Induction Motor Drive for Smart Electric Vehicles

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Declaration

I declare that the work contained in this thesis is my own, except where explicitly stated otherwise. In addition this work has not been submitted to obtain another degree or professional qualification.

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Dedicated to our Teachers, Parents and Friends...

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Abbreviations

DC	**D**irect **C**urrent
AC	**A**lternating **C**urrent
IM	**I**nduction **M**otor
ACIM	**A**lternating **C**urrent **I**nduction **M**otor
SPWM	**S**inosoidal **P**ulse **W**idth **M**odulation
IGBT	**I**nsulated **G**ate **B**ipolar **T**ransistor

List of Symbols

Rr	Rotor Resistance
Rs	Stator Resistance
T	Electromechanical Torque
T_r	Rotor Time Constant
ω_r	Angular Rotor Speed
ω_e	Angular Synchronous Speed
θ_r	Rotor Angle
θ_s	Stator Angle
ψ_d	D-axis flux linkage
ψ_q	Q-axis flux linkage
iar	Phase Rotor Current
ibr	Phase Rotor Current
icr	Phase Rotor Current
ias	Phase Stator Current
ibs	Phase Stator Current
ics	Phase Stator Current
V_{ar}	Rotor Voltage
V_{br}	Rotor Voltage Phase
V_{cr}	Rotor Voltage Phase
V_{as}	Stator Voltage Phase A
V_{bs}	Stator Voltage Phase B
V_{cs}	Stator Voltage Phase C
L_{ls}	Leakage Inductance of Stator
L_{lr}	Leakage Inductance of Rotor
L_m	Main Magnetizing Inductance

ids	D-axis Stator Current in Synchronous Frame
iqs	Q-axis Stator Current in Synchronous Frame
$i_{\alpha s}$	α-axis Stator Current in Stationary Frame
$i_{\beta s}$	β-axis Stator Current in Stationary Frame
V_{ds}	D-axis Stator Voltage in Synchronous Frame
V_{qs}	Q-axis Stator Voltage in Synchronous Frame
$V_{\alpha s}$	Q-axis Stator Voltage in Stationary Frame
$V_{\beta s}$	Stator Voltage in Stationary Frame
L_{ms}	Magnetizing Inductance of Stator
L_{msr}	Mutual Inductance of Stator and Rotor
$\psi_{\alpha s}$	α -axis Stator Flux in Stationary Frame
$\psi_{\beta s}$	β -axis Stator Flux in Stationary Frame
ψ_{ds}	D-axis Flux Linkage in Synchronous Frame
ψ_{qs}	Q-axis Flux Linkage in Synchronous Frame
ψ_e	Angle between Synchronous Frame and Stationary Frame

Abstract

The new revolutionary age is demanding more and more vehicles that are both user and environment-friendly. Smart Electric Vehicles draw massive attention to the public. It is efficient in energy and lower carbon component tool. An induction motor operates inside these vehicles and takes care of the speed and torque. Induction motor drive provides these vehicles the best optimum speed and torque to balance themselves with the utilization of minimum power in minimum time. In this project, we will apply Vector Control techniques to get the best efficient results. The motor current fed to the Field Oriented Control to generate correction voltages after comparing actual and desired values. The Space Vector Pulse Width Modulation (SVPWM) converts the correction voltages to three-phase inverter gate signals. This three-phase inverter drives the motor. This whole system works in a closed-loop and maintains the output at the desired value.

Chapter 1

Introduction

In this chapter, the introduction of the thesis will be explained in detail that consists of research background, focus of the study, problem statements, research objectives, scope and outlines.

1.1 Problem Statement

This project is about controlling the speed and torque of the induction motor to provide an automatic control to a smooth ride to the electric vehicle. The system will work in a close loop to readjust itself quickly by using a micro-controller to provide the system with the best possible choice of speed to retain or readjust itself. We will be using SVPWM instead of SPWM technique because it is superior in advanced technology.

1.2 Theoretical Background

1.2.1 Electric Motors

An electric motor is a machine that converts electrical energy to mechanical energy. Electric Motors are of two different categories based on the current input. Smart Electric Vehicles can use DC motor drives, but they have significant disadvantages with the usage of commutators and brushes, which add maintenance requirements and costs. And the drawback is spark production from old brushes, which can even lead to an explosion. So, the AC motors selected; are considered to be more powerful for generating higher currents, achieving high torque, and can give variable voltages easily. Now there are two types of motors: asynchronous motors and synchronous motors. AC Asynchronous induction Motors with different poles have been dominating in industry.

Single-phase induction motor does not have a self-starting torque, the efficiency of the motor is low due to high starting current, attaining speed control is challenging. So, a three-phase induction motor is better to use in Electric Vehicles. We will be working on a 750W squirrel cage induction motor for our thesis. Squirrel Cage induction motors are used up to 70% in industries. We will be working on a 750W squirrel cage induction motor for the project in which we will apply a vector control technique to control the torque and speed of the induction motor. The induction motor has a limitation in that it has a complex mathematical model and is non-linear in a highly saturated region. So, an AC drive should be so accurate that it can rapidly control the variations in the load and disturbance. Nowadays, these drives are so demanding to have excellent control over IM.

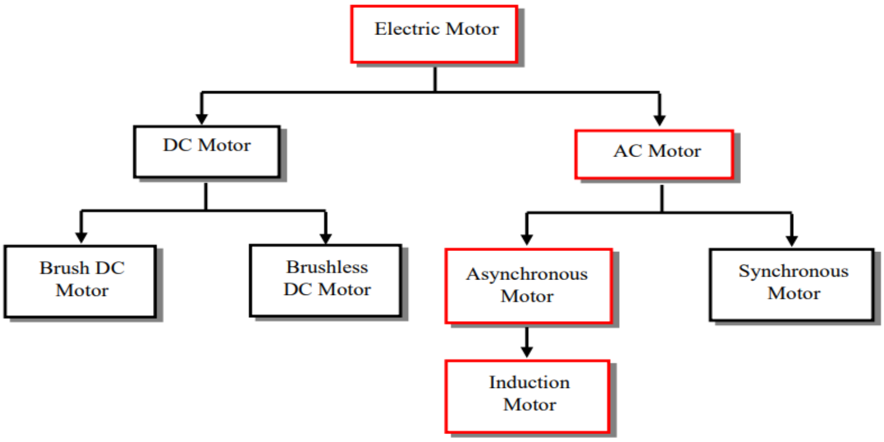

FIGURE 1.1: Types of Motors

1.2.2 Control Methods

Now, the control methods of an induction motor can be divided into two types of techniques, i.e. Scalar Control and Vector Control.

1.2.2.1 Scalar method

Scalar control for a VFD control is implemented by enhancing the motor flux and making a constant magnetic field, which produces a constant torque production. It is also called as V/Hz or V/f control. Scalar control methods vary both the voltage and frequency of power to the motor to maintain a constant V/f ratio and the magnetic field will be constant whatever the motor speed is.

1.2.2.2 Vector control

is also known as field-oriented control (FOC). It controls the speed or torque of an AC motor by controlling the stator current space vectors. Field-oriented control is a bit more complex mathematics to transform a three-phase system that depends on time and speed to a two-phase (d and q) time-invariant system.

The stator current in an AC motor consists of two components: a magnetizing component (d) of the current and a torque-producing component (q). With FOC, these components behave independently (each with its PI controller). It produces the torque-producing component q, orthogonal to the rotor flux for maximum torque production, and therefore, optimum speed control.

The vector control method is more complex than the scalar control method, but it has some benefits over scalar methods in some applications. For example, open-loop vector control enables the motor to produce high torque at low speeds, and closed-loop vector control allows a motor to produce up to 200 percent of its rated torque at zero speed, useful for holding loads at standstill. Closed-loop vector control also provides very accurate torque and speed control for industrial applications.

Advantages of Field-Oriented Control

The advantages of Field-Oriented Control over scalar control are given below;

1. Decoupled torque and flux control
2. Four quadrant operation
3. Lower power consumption
4. Better torque response
5. Better dynamic response
6. Torque control at low frequencies and low speed.
7. Lower cost and size of motor

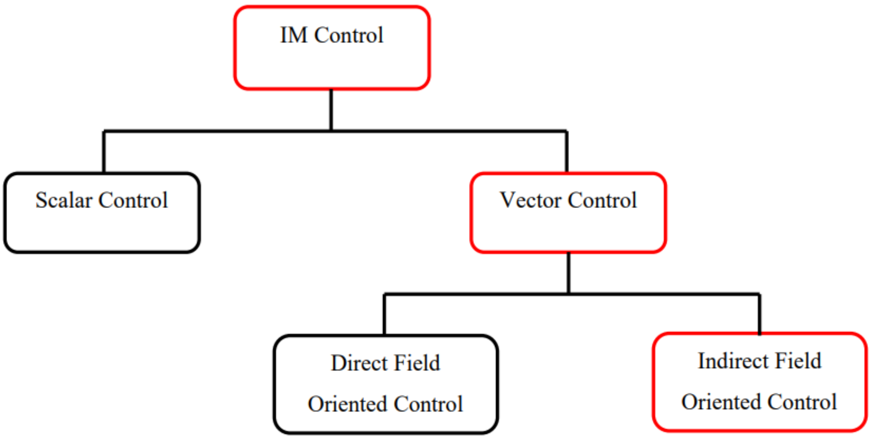

FIGURE 1.2: classification of IM control methods

Direct Field-Oriented Control

In direct FOC the rotor angle or control vector is calculated by the terminal voltages currents directly by using flux estimators. The direct method is the most the desirable control scheme, but it consumes high cost and the flux measurement is unreliable. The major shortcoming of this the approach relies upon the accuracy of the control gains which, depend heavily on the motor parameters assumed in the feed-forward control algorithm.

Indirect Field-Oriented Control

Indirect Field Oriented Control (IFOC) can generate high performance in induction Motor (IM) drives by decoupling rotor flux and torque-producing stator current components. In IFOC, the angle is determined by the rotor position measurement and machine parameter estimation.

Advantages of Indirect Field-Oriented Control

The advantages of Indirect Field-Oriented Control over Direct Field-Oriented Control are given below;

1. Flux Sensors are eliminated
2. dynamic performance of IFOC is better than DFOC
3. Cost is reduced
4. There is no drift problem as in direct vector control

Chapter 2

Literature Review

Throughout history, scientists worked to make the best efficient thing. One of the main hard work in the domain of electric transport Vehicles is to get stability in Electric cars as these are efficient and eco-friendly.[1] The idea of electrical energy use for transport purposes has arisen in 1834 when American scientists fed a small wagon an electric motor. [2] The electric cars were not fully implemented and one of the main reasons was 1. heavy batteries which occupy greater volume and were heavy. The battery voltages are Direct-Current and Current is inverted into a switch-mode signal through a power electronic inverter to drive the motor.[3] 2. These low-rated batteries were also less efficient and highly rated. And specifically in Europe and in some parts of Asia, the commutator motors were used which was not so efficient due to wear and tear and power losses. Now, in recent times, this problem is to overcome by introducing new types of commutator-less motors (a-synchronous or induction and synchronous). The main advantages of using the induction motor in electric cars were maximum simplified construction without commutator;

1. the proportion power/volume is about 1.5 times better than DC motors one
2. rated performance torque-speed characteristics are comparatively steady and thus allow self-protection against slippage without special measures
3. maximum simplified construction without commutator
4. the proportion power/volume is about 1.5 times better than DC motors one
5. rated performance torque-speed characteristics are comparatively steady and thus allow self-protection against slippage without special measures

Simplified construction without a commutator, More power than other Dc batteries Torque speed characteristics were steady and provide better protection.[4] But the problem faced after making these induction drives, we needed something to operate this. So for that, we required converters to make it functional, So first we have to convert our Dc supplies to Ac by using Inverters.[6] In recent times, these converters and inverters are made by using semi-conductors and can be fit in small size as compared to generators. The main advantage of the Induction motor driver over Dc batteries was good maintenance and reliability. Different techniques are supposed to be applied to these induction motors for perfect working. One of these techniques were invented as

1. Scalar Control method
2. Vector Control method

As time passed, the scientist went toward the vector control method from the scalar control method as it was more efficient. In the beginning, the scientist used the Scalar method Voltzhertz method. The other method is the vector control method which includes

1. Field Oriented Control
2. Direct Torque control
3. Model Predictive control

But in recent times, other efficient techniques like SVPWM techniques and other techniques like Fuzzy Logic were implemented. For this technique, scientists used different micro-controllers through which these techniques were implemented. A three-phase inverter will control all the variables of motor drive and adjusting it to the best possible value, will compute the variable. This three-phase inverter will be controlled by a micro controller. There has been a bit of research considering that different Electric vehicle users have their tolerance of Ëarange anxiety which means that drivers will not charge their batteries until the batteries are running out. So, the Stochastic range anxiety of Electric vehicle drivers will affect the charging station location scheme because people will react differently when they arrive at a charging station. The most often exploited drive system is the induction motor supplied from the inverter therefore strategy of its control has a direct influence on reliability. Control techniques exploited in traction drives are field-oriented control and direct torque control. We will be considering Field oriented control of vector control technique more as its results are more desirable than scalar control. We can use STM or FPGA for this purpose, this helps to produce required gating signals. In this project, we use the SVPWM technique by using PID.

Chapter 3

Methodology

In this project, a control technique was implemented to control the speed and torque of the induction motor. We have used Vector Control over our drive. A three-phase inverter is implemented on Space Vector Pulse Width Modulation. Space Vector Pulse Width Modulation generates less Total Harmonic Distortion (THD) and has higher output quality. It provides flexible control of output voltage and output frequency. Field Oriented Vector Control Technique which makes two independents; The flux-producing current and the torque producing current, helps to achieve tighter speed control, higher starting torque, and higher low-speed torque. Feedback through the PI controller is given to the system which is used to minimize the error. The whole process is mentioned below;

1. Stator phase currents are measured.
2. Current is converted to $\alpha\beta$ coordinate system. Rotor position is derived by integrating the speed through a speed measurement sensor.
3. Rotor flux linkage vector is estimated by multiplying the stator current vector with magnetizing inductance Lm and low-pass filtering the result with the rotor no-load time constant Lr/Rr.
4. Current vector is converted to DQ coordinate system.
5. d-axis component of the stator current vector is used to control the rotor flux linkage and the q-axis component is used to control the motor torque. PI controllers are used to controlling these currents.
6. PI controllers provide DQ correction component voltage.
7. Voltage components are transformed from (d,q) coordinate system to coordinate system.
8. $\alpha\beta$ voltage components are fed in Space Vector PWM (SVPWM) modulator, for signaling to the power inverter.

Chapter 4

System Architecture

Our System is made of components including an inverter, a booster, gate drivers, micro-controller, Squirrel cage Induction motor, Filters, Power Supplies, etc. Our main concern is our drive system which is based on Field oriented Vector Control, the details are given below in the block diagram.

4.1 Block Diagram

Another frequent, modern method of controlling three-phase input motors and compatible permanent magnet motors (aka BLAC or PMAC motors) is a field-based control, which independently controls the magnetic field output and the current stator torque. It allows the torque-producing component to be orthogonal to the rotor flux, producing maximum torque.

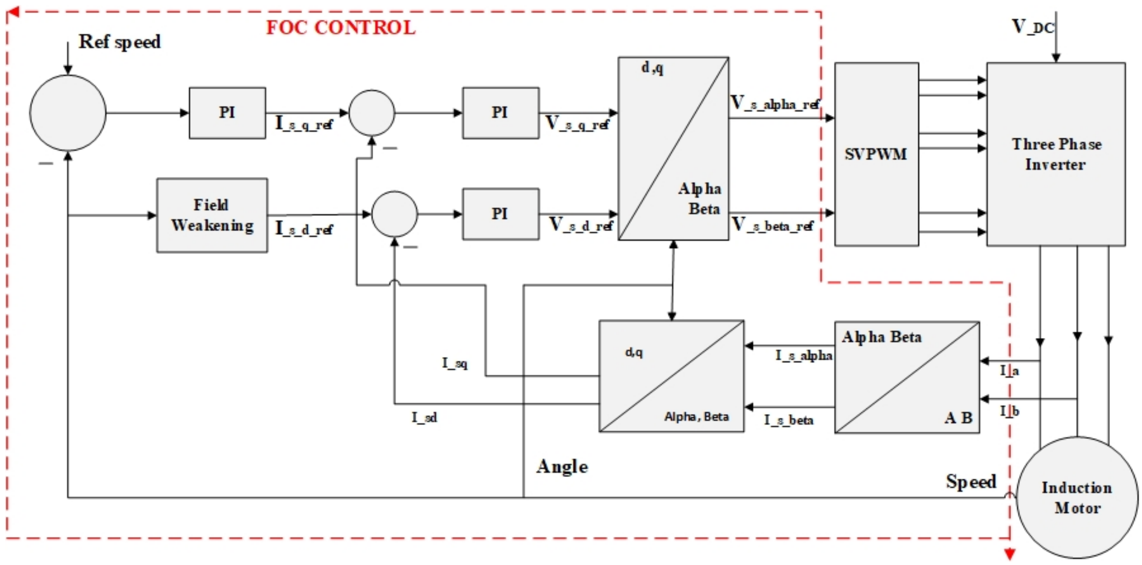

Figure 4.1: FOC Control Block Diagram in System

Space vector pulse width modulation (SVPWM) is a method used in the last step of field control (FOC) to determine pulse-wide modulated signals for the inverter switch to produce the required 3-phase voltages in the vehicle.

The following is a summary of how FOC with SVPWM works:

1. Measure two of the three currents of the car section and supply it to the Clarke transform to convert it from a three-phase system (ia, ib, ic) to a two-dimensional system (icy, i β). Note that it is not necessary to measure all three currents, because the sum of these three must be equal to the unit (0). Therefore the third current must be a negative sum of the first two.

2. Use Park transformer to convert a two-axis suspension system (iα, iβ) into a rotating two-axis system (iq, id), where the current id axis aligned with the rotor flux and the current d axis (the part that produces the torque) orthogonal in rotor flux.

3. The stator flux current and torque are controlled independently, usually by PI controllers. The parameters to be used in the vehicle, Vd and Vq, are determined by the PI directors.

4. Next, the inverse Park transform transforms a two-axis rotating system (Vsqref, Vsdref) back into a two-axis positioning system (Vscref, Vs .ref). These are the components of the stator voltage vector and are the input components of SVPWM, which generate 3-phase output power from the vehicle. (Note that the use of SVPWM eliminates the need for inverse Clarke transform to obtain three-phase voltages.)

