamic performance of an ac induction machine is some what complex because the three phase rotor windings moves with respect to stator windings , basically it can be looked on as a transformer with a moving secondary , where the coupling coefficients between the rotor and stator phases changes continuously with the change of rotor position θr . The machine model can be described by differential equations with time varying inductance .but such model is very complex. This can be over come with help of d-q model.

Symmetrical three phase induction machine with stationary as-bs-cs axes at 120° as shown in the figure. The transformation of three phase variable in to two phase is derived as follows. Initially the three stationary frame is transformed in to two phase stationary reference frame (d^s-q^s) variables and then transformed to synchronously rotating frame (d^e-q^e) .The d^s-q^s axes are oriented at θ angle, as shown in the figure. The voltages $v_{ds}{}^s$ and $v_{qs}{}^s$ can be resolved in to as-bs-cs components and can be represented in matrix form as

$$= \begin{bmatrix} \cos\theta e & \sin\theta e & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} Vqs\ s \\ Vds\ s \\ Vos\ s \end{bmatrix} \quad (1.6)$$

The corresponding inverse relation is

$$\begin{bmatrix} Vqs\ s \\ Vds\ s \\ Vos\ s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta e & \cos\left(\theta - \frac{2\Pi}{3}\right) & \cos\left(\theta + \frac{2\Pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\Pi}{3}\right) & \sin\left(\theta + \frac{2\Pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Vas \\ Vbs \\ Vcs \end{bmatrix} \quad (1.7)$$

Where Vos s is added as zero sequence component, which may or may not be present. The current and flux linkages can be transformed by similar equations.

It is convenient to set θ=0, so that qs axis as in the figure 1.1 is aligned with as-axis. Ignoring the zero sequence components, the transformation relations can be simplified as

$$V_{as}=V_{qs}{}^{s} \quad (1.8)$$

$$V_{bs}=-\frac{1}{2}V_{qs}{}^{s}-\frac{\sqrt{3}}{2}V_{ds}{}^{s} \quad (1.9)$$

$$V_{cs}=-\frac{1}{2}V_{qs}{}^{s}+\frac{\sqrt{3}}{2}V_{ds}{}^{s} \quad (1.10)$$

And inversely

$$V_{qs}{}^{s} = \frac{2}{3}V_{as} - \frac{1}{3}V_{bs} - \frac{1}{3}V_{cs} = V_{as} \quad (1.11)$$

$$V_{ds}{}^{s} = -\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs} \quad (1.12)$$

The figure below shows the synchronously rotating de-qe axes, which rotate at synchronous speed ωe with respect to ds-qs axes and the angle $\theta e = \omega t$. the two phase ds-qs windings are transformed into hypothetical windings mounted on the de-qe axes. The voltages on ds-qs axes can be converted into de-qe frames as follows.

$$V_{qs} = V_{qs}{}^{s}\cos\theta e - V_{ds}{}^{s}\sin\theta e \quad (1.13)$$

$$V_{ds} = V_{qs}{}^{s}\sin\theta e + V_{ds}\cos\theta e \quad (1.14)$$

Similarly from rotating frame into stationary frame, the relations are

$$V_{qs}{}^{s} = V_{qs}{}^{s}\cos\theta e + V_{ds}{}^{s}\sin\theta e \quad (1.15)$$

$$V_{ds}{}^{s} = -V_{qs}{}^{s}\sin\theta e + V_{ds}{}^{s}\cos\theta e \quad (1.16)$$

1.7 Induction machine dynamic model

The stator circuit equations in ds-qs axis is shown below.

$$V_{qs}{}^{s} = Rsi_{qs}{}^{s} + \frac{d}{dt}\psi_{qs}{}^{s} \quad (1.17)$$

$$V_{ds}{}^{s} = Rsi_{ds}{}^{s} + \frac{d}{dt}\psi_{ds}{}^{s} \quad (1.18)$$

Where ψ qs s and ψ ds s are the d-axis and q-axis stator flux linkages, respectively when these equations are converted into d_e-q_e frame, equations can be written as

$$V_{qs}{}^{s} = Rsi_{qs}{}^{s} + \frac{d}{dt}\psi_{qs}{}^{s} + \omega_e \psi_{ds}{}^{s} \quad (1.19)$$

$$V_{ds}{}^{s} = Rsi_{ds}\,s + \frac{d}{dt}\psi_{ds}{}^{s} + \omega_e \psi_{qs} \quad (1.20)$$

Where all these variables are in rotating frame. The last terms in equations can be defined as speed emf due to rotation of the axes.

If the rotor is not moving, that is , $\omega r = 0$, the rotor equation can be written as

$$V_{qr}=R_r i_{qr}+\frac{d}{dt}\psi_{qr}+\omega_e\ {}_{dr} \quad (1.21)$$

$$V_{dr}=R_r i_{dr}+\frac{d}{dt}\psi_{dr}-\omega_e\psi_{qr} \quad (1.22)$$

Where all these variables are referred to stator. Since the rotor moves at speed w_r the d-q axes fixed on the rotor move at a speed $\omega_e-\ {}_r$ relative to the synchronously rotating frame. Therefore in de-qe axis the rotor equation has modified as

$$V_{qr}=R_r i_{qr}+\frac{d}{dt}\psi_{qr}+(\omega_e-\omega_r)\psi_{dr} \quad (1.23)$$

$$V_{dr}=R_r i_{dr}+\frac{d}{dt}\psi_{dr}-(\omega_e-\omega_r)\psi_{qr} \quad (1.24)$$

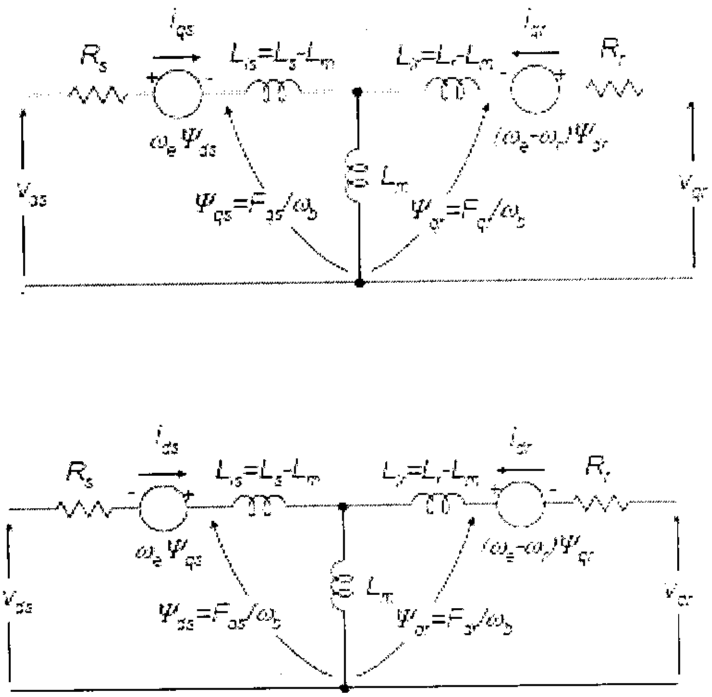

Figure 1.2 Dynamic d^e-q^e equivalent circuits of Induction the machine

Figure 1.2 shows the dynamic d^e-q^e equivalent circuits that satisfy the dynamic equations above , The flux linkage equation interms of the currents can be written as follows.

$\psi_{qs} = L_{ls}\, i_{qs} + L_m(i_{qs} + i_{qr})$ (1.25)

$\psi_{qr} = L_{lr}\, i_{qr} + L_m(i_{qs} + i_{qr})$ (1.26)

$\psi_{qm} = L_m(i_{qs} + i_{qr})$ (1.27)

$\psi_{ds} = L_{ls}\, i_{ds} + L_m\,(i_{ds} + i_{dr})$ (1.28)

$\psi_{dr} = L_{lr}\, i_{dr} + L_m\,(i_{ds} + i_{dr})$ (1.29)

$I_{a\ dm} = L_m(i_{ds} + i_{dr})$ (1.30)

Combining the above equations the electrical transient model in terms of voltage and currents can be given in matrix form as

$$\begin{bmatrix} Vqs \\ Vds \\ Vqr \\ Vdr \end{bmatrix} = \begin{bmatrix} Rs + sLs & \omega eLs & SLm & \omega eLm \\ -\omega eLs & Rs + SLs & -\omega eLm & SLm \\ SLm & (\omega e - \omega r)Lm & Rr + SLr & (\omega e - \omega r)Lr \\ -(\omega e - \omega r)Lm & SLm & \_(\omega e - \omega r)Lr & Rr + SLr \end{bmatrix} \begin{bmatrix} iqs \\ ids \\ iqr \\ idr \end{bmatrix} \quad (1.31)$$

Where s is the Laplace operator for a singly-fed machine, such as a cage motor.

Vqr=Vdr=0.

The torque equation is given as

$$Te = TL + J\frac{d_{\omega m}}{dt} = T_L + \frac{2}{p} J \frac{d_{\omega r}}{dt} \quad (1.32)$$

T_L= load torque, J= rotor inertia and ω_m=mechanical speed.

CHAPTER 2

Simulink Implementation of Induction motor

2.1 block diagram for vector control of induction motor

The usual method of induction motor position and torque control, which is becoming an industrial standard, uses the indirect field orientation principle in which the rotor speed is sensed and used to estimate the stator impressed frequency. This paper proposes indirect vector control technique applied to small induction motor using space vector pulse width modulation for torque control. .The closed loop control is achieved by sensing the machine terminal currents and angular velocity. The terminal currents are sensed and converted in to direct axis and quadrate axis current by three phases to two phase transformation technique. . The torque and flux command are used in comparison with the torque and flux component of current obtained using the transformation technique to achieve the desire torque control. In the simulation study the induction machine is modeled using dynamic state space equations, with the modular system each equation is solved by individual subsystem. The space vector PWM together with the vector control block will used to obtain the desired closed loop operation.

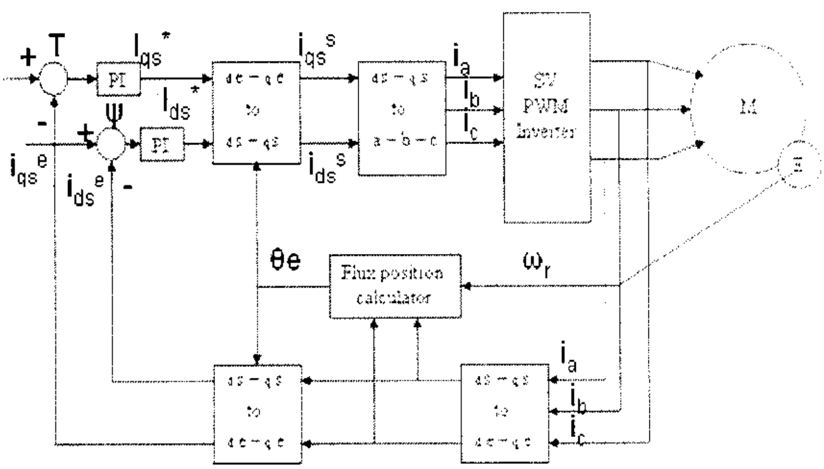

Figure 2.1 Block diagram of closed loop control of Induction motor

For the complete closed loop operation the induction machine dynamic equations has been derived based on induction machine modeling .The commands generated from the vector control block is used to generate the required voltage with magnitude and phase to obtain the desired response with the help of space vector PWM inverter.

The simulation study consists of modeling of induction machine , space vector PWM and vector control block.

2.2 Introduction to simulink implementation

Usually, when an electrical machine is simulated in circuit simulators like PSpice, its steady state model is used, but for electrical drive studies, the transient behavior is also important. Advantage of simulink over circuit simulators is the ease of modeling the transients of electrical machines and drives and to include drive controls in the simulation.

As long as the equations are known, any drive or control algorithm can be modeled in simulink. However, the equations by themselves are not always enough , some experience in the differential equation solving also required.

A modular approach easy to understand simulink induction machine model is described. With the modular system each block solves one of the model equations; therefore, unlike a black box models, all of the machine parameters are accessible for control and verification purposes

2.3 Induction machine dynamic equations

The induction machine d-q or dynamic equivalent circuit is shown in the figure1.2 One of the most popular induction motor models derived from the equivalent circuit is Krause's model. According to this modeling the equations in flux linkage form are as follows.

$$\frac{dF_{qs}}{dt} = \omega_b\left[V_{qs} - \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{X_{ls}}\left(F_{mq} + F_{qs}\right)\right] \qquad (2.1)$$

$$\frac{dF_{ds}}{dt} = \omega_b\left[V_{ds} + \frac{\omega_e}{\omega_b} F_{qs} + \frac{R_s}{X_{ls}} \left(F_{md} + F_{ds}\right)\right] \quad (2.2)$$

$$\frac{dF_{qs}}{dt} = \omega_b\left[V_{qr} - \frac{\left(\omega_e - \omega_r\right)}{\omega_b} F_{dr} + \frac{R_r}{X_{lr}} \left(F_{mq} - F_{qr}\right)\right] \quad (2.3)$$

$$\frac{dF_{ds}}{dt} = \omega_b\left[V_{dr} + \frac{\left(\omega e - \omega r\right)}{\omega_b} F_{qr} + \frac{R_r}{X_{lr}} \left(F_{md} - F_{dr}\right)\right] \quad (2.4)$$

$$F_{mq} = X_{ml}{*} \left[\frac{F_{qs}}{X_{ls}} + \frac{F_{qr}}{X_{lr}} \right] \quad (2.5)$$

$$F_{md} = X_{ml}{*} \left[\frac{F_{ds}}{X_{ls}} + \frac{F_{dr}}{X_{lr}} \right] \quad (2.6)$$

$$iq_s = \frac{1}{X_{ls}}\left(F_{qs} - F_{mq}\right) \quad (2.7)$$

$$i_{ds} = \frac{1}{X_{ls}}\left(F_{ds} - F_{md}\right) \quad (2.8)$$

$$i_{qr} = \frac{1}{X_{lr}}\left(F_{qr} - F_{mq}\right) \quad (2.9)$$

$$i_{dr} = \frac{1}{X_{lr}}\left(F_{dr} - F_{md}\right) \quad (2.10)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{1}{\omega_b}\left(F_{ds}\, i_{qs} - F_{qs}\, i_{ds}\right) \tag{2.11}$$

$$Te - T_L = J\left(\frac{2}{p}\right)\frac{d_{\omega r}}{dt} \tag{2.12}$$

Where,

d: direct axis,

q: quadrature axis,

s: stator variable

r: rotor variable

Fij: is the flux linkage (i=q or d and j = s or r),

V_{qs} V_{ds} : q and d axis stator voltages,

Vqr V_{dr} : q and d axis rotor voltages,

F_{mq} F_{md}: q and d axis magnetizing flux linkages,

R_r: rotor resistance,

R_s: stator resistance,

X_{ls}: stator leakage reactance ($\omega_e L_{ls}$)

X_{lr}: rotor leakage reactance (ωeLlr)

X_{ml} : $1 \Big/ \left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}\right)$,

i_{qs} i_{ds}: q and d axis stator currents,

i_{qr} i_{dr}: q and d axis magnetizing flux linkages,

P: number of poles,

J: moment of inertia,

Te: electrical output torque,

T_L: load torque,

ω_e: stator angular electrical frequency,

ω_b: motor angular electrical base frequency,

ω_r : rotor angular electrical speed.