5. Feedback provides minimum error and improves the performance of an encoder or tachometer used to measure the speed of the Induction motor.

System based on its phases and frames of references along with the wave-forms demonstrated in the figure shown below;

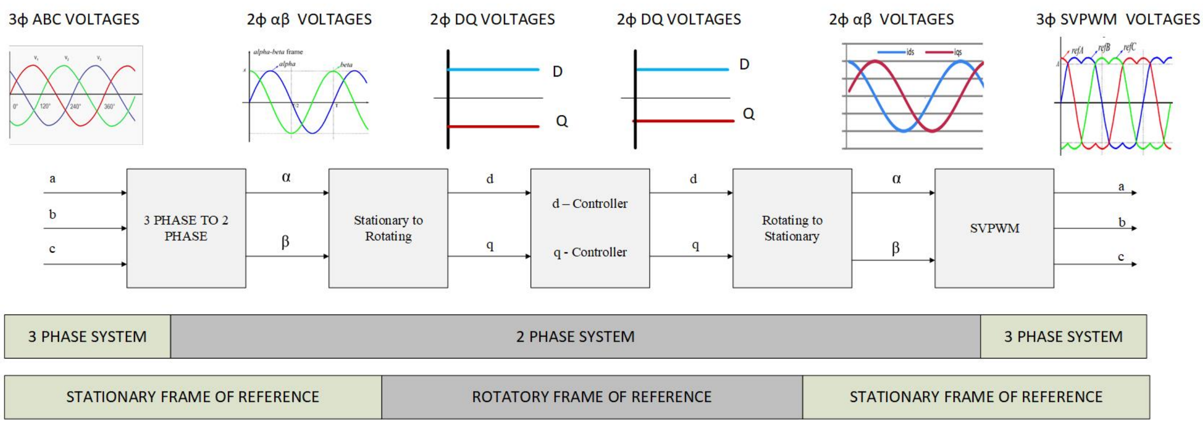

FIGURE 4.2: Stationary and Rotatory Frame of reference in FOC Control

4.2 Flow Diagram

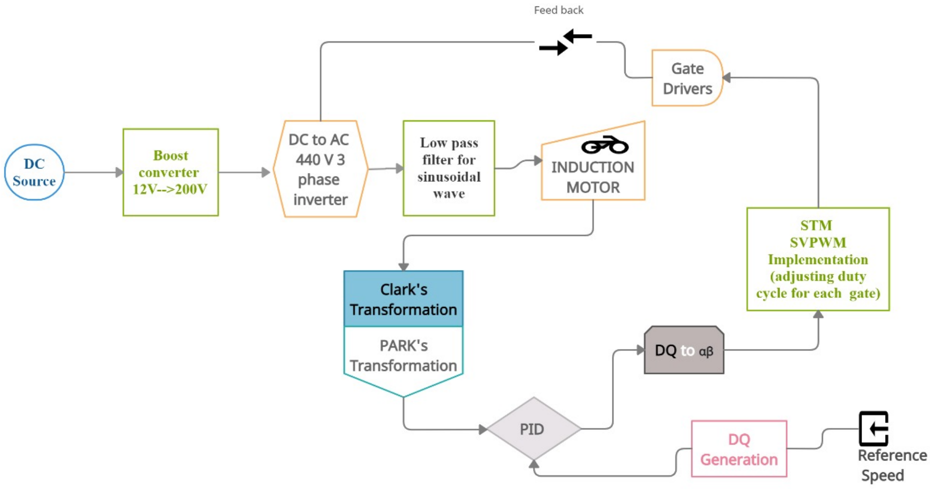

FIGURE 4.3: Flow Diagram of System

Chapter 5

Induction Motor Modelling

5.1 Induction Motor Derivation

An induction motor is also referred to as an asynchronous motor, in which a field is induced in the rotor by the stator. Also, rotor speed can never be equal to the stator. There are no brushes or permanent magnets needed for an induction motor to work. Its modeling is simple, and it is cheap to manufacture. Like other motors require high maintenance its maintenance is quite low.

Modeling is in the general frame of reference, while Voltage equation of stator and rotor in the natural frame of reference.

$$V_{abcs} = R_s i_{abcs} + \frac{d}{dt}\psi_{abcs} \tag{5.1}$$

$$V_{abcr}{=}R_r i_{abcr}{+}\frac{d}{dt}\psi_{abcr} \tag{5.2}$$

$$V_{abcs}{=}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{5.3}$$

$$V_{abcr}{=}\begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} \tag{5.4}$$

$$I_{abcs}{=}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{5.5}$$

$$I_{abcr}= \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix} \tag{5.6}$$

Now below are the equations for flux linkages.

$$\psi_{abcs}=L_{abcs}i_{abcs}+L_{abcsr}i_{abcr} \tag{5.7}$$

$$\psi_{abcr}=L_{abcrs}\ i_{abcs}+L_{abcr}i_{abcr} \tag{5.8}$$

Now presenting self inductance in matrices.

$$L_{abcr}= \begin{bmatrix} L_{rr} & \frac{-1}{2}L_{mr} & \frac{-1}{2}L_{mr} \\ \frac{-1}{2}L_{mr} & Ł_{rr} & \frac{-1}{2}L_{mr} \\ \frac{-1}{2}L_{mr} & \frac{-1}{2}L_{mr} & Ł_{rr} \end{bmatrix} \tag{5.9}$$

$$L_{abcs}= \begin{bmatrix} L_{ss} & \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & Ł_{ss} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{mr} & Ł_{ss} \end{bmatrix} \tag{5.10}$$

L_{abcsr} and L_{abcrs} represents the coupling between stator and rotor variable.

$$L_{abcrs} \ = L_{abcsr} \tag{5.11}$$

$$L_{abcsr}= \begin{bmatrix} L_{sara} & L_{sarb} & L_{sarc} \\ L_{sbra} & L_{sbrb} & L_{sbrc} \\ L_{scra} & L_{scrb} & L_{scrc} \end{bmatrix} \tag{5.12}$$

$$L_{abcrs} = \begin{bmatrix} L_{rasa} & L_{rasb} & L_{rasc} \\ L_{rbsa} & L_{rbsb} & L_{rbsc} \\ L_{rcsa} & L_{rcsb} & L_{rcsc} \end{bmatrix} \tag{5.13}$$

$$L_{sara} = Lrasa = L_{srm}cos\Theta_r \tag{5.14}$$

$$L_{sarb} = L_{rbas} = L_{srm}cos(\Theta_r + \frac{2\pi}{3}) \tag{5.15}$$

$$L_{sarc} = L_{rcsa} = L_{srm}cos(\Theta_r - \frac{2\pi}{3}) \tag{5.16}$$

$$L_{sbra} = L_{rbsb} = L_{srm}cos(\Theta_r - \frac{2\pi}{3}) \tag{5.17}$$

$$L_{sbrb} = L_{rbsb} = L_{srm}cos(\Theta_r) \tag{5.18}$$

$$L_{sbrc} = L_{rcsb} = L_{srm}cos(\Theta_r + \frac{2\pi}{3}) \tag{5.19}$$

$$L_{scra} = L_{rasc} = L_{srm}cos(\Theta_r + \frac{2\pi}{3}) \tag{5.20}$$

$$L_{scrb} = L_{rbsc} = L_{srm}cos(\Theta_r - \frac{2\pi}{3}) \tag{5.21}$$

$$L_{scrc} = L_{rcsc} = L_{srm}cos(\Theta_r) \tag{5.22}$$

$$L_{abcsr = }L_{abcrs}\begin{bmatrix} cos(\Theta_r) & cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r - \frac{2\pi}{3}) \\ cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r) & cos(\Theta_r + \frac{2\pi}{3}) \\ cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r) \end{bmatrix} L_{srm} \tag{5.23}$$

$$L^T_{abcsr} = \begin{bmatrix} cos(\Theta_r) & cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r + \frac{2\pi}{3}) \\ cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r) & cos(\Theta_r - \frac{2\pi}{3}) \\ cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r) \end{bmatrix} L_{srm} \tag{5.24}$$

$$L_{srm} = \frac{N_s N_r}{R_m} \tag{5.25}$$

$$\int_0^t \omega_r \, dt \tag{5.26}$$

Now referring all the rotor variables to stator.

$$i'_{abcr} = (\frac{Nr}{Ns})i_{abcr} \tag{5.27}$$

$$r'_{abcr} = (\frac{Ns}{Nr})^2 r_{abcr} \tag{5.28}$$

$$L'_{abcr} = (\frac{Ns}{Nr})^2 L_{abcr} \tag{5.29}$$

$$L'_{abcr = }\begin{bmatrix} L_{rs} + L_{mr} & \frac{-1}{2}L_{mr} & \frac{-1}{2}L_{mr} \\ \frac{-1}{2}L_{mr} & \text{Ł}_{rr} + L_{mr} & \frac{-1}{2}L_{mr} \\ \frac{-1}{2}L_{mr} & \frac{-1}{2}L_{mr} & \text{Ł}_{rr} + L_{mr} \end{bmatrix} (\frac{N_s}{N_r})^2 \tag{5.30}$$

$$L_{ms} = (\frac{Ns}{Nr})L_{srm} \tag{5.31}$$

$$L'_{rr} = (\frac{Ns}{Nr})^2 L_{rr} \tag{5.32}$$

$$L_{ms} = (\frac{Ns}{Nr})^2 L_{mr} \tag{5.33}$$

$$L'_{abcr} = \begin{bmatrix} L'_{lr} + L_{ms} & \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & L'_{lr} + L_{ms} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{ms} & L'_{lr} + L_{ms} \end{bmatrix} \tag{5.34}$$

$$L_{abcs} = \begin{bmatrix} L_{ls} + L_{ms} & \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & L_{ls} + L_{ms} & \frac{-1}{2}L_{ms} \\ \frac{-1}{2}L_{ms} & \frac{-1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \tag{5.35}$$

Now eq 1.1 and 1.2 will become as follows;

$$L'_{abcsr} = (\frac{Ns}{Nr})L_{abcsr} = \begin{bmatrix} cos(\Theta_r) & cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r - \frac{2\pi}{3}) \\ cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r) & cos(\Theta_r + \frac{2\pi}{3}) \\ cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r) \end{bmatrix} L_{sm} \tag{5.36}$$

$$L'_{abcrs} = (\frac{Ns}{Nr})L_{abcrs} = \begin{bmatrix} cos(\Theta_r) & cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r + \frac{2\pi}{3}) \\ cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r) & cos(\Theta_r - \frac{2\pi}{3}) \\ cos(\Theta_r - \frac{2\pi}{3}) & cos(\Theta_r + \frac{2\pi}{3}) & cos(\Theta_r) \end{bmatrix} L_{sm} \tag{5.37}$$

$$V_{abcs=}R_s i_{abcs+}\frac{d}{dt}\psi_{abcs}(5.38)$$

$$V'_{abcr=}R_r i'_{abcr+}\frac{d}{dt}\psi'_{abcr}(5.39)$$

$$\psi_{abcs=}L_{abcs}i_{abcs+}L'_{abcsr}i'_{abcr}(5.40)$$

$$\psi'_{abcr=}L'_{abcrs}i_{abcs+}L'_{abcr}i'_{abcr}(5.41)$$

Putting equation 1.40 and 1.41 in equations 1.38 and 1.39 respectively

$$V_{abcs=}R_s i_{abcs+}\frac{d}{dt}(L_{abcs}i_{abcs+}L'_{abcsr}i'_{abcr)} \tag{5.42}$$

$$V'_{abcr=}R_r i'_{abcr+}\frac{d}{dt}\psi'(L'_{abcrs}i_{abcs+}L'_{abcr}i'_{abcr)} \tag{5.43}$$

Now transforming from abc to dq frame of reference i.e. Park Transformation

$$f_{dqs} = k_s f_{abcs} \tag{5.44}$$

$$k_s = \frac{2}{3}\begin{bmatrix} cos(\Theta_g) & cos(\Theta_g - \frac{2\pi}{3}) & cos(\Theta_g + \frac{2\pi}{3}) \\ -sin(\Theta_g) & -sin(\Theta_g - \frac{2\pi}{3}) & -sin(\Theta_g + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{5.45}$$

Now reverse Park Transformation will be;

$$f_{abcs} = k_s^{-1} f_{dqs} \tag{5.46}$$

$$k_s^{-1} = \begin{bmatrix} cos(\Theta_g) & -sin(\Theta_g) & 1 \\ cos(\Theta_g - \frac{2\pi}{3}) & -sin(\Theta_g - \frac{2\pi}{3}) & 1 \\ cos(\Theta_g + \frac{2\pi}{3}) & -sin(\Theta_g + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{5.47}$$

Similarly rotor variables;

$$f_{dqr} = k_r f_{abcr} \tag{5.48}$$

$$k_r = \frac{2}{3}\begin{bmatrix} cos(\Theta_g - \Theta_r) & cos(\Theta_g - \Theta_r - \frac{2\pi}{3}) & cos(\Theta_g - \Theta_r + \frac{2\pi}{3}) \\ -sin(\Theta_g - \Theta_r) & -sin(\Theta_g - \Theta_r - \frac{2\pi}{3}) & -sin(\Theta_g - \Theta_r + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{5.49}$$

Now reverse Park Transformation will be;

$$f_{abcr} = k_r^{-1} f_{dqr} \tag{5.50}$$

$$k_r^{-1} = \begin{bmatrix} cos(\Theta_g - \Theta_r) & -sin(\Theta_g - \Theta_r) & 1 \\ cos(\Theta_g - -\Theta_r \frac{2\pi}{3}) & -sin(\Theta_g - \Theta_r - \frac{2\pi}{3}) & 1 \\ cos(\Theta_g - \Theta_r + \frac{2\pi}{3}) & -sin(\Theta_g - \Theta_r + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{5.51}$$

Now transforming 1.37 and 1.38 equation

$$k_s^{-1} V_{dqs} = R_s k_s^{-1} i_{dqs} + \frac{d}{dt} k_s^{-1} \psi_{dqs} \tag{5.52}$$

Multiply both sides with k_s

$$V_{dqs} = R_s i_{dqs} + k_s(\frac{d}{dt} k_s^{-1} \psi_{dqs} + k_s^{-1} \frac{d}{dt} \psi_{dqs}) \tag{5.53}$$

$$V_{dqs} = R_s i_{dqs} + k_s \frac{d}{dt} k_s^{-1} \psi_{dqs} + k_s k_s^{-1} \frac{d}{dt} \psi_{dqs}) \tag{5.54}$$

$$V_{dqs} = R_s i_{dqs} + k_s \frac{d}{dt} k_s^{-1} \psi_{dqs} + \frac{d}{dt} \psi_{dqs}) \tag{5.55}$$

Now similarly for equation 1.38 or 1.44

$$k_r^{-1} V'_{dqr} = R_r k_r^{-1} i'_{dqr} + \frac{d}{dt} k_r^{-1} \psi'_{dqr} \tag{5.56}$$

Multiply by Kr on both sides;

$$k_r k_r^{-1} V'_{dqr} = k_r R_r k_r^{-1} i'_{dqr} + k_r (\frac{d}{dt} k_r^{-1} \psi'_{dqr} + k_r^{-1} \frac{d}{dt} \psi'_{dqr}) \tag{5.57}$$

$$V'_{dqr} = R_r i'_{dqr} + \frac{d}{dt} \psi'_{dqr} + \frac{d}{dt} k_r^{-1} \psi'_{dqr} \tag{5.58}$$

$$k_s \frac{d}{dt}[k_s^{-1}] = K_s \frac{d}{dt}[k_s^{-1}] = \omega_g \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \omega_g W_g \tag{5.59}$$

Now equation 1.56 will become

$$V_{dqs} = R_s i_{dqs} + \omega_g W_g \frac{d}{dt} \psi_{dqs} + \frac{d}{dt} \psi_{dqs}) \tag{5.60}$$

$$k_r \frac{d}{dt}[k_r^{-1}] = (\omega_g - \omega_r) \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = (\omega_g - \omega_r) W g \tag{5.61}$$

Now equation 1.59 will become

$$V'_{dqr} = R_r i'_{dqr} + (\omega_g - \omega_r) W g \psi'_{dqr} + \frac{d}{dt} \psi'_{dqr} \tag{5.62}$$

Now transforming equation 1.7 and 1.8

$$k_s^{-1} \psi_{dqs} = L_{abcs} k_s^{-1} i_{dqs} + L'_{abcsr} k_r^{-1} i_{dqr} \tag{5.63}$$

Multiply both sides with ks

$$\psi_{dqs} = k_s L_{abcs} k_s^{-1} i_{dqs} + k_s L'_{abcsr} k_r^{-1} i_{dqr} \tag{5.64}$$

Similarly for rotor;

$$k_r^{-1}\psi_{dqr} = L'_{abcrs}k_s^{-1}\ i_{dqs} + L'_{abcr}k_r^{-1}i'_{dqr} \tag{5.65}$$

Multiply both sides with kr

$$\psi_{dqr} = k_r L'_{abcrs}k_s^{-1}\ i_{dqs} + k_r L'_{abcr}k_r^{-1}i'_{dqr} \tag{5.66}$$

$$k_s L_{abcs} k_s^{-1} = L_s = \begin{bmatrix} L_{ls} + \frac{3}{2}L_{ms} & 0 & 0 \\ 0 & L_{ls} + \frac{3}{2}L_{ms} & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} \tag{5.67}$$

$$k_r L_{abcr} k_r^{-1} = L'_r = \begin{bmatrix} L_{lr} + \frac{3}{2}L_{ms} & 0 & 0 \\ 0 & L_{lr} + \frac{3}{2}L_{ms} & 0 \\ 0 & 0 & L_{lr} \end{bmatrix} \tag{5.68}$$

$$L_s L'_{abcsr} k_r^{-1} = \frac{3}{2}\begin{bmatrix} L_{ms} & 0 & 0 \\ 0 & L_{ms} & 0 \\ 0 & 0 & 0 \end{bmatrix} = M = \begin{bmatrix} L_m & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5.69}$$

$$k_r L'_{abcrs} k_s^{-1} = \frac{3}{2}\begin{bmatrix} L_{ms} & 0 & 0 \\ 0 & L_{ms} & 0 \\ 0 & 0 & 0 \end{bmatrix} = M = \begin{bmatrix} L_m & 0 & 0 \\ 0 & L_m & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5.70}$$