For a squirrel cage induction machine as in the case of this proiect V_{qr} and V_{dr} in (2.3) and (2.4) are set to zero.

An induction machine model can be represented with five differential equations as seen above. To solve the equations, they have to be arranged in the state space form, $x = Ax + b$ where $x = [F_{qs}\ F_{ds}\ F_{qr}\ F_{dr}\ \omega_r]^T$ is the state vector. Note that $Fij = \psi ij.\omega b$, where Fij is the flux linkage $(i = q \text{ or } d \text{ and } j = s \text{ or } r)$ and ψij is the flux.

In this case , state – space form can be achieved by inserting (2.5) and (2.6) in (2.1– 2.4)and collecting the similar terms together so that the state space derivative is a function of only other state equations (2.1-2.4 and 2.12) of a squirrel cage induction motor in state space become

$$\frac{dF_{qs}}{dt} = \omega_b\left[V_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{X_{ls}}\left(\frac{X_{ml}^*}{X_{lr}}F_{qr} + \left(\frac{X_{ml}^*}{X_{lr}} - 1\right)F_{qs}\right)\right] \tag{2.13}$$

$$\frac{dF_{ds}}{dt} = \omega_b\left[V_{ds} + \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{X_{ls}}\left(\frac{X_{ml}^*}{X_{lr}}F_{dr} + \left(\frac{X_{ml}^*}{X_{ls}} - 1\right)F_{ds}\right)\right] \tag{2.14}$$

$$\frac{dF_{dr}}{dt} = \omega_b\left[-\frac{(\omega_e - \omega r)}{\omega b}F_{dr} + \frac{R_r}{X_{lr}}\left(\frac{X_{ml}^*}{X_{ls}}F_{qs} + \left(\frac{X_{ml}^*}{X_{lr}} - 1\right)F_{qr}\right)\right] \tag{2.15}$$

$$\frac{dF_{dr}}{dt} = \omega_b\left[\frac{(\omega_e - \omega_r)}{\omega b}F_{qr} + \frac{R_r}{X_{lr}}\left(\frac{X_{ml}^*}{X_{ls}}F_{ds} + \left(\frac{X_{ml}^*}{X_{lr}} - 1\right)F_{dr}\right)\right] \tag{2.16}$$

$$\frac{d\omega r}{dt} = \left(\frac{p}{2J}\right)(Te - T_L) \tag{2.17}$$

2.4 Modeling of induction machine

The input to the induction machine model is the three phase voltage and the machine rated frequency and the load torque. The output of the induction machine is the three phase currents, the electrical torque and the rotor speed.

The d-q model requires that all the three phase variables have to be transformed in to two phase synchronously rotating frame. Consequently the induction machine model will have blocks transforming the three phase voltages to the d-q frame and the d-q currents back to three phase.

The induction machine model implemented in this paper is shown in fig2.4 .It consists of five major blocks: the o-n converter, abc-syn conversion, syn-abc conversion, unit vector calculation, and the induction machine d-q model blocks.

2.4.1. Isolated neutral – neutral conversion

This block is required for an isolated neutral system, otherwise it can be bypassed. The transformation done by this block can be represented as follows.

$$\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} = \begin{bmatrix} +\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & +\frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & +\frac{2}{3} \end{bmatrix} \begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix} \qquad (2.18)$$

This is implemented in simulink with the help of math functions, which converts the above transformation matrix in equation 2.18.

2.4.2 Unit vector calculation block

Unit vectors $\cos\theta e$ and $\sin\theta e$ are used in vector transformation blocks such as abc-syn and syn-abc. The angle θe is directly calculated by integrating the frequency of the input three phase voltage ω_e.

$$\theta_e = \int \omega_e \, dt \qquad (2.19)$$

The unit vectors are obtained by taking the sine and cosine of θe

2.4.3 Syn-abc conversion block

To convert the three phase voltage in to two phase synchronously rotating frame, they are first converted in to stationary frame and then from the stationary frame to two phase synchronously rotating frame using the equations below.

$$\begin{bmatrix} V_{qs\,S} \\ V_{ds\,S} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \qquad (2.20)$$

The above equation 2.19is used to transform in to stationary reference frame.

$$\begin{Bmatrix} V_{qs} = V_{qs}\ s\cos\theta_e - V_{ds}\ s\sin\theta_e \\ V_{ds} = V_{qs}\ s\sin\theta_e + V_{ds}\ s\cos\theta_e \end{Bmatrix} \tag{2.21}$$

Where the subscript refers to stationary reference frame.

Equation No.2.20 is implemented using math function available in simulink. Equation No.2.21 is implemented with math function together with sum and the product blocks.

2.4.4 syn-abc conversion block

This block does the opposite of the abc-syn conversion block for the current variable using the equation No2.22 and equation No.2.23 shown below.

$$\begin{Bmatrix} i_{qs}\ s = i_{qs}\cos\theta_e + i_{ds}\ s\sin\theta_e \\ i_{ds}\ s = -\ i_{qs}\sin\theta_e + i_{ds}\ s\cos\theta_e \end{Bmatrix} \tag{2.22}$$

$$\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{qs}\ s \\ i_{ds}\ s \end{bmatrix} \tag{2.23}$$

2.4.5. Induction machine d q model block

Fig4 shows the inside of the block where each equation from the induction machine model is implemented in a different block

First consider the flux linkage state equations because flux linkages are required to calculate all other variables these equations are implemented with the help of discrete block in order to have access to each point of the block. Once the flux linkages are calculated the rest of the equations can be implemented without any difficulty. The blocks solving the rest of the equations are shown in columns. The blocks in the column 2 of fig.2.2 used to solve the equations 2.5 and 2.6. Equation 2.7-2.10 uses the flux linkages to solve fro the stator and rotor d and q currents. The forth column is used to solve electrical torque calculation from the equation 2.16 and the rotor speed calculation using the last state equation 2.17.the rotor speed information is required for the calculation of the rotor flux linkages in column 1 therefore is the feedback to this column. The resulting modular system can be easily traced using simulink scope blocks.

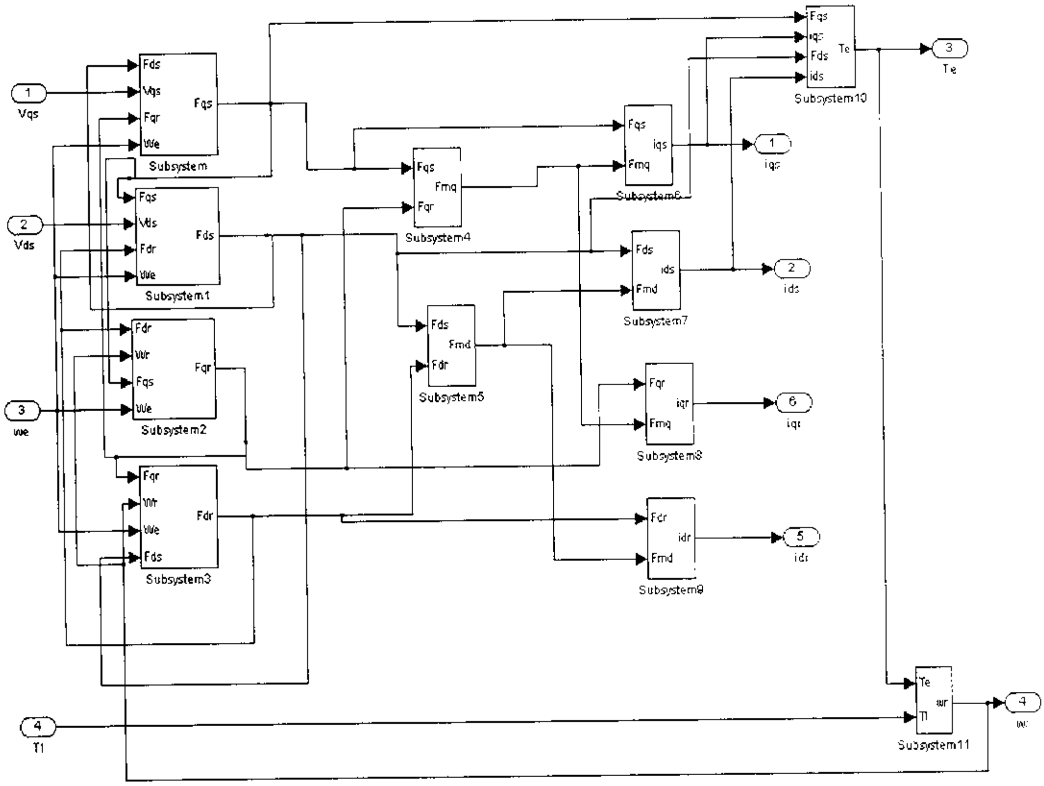

Figure 2.2 Induction machine dynamic model in simulink

2.4.6 DQ model subsystem design

The implementation subsystem Fqs of figure as in the first column of induction machine model is shown below. The dynamic equation 2.13 of Fqs has implemented using the basic building blocks of simulink.

$$\frac{dF_{qs}}{dt} = \omega_b\left[V_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{X_{ls}}\left(\frac{X_{ml}{}^*}{X_{lr}}F_{qr} + \left(\frac{X_{ml}{}^*}{X_{lr}} - 1\right)F_{qs}\right)\right] \qquad (2.13)$$

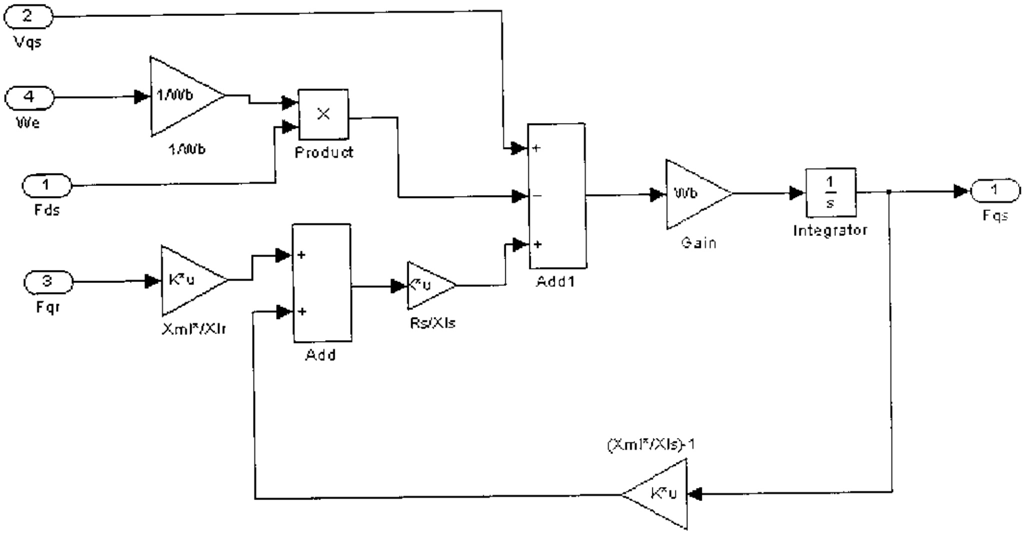

Figure 2.3 implementation of Subsystem Fqs in simulink

2.5 Complete induction machine model

The complete induction machine model has obtained by combining five major blocks, the o-n converter, abc-syn conversion, syn-abc conversion, unit vector calculation, and the induction machine d-q model blocks.

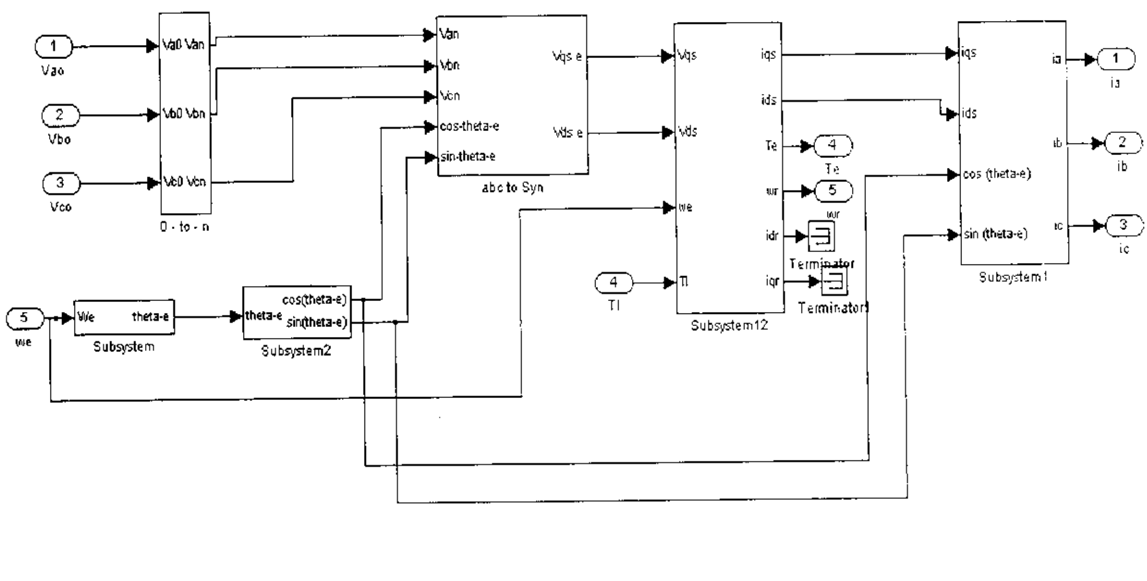

Figure 2.4 The complete Induction machine simulink model

2.6 Indirect vector control block

The vector control block as shown in fig.2.5 is used to obtain the reference value of voltage Vqs* and Vds* and also the angular frequency based on speed reference and the feed back currents iqs and ids obtained from the feedback and inverse transformation technique.

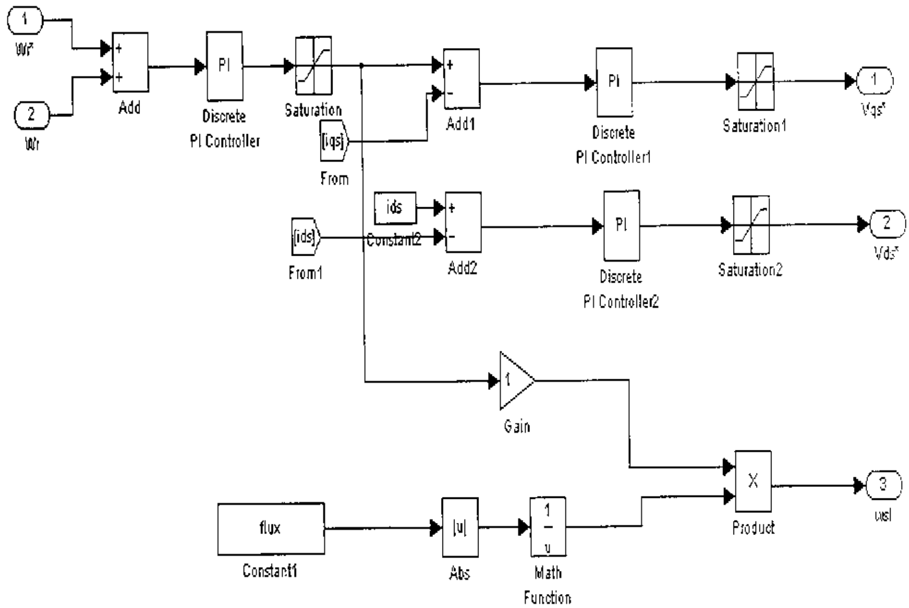

Figure 2.5 Indirect Vector Control Block

PI controllers together with the saturation limiter helps to track the required value of the speed and torque. The voltage values obtained from the vector controller block is given as an input to the space vector PWM inverter.

CHAPTER 3

Simulink Implementation of Space vector PWM inverter

3.1 PWM inverter model

The circuit model of PWM inverter is shown below.It consists of center tapped dc voltage source . the upper arm consists of three IGBTs forming one group, similarly the lower arm consists of three IGBTs forming other group.At any point of time IGBTs belong to the same arm should not be turned on , it will lead to short cicuit of dc source.

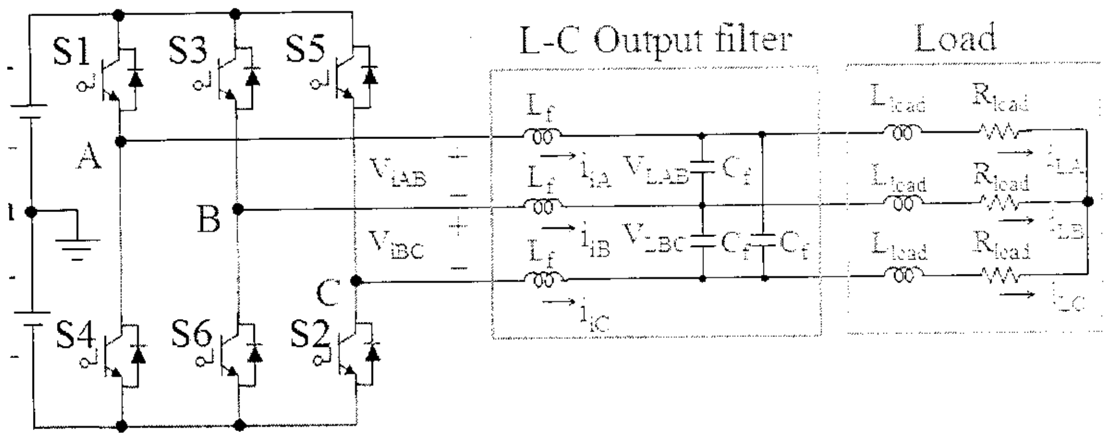

Figure 3.1 Circuit model of three phase PWM inverter

The system parameters for the system is as mentioned below.

DC- link voltage: V_{dc} = 400 V

Fundamental frequency: f = 50 Hz

PWM (carrier) frequency: f_z = 3 kHz

Modulation index: a = 0.78

Output filter: L_f = 800 μH and C_f = 400 μF

Load: L_{load} = 2 mH and R_{load} = 5 Ω

3.2 principle of pulse width modulation technique

Figure shows the circuit model of single phase inverter with center tapped grounded DC bus.

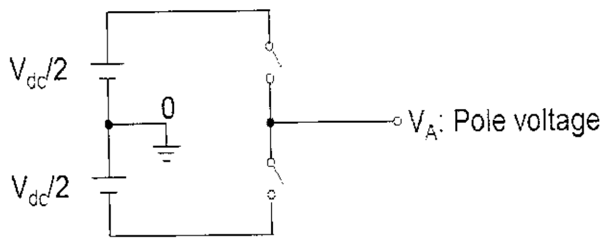

Figure 3.2 Circuit model of single Phase inverter

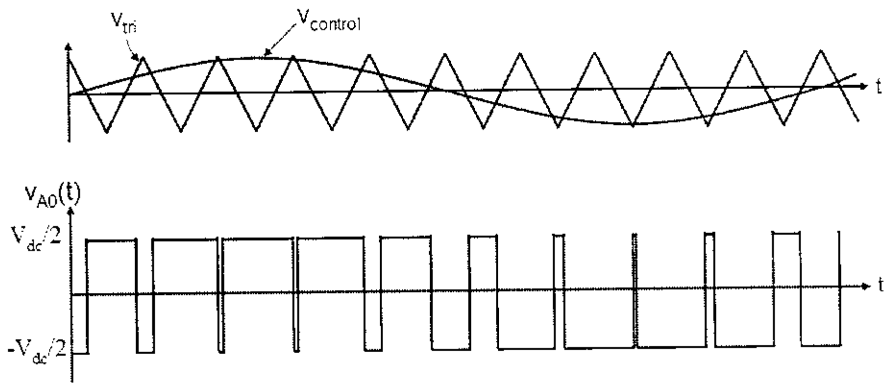

Figure 3.3 waveform of pulse width modulation technique

The inverter output voltage is determined in the following

When $V_{control} > V_{tri}$, $V_{A0} = V_{dc}/2$

When $V_{control} < V_{tri}$, $V_{A0} = -V_{dc}/2$

Also, the inverter output voltage has the following features:

PWM frequency is the same as the frequency of V_{tri}

Amplitude is controlled by the peak value of $V_{control}$

Fundamental frequency is controlled by the frequency of $V_{control}$

That is when the is $V_{control}$ greater than the Vtri the output voltage is $V_{dc}/2$ and when it is less than Vtri the output voltage is $-V_{dc}/2$.

Modulation index is defined as

$$M = \frac{Vcontrol}{Vtriangle}$$

3.3 Principle of space vector PWM

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig. 3.1. .S_1 to S_6 are the six power switches that shape the output, which are controlled by the switchingvariables a, a′, b, b′, c and c′. When an upper transistor is switched on, i.e., when a, b or c is 1,the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0.Therefore, the on and off states of the upper transistors S_1, S_3 and S_5 can be used to determine theoutput voltage.Fig. 4 Three-phase voltage source PWM Inverter.5The relationship between the switching variable vector $[a, b, c]_t$ and the line-to-line voltage
vector $[V_{ab}\ V_{bc}\ V_{ca}]_t$ is given by (3.1) in the following:

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = Vdc \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \qquad (3.1)$$

Also, the relationship between the switching variable vector $[a, b, c]_t$ and the phase voltagevector $[V_a\ V_b\ V_c]_t$ can be expressed below.

$$\begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \qquad (3.2)$$

As illustrated in Fig. 4, there are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. According to equations (2.1) and (2.2), the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link V_{dc} , are given in Table1 and Fig3.4 shows the eight inverter voltage vectors (V_0 to V_7).

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

Table 1 Switching Vectors and phase to phase, line to line voltages

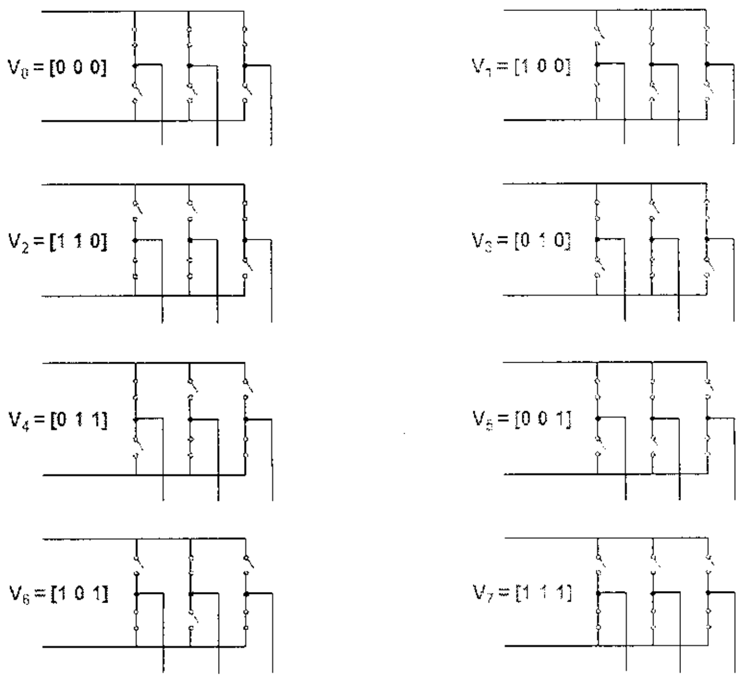

Figure3.4 The eight inverter voltage vectors (V_0 to V_7).

space Vector PWM (SVPWM) refers to a special switching sequence of the upper threepower transistors of a three-phase power inverter. It has been shown to generate less harmonic distortion in the output voltages and or currents applied to the phases of an AC motor and to provide more efficient use of supply voltage compared with sinusoidal modulation technique

implementation of the space vector PWM involves the voltage equations in the *abc* reference frame

to be transformed into the stationary *dq* reference frame

$$\mathbf{f}_{dq0} = \mathbf{K}_s \mathbf{f}_{abc} \tag{3.3}$$

$$K_s = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.4}$$

$\mathbf{f}_{dq0}=[f_d f_q f_0]^T$, $\mathbf{f}_{abc}=[f_a f_b f_c]^T$, and f denotes either a voltage or a current variable.

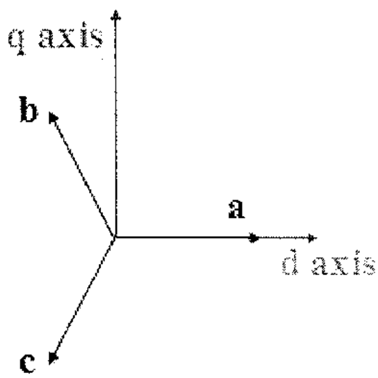

Figure 3.5 Relationship of abc frame and reference frame

As described in Fig. 3.5, this transformation is equivalent to an orthogonal projection of $[a, b, c]^t$ onto the two-dimensional perpendicular to the vector $[1, 1, 1]^t$ (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six nonzero vectors (V_1 - V_6) shape the axes of a hexagonal as depicted in Fig. 3.6, and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V_0 and V_7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V_0, V_1, V_2, V_3, V_4, V_5, V_6, and V_7. The same transformation can be applied to the desired output voltage to get the desired reference voltage vector V_{ref} in the d-q plane. The objective of space vector PWM technique is to approximate the reference voltage vector V_{ref} using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of V_{ref} in the same period.