Now equation 1.65 and 1.67 will be

$$\psi_{dqs} = L_s i_{dqs} + M i'_{dqr} \tag{5.71}$$

$$\psi_{dqr} = M i_{dqs} + L'_r i'_{dqr} \tag{5.72}$$

Substituting above equations in 1.59 and 1.63

$$V_{dqs} = R_s i_{dqs} + \omega_g W_g L_s i_{dqs} + \omega_g W_g M i'_{dqr} + \frac{d}{dt}L_s i_{dqs} + \frac{d}{dt}M i'_{dqr} \tag{5.73}$$

$$V'_{dqr} = R'_r i'_{dqr} + (\omega_g - \omega_r)W_g M i_{dqs} + (\omega_g - \omega_r)W_g L'_r i'_{dqr} + \frac{d}{dt}M i_{dqs} + \frac{d}{dt}L'_r i'_{dqr} \tag{5.74}$$

expanding above equations

$$V_{ds} = (R_s + \frac{d}{dt}L_s)i_{ds} - \omega_g L_s i_{qs} + \frac{d}{dt}L_m i'_{dr} - \omega_g L_m i'_{dqr} \tag{5.75}$$

$$V_{qs} = \omega_g L_s i_{ds} + (R_s + \frac{d}{dt}L_s)i_{qs} + \omega_g L_m i'_{dr} + \frac{d}{dt}L_m i'_{qr} \tag{5.76}$$

$$V_{os} = (R_s + \frac{d}{dt}L_s)i_{os} \tag{5.77}$$

$$V'_{dr} = \frac{d}{dt}L_m i_{ds} - (\omega_g - \omega_r)L_m i_{qs} + (R'_r + \frac{d}{dt}L_r)i'_{dqr} - (\omega_g - \omega_r)L'_r i'_{qr} \tag{5.78}$$

$$V'_{qr} = \frac{d}{dt}L_m i_{qs} + (\omega_g - \omega_r)L_m i_{ds} + (R'_r + \frac{d}{dt}L_r)i'_{dqr} + (\omega_g - \omega_r)L'_r i'_{dr} \tag{5.79}$$

$$V'_{or} = (R'_r + \frac{d}{dt}L'_r)i'_{or} \tag{5.80}$$

Zero sequence is neglected for balanced system

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} r_s + \frac{d}{dt}L_s & -\omega_g L_s & \frac{d}{dt}L_m & -\omega_g L_m \\ \omega_g L_s & r_s + \frac{d}{dt}L_s & \omega_g L_m & \frac{d}{dt}L_m \\ \frac{d}{dt}L_m & -(\omega_g - \omega_r)L_m & r_s + \frac{d}{dt}L_r & -(\omega_g - \omega_r)L_r \\ (\omega_g - \omega_r)L_m & \frac{d}{dt}L_m & (\omega_g - \omega_r)L_r & r_s + \frac{d}{dt}L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{5.81}$$

where

$$L_s = L_l s + \frac{3}{2}L_{ms} \tag{5.82}$$

$$L_r = L_l r + \frac{3}{2}L_{ms} \tag{5.83}$$

$$L_m = \frac{3}{2}L_{ms} \tag{5.84}$$

$$L_{ss} = L_{ls} + L_m \; and \; L_{rr} = L_l r + L_m \tag{5.85}$$

$$V_{ds} = r_s i_{ds} + (L_{ls} + L_m)\frac{d}{dt}[i_{ds}] - \omega_g(L_{ls} + L_m)i_{qs} + L_m\frac{d}{dt}[i'_{dr}] - \omega_g L_m[i'_{qr}] \tag{5.86}$$

$$V_{qs} = \omega_g(L_{ls} + L_m)i_{ds} + (L_{ls} + L_m)\frac{d}{dt}[i_{qs}] + r_s i_{qs} + L_m\frac{d}{dt}[i'_{qr}] + \omega_g L_m[i'_{dr}] \tag{5.87}$$

$$V'_{dr} = L_m\frac{d}{dt}i_{ds} - (\omega_g - \omega_r)L_m i_{qs} + r'_r[i'_{dr}] + (L'_{lr} + L_{lm})\frac{d}{dt}i'_{dr} - (\omega_g - \omega_r)(L'_{lr} + L_m)[i'_{qr}] \tag{5.88}$$

$$V'_{qr} = L_m\frac{d}{dt}i_{qs} + (\omega_g - \omega_r)L_m i_{ds} + r'_r[i'_{qr}] + (L'_{lr} + L_{lm})\frac{d}{dt}i'_{qr} + (\omega_g - \omega_r)(L'_{lr} + L_m)[i'_{dr}] \tag{5.89}$$

5.1.1 Transient Torque Expression in DQ

The transient expression for the machine torque is the derivative of the instantaneous total mutual inductance energy over the angular displacement $\frac{2}{P}\theta_r$ (assuming general case with pole-pair number of $\frac{P}{2}$). Then, we have:

$$T_e = \begin{bmatrix} i_{sa} & i_{sb} & i_{sc} \end{bmatrix} \frac{d}{d(\frac{2}{P})} \begin{bmatrix} L_{ms}\cos\theta_r & L_{ms}\cos\theta_r + \frac{2\pi}{3} & L_{ms}\cos\theta_r - \frac{2\pi}{3} \\ L_{ms}\cos\theta_r - \frac{2\pi}{3} & L_{ms}\cos\theta_r & L_{ms}\cos\theta_r + \frac{2\pi}{3} \\ L_{ms}\cos\theta_r + \frac{2\pi}{3} & L_{ms}\cos\theta_r - \frac{2\pi}{3} & L_{ms}\cos\theta_r \end{bmatrix} \begin{bmatrix} i'_{ra} \\ i'_{rb} \\ i'_{rc} \end{bmatrix} \tag{5.90}$$

Find the transient torque expression as a function of the DQ variables in synchronous rotating reference frame.

$$[i_{abcs}]^T \frac{d}{d(\frac{2\theta_r}{P})}[L_{abcsr}]i'_{abcr} \tag{5.91}$$

where

$$i_{abcs} = \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{5.92}$$

$$i'_{abcr} = \begin{bmatrix} i'_{ar} \\ i'_{br} \\ i'_{cr} \end{bmatrix} \tag{5.93}$$

$$L_{abcsr} = \begin{bmatrix} L_{ms}\cos(\theta_r) & L_{ms}\cos(\theta_r + \frac{2\pi}{3}) & L_{ms}\cos(\theta_r - \frac{2\pi}{3}) \\ L_{ms}\cos\theta_r - \frac{2\pi}{3} & L_{ms}\cos\theta_r & L_{ms}\cos(\theta_r + \frac{2\pi}{3}) \\ L_{ms}\cos(\theta_r + \frac{2\pi}{3}) & L_{ms}\cos(\theta_r - \frac{2\pi}{3}) & L_{ms}\cos(\theta_r) \end{bmatrix} \tag{5.94}$$

Now transforming to DQ frame of reference assume P=2

$$T_e = (k_s^{-1} i_{dqs})^T \frac{d}{d\theta_r}[L_{abcsr}][k_r^{-1} i'_{dqr}] \tag{5.95}$$

$$k_s^{-1} i_{dqs} = \begin{bmatrix} \cos(\theta_g) & -\sin(\theta_g) & 1 \\ \cos(\theta_g - \frac{2\pi}{3}) & -\sin(\theta_g - \frac{2\pi}{3}) & 1 \\ \cos(\theta_g - \frac{2\pi}{3}) & -\sin(\theta_g - \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{0s} \end{bmatrix} \tag{5.96}$$

$$k_s^{-1} i_{dqs} = \begin{bmatrix} \cos(\theta_g) i_{ds} - \sin(\theta_g) i_{qs} + i_{0s} \\ \cos(\theta_g - \frac{2\pi}{3} i_{ds}) - \sin(\theta_g - \frac{2\pi}{3} i_{qs}) + i_{0s} \\ \cos(\theta_g - \frac{2\pi}{3}) i_{ds} - \sin(\theta_g - \frac{2\pi}{3}) i_{qs} + i_{0s} \end{bmatrix} \tag{5.97}$$

$$\frac{d}{d\theta_r}L_{abcsr} = \frac{d}{d\theta_r}\begin{bmatrix} L_{ms}\cos(\theta_r) & L_{ms}\cos(\theta_r + \frac{2\pi}{3}) & L_{ms}\cos(\theta_r - \frac{2\pi}{3}) \\ L_{ms}\cos(\theta_r - \frac{2\pi}{3}) & L_{ms}\cos(\theta_r) & L_{ms}\cos(\theta_r + \frac{2\pi}{3}) \\ L_{ms}\cos(\theta_r + \frac{2\pi}{3}) & L_{ms}\cos(\theta_r - \frac{2\pi}{3}) & L_{ms}\cos\theta_r \end{bmatrix} \tag{5.98}$$

$$\frac{d}{d\theta_r}L_{abcsr} = L_{ms}\begin{bmatrix} -\sin(\theta_r & -\sin\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) \\ -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r) & -\sin(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r) \end{bmatrix} \tag{5.99}$$

$$[k_r'^{-1}i_{dqr}'] = \begin{bmatrix} \cos(\theta_g - \theta_r) & -\sin(\theta_g - \theta_r) & 1 \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3}) & -\sin(\theta_g - \theta_r - \frac{2\pi}{3}) & 1 \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3}) & -\sin(\theta_g - \theta_r - \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} i_{dr}' \\ i_{qr}' \\ i_{0r}' \end{bmatrix} \tag{5.100}$$

$$[k_r'^{-1}i_{dqr}'] = \begin{bmatrix} \cos(\theta_g - \theta_r)i_{dr}' - \sin(\theta_g - \theta_r)i_{qr}' + i_{0r}' \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3})i_{dr}' - \sin(\theta_g - \theta_r - \frac{2\pi}{3})i_{qr}' + i_{0r}' \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3})i_{dr}' - \sin(\theta_g - \theta_r - \frac{2\pi}{3})i_{qr}' + i_{0r}' \end{bmatrix} \tag{5.101}$$

$$\mathrm{T}_e = \begin{bmatrix} \cos(\theta_g)i_{ds} - \sin(\theta_g)i_{qs} \\ \cos(\theta_g - \frac{2\pi}{3}i_{ds}) - \sin(\theta_g - \frac{2\pi}{3}i_{qs}) \\ \cos(\theta_g - \frac{2\pi}{3})i_{ds} - \sin(\theta_g - \frac{2\pi}{3})i_{qs} \end{bmatrix} \cdot \begin{bmatrix} -\sin(\theta_r & -\sin\theta_r + \frac{2\pi}{3}) & -\sin(\theta_r - \frac{2\pi}{3}) \\ -\sin(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r) & -\sin(\theta_r + \frac{2\pi}{3}) \\ -\sin(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & -\sin(\theta_r) \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta_g - \theta_r)i_{dr}' - \sin(\theta_g - \theta_r)i_{qr}' \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3})i_{dr}' - \sin(\theta_g - \theta_r - \frac{2\pi}{3})i_{qr}' \\ \cos(\theta_g - \theta_r - \frac{2\pi}{3})i_{dr}' - \sin(\theta_g - \theta_r - \frac{2\pi}{3})i_{qr}' \end{bmatrix} \tag{5.102}$$

After this matrix multiplication, this will be the torque for an 8 pole machine.

$$6L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{5.103}$$

for any pole machine,

$$\frac{3}{2}\frac{p}{2}L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \tag{5.104}$$

5.2 Induction Motor SIMULINK Model

Field oriented vector Control is based on the DQ model of the import vehicle. The dynamic model in the state space form is important to the temporary analysis of the import vehicle mainly computer simulation lesson in MATLAB / SIMULINK. Therefore SIMULINK software for powerful import modeling The car can be modeled by a rotation indicator of the frame and stop-frame. We have made the entire model based on all the calculations previously done. This is the main block of the IM simulated in Simulink. The three-phase supply is provided to the stator three-phase winding and the model calculates the DQ components of stator voltage and current, rotor voltage and current, three-phase current of stator and rotor, and electromechanical torque produced. The input parameters are 3 phase voltages and output parameters Voltages and Currents of stator and rotor in DQ reference frame. Rotor voltage is zero because its squirrel cage induction motor and its bars are very short so the voltage will be zero.

5.2.1 Internal Structure

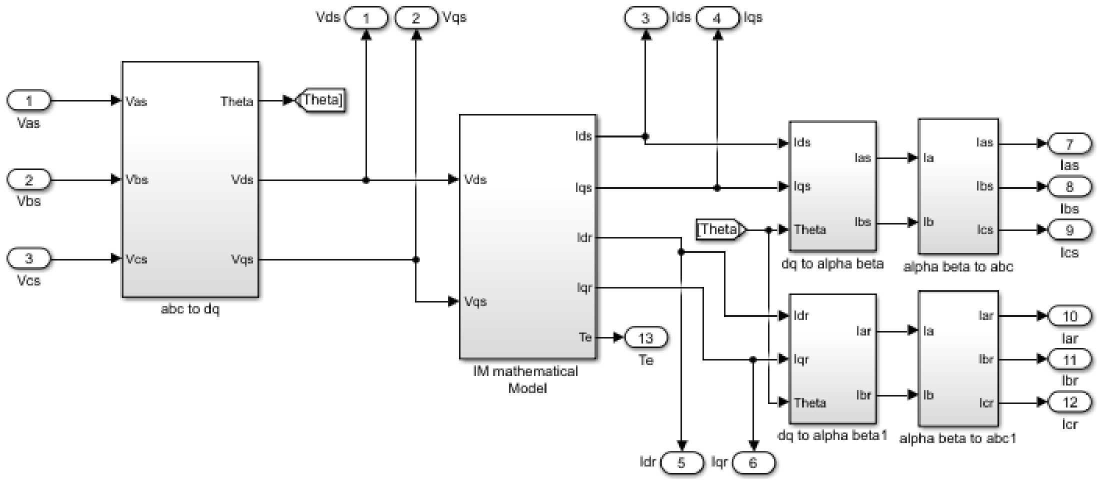

FIGURE 5.1: Internal Structure of Model

Motor Parameters are defined in callbacks function of simulink.

Now, This is the internal model of induction motor 5.1, three functions are implements in form of blocks. The left most block is converting three phase system (abc) to two phase system (dq) using the Clark and Park transformation. The center block is the most important one. The IM voltage differential equations derived above are implemented in this block to calculate the stator and rotor dq currents and electromechanical torque produced. All the calculations are done in dq ref frame because in this system the vectors are of DC nature that done not change like AC signal, so it makes our calculations easy. The right most two blocks are simply converting dq system back to three phase system using the inverse Park and then inverse Clark transformation.

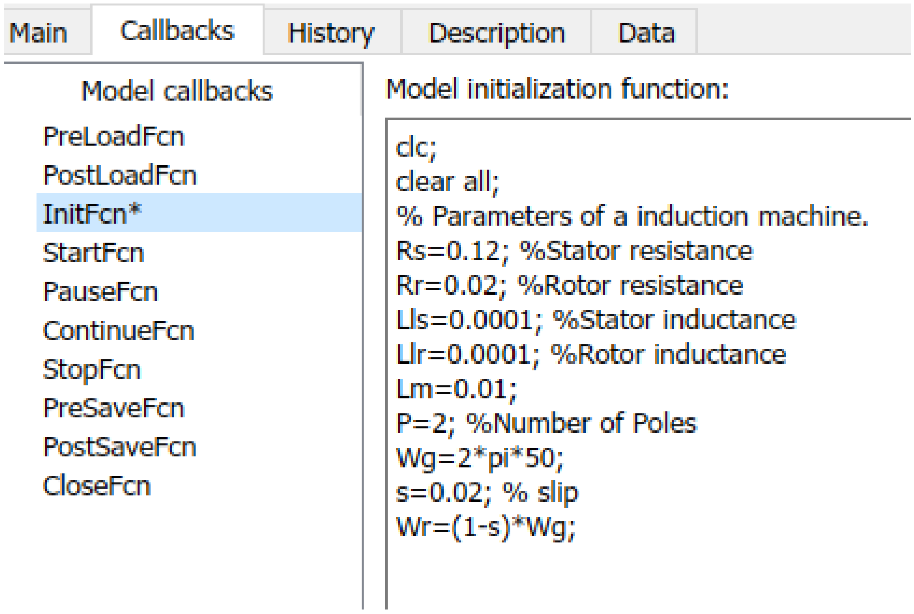

FIGURE 5.2: Model Parameters for Block

5.2.2 Clark Transformation

This is the internal structure of abc to dq transformation block 5.3. Then the Park transformation block include conversion from abc to $\alpha\beta$ reference frame using the conversion matrix.

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_\gamma \end{bmatrix} = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5.105}$$

Using this conversion equation abc to $\alpha\beta$. Then we find angle which is rotating with syn-

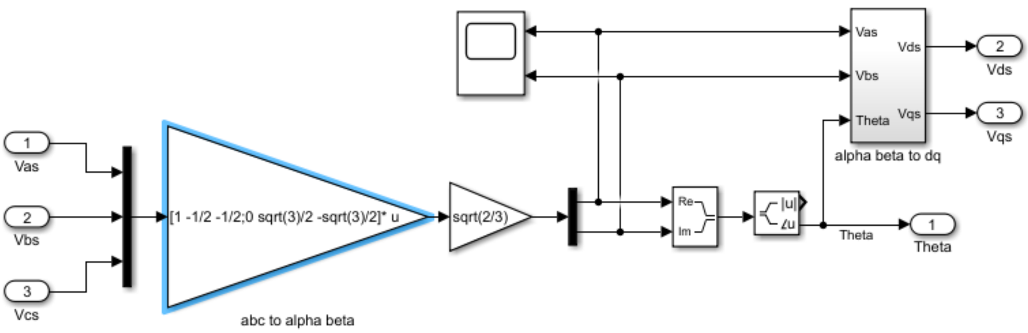

FIGURE 5.3: ABC TO DQ Transformation Block

chronous frequency.

In the abc to dq block the two transformations (Clark and Park) are performed which transform three-phase stator voltage to two-phase dq time invariant stator voltage. The Clark and

Park transformation equations are shown in the figure and these equations are implemented using the simple mathematical blocks. The theta is the electrical angle which is rotating with fundamental frequency of 50 Hz. This angle is necessary to calculate because it is needed for the Park and inverse Park transformation.