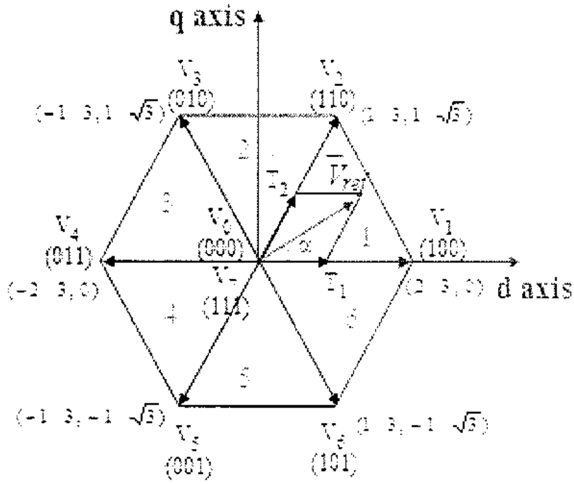

Figure 3.6 Basic switching vectors and switching sectors

Therefore, space vector PWM can be implemented by the following steps:

Step 1. Determine V_d, V_q, V_{ref}, and angle (α)

Step 2. Determine time duration T_1, T_2, T_0

Step 3. Determine the switching time of each transistor (S_1 to S_6)

3.4 Determining V_d, V_q, V_{ref}, and angle (α)

From Fig.3.7, the V_d, V_q, V_{ref}, and angle (α) can be determined as follows:

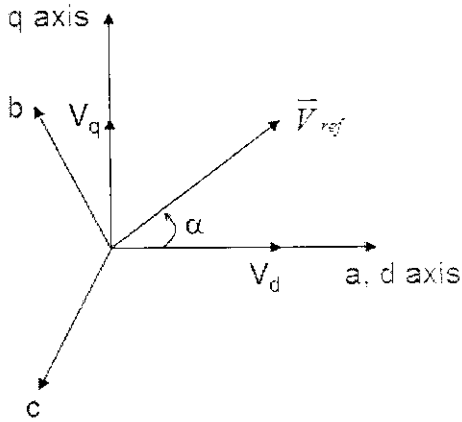

Figure 3.7 Voltage space vectors and its components in dq axis

$$V_d = V_{an} - V_{bn}.\cos 60 - V_{cn}.\cos 60 \tag{3.5}$$

$$Vq = 0 + Vbn.\cos 30 - Vcn.\cos 30 \tag{3.6}$$

$$= 0 + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn}$$

$$\alpha = \tan^{-1}\left[\frac{Vq}{Vd}\right] = \omega t = 2\pi ft \tag{3.7}$$

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} \tag{3.8}$$

3.5 Determine time duration period for switching

Switching Time duration at sector1

$$\int_0^{Tz} Vref\, dt = \int_0^{T1} V1\, dt + \int_{T1}^{T1+T2} V2\, dt + \int_{T1+T2}^{Tz} Vo \tag{3.9}$$

$$Tz.Vref = (T1.V1 + T2.V2) \tag{3.10}$$

(3.11)

$$T1 = Tz.a.\frac{\sin(\frac{\Pi}{3} - \alpha)}{\sin(\Pi/3)} \quad (3.12)$$

$$T2 = Tz.a.\frac{\sin(\alpha)}{\sin(\frac{\Pi}{3})} \quad (3.13)$$

(3.14)

$$To = Tz - (T1 + T2)$$

3.6 Genralized Switching time for any vector

$$T1 = \frac{\sqrt{3}.Tz.|Vref|}{Vdc}\left(\sin\frac{n}{3}\Pi - \alpha\right) \quad (3.15)$$

$$T2 = \frac{\sqrt{3}.Tz.|Vref|}{Vdc}\left(\sin\left(\alpha - \frac{n-1}{3}\Pi\right)\right) \quad (3.16)$$

$$To = Tz - T1 - T2$$

$$\left(\text{where, n = 1 through 6(that is, sec tor 1 to 6}\right)$$

Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1+T_2+T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1+T_2+T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_2 + T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_2 + T_0/2$

Table 2.Switching time calculation of each sector

3.7 State-Space Model of output filter

Fig. 3.8 shows L-C output filter to obtain current and voltage equations.

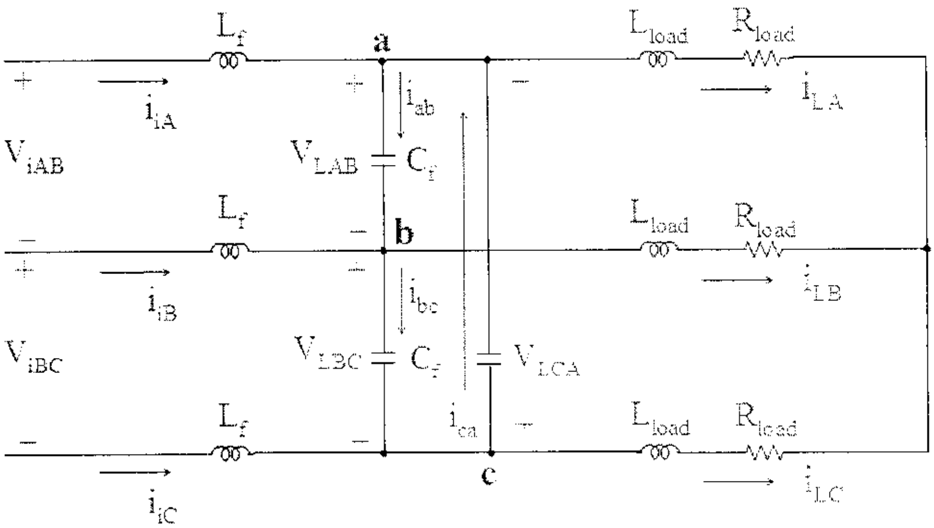

Figure 3.8 L-C output filter for current and voltage equations

By applying Kirchoff's current law to nodes a, b, and c, respectively, the following current equations are derived:

<u>In node"A",</u>

$$i_{iA} - i_{ca} = i_{ab} - i_{LA} \quad \Rightarrow \quad i_{iA} + C_f \frac{dV_{LCA}}{dt} = C_f \frac{dV_{LAB}}{dt} - i_{LA} \qquad (3.17)$$

<u>In node "B",</u>

$$i_{iB} + i_{ab} = i_{bc} + i_{LB} \quad \Rightarrow \quad i_{iB} + C_f \frac{dV_{LAB}}{dt} = C_f \frac{dV_{LBC}}{dt} + i_{LB} \qquad (3.18)$$

<u>In node "C",</u>

$$i_{iC} + i_{bc} = i_{ca} + i_{LC} \quad \Rightarrow \quad i_{iC} + C_f \frac{dV_{LBC}}{dt} = C_f \frac{dV_{LCA}}{dt} + i_{LC} \qquad (3.19)$$

$$\text{where. } i_{ab} = C_f \frac{dV_{LAB}}{dt}, \quad i_{bc} = C_f \frac{dV_{LBC}}{dt}, \quad i_{ca} = C_f \frac{dV_{LCA}}{dt} \qquad (3.20)$$

Also the equations 3.17 to 3.19 can be rewritten as the following equations respectively

Subtracting the equation 3.17 from 3.18

$$i_{iA} - i_{iB} + C_f\left(\frac{dV_{LCA}}{dt} - \frac{dV_{LAB}}{dt}\right) = C_f\left(\frac{dV_{LAB}}{dt} - \frac{dV_{LBC}}{dt}\right) + i_{LA} - i_{LB}$$

$$\Rightarrow \quad C_f\left(\frac{dV_{LCA}}{dt} + \frac{dV_{LBC}}{dt} - 2\cdot\frac{dV_{LAB}}{dt}\right) = -i_{iA} - i_{iB} - i_{LA} - i_{LB} \qquad (3.21)$$

Subtracting the equation 3.17 from equation 3.18

$$i_{iB} - i_{iC} + C_f\left(\frac{dV_{LAB}}{dt} - \frac{dV_{LBC}}{dt}\right) = C_f\left(\frac{dV_{LBC}}{dt} - \frac{dV_{LCA}}{dt}\right) + i_{LB} - i_{LC}$$

$$\Rightarrow \quad C_f\left(\frac{dV_{LAB}}{dt} + \frac{dV_{LCA}}{dt} - 2\cdot\frac{dV_{LBC}}{dt}\right) = -i_{iB} + i_{iC} - i_{LB} - i_{LC} \qquad (3.22)$$

Subtracting equation 3.17 from equation 3.19

$$i_{iC} - i_{iA} + C_f\left(\frac{dV_{LBC}}{dt} - \frac{dV_{LCA}}{dt}\right) = C_f\left(\frac{dV_{LCA}}{dt} - \frac{dV_{LAB}}{dt}\right) - i_{LC} - i_{LA}$$

$$\Rightarrow \quad C_f\left(\frac{dV_{LAB}}{dt} + \frac{dV_{LBC}}{dt} - 2\cdot\frac{dV_{LCA}}{dt}\right) = -i_{iC} + i_{iA} + i_{LC} - i_{LA} \qquad (3.23)$$

$V_{LAB} + V_{LBC} + V_{LCA} = 0.$ (3.24)

To simplify 3.21 to 3.23 the equation 3.24is used.

Based on equation 3.24 the equations 3.21 to 3.23 can be modified to first order differential equations

$$\begin{cases} \frac{dV_{LAB}}{dt} = \frac{1}{3C_f} i_{iAB} - \frac{1}{3C_f}\left(i_{LAB}\right) \\ \frac{dV_{LBC}}{dt} = \frac{1}{3C_f} i_{iBC} - \frac{1}{3C_f}\left(i_{LBC}\right) \\ \frac{dV_{LCA}}{dt} = \frac{1}{3C_f} i_{iCA} - \frac{1}{3C_f}\left(i_{LCA}\right) \end{cases} \qquad (3.25)$$

where, $i_{iAB} = i_{iA} - i_{iB}$, $i_{iBC} = i_{iB} - i_{iC}$, $i_{iCA} = i_{iC} - i_{iA}$ and $i_{LAB} = i_{LA} - i_{LB}$, $i_{LBC} = i_{LB} - i_{LC}$, $i_{LCA} = i_{LC} - i_{LA}$.

By applying Kirchoff's voltage law on the side of inverter output , the following voltage equation 3.26 is derived

$$\begin{cases} \frac{di_{iAB}}{dt} = -\frac{1}{L_f}V_{LAB} + \frac{1}{L_f}V_{iAB} \\ \frac{di_{iBC}}{dt} = -\frac{1}{L_f}V_{LBC} + \frac{1}{L_f}V_{iBC} \\ \frac{di_{iCA}}{dt} = -\frac{1}{L_f}V_{LCA} + \frac{1}{L_f}V_{iCA} \end{cases} \quad (3.26)$$

By applying Kirchoff's voltage law on the load side , the following voltage equation 3.27 is derived.

$$\begin{cases} V_{LAB} = L_{load}\frac{di_{LA}}{dt} + R_{load}i_{LA} - L_{load}\frac{di_{LB}}{dt} - R_{load}i_{LB} \\ V_{LBC} = L_{load}\frac{di_{LB}}{dt} + R_{load}i_{LB} - L_{load}\frac{di_{LC}}{dt} - R_{load}i_{LC} \\ V_{LCA} = L_{load}\frac{di_{LC}}{dt} + R_{load}i_{LC} - L_{load}\frac{di_{LA}}{dt} - R_{load}i_{LA} \end{cases} \quad (3.27)$$

Equation 3.27 can be written as

$$\begin{cases} \frac{di_{LAB}}{dt} = -\frac{R_{load}}{L_{load}}i_{LAB} + \frac{1}{L_{load}}V_{LAB} \\ \frac{di_{LBC}}{dt} = -\frac{R_{load}}{L_{load}}i_{LBC} + \frac{1}{L_{load}}V_{LBC} \\ \frac{di_{LCA}}{dt} = -\frac{R_{load}}{L_{load}}i_{LCA} + \frac{1}{L_{load}}V_{LCA} \end{cases} \quad (3.28)$$

Therefore, the equations 3.26 to 3.28 can be written into marix form respectively.

$$\frac{d\mathbf{V}_L}{dt} = \frac{1}{3C_f}\mathbf{I}_i - \frac{1}{3C_f}\mathbf{I}_L$$
$$\frac{d\mathbf{I}_i}{dt} = -\frac{1}{L_f}\mathbf{V}_L - \frac{1}{L_f}\mathbf{V}_i$$
$$\frac{d\mathbf{I}_L}{dt} = \frac{1}{L_{load}}\mathbf{V}_L - \frac{R_{load}}{L_{load}}\mathbf{I}_L \tag{3.29}$$

where, $\mathbf{V}_L = [V_{LAB}\ V_{LBC}\ V_{LCA}]^T$. $\mathbf{I}_i = [i_{iAB}\ i_{iBC}\ i_{iCA}]^T = [i_{iA}\text{-}i_{iB}\ i_{iB}\text{-}i_{iC}\ i_{iC}\text{-}i_{iA}]^T$. $\mathbf{V}_i = [V_{iAB}\ V_{iBC}\ V_{iCA}]^T$
$\mathbf{I}_L = = [i_{LAB}\ i_{LBC}\ i_{LCA}]^T = [i_{LA}\text{-}i_{LB}\ i_{LB}\text{-}i_{LC}\ i_{LC}\text{-}i_{LA}]^T$.

Finally, the given plant model 3.29 can be expressed as state space equation 3.30 shown delow.