Park Transform Block

This is the $\alpha\beta$ to dq transformation block' internal structure in figure 5.4. The conversion equation used to find V_d and V_q is given below.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos & \sin \\ -\sin & \cos \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{5.106}$$

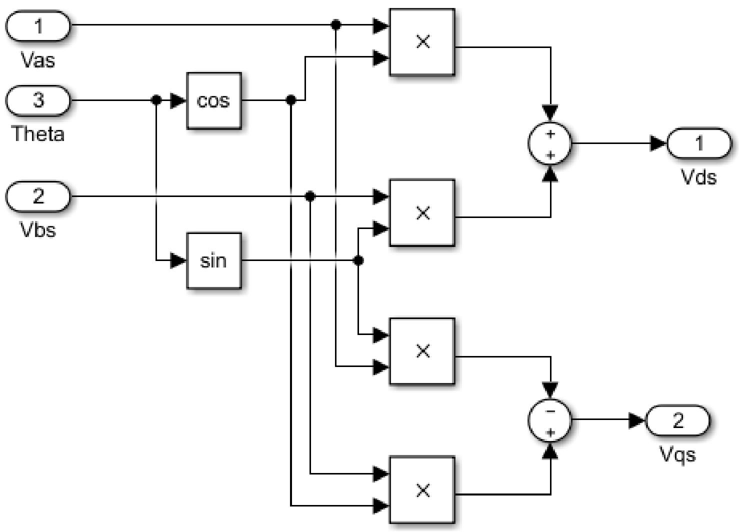

FIGURE 5.4: $\alpha\beta$ to dq transformation Block

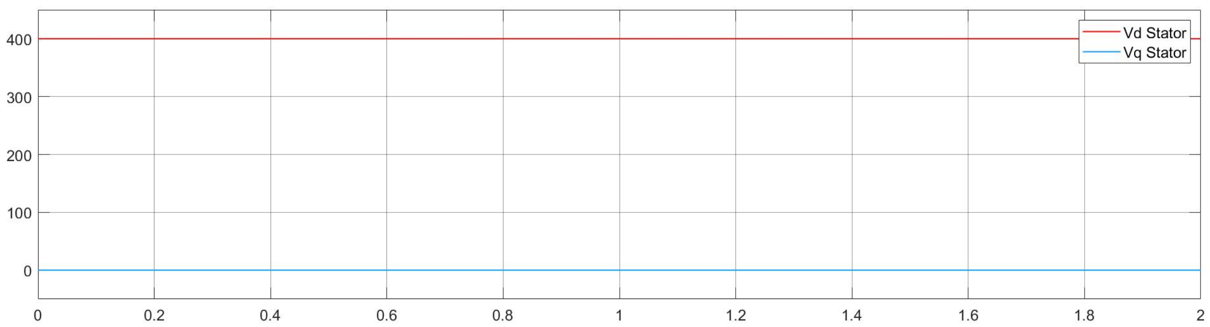

FIGURE 5.5: Vd and Vq of Stator Waveform

5.3 Torque and Current Model

This is the internal structure of mathematical model of Induction Motor.In IM mathematical block the bottom four blocks calculate stator and rotor dq current using the differential equations derived above. The Te block calculate the electromechanical torque produced by the induction motor at a specific slip. 5.6

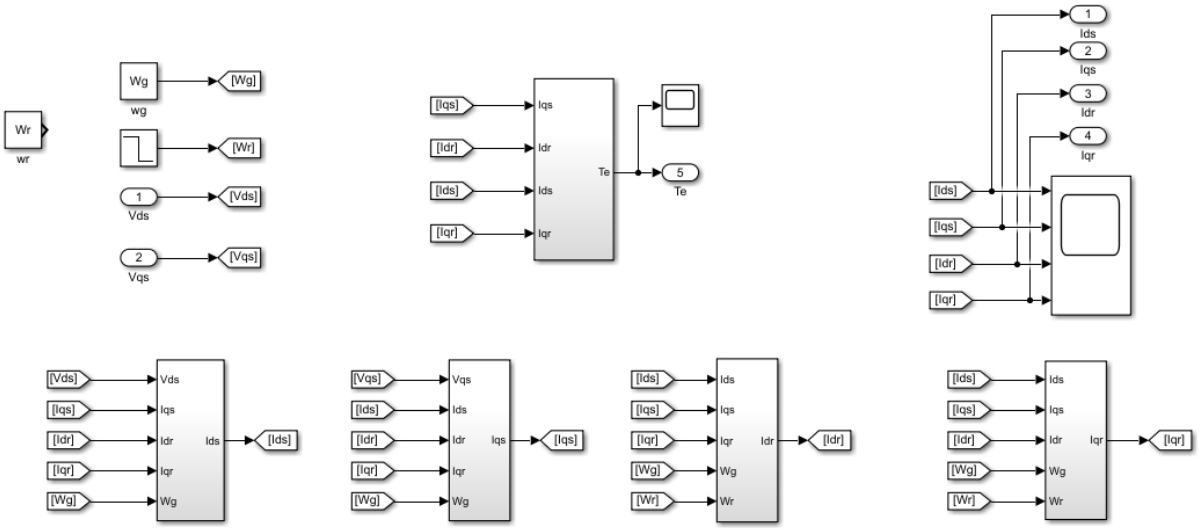

FIGURE 5.6: IM Mathematical Model Block Internal Structure

The next figures show the inside of the blocks in which stator and rotor dq currents are calculated. The differential equations are also shown in the figure. In the equations small p denote the differential term d/dt. Rs and Rr is the stator and rotor resistance respectively. Lls and Llr is the stator and rotor inductance respectively. Lm is the main magnetizing inductance. The differential equations in all four blocks are implemented using the simple mathematical blocks.

5.3.1 DQ Components of Stator Current

This block model is used to find the dq component of stator current. Figure 5.7 is implemented by this equation.

$$\frac{d}{dt}i_{qs} = [\frac{1}{L_{ls} + L_m}][V_{qs} - r_s i_{qs} + \omega_g[(L_{ls} + L_m)i_{ds} + L_m i'_{dr}] - L_m \frac{d}{dt}[i'_{qr}]] \tag{5.107}$$

Figure 5.8 is implemented by this equation.

$$\frac{d}{dt}i'_{ds} = [\frac{1}{L'_{lr} + L_m}][V'_{dr} - r'_r i'_{dr} + (\omega_g - \omega_r)[(L'_{lr} + L_m)i'_{qr} + L_m i'_{qs}] - L_m \frac{d}{dt}[i_{ds}]] \tag{5.108}$$

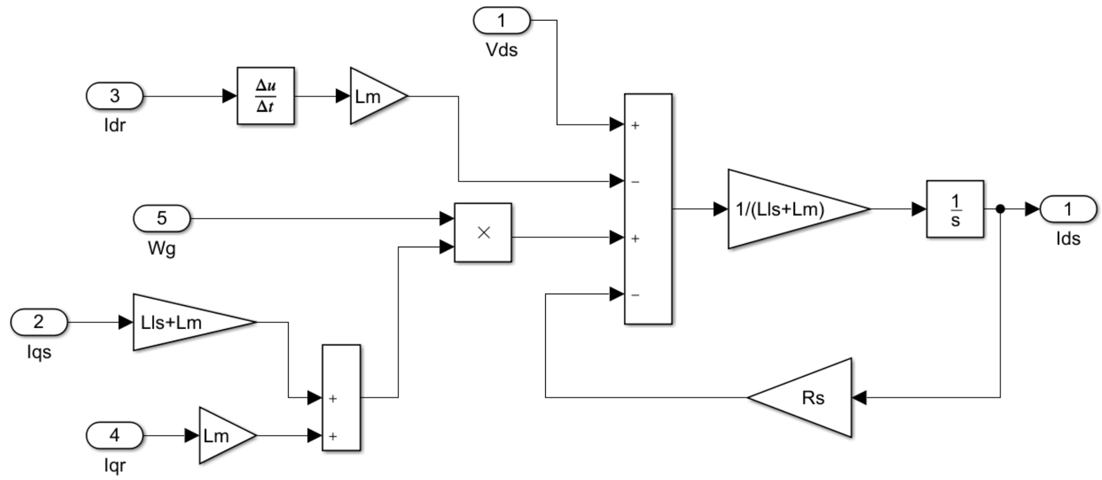

FIGURE 5.7: Ids Internal Structure

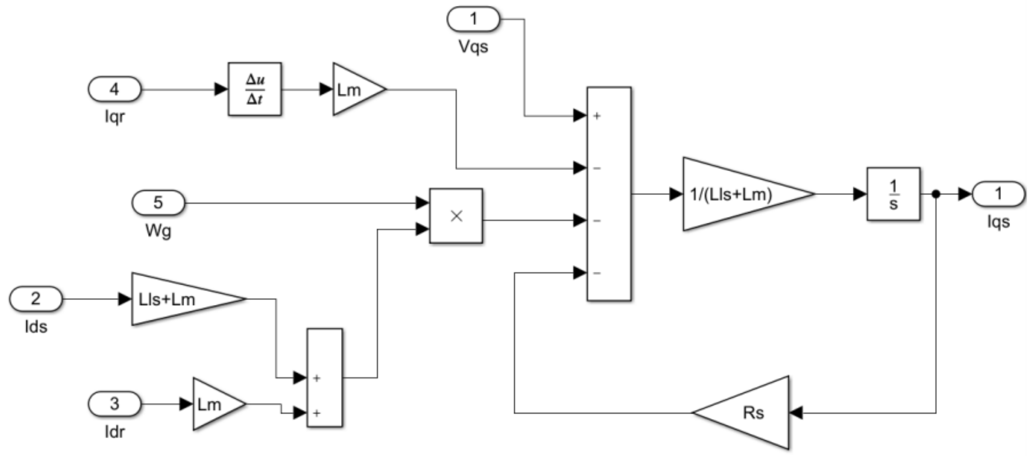

FIGURE 5.8: Iqs Internal Structure

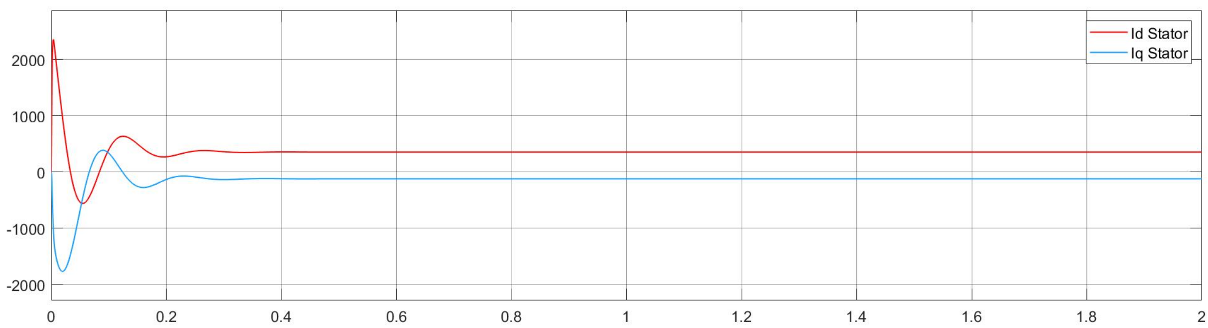

FIGURE 5.9: Id and Iq of Stator Waveform

5.3.2 DQ Components of Rotor Currents

Figure 5.11 is implemented by this equation.

$$\frac{d}{dt}i'_{dr} = [\frac{1}{L'_{lr} + L_m}][V'_{qr} - r'_r i'_{qr} + (\omega_g - \omega_r)[(L'_{lr} + L_m)i'_{dr} + L_m i'_{ds}] - L_m \frac{d}{dt}[i_{qs}]] \tag{5.109}$$

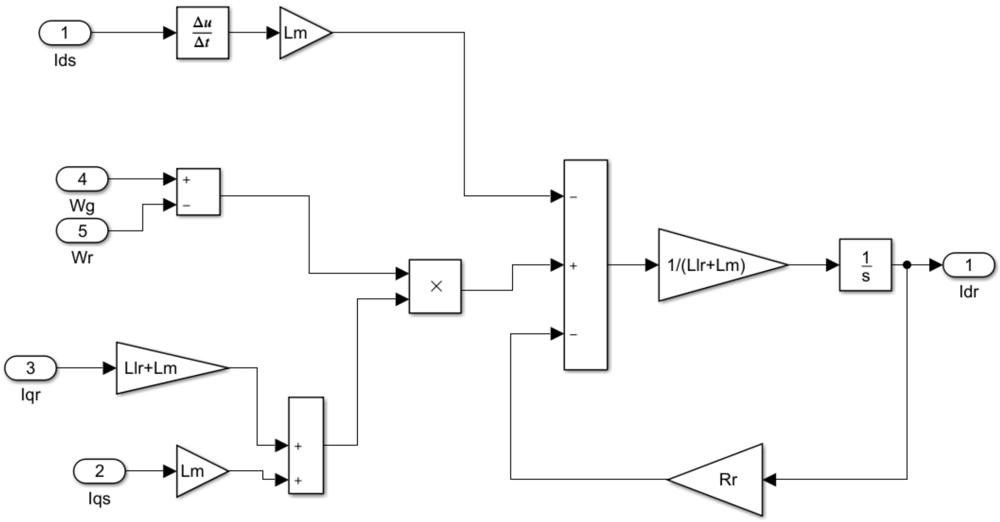

FIGURE 5.10: Iqr Internal Structure

Figure 5.11 is implemented by this equation.

$$\frac{d}{dt}i'_{dr} = [\frac{1}{L'_{lr} + L_m}][V'_{qr} - r'_r i'_{qr} + (\omega_g - \omega_r)[(L'_{lr} + L_m)i'_{dr} + L_m i'_{ds}] - L_m \frac{d}{dt}[i_{qs}]] \tag{5.110}$$

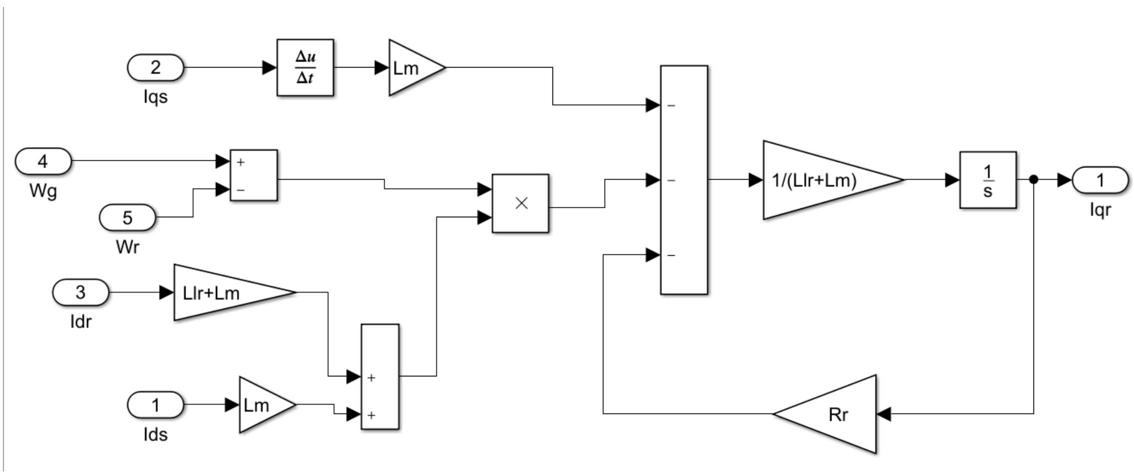

FIGURE 5.11: Idr Internal Structure

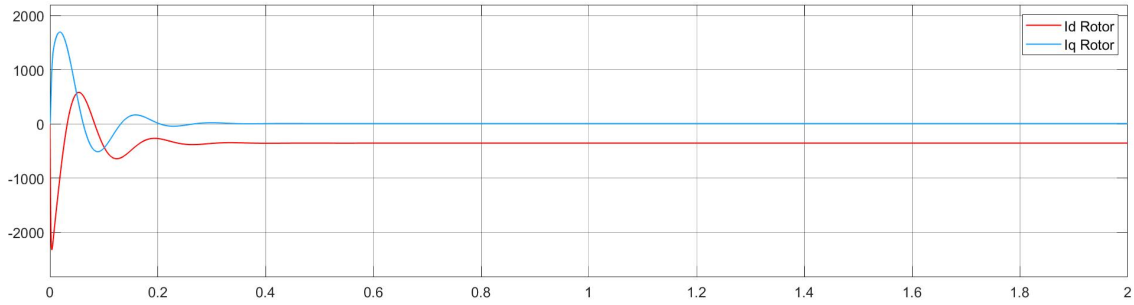

FIGURE 5.12: DQ Component of of Rotor Current Waveform

5.3.3 Torque Calculation

The equation given below is used to find torque by using the dq components of rotor and stator currents;

$$T = \frac{3}{2}\frac{P}{2}\frac{d}{dt}L_m(i_{qs}i_{qr} - i_{ds}i_{dr}) \tag{5.111}$$