The state space model is given by

$$X = \begin{bmatrix} VL \\ Ii \\ IL \end{bmatrix}, A = \begin{bmatrix} 0(3x3) & \frac{1}{3Cf}I(3x3) & -\frac{1}{3Cf}I(3x3) \\ \frac{-1}{Lf}I(3x3) & 0(3x3) & 0(3x3) \\ \frac{1}{Lload}I(3x3) & 0(3x3) & -\frac{Rload}{Lload}I(3x3) \end{bmatrix}, B = \begin{bmatrix} 0(3x3) \\ \frac{1}{Lf}I(3x3) \\ 0(3x3) \end{bmatrix}, u = [Vi](3x3) \tag{3.30}$$

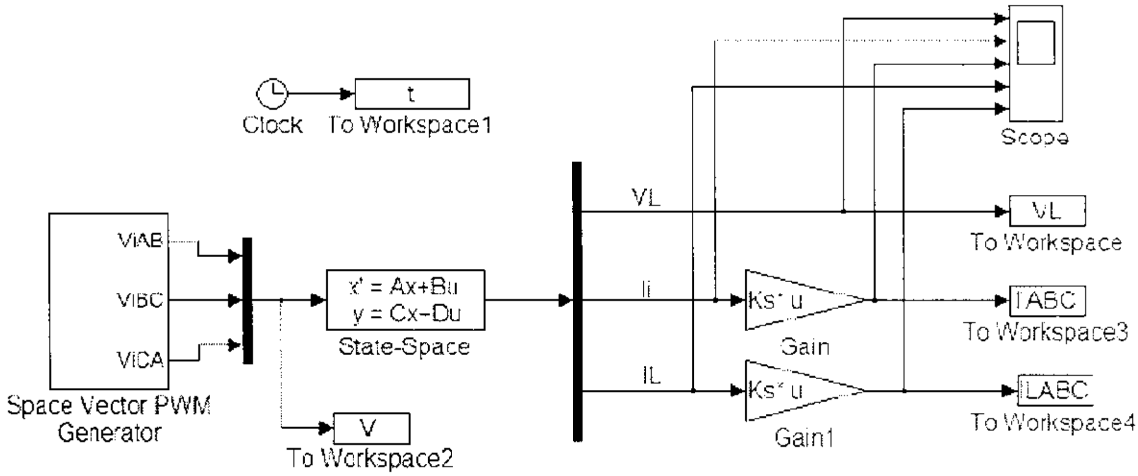

Figure 3.9 Simulink Model for Overall SVPWM

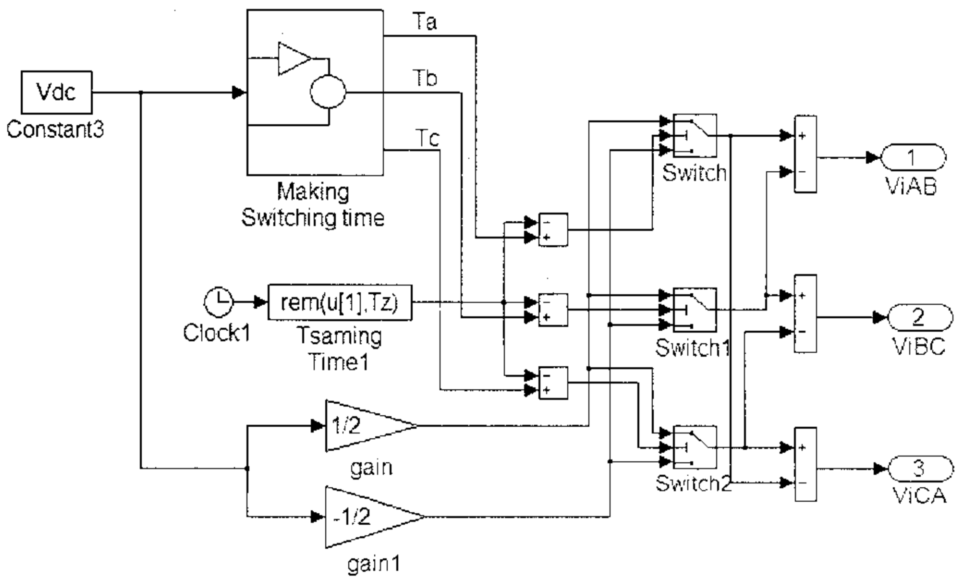

Figure 3.10 Subsystem Simulink Model for Space Vector PWM Generator

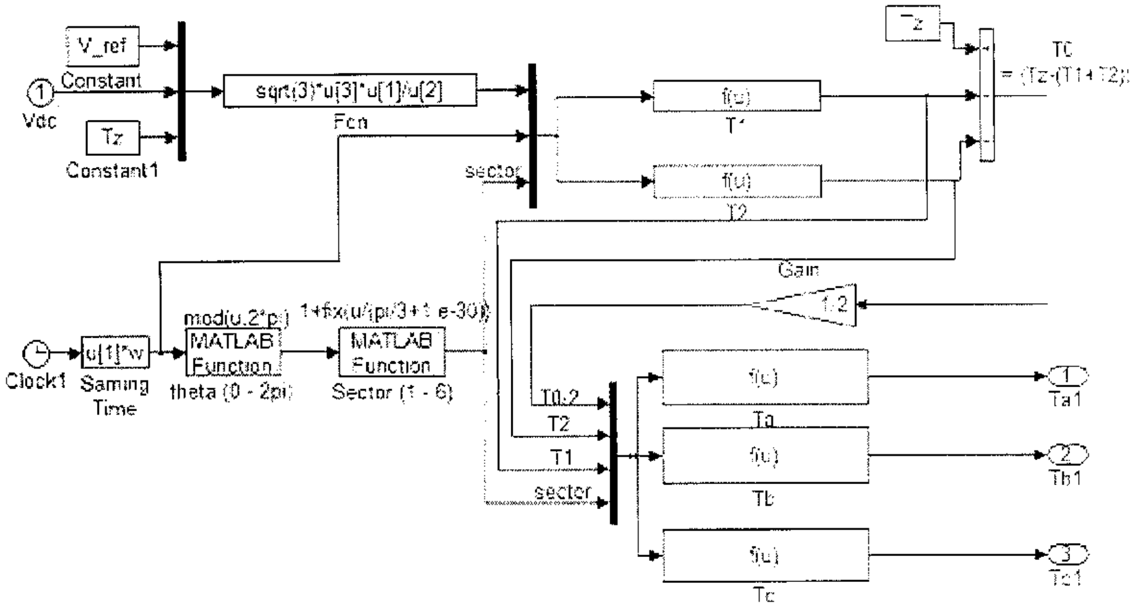

Figure 3.11 Subsystem Simulink Model for Making Switching Time

T1 = u[1]*(sin(u[3]*pi/3)*cos(u[2])-cos(u[3]*pi/3)*sin(u[2]))

T2 = u[1]*(cos((u[3]-1)*(pi/3))*sin(u[2])-sin((u[3]-1)*(pi/3))*cos(u[2]))

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

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

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

3.8 Initialization parameters for SVPWM

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```
% initalization of parameters
Vdc=400;     %dc-link voltage
Lf=800e-06;  %inductance for output filter
Cf=400e-06;   %capacitance for output filter
Lload=100e-06;    %load resistance
Rload=5;          %load resistance
f=50;              %fundamental frequency
fs=3e3;           %switching frequency
a=0.78;
W=2*pi*50;          %angular frequency
Ts=1/fs;           %sampling time
V_ref=(2/3)*a*Vdc;  %reference voltage

% co efficients for state-space model
A=[zeros(3,3) eye(3)/(3*Cf) -eye(3)/(3*Cf)
    -eye(3)/Lf   zeros(3,3) zeros(3,3)
    eye(3,3)/Lload zeros(3,3) -eye(3)*Rload/Lload];%system matrix
B=[zeros(3,3)
    eye(3)/Lf
    zeros(3,3)];% coefficent for the control variable u
C=[eye(9)]; %co efficient for the output y
D=[zeros(9,3)];%co efficient for the output y
Ks=1/3*[-1 0 1; 1 -1 0; 0 1 -1];%conversion matrix to transform [illegible] to [illegible]
```

Figure 3.12 Initialization of parameters for inverter

3.9 Simulation results of Space vector PWM inverter

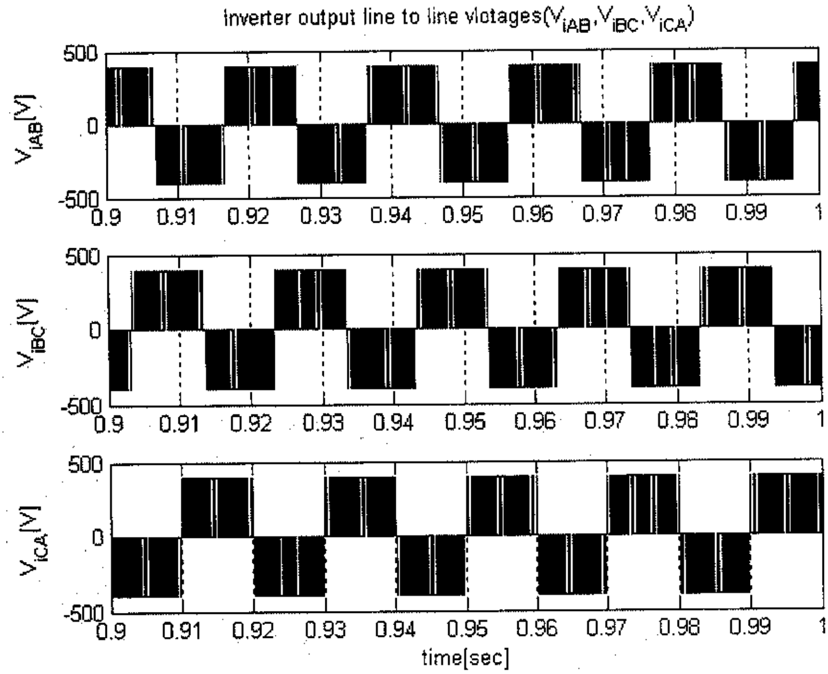

Figure3.13 Inverter output line to line voltage

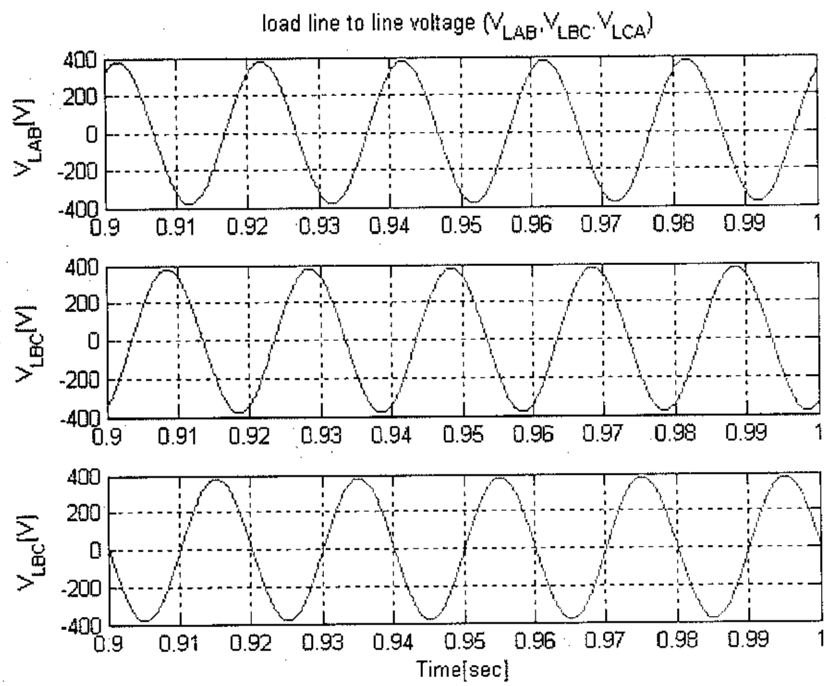

Figure3.14 load line to line voltage

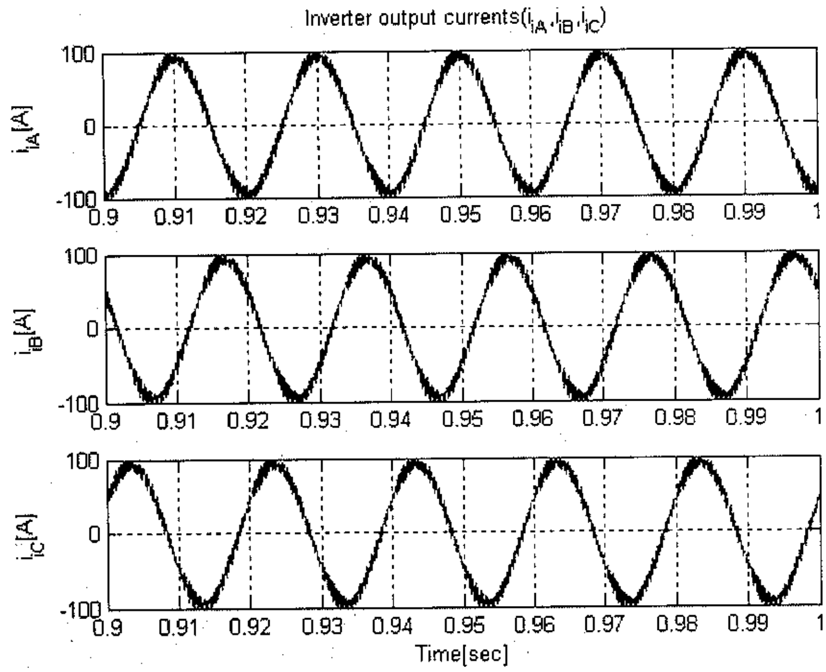

Figure3.15 inverter output currents

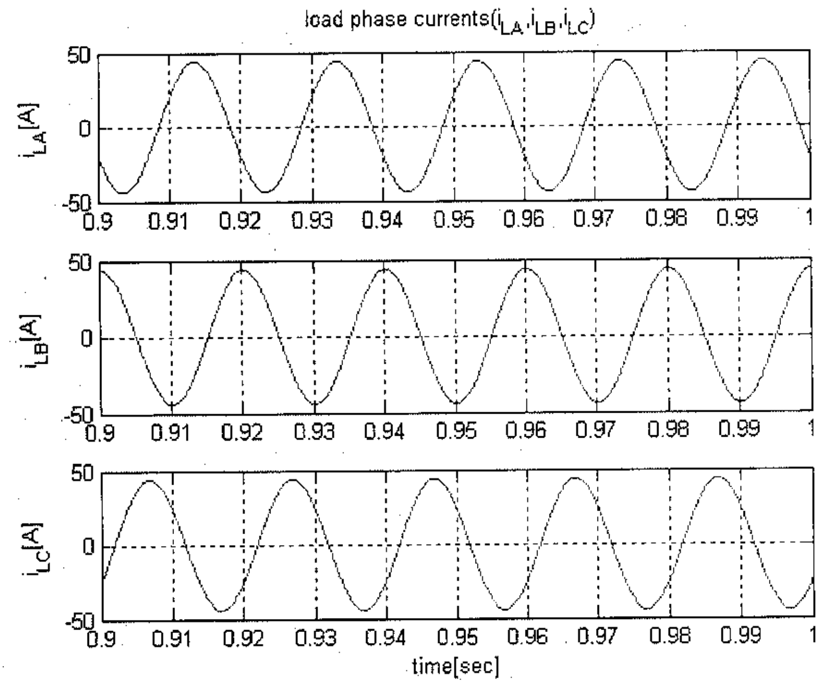

Figure3.16 load phase currents

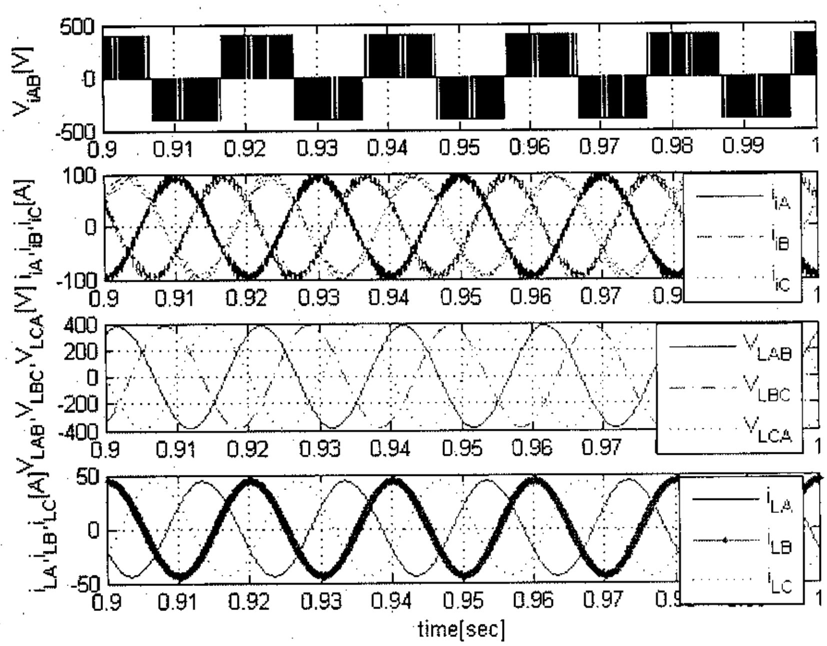

Figure3.16 complete wave forms of inverter

3.10 Initialization of parameters for Induction Motor

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```
%initalization
Rr=0.816;    %rotor resistance
Rs=0.435;      %stator resistance
Lls=0.002; %rotor resistamce
Llr=0.002; % rotor inductamce
Lm=0.0693;     %maganetizing inductance
fb=50;      %base frequency
p=4;          %number of poles
J=.089;     %moment of inertia
Lr=Llr+Lm;
Tr=Lr/Rr;

% impendence and angular speed cakculations
Wb=2*pi*fb;     %base speed
Xls=Wb*Lls;     %stator impedence
Xlr=Wb*Llr;     %rotor impedence
Xm=Wb*Lm;      %Magenetizing impedence
Xmstar=1/Xls+1/Xm+1/Xlr;
Tl=10;
```

Figure 3.18 Initialization of parameters for Induction motor

3.11 Simulation results of vector controlled induction motor

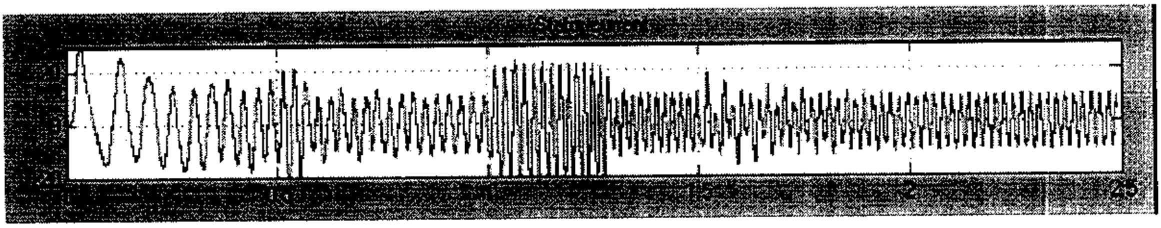

Figure 3.18 stator current in Amps Versus time in sec

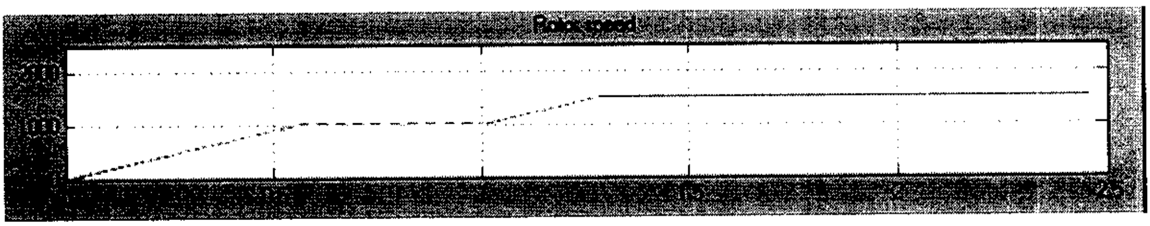

Figure3.19 Rotor speed in RPM Versus time in sec

CHAPTER 4

Hardware control logic

4.1 Introduction to PWM Technique

In many industrial applications, it is often required to control the output voltage of the inverters to in order to control the speed of the induction motor. This can be achieved with various modulation techniques. The inverter gain is governed by these modulation techniques. The different types of modulation techniques are single pulse width modulation, multi pulse width modulation and sinusoidal pulse width modulation. The harmonic content can be reduced with the help of multi pulse width modulation as well as space vector pulse width modulation. The SVPWM gives very low distortion in the output current and voltage compared width multi pulse width modulation. It effectively utilizes the input dc voltage and reduces the harmonic content.

4.2 Introduction to Microcontrollers

Microcontrollers are destined to play an increasingly important role in revolutionizing various industries and influencing our day to day life more strongly than one can imagine. Since its emergence in the early 1980's the microcontroller has been recognized as a general purpose building block for intelligent digital systems. It is finding using diverse area, starting from simple children's toys to highly complex spacecraft. Because of its versatility and many advantages, the application domain has spread in all conceivable directions, making it ubiquitous. As a consequence, it has generate a great deal of interest and enthusiasm among students, teachers and practicing engineers, creating an acute education need for imparting the knowledge of microcontroller based system design and development. It identifies the vital features responsible for their tremendous impact; the acute educational need created by them and provides a glimpse of the major application area.

A microcontroller is a complete microprocessor system built on a single IC. Microcontrollers were developed to meet a need for microprocessors to be put into low cost products. Building a complete microprocessor system on a single chip substantially reduces the cost of building simple products, which use the microprocessor's power to implement their function, because the microprocessor is a natural way to implement many products. This means the idea of using a microprocessor for low cost products comes up often. But the typical 8-bit microprocessor based system, such as one using a Z80 and 8085 is expensive. Both 8085 and Z80 system need some additional circuits to make a microprocessor system. Each part carries costs of money. Even though a product design may requires only very simple system, the parts needed to make this system as a low cost product.

To solve this problem microprocessor system is implemented with a single chip microcontroller. This could be called microcomputer, as all the major parts are in the IC. Most frequently they are called microcontroller because they are used they are used to perform control functions.

The microcontroller contains full implementation of a standard MICROPROCESSOR, ROM, RAM, I/0, CLOCK, TIMERS, and also SERIAL PORTS. Microcontroller also called "system on a chip" or "single chip microprocessor system" or "computer on a chip".

A microcontroller is a Computer-On-A-Chip, or, if you prefer, a single-chip computer. Micro suggests that the device is small, and controller tells you that the device' might be used to control objects, processes, or events. Another term to describe a microcontroller is embedded controller, because the microcontroller and its support circuits are often built into, or embedded in, the devices they control.

Today microcontrollers are very commonly used in wide variety of intelligent products. For example most personal computers keyboards and implemented with a microcontroller. It replaces Scanning, Debounce, Matrix Decoding, and Serial transmission circuits. Many low cost products, such as Toys, Electric Drills, Microwave Ovens, VCR and a host of other consumer and industrial products are based on microcontrollers.

4.3 PIC 16F877A Microcontroller:

a) High-Performance RISC CPU:

- Only 35 single-word instructions to learn
- All the single instructions except for program branches, which are two cycles
- Operating speed: dc-20 Mhz clock input dc-200 ns Instruction cycle
- Pinout compatible to other 28 pin or 40/44 pin pic16cxxx and pic16fxxx
- Up to 8k x 14 words of flash program memory , up to 368 x 8 bytes of data memory , Up to 256 x 8 bytes of EEPROM data memory

b) Peripheral Features:

- Timer0: 8-bit timer/counter with 8-bit prescaler
- Timer1: 16-bit timer/counter with prescaler, can be incremented during Sleep via external crystal/clock
- Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler
- Two Capture, Compare, PWM modules
- -Capture is 16-bit, max. resolution is 12.5 ns
- -Compare is 16-bit, max. resolution is 200 ns
- -PWM max. resolution is 10-bit
- Synchronous Serial Port (SSP) with SPI™ (Master mode) and I2C™ (Master/Slave)
- Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) with 9-bit address detection
- Parallel Slave Port (PSP) – 8 bits wide with external RD, WR and CS controls (40/44-pin only), Brown-out detection circuitry for Brown-out Reset (BOR)

c) Analog to Digital converter:

The Analog to Digital Converter (A/D) module has five inputs for the 28-pin devices and eight for the 40/44-pin devices. The conversion of an analog input signal results in a corresponding 10-bit digital number. The A/D module has high and low-voltage reference input that is soft-ware selectable to some combination of VDD, VSS, RA2 or RA3.

The A/D converter has a unique feature of being able to operate while the device is in sleep mode. To operate in sleep, the A/D clock must be derived from the A/Ds internal RC oscillator.

4.4 Introduction to Power supply unit

The present chapter introduces the operation of power supply circuits built using filters, rectifiers, and then voltage regulators. Starting with an ac voltage, a steady dc voltage is obtained by rectifying the ac voltage, then filtering to a dc level, and finally, regulating to obtain a desired fixed dc voltage. The regulation is usually obtained from an IC voltage regulator unit, which takes a dc voltage and provides a somewhat lower dc voltage, which remains the same even if the input dc voltage varies, or the output load connected to the dc voltage changes.

A block diagram containing the parts of a typical power supply and the voltage at various points in the unit is shown in fig 4.1. The ac voltage, typically 120 V rms, is connected to a transformer, which steps that ac voltage down to the level for the desired dc output. A diode rectifier then provides a full-wave rectified voltage that is initially filtered by a simple capacitor filter to produce a dc voltage. This resulting dc voltage usually has some ripple or ac voltage variation. A regulator circuit can use this dc input to provide a dc voltage that not only has much less ripple voltage but also remains the same dc value even if the input dc voltage varies somewhat, or the load connected to the output dc voltage changes. This voltage regulation is usually obtained using one of a number of popular voltage regulator IC units.

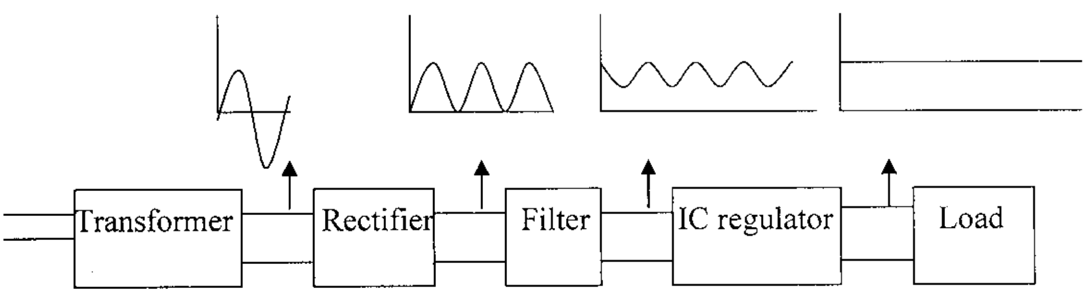

Figure 4.1 Block diagram of power supply unit

4.4.1 IC Voltage Regulators

Voltage regulators comprise a class of widely used ICs. Regulator IC units contain the circuitry for reference source, comparator amplifier, control device, and overload protection all in a single IC. Although the internal construction of the IC is somewhat different from that described for discrete voltage regulator circuits, the external operation is much the same. IC units provide regulation of either a fixed positive voltage, a fixed negative voltage, or an adjustably set voltage.

A power supply can be built using a transformer connected to the ac supply line to step the ac voltage to a desired amplitude, then rectifying that ac voltage, filtering with a capacitor and RC filter, if desired, and finally regulating the dc voltage using an IC regulator. The regulators can be selected for operation with load currents from hundreds of milli amperes to tens of amperes, corresponding to power ratings from milliwatts to tens of watts.