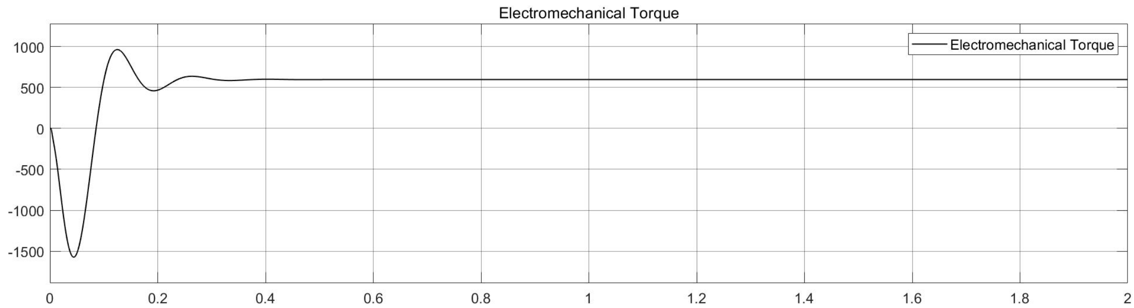

FIGURE 5.13: Torque Waveform

5.3.4 Inverse Park Transformation on Stator Currents

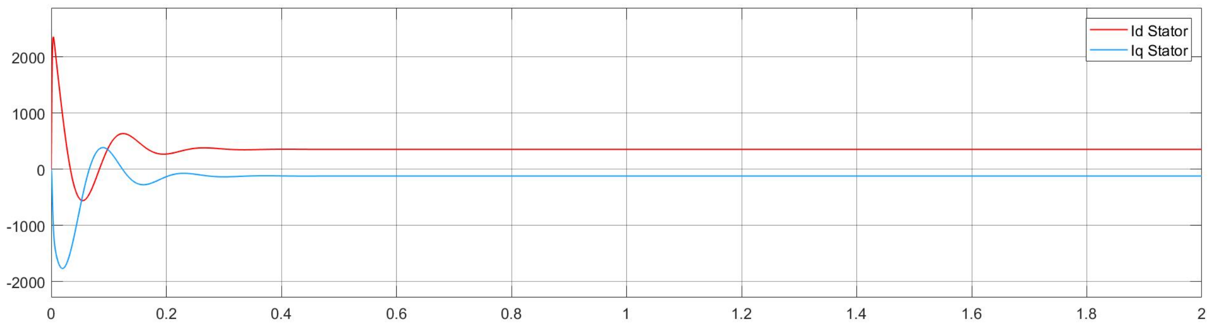

FIGURE 5.14: Id and Iq of Stator Waveform

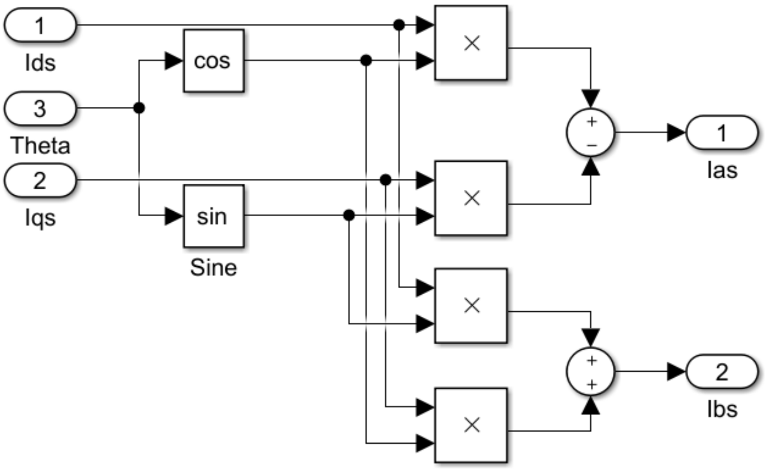

FIGURE 5.15: DQ to $\alpha\beta$ of Stator Transformation

5.3.5 Park Transformation on Stator Currents

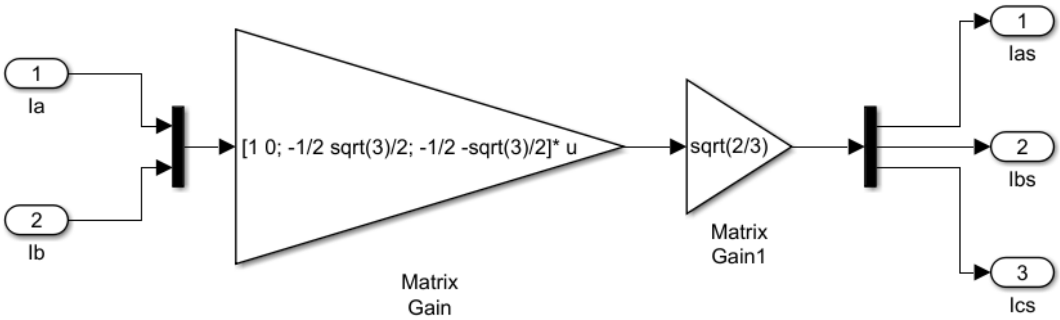

FIGURE 5.16: $\alpha\beta$ to DQ of Stator Transformation

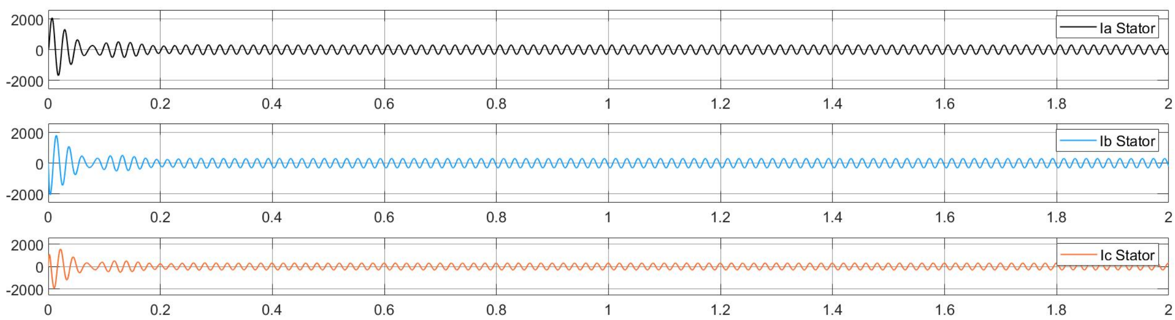

FIGURE 5.17: Iabc of Stator Waveform

As stator and rotor dq currents are calculated. It needs to be converted back to the natural reference frame (abc). For this purpose inverse Park and Clark transformation is performed.

5.3.6 Inverse Park Transformation on Rotor Currents

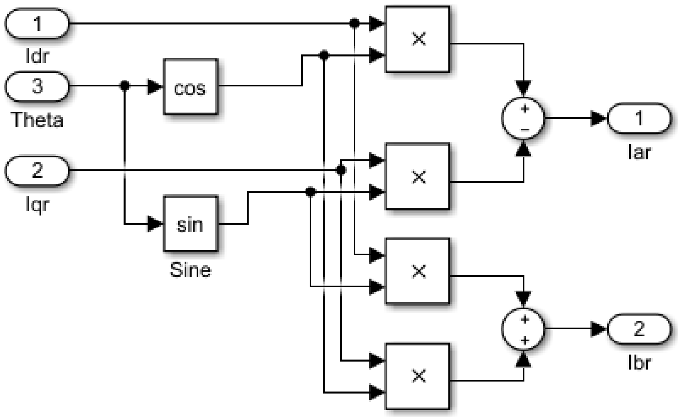

FIGURE 5.18: DQ to $\alpha\beta$ of Rotor Transformation

5.3.7 Park Transformation on Rotor Currents

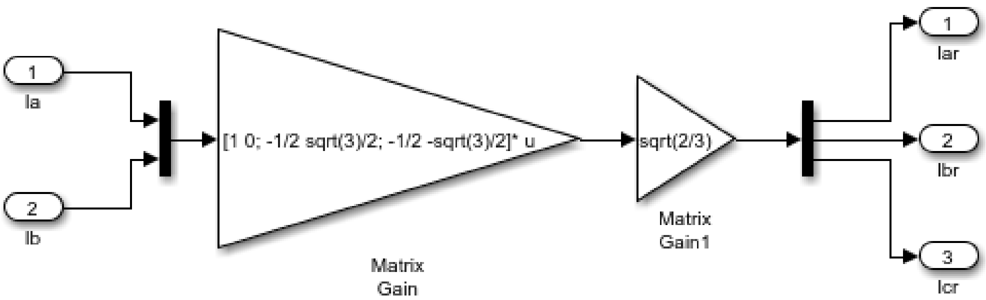

FIGURE 5.19: $\alpha\beta$ to DQ of Rotor Transformation

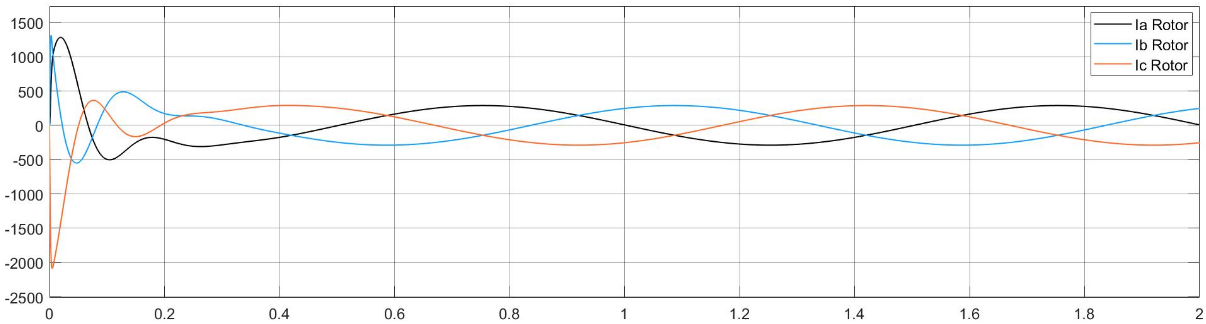

FIGURE 5.20: Iabc of Rotor Waveform

Chapter 6

Space Vector Pulse Width Modulation

6.1 SVPWM Simulink Model

The space vector PWM technique is used to generate the gate signals for the three-phase inverter using the alpha and beta component of voltage. The space vector PWM is so far one of the best PWM technique to provide the variable voltage to the motor to operate it at a different speed. The output of the SVPWM inverter contains fewer harmonic components than any other technique. The alpha-beta component of voltage is fed to SVPWM controller that generates a gate signal for the three-phase inverter. The below figure 6.2 shows the insight of the SVPWM

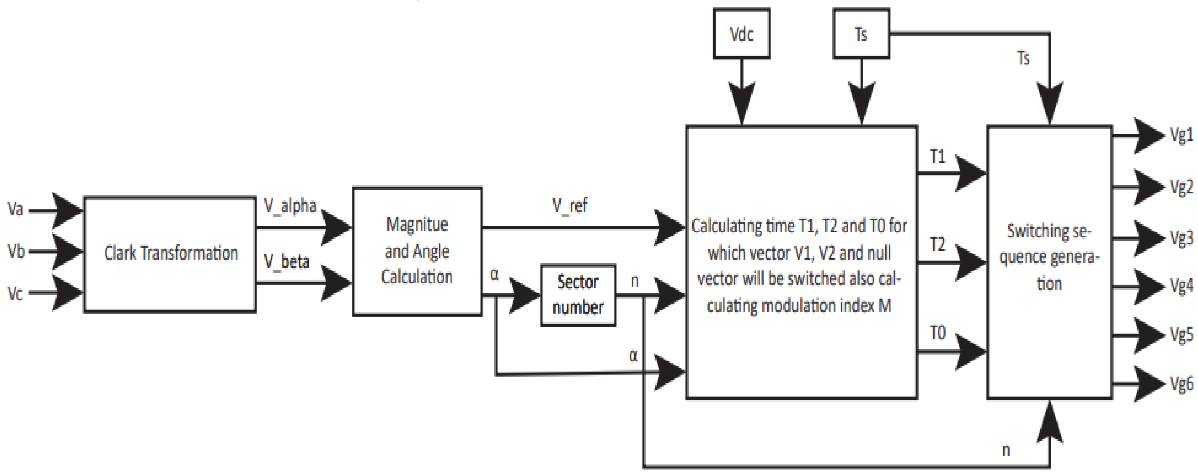

Figure 6.1: SVPWM Block Diagram

block.

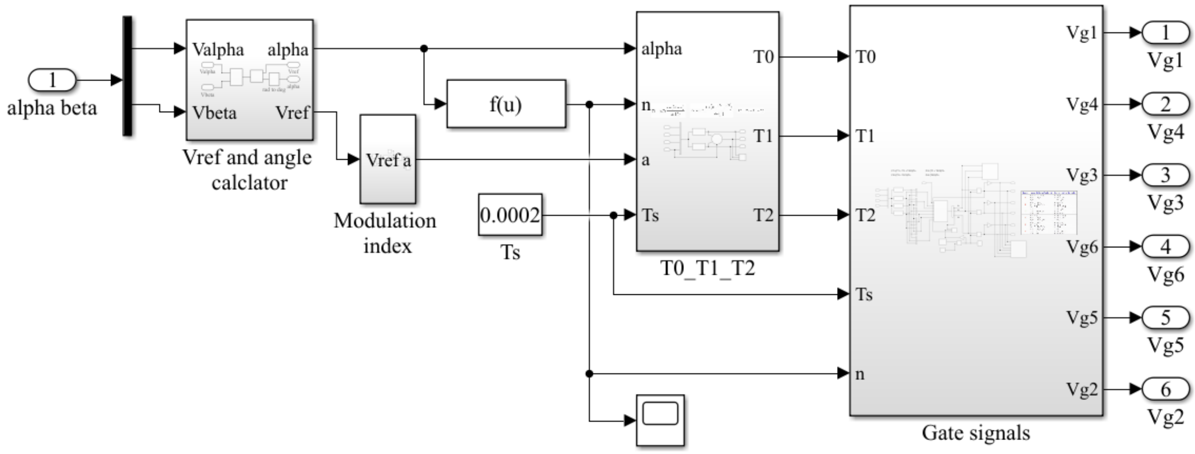

Figure 6.2: SVPWM Model

6.2 V Reference and angle Calculation

The V α and Vβ are converted to its magnitude and angle part using matlab blocks. The angle is in radian which is converted to degreed using rad to degree conversion block. The block insight is shown in the figure 6.3.

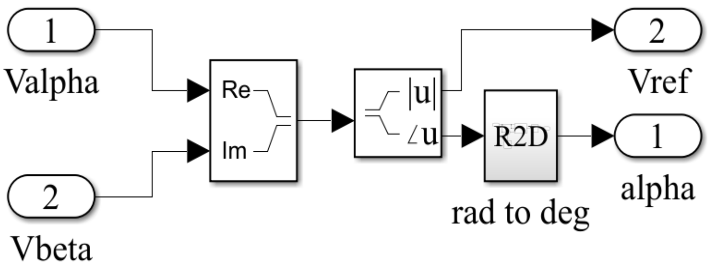

Figure 6.3: Reference Voltage and angle Calculation

6.3 Sector Number and Modulation index calculation

Vref is used to calculate the modulation index using he formula (6.1).

$$a = \frac{|Vref|}{(2/3)Vs} \tag{6.1}$$

The modulation index cannot be greater than 0.866. It is the upeer limit of the modulation index because beyond this value the switching time of vectors will be negative which cannot possible. Figure 6.4 Shoes the modulation index calculation block. The angle in degrees is used to calculate the sector number using the formula (6.2).

$$Quotient(angle/60) + 1 \tag{6.2}$$

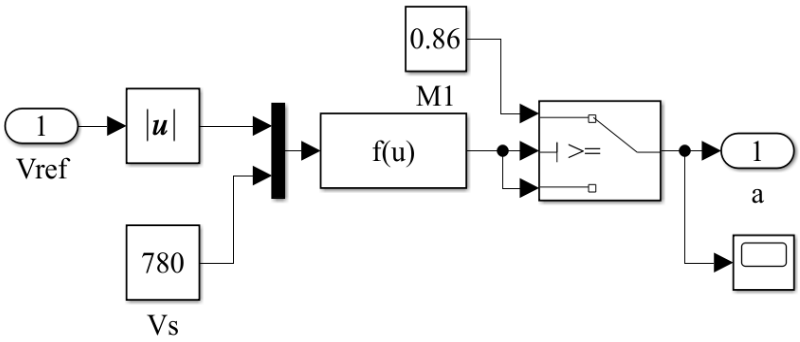

FIGURE 6.4: Modulation index calculation

6.4 On Time calculation of 3 vectors

The on time of 2 vectors T1 T2 and of a null vector T0 are calculated in the time calculation block. This time will be used to calculate the duty cycle of high side switches by dividing the on time of these three vectors by total time period. The formulas to calculate T0 T1 and T2 are give in equation (6.3),(6.4) and (6.5) and the simulink implementation are shown in figure. 6.5

$$T1 = a.Ts\frac{\sin\frac{n\pi}{3} - \alpha}{\sin\frac{\pi}{3}} \tag{6.3}$$

$$T2 = a.Ts\frac{\sin\alpha - \frac{(n-1)\pi}{3}}{\sin\frac{\pi}{3}} \tag{6.4}$$

$$T0 = Ts - T1 - T2 \tag{6.5}$$

6.5 Duty cycle and Pulse generation:

In this section, we will be generating, duty cycle corresponding to time signal and then we will be creating pulses by comparing it with saw tooth waveform. From our past knowledge and observation, we can know that we need to apply "Centrally aligned" technique in our inverter, as it has advantages over other method, which includes less switching loss and a pattern of signal.

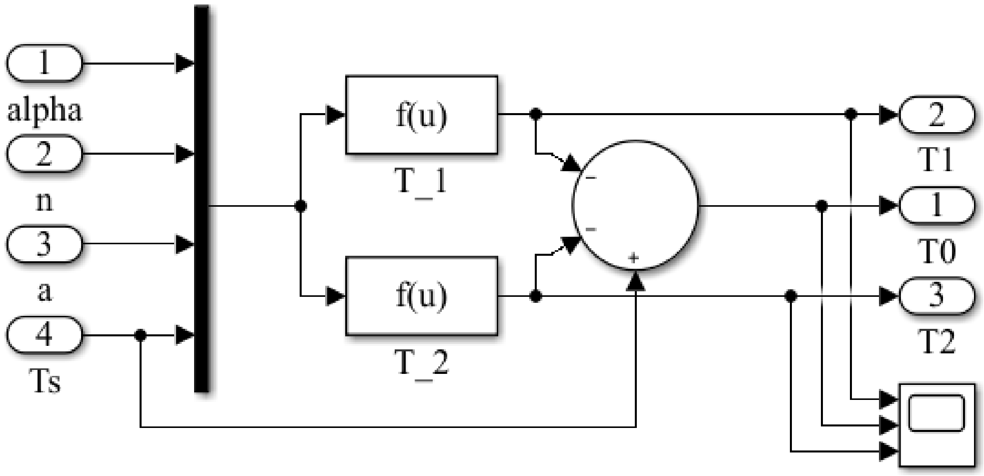

Figure 6.5: Time Calculation in Simulink

1. First of all, we concluded from central aligned signal, that there are total 4 time signal for 6 sectors which repeat in different sectors so we made function block and we used a compared block with 6 mux (which take input from that 4 gating time signals), Which will pass that combination of duty cycle with which out sector number will match. So let's suppose, we have n=1 , our first Mux will give output as duty cycle and so on.

2. After calculating duty cycle for each sector number from 1 to 6, we then need to create pulse for gating signals as output and these output will be given as input to our inverted BJTs. For that, we have compared this value with Saw tooth waveform with reference voltage= 1 and this will produce difference pulse for each duty cycle. These three pulses for high side switches, so for low side switches we have taken Not gate and that will be given to corresponding low side switches , the output of svpwm is given below in Output section.

Sector	Upper Switches S1,S3,S5	Lower Switches S4,S6,S2
1	S1=T1+T2+T0/2 S3=T2+T0/2 S5=T0/2	S4=T0/2 S6=T1+T0/2 S2=T1+T2+T0/2
2	S1=T1+T0/2 S3=T1+T2+T0/2 S5=T0/2	S4=T2+T0/2 S6=T0/2 S2=T1+T2+T0/2
3	S1=T0/2 S3=T1+T2+T0/2 S5=T2+T0/2	S4=T1+T2+T0/2 S6=T0/2 S2=T1+T2+T0/2
4	S1=T0/2 S3=T1+T0/2 S5=T1+T2+T0/2	S4=T1+T2+T0/2 S6=T2+T0/2 S2=T0/2
5	S1=T2+T0/2 S3=T0/2 S5=T1+T2+T0/2	S4=T1+T0/2 S6=T1+T2+T0/2 S2=T0/2
6	S1=T1+T2+T0/2 S3=T0/2 S5= T1+T0/2	S4=T0/2 6=T1+T2+T0/2 S2=T2+T0/2

TABLE 6.1: Sector Number and Switching Sequence

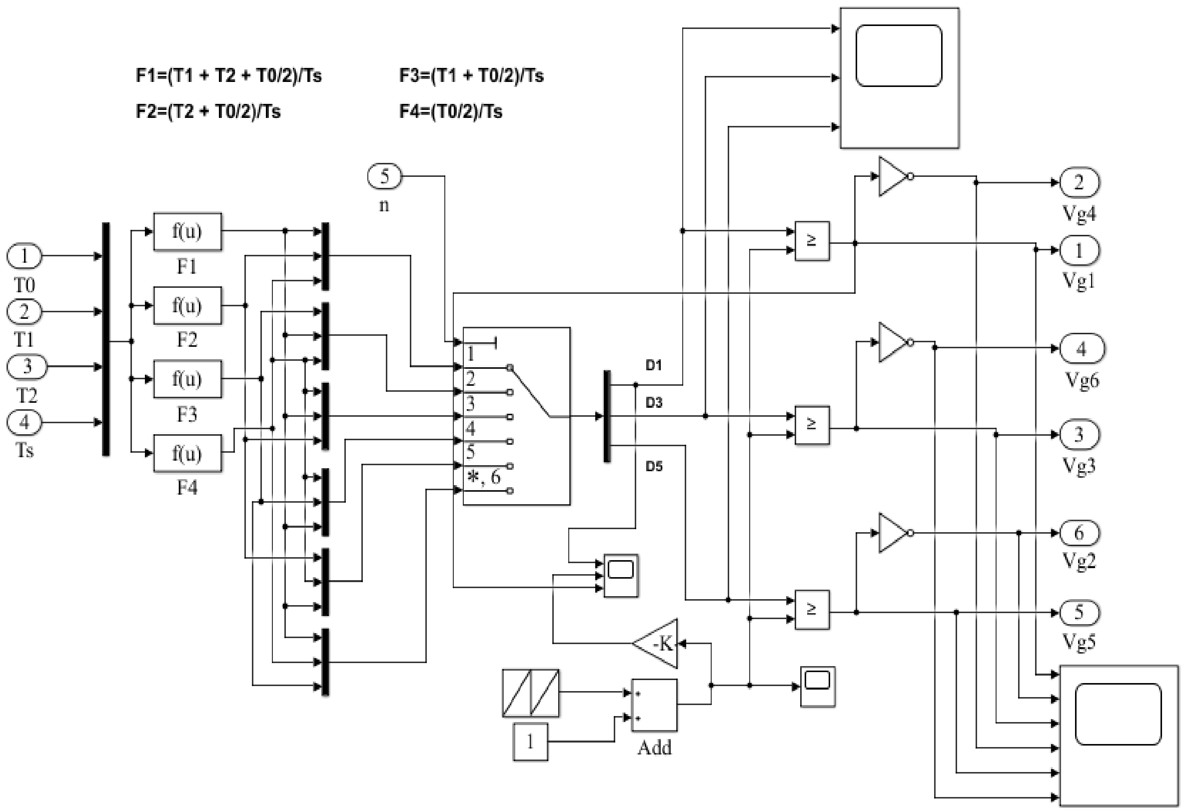

FIGURE 6.6: Duty cycle and Pulse generation in Simulink

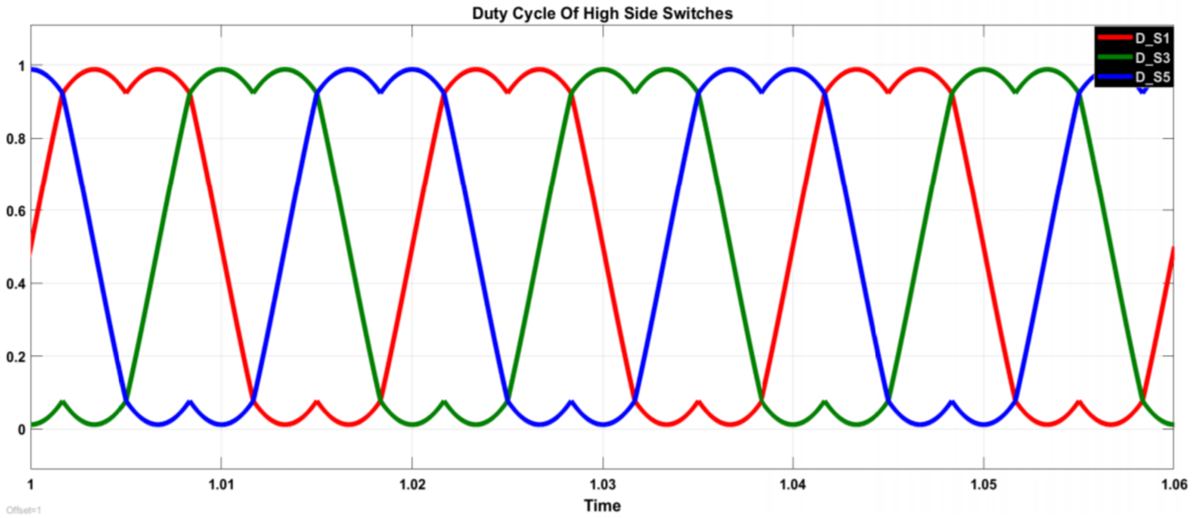

FIGURE 6.7: Duty Cycle for SVPWM

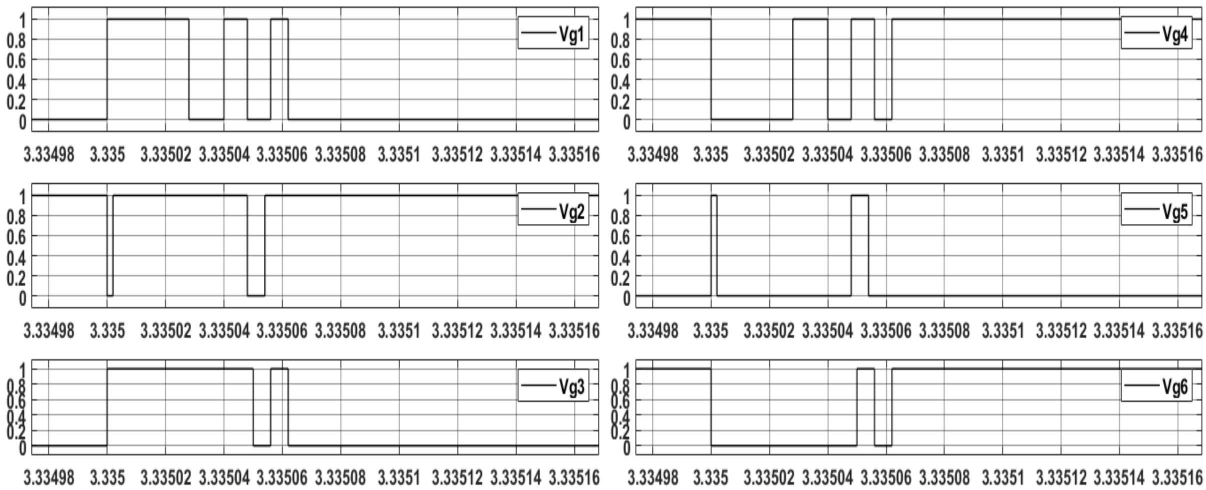

FIGURE 6.8: Gate Signals

Chapter 7

Sensored FOC Implementation on Induction Motor

Field-oriented control (FOC) also known as vector control, FOC is the first technology to control the motor flux and torque by converting the stator currents of a three-phase induction motor to two orthogonal components (dq) that can be represented with a vector. One component (d) defines the magnetic flux of the motor, while the other component (q) defines the torque. Both components are controlled independently that provides more control over the motor. The control system of the field-oriented control drive calculates the corresponding d and q component of current from the flux and torque references currents provided by the drive's flux and speed control. The q component is always adjusted such that it is quadrature to the rotor flux to produce the maximum torque for that current. Proportional-integral (PI) controllers are used to keep the measured motor current component to the desired current component values. The space vector pulse-width modulation provides the transistor switching signals according to the stator voltage references that are the output of the PI current controllers.

First, the stator phase currents are measured. These measured currents are passed through the Clarke transformation block. The outputs of this blocks are isα and isβ. These two components of the current are then passed through the Park transformation block that convert the current in the d, q or synchronous reference frame. The isd and isq components are compared to the references: isdref (the flux reference) and isqref (the torque reference). The error is fed to the PI controller which map the current error to the d and q components of voltage to achieve the desired speed and torque. The outputs of the PI controllers are Vsdref and Vsqref. They are passed through the inverse Park transformation block. The outputs of this block are Vsαref hbt!

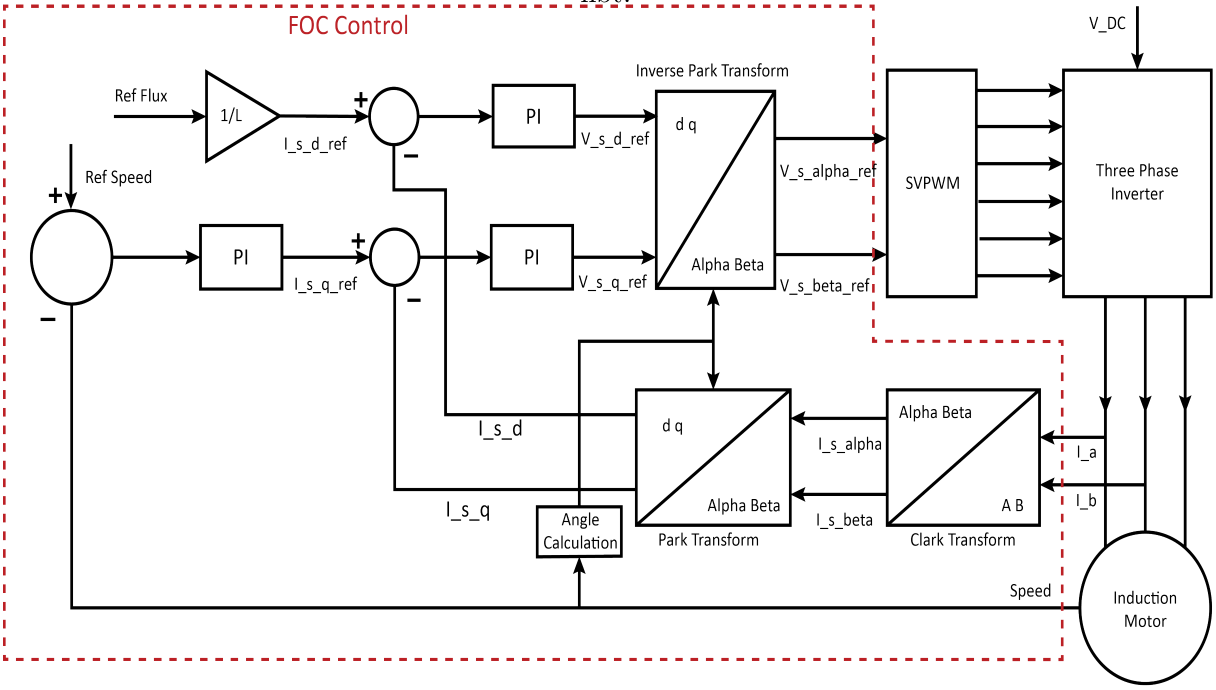

FIGURE 7.1: Block Diagram of Sensored FOC

and Vsβref and are fed to the space vector pulse width modulation (SVPWM) algorithm block. The outputs of this block provide signals that drive the inverter. Here both Park and inverse Park transformations need the rotor flux position. Hence rotor flux position is essence of FOC.

7.1 Main Block

The below figure 8.13 shows the complete model of the field-oriented control drive of an induction motor.

7.1.1 Model Parameters

All defined model parameters are given below;

$Sampling\ Time\ Ts\ =\ 2e-6;$

$Nominal\ Power\ S\ =\ 50*746;$

$Stator\ Voltage\ Vs\ =\ 460;$

$Supply\ Frequency\ f\ =\ 50;$

$Stator\ Resistance\ Rs\ =\ 0.087;$

$Rotor\ Resistance\ Rr\ =\ 0.228;$

$Stator\ Inductance\ Lls\ =\ 0.0001;$

$Rotor\ Inductance\ Llr\ =\ 0.0008;$

$Magnetizing\ Inductance\ Lm\ =\ 0.0347;$

$Number\ of\ Poles\ P\ =\ 4;$

$Time\ constant\ of\ Rotor\ Tr\ =\ (Llr + Lm)/Rr;$

$Inertia\ J\ =\ 0.662;$

$Friction\ Factor\ F\ = 0.1;$

The motor stator currents, and rotor speed is measured using the sensors. The stator current is passed through forward Clarke and park transformation to convert the stator currents from ABC reference frame to the DQ (synchronous) reference frame to simplify the control algorithm.

7.2 Forward Clarke Transformation

Clarke transformation converts three-phase stator currents (abc frame) to two components in an orthogonal stationary reference frame ($\alpha\beta$ frame). The block 7.2 given below is the implementation on the base of these two equations for Forward Clarke Transformation. (7.1) and (7.2)

$$\alpha(t) = \frac{2}{3}a(t) - \frac{1}{3}b(t) - \frac{1}{3}c(t) \tag{7.1}$$

$$\beta(t) = \frac{1}{\sqrt{3}}b(t) - \frac{1}{\sqrt{3}}c(t) \tag{7.2}$$

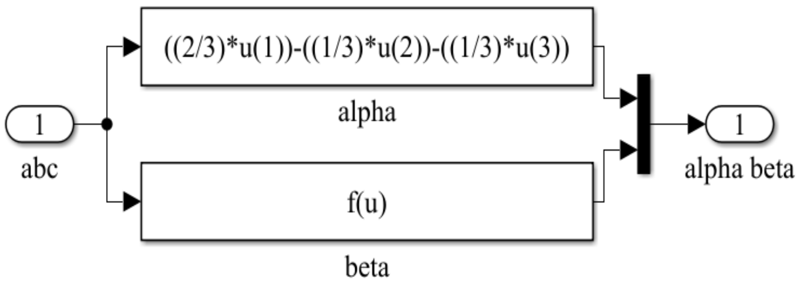

FIGURE 7.2: Forward Clark Transformation Block

7.3 Forward Park Transformation

Park transformation converts two components in an orthogonal stationary reference frame ($\alpha\beta$) frame) into orthogonal rotating reference frame (dq frame). Orthogonal stationary reference frame, in which Iα (along α axis) and Iβ (along β axis) are perpendicular to each other, but in the same plane as the three-phase reference frame. Orthogonal rotating reference frame, in which Id is at an angle θ (rotation angle) to the α axis and Iq is perpendicular to Id along the q axis.

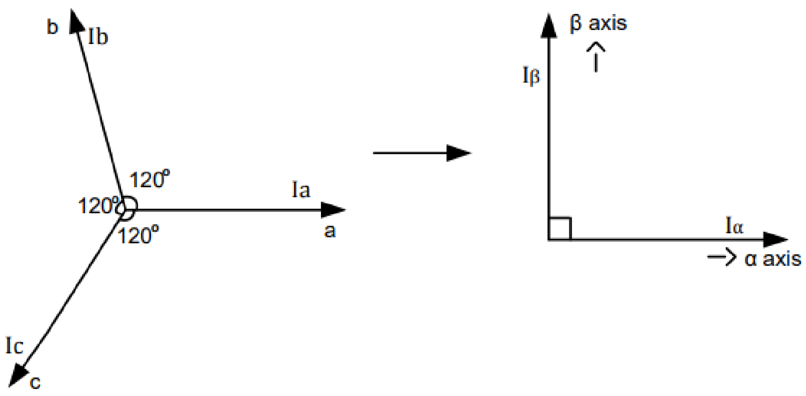

FIGURE 7.3: Clarke Transformation

The block 7.5 given below is the implementation on the base of these two equations for forward Park Transformation. (7.3) and (7.4)

$$i_d = i_\alpha cos\theta + i_\beta sin\theta \tag{7.3}$$

$$i_q = -i_\alpha sin\theta + i_\beta cos\theta \tag{7.4}$$

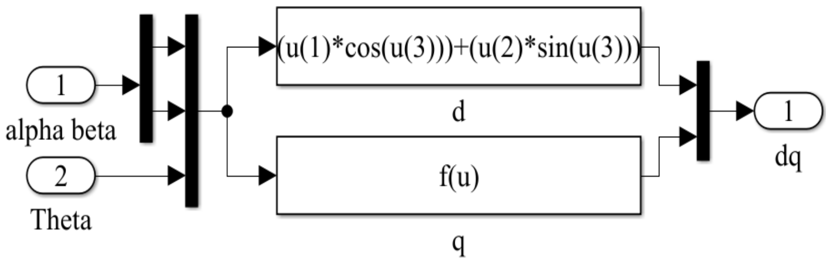

FIGURE 7.4: Forward Park Transformation Block

The main purpose of using the Clarke and park transform is to convert the three phase currents and voltages system into a two-coordinate linear time-invariant system. After making the system LTI is very simple and easy to implement PI controllers and simplifies the control of flux and torque producing currents components (dq). This reduces our calculation by about 40%. The d-axis component of the stator current vector is used to control the rotor flux linkage and the imaginary q-axis component is used to control the motor torque.

7.4 FOC Block

The below figure 7.6 shows the insight of the field-oriented control block. The DQ currents and rotor mechanical speed are the main inputs.