Fig4.2 shows the basic connection of a three-terminal voltage regulator IC to a load. The fixed voltage regulator has an unregulated dc input voltage, Vi, applied to one input terminal, a regulated output dc voltage, Vo, from a second terminal, with the third terminal connected to ground. For a selected regulator, IC device specifications list a voltage range over which the input voltage can vary to maintain a regulated output voltage over a range of load current. The specifications also list the amount of output voltage change resulting from a change in load current (load regulation) or in input voltage (line regulation).

Fixed Positive Voltage Regulators:

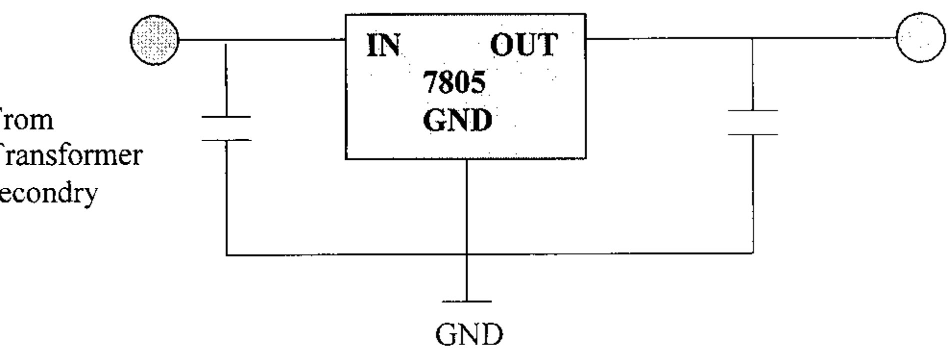

Figure4.2 Three terminal voltage regulator IC

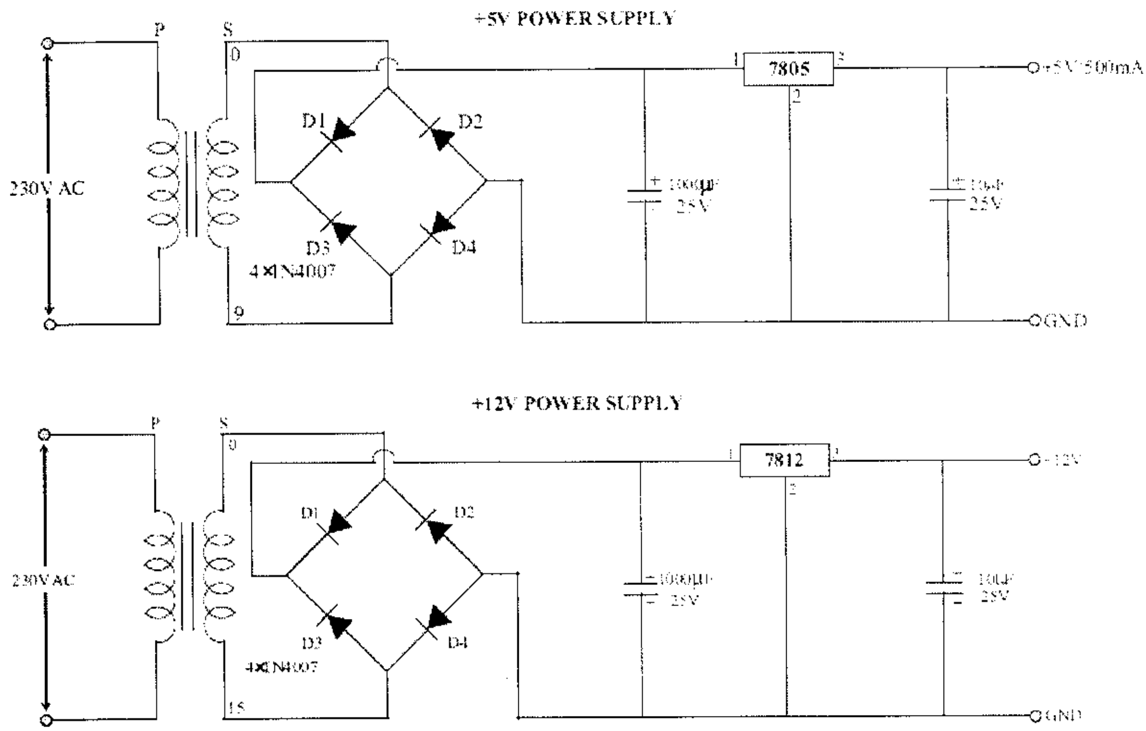

Figure4.3 power supply circuit Diagram

The series 78 regulators provide fixed regulated voltages from 5 to 24 V. Figure 4.3 shows how one such IC, a 7812, is connected to provide voltage regulation with output from this unit of +12V dc. An unregulated input voltage Vi is filtered by capacitor C1 and connected to the IC's IN terminal. The IC's OUT terminal provides a regulated + 12V which is filtered by capacitor C2 (mostly for any high-frequency noise). The third IC terminal is connected to ground (GND). While the input voltage may vary over some permissible voltage range, and the output load may vary over some acceptable range, the output voltage remains constant within specified voltage variation limits. These limitations are spelled out in the manufacturer's specification sheets. A table of positive voltage regulated ICs is provided in table 3.

IC Part p	Output Voltage (V)	Minimum Vi (V)
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

TABLE 3. Positive Voltage Regulators in 7800 series

4.5 PWM generation

The figure 4.4 source the overall circuit diagram for PWM generator. The power supply unit is connected with a VCC pins (Pin No. 11and 32 and with ground pins, (pin no: 12 and 31) . A crystal oscillator of 12 MHz clock is connected to pin no.13 and 14 of micro controller to provide clock signal .Pin No.18 and 23 are the port c output pins used to deliver the switching timings to the driver transistors. The timing signals are generated through the inbuilt program loaded inside the controller. Depending upon the frequency set through the keypad interface timing signals are generated.

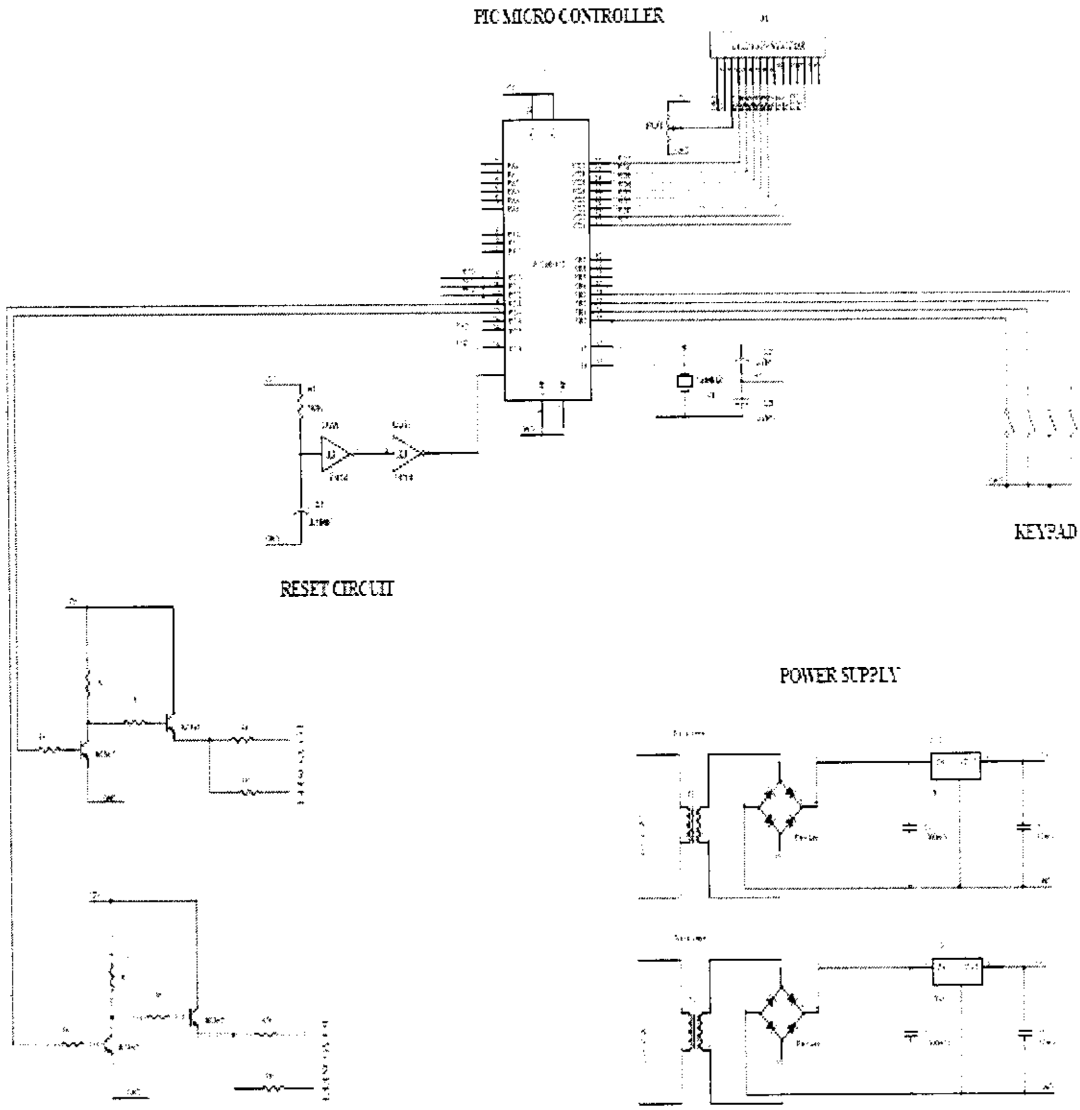

Figure 4.4 Overall circuit Diagram of PWM generator

4.6 HARDWARE SETUP

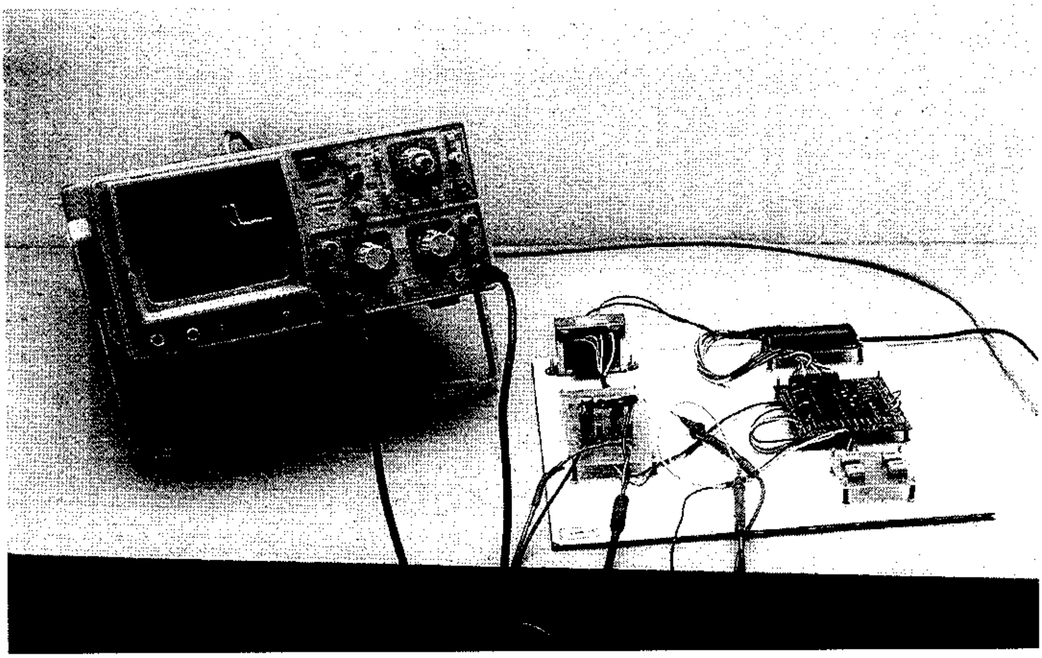

Figure 4.5 Control logic for PWM Generator

4.7 HARDWARE RESULTS

The speed of induction motor can be controlled by varying the supply frequency and voltage.