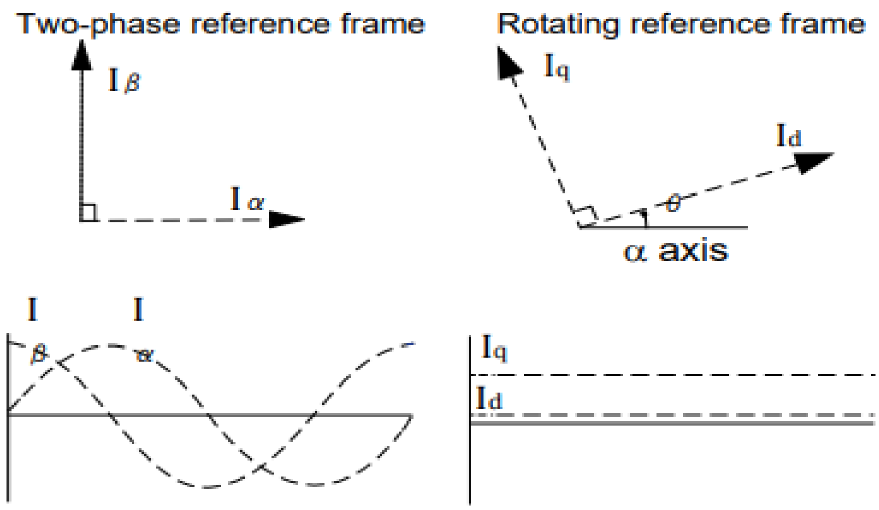

FIGURE 7.5: Park Transformation

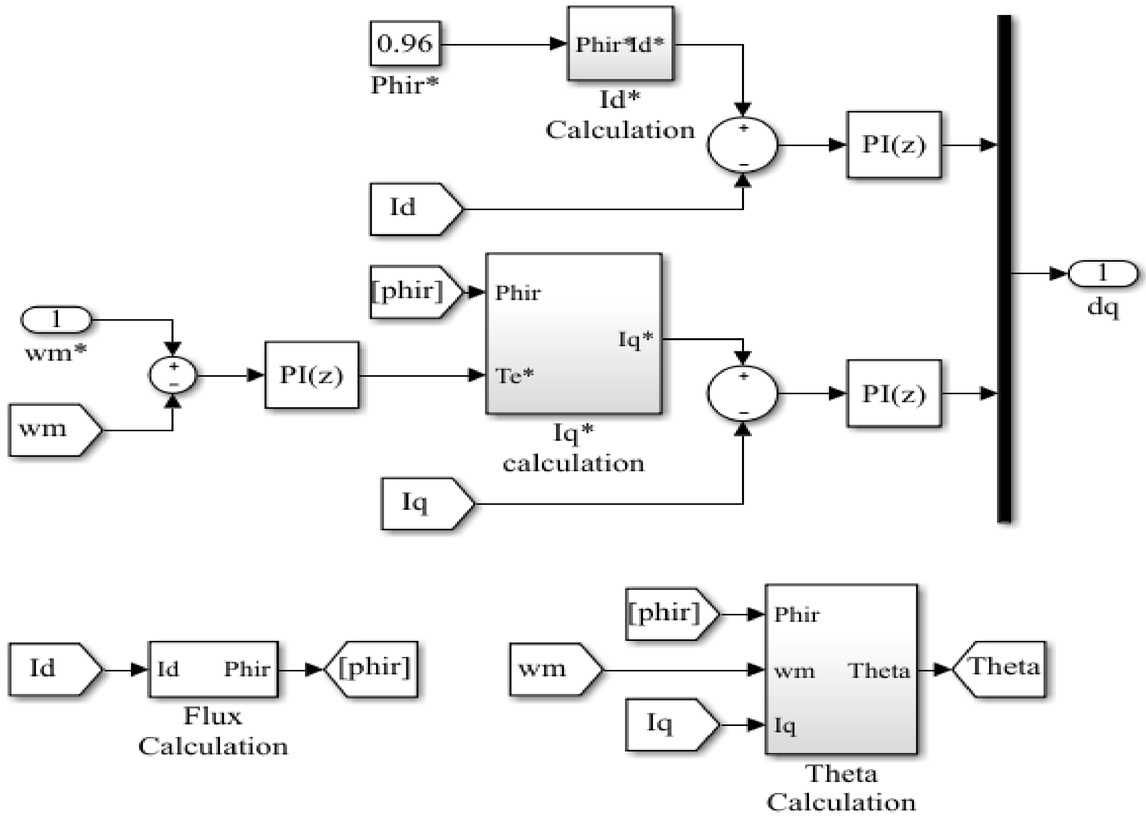

FIGURE 7.6: FOC Complete Model

7.4.1 Rotor Flux Estimation Block

Rotor flux linkage is calculated by multiplying the d component (which is responsible for the flux in the rotor) of stator current with magnetizing inductance Lm and passing the result through a low pass filter with the rotor no-load time constant Tr=Lr/Rr which is the rotor inductance to rotor resistance ratio.The formulas for rotor flux are in equation (7.5),(7.6) and (7.7).

$$\phi_r = L_m I_d \frac{1}{1 + T_r s} \tag{7.5}$$

$$Passing\ {}_r \ = \ L_m I_d \ through\ low\ pass\ filter \tag{7.6}$$

$$\therefore\ rotor\ time\ constant\ T_r \ = \ \frac{(L_{lr} + L_m)}{R_r} \tag{7.7}$$

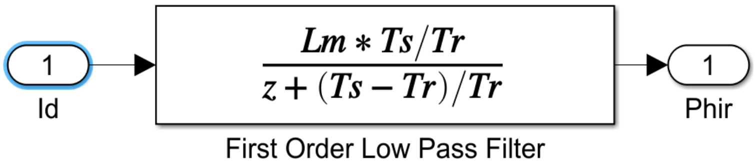

FIGURE 7.7: Rotor Flux Calculation Block

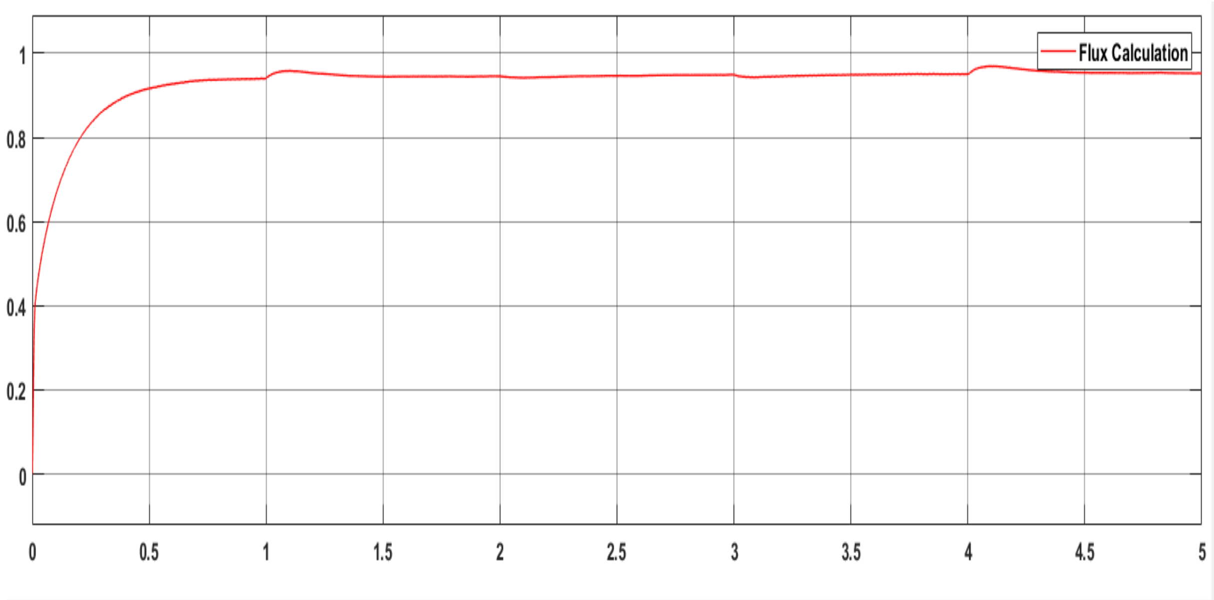

FIGURE 7.8: Rotor Flux Waveform

7.4.2 Rotor Flux Angle Estimation Block

Rotor flux angle is needed for the forward and reverse park transformation. It is calculated using the rotor flux calculated above, rotor speed and the quadrature component of current I_q. The electrical angle is calculated by integrating the sum of rotor flux frequency and rotor mechanical speed. The frequency of electric flux produced in the rotor is calculated by dividing the quadrature component of flux with the direct component of flux. The formulas for rotor flux angle are in equation (7.8),(7.9) and (7.10).

$$Rotor\ Flux\ angle\ \ =\ \phi_r = \int(\omega_r + \omega m) \tag{7.8}$$

$$Rotor\ Frequency\ \ = \omega_r = \frac{(L_m * I_q)}{(T_r * \theta_r)} \tag{7.9}$$

$$\therefore \omega_m = Rotor\ mechanical\ speed\ (rad/s) \tag{7.10}$$

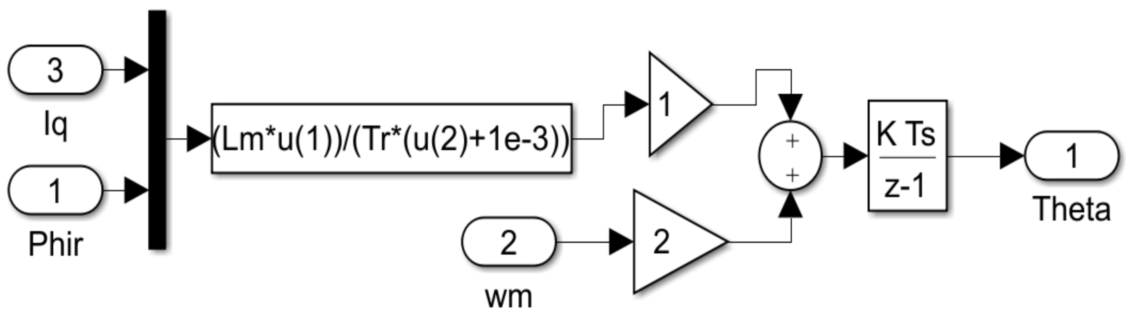

FIGURE 7.9: Electrical Flux Angle Calculation Block

7.4.3 Reference Id estimation block

The desired direct and quadrature component of current corresponding to the desired or required speed is calculated. For the calculation of the direct component of current (Id), the rotor flux is set to a constant positive value. It cannot set to be zero unlike permanent magnet synchronous motor because the flux is to be induced in the rotor through the stator. This flux is then divided by mutual inductance L_m to calculate the required direct component of current (I_d). This figure 7.10 shows the insight of the required Id current calculation and is implemented by using these equations(7.11)

$$I_d = \frac{\phi_r}{L_m} \tag{7.11}$$

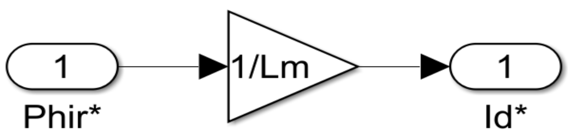

FIGURE 7.10: Reference Id estimation block

7.4.4 Reference Iq estimation block

The difference or error in the required rotor speed and desired rotor speed is fed to PI controller which map the error to the reference torque which is required to rotate the rotor at the desired speed. This required torque and the rotor flux (which is responsible for the torque induced in the motor) are used to calculate the required quadrature component of current (which is responsible for the torque generated by the motor). The figure 7.11 shows the insight of the reference Iq current block

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_{lr}+L_m}I_q\phi_r \tag{7.12}$$

$$I_q = \frac{3}{2}\frac{2}{P}\frac{L_{lr}+L_m}{L_m}\frac{T_e}{\phi_r} \tag{7.13}$$

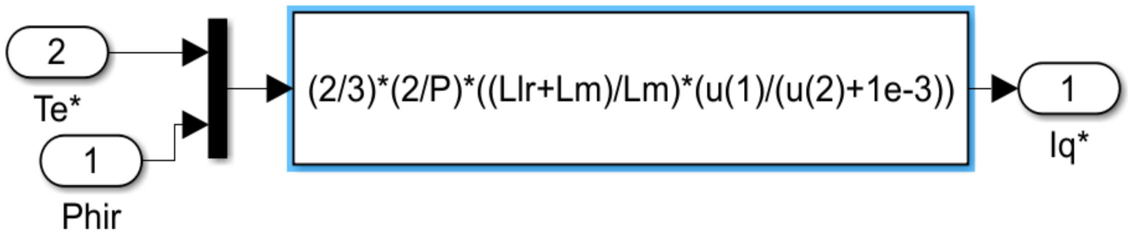

FIGURE 7.11: Reference Iq estimation block

7.5 PI Controller

The required direct and quadrature component of current and the actual direct and quadrature component of current are compared, and the error is fed to the two separate PI controllers (one for I_d and one for I_q). The PI controller maps the error current to the required direct and quadrature component of voltage which is required to produce the desired torque and speed.

7.6 Inverse Park Transformation

The required direct and quadrature component of current and the actual direct and quadrature component of current are compared, and the error is fed to the two separate PI controllers (one for Id and one for Iq). The PI controller maps the error to the required direct and quadrature component of voltage which is required to run the motor at the desired speed. Vd=(Kp+(Ki/s))id and Vq=(Kp+(Ki/s))iq. Here Kp and Ki are the proportional and integral gains. Which can bhe adjusted to obtain a better performance. The direct and quadrature component of voltage is converted to alpha and beta components using the inverse park transformation. The below figure 7.13 shows the insight of the inverse park transform block.

$$v_\alpha = v_d cos - v_q sin\theta \tag{7.14}$$

$$v_\beta = v_q sin + v_d cos\theta \tag{7.15}$$

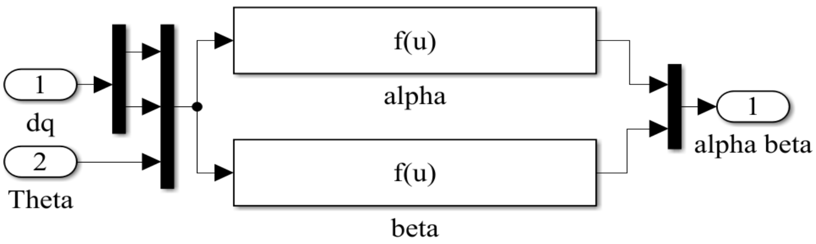

Figure 7.12: Inverse Park Transformation Block

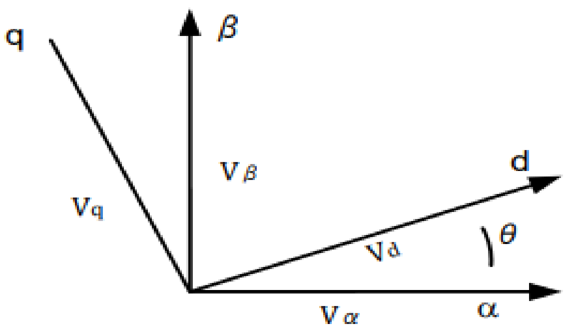

Figure 7.13: Inverse Park Transformation

7.7 Output Waveform

7.7.1 Comparison between Desired and Actual Speed

In the figure 7.14 the blue line represents the reference speed of the motor while the red line is the actual speed of the motor. PI controller are tuned to obtain the closed speed of the rotor to the desired speed.PI controller can be further tuned to achieve maximum possible Rotor Speed.

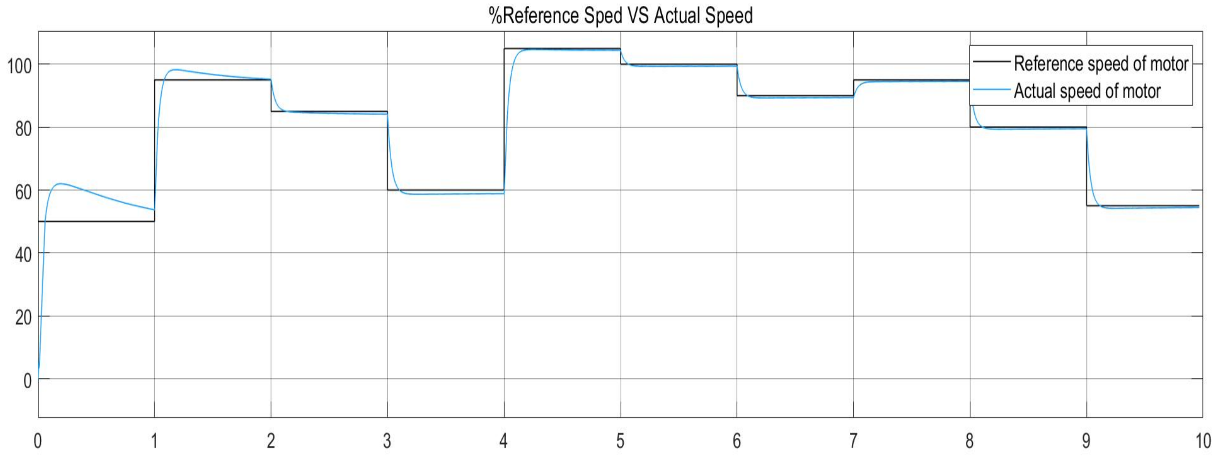

Figure 7.14: Reference Speed and Rotor Speed Comparison

7.7.2 DQ Components of Current

In above graph 7.15 Blue waveform indicate D component of stator Current and Orange waveform shows Q component of stator current.