The PWM pulses for different frequency values has been generated and shown in figures 4.6 to 4.8

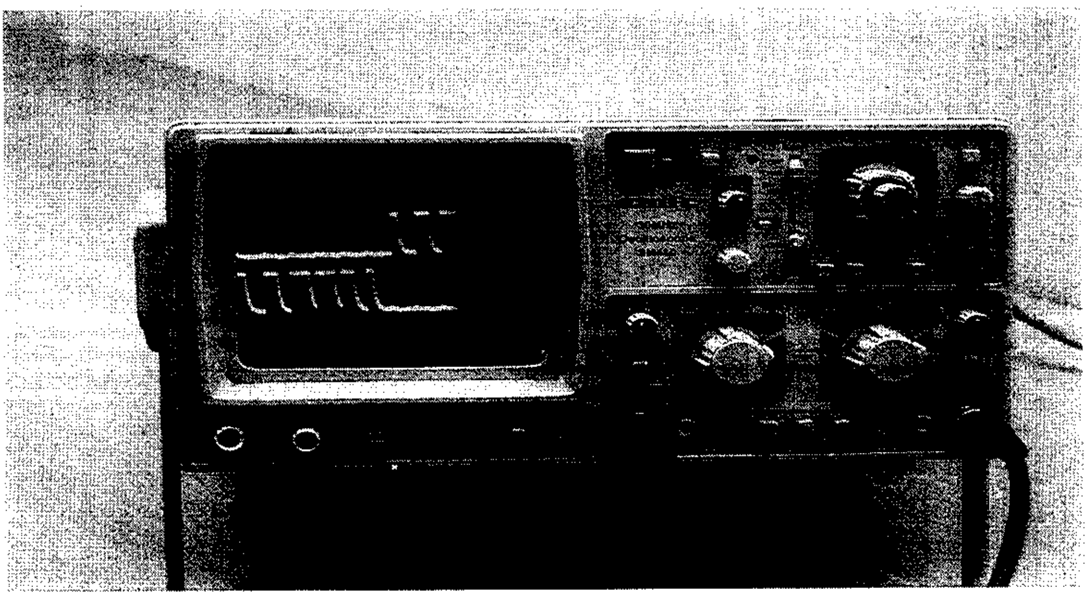

Figure 4.6 Frequency at 50 Hz

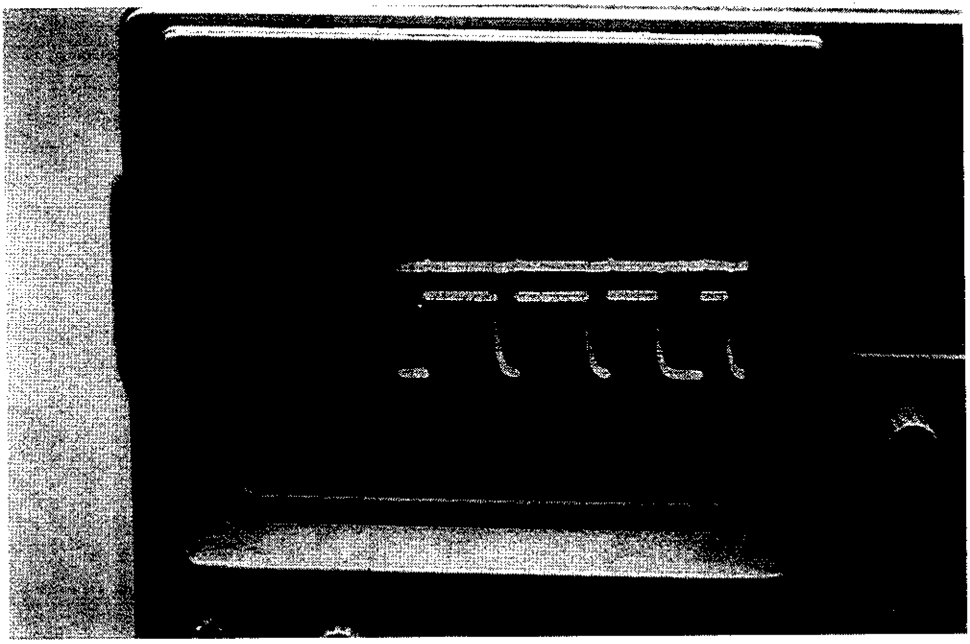

Figure 4.7 Frequency at 13 Hz

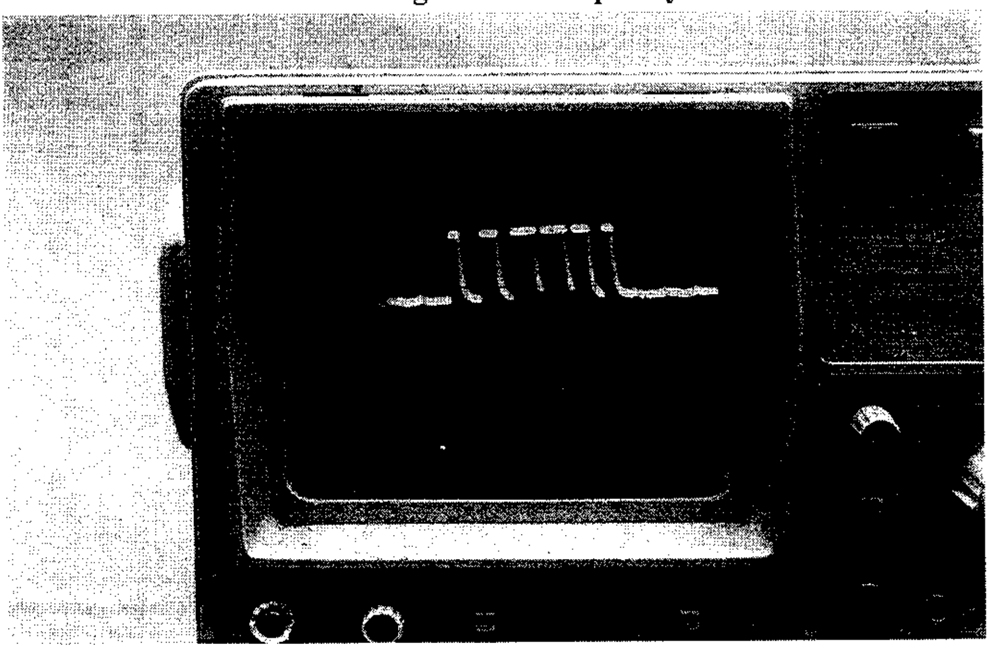

Figure 4.8 Frequency at 30 Hz

CHAPTER 5

CONCLUSION

5.1 Conclusion

In this project, implementation of a simulink model for induction motor has been done and the simulation study has been performed. Unlike other induction machine model implementations, with this model, the user can access to all the internal variables for future design and development. The space vector PWM inverter has been used as the voltage source for the induction motor since it has the advantage of giving very low distorted sine output. It enhanced the dynamic operation of induction motor drive.

The control logic has been implemented in hardware to generate PWM pulses.

5.2 Future Scope

The three phase vector control operation involves intensive math calculations which can be implemented with the help of Digital Signal Processor to enhance the desire closed loop operation.

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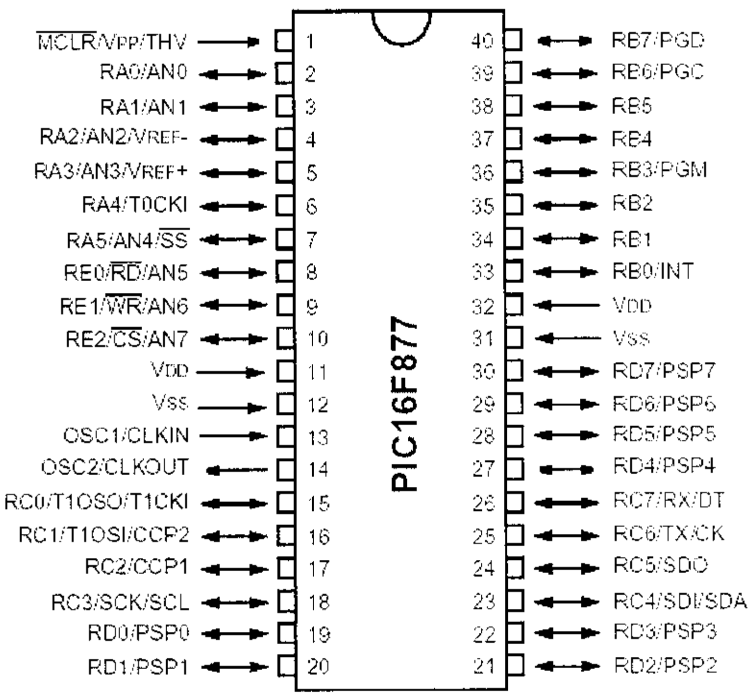
[8] www.microchip.com

APPENDICES

APPENDIX: A
PIN DIAGRAM OF PIC 16F877

PIC16F873A/876A devices are available only in 28-pin packages, while PIC16F874A/877A devices are avail- able in 40-pin and 44-pin packages. All devices in the PIC16F87XA family share common architecture with the following differences:

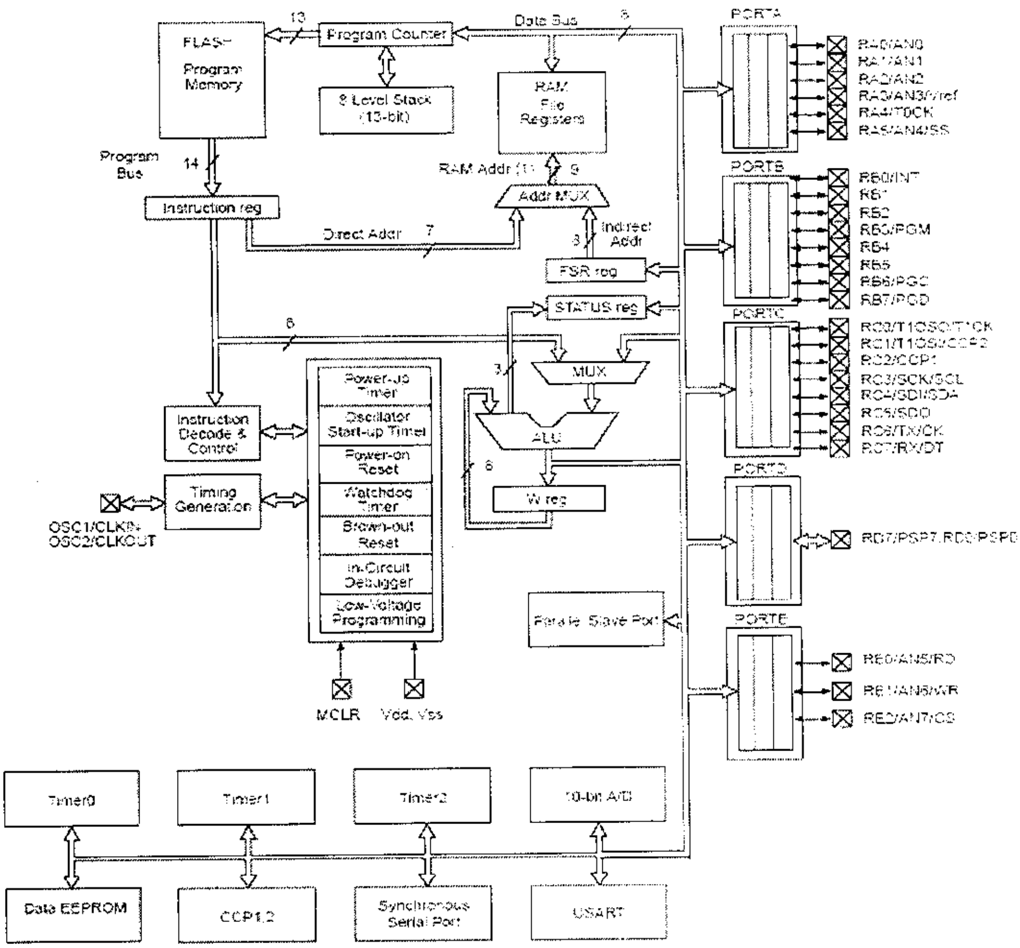
- The PIC16F873A and PIC16F874A have one-half of the total on-chip memory of the PIC16F876A and PIC16F877A
- The 28-pin devices have three I/O ports, while the 40/44-pin devices have five
- The 28-pin devices have fourteen interrupts, while the 40/44-pin devices have fifteen
- The 28-pin devices have five A/D input channels, while the 40/44-pin devices have eight
- The Parallel Slave Port is implemented only on the 40/44-pin devices



APPENDIX: B

ARCHITECTURE OF PIC 16F877

The complete architecture of PIC 16F877 is shown in the fig 2.1. Table 2.1 gives details about the specifications of PIC 16F877. Fig 2.2 shows the complete pin diagram of the IC PIC 16F877.



Note 1: Higher order bits are from the STATUS register.

APPENDIX :C

LM7805/ LM7812

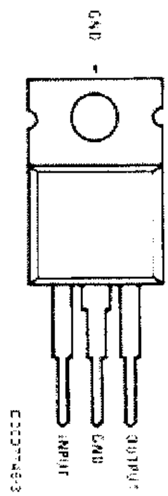
The LM78XX series of three terminal regulators is available with several fixed output voltages making them useful in a wide range of applications. One of these is local on cardregulation, eliminating the distribution problems associated with single point regulation. The voltages available allow these regulators to be used in logic systems, instrumentation, HiFi, and other solid state electronic equipment. Althoughdesigned primarily as fixed voltage regulators these devices can be used with external components to obtain adjustable voltages and currents.

Voltage Range

LM7805C 5V

LM7812C 12V

LM7815C 15V



APPENDIX :D
Electrical Charecterstics of LM7805/LM7812

Output Voltage			5V			12V			15V			Units
Input Voltage (unless otherwise noted)			10V			19V			23V			
Symbol	Parameter	Conditions	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
	Short-Circuit Current	Tj = 25°C		2.1			1.5			1.2		A
	Peak Output Current	Tj = 25°C		2.4			2.4			2.4		A
	Average TC of V_{OUT}	0°C ≤ Tj ≤ +125°C, I_O = 5 mA		0.6			1.5			1.8		mV/°C
V_{IN}	Input Voltage Required to Maintain Line Regulation	Tj = 25°C, I_O ≤ 1A		7.5		14.6			17.7			V

APPENDIX :E

HARDWARE CODING

```
#include <pic.h>
#include <lcd.h>

static bit r1 @((unsigned) &PORTC*8+0);
static bit r2 @((unsigned) &PORTC*8+1);
static bit p1 @((unsigned) &PORTC*8+2);
static bit p2 @((unsigned) &PORTC*8+3);

void main()
{
        TRISC=0X0C;
        r1=r2=1;
        lcd_init();
        command(0x80);
        lcd_dis("Relay controlled",16);
        command(0xc0);
        lcd_dis("    by wheel    ",16);
        del();
        while(1)
        {
                command(0xcf);
                write('0');
                while(!p1 || p2);        //01
                r1=0;
                while(p1 && !p2);

                command(0xcf);
```

```
            write('1');
            while(!p1 || !p2);        //00
            r1=1;
            while(p1 && p2);

            command(0xcf);
            write('2');
            while(p1 || p2);          //11
            while(!p1 && !p2);

            command(0xcf);
            write('3');
            while(p1 || p2);          //11
            r2=0;
            while(!p1 && !p2);

            command(0xcf);
            write('4');
            while(!p1 || p2);         //01
            r2=1;
            while(p1 && !p2);

      }
}
```