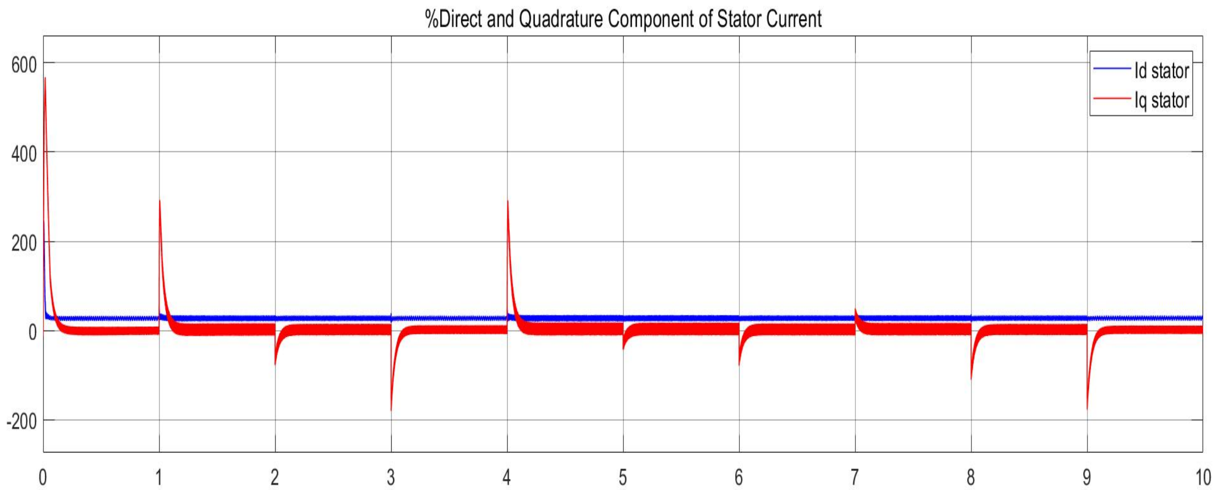

Figure 7.15: DQ components of stator Current Waveform

7.7.3 Three Phase Motor Current

The below graph 7.16 shows the Three phase stator current of the motor.

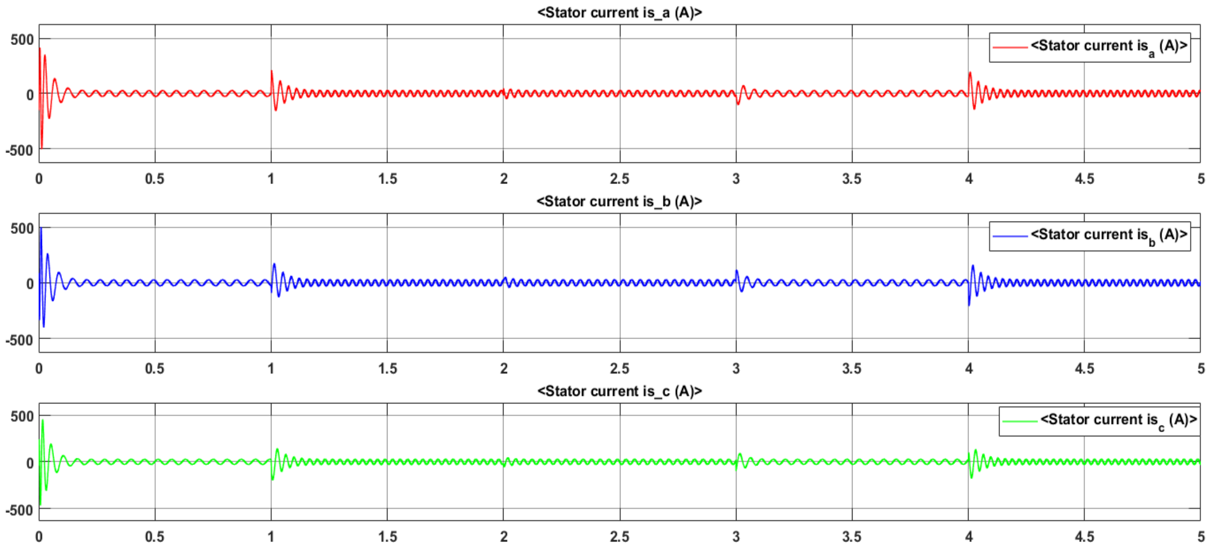

FIGURE 7.16: Three Phase Stator Current Waveform

7.7.4 Electromagnetic Torque

The Electromagnetic torque output waveform is shown in figure. 7.17

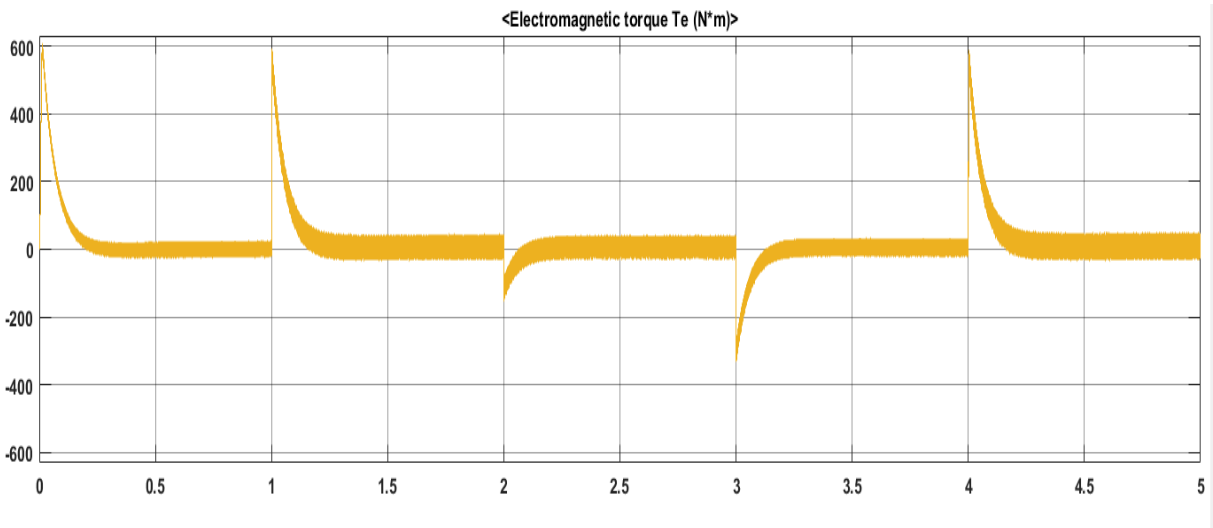

FIGURE 7.17: Motor Torque Waveform

Chapter 8

Sensor-less FOC Implementation on Induction Motor

This is the sensor less Field Oriented Control Implementation on Induction Motor using SVPWM, the only difference is with flux and speed estimation which is explained in further sections.

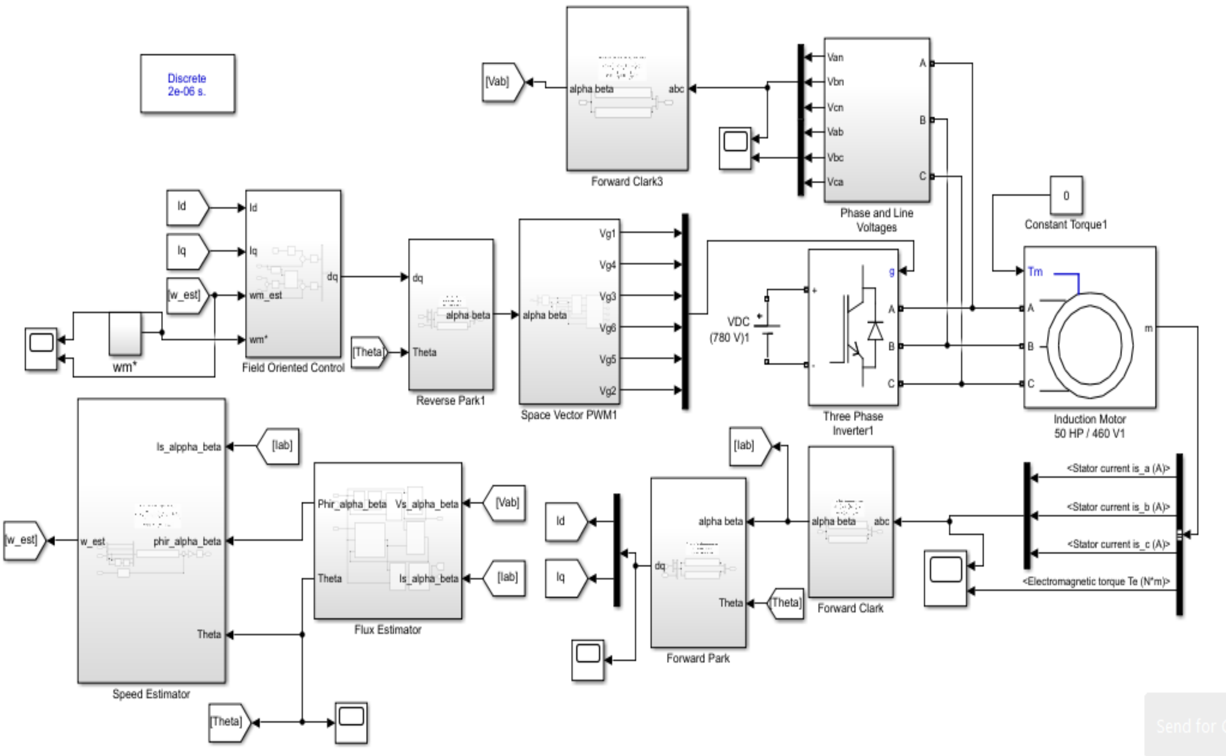

Figure 8.1: Complete Model of Sensor-less FOC implemented on Induction Motor

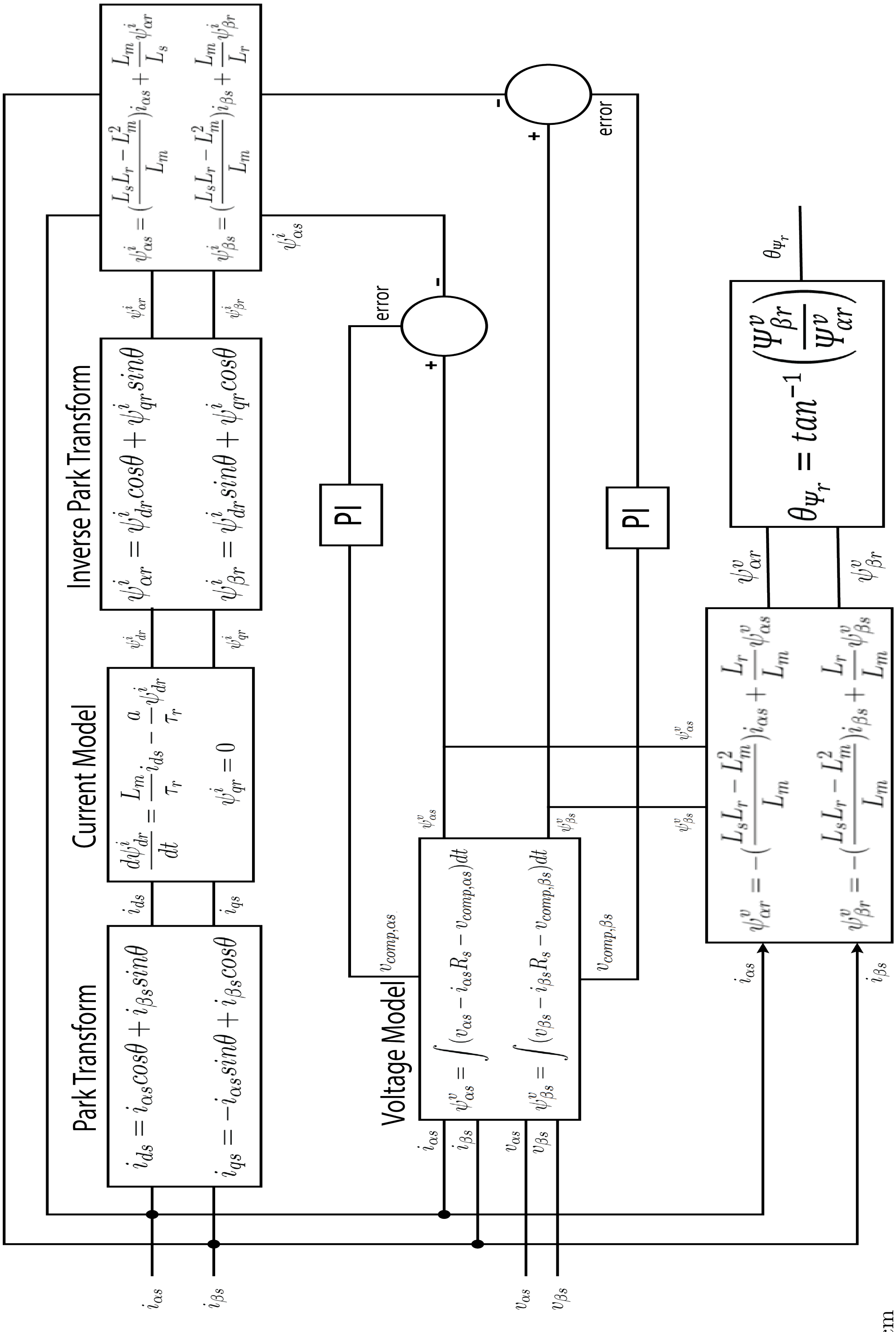

FIGURE 8.2: Flux Estimation Block Diagram

cm

8.1 Flux Estimation

Flux estimation is used in this section will compute both the synchronous speed And the rotor speed. The logic behind the flux observer is an advanced A voltage model approach in which the integration of back-emf is computed and compensated for the errors associated with the Integrator and stator resistance Rs Measurement at low speeds. The voltage model provides an accurate stator flux estimation at high speeds because the machine back emf dominates the measured terminal voltage. At low speeds, the stator IR drop becomes significant, causing the accuracy of the flux estimates to be sensitive to the estimated stator resistance and at low excitation frequencies, flux estimation based upon voltage model are generally not capable of achieving good dynamic performance at low speed. The consequences of these problems are compensated with the addition of a closed-loop in the flux observer.[5] The fluxes obtained by the current model are compared with those obtained by the voltage model regarding the current model, or the current model regarding the voltage model.

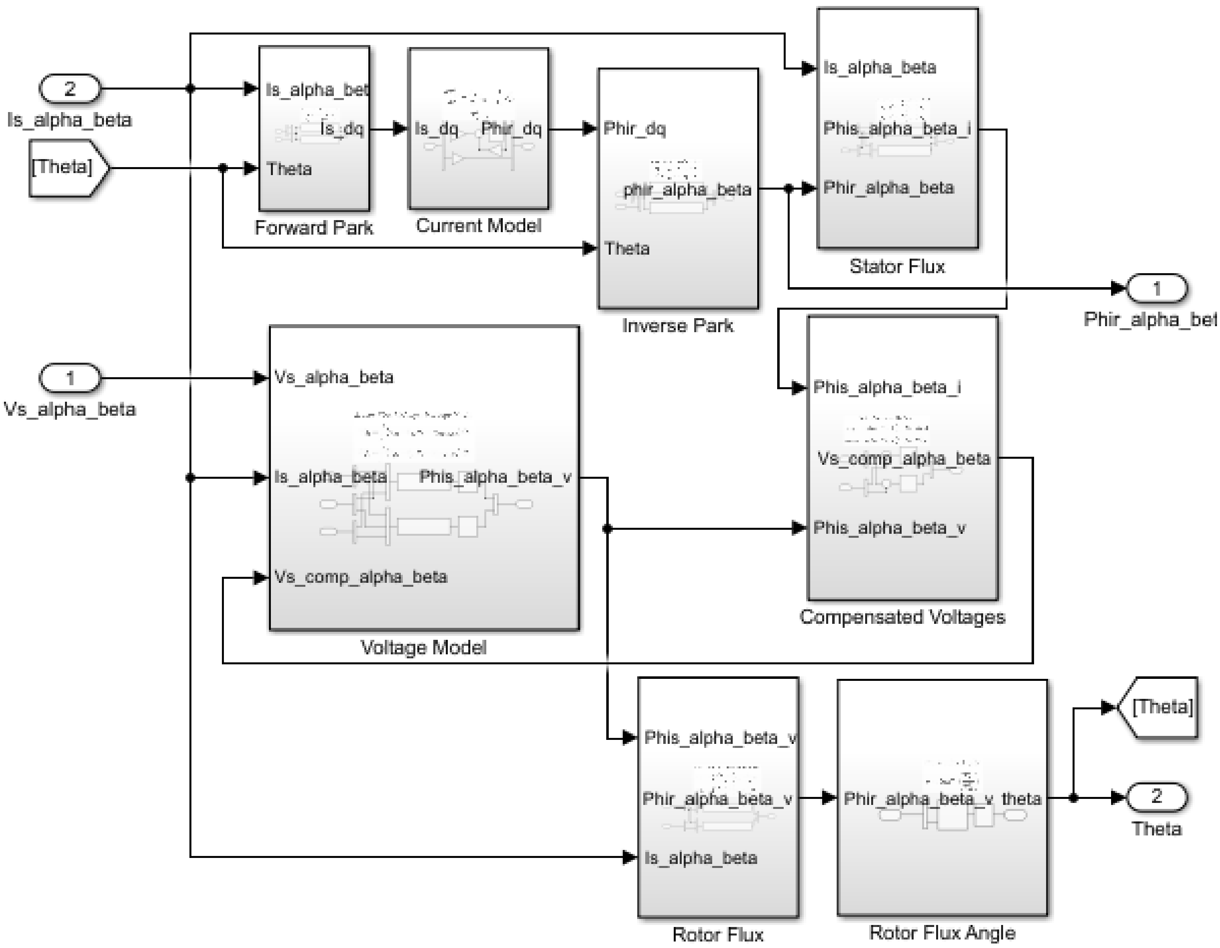

FIGURE 8.3: Flux Estimation Block

8.1.1 Forward Park Transformation

$$i_{ds} = i_{\alpha s} cos\theta + i_{\beta s} sin\theta \tag{8.1}$$

$$i_{qs} = -i_{\alpha s} sin\theta + i_{\beta s} cos\theta \tag{8.2}$$

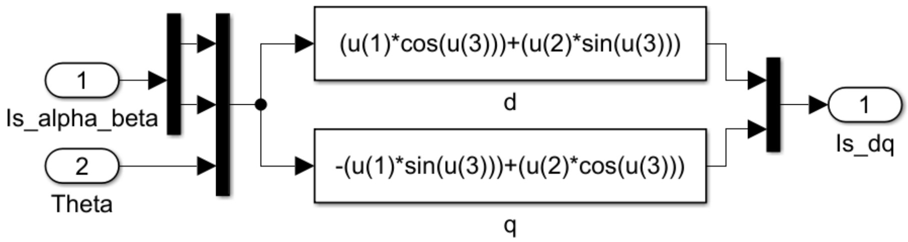

FIGURE 8.4: Forward Park Transformation

8.1.2 Current Model

$$\frac{d\psi^i_{dr}}{dt} = \frac{L_m}{\tau_r} i_{ds} - \frac{a}{\tau_r} \psi^i_{dr} \tag{8.3}$$

$$\psi^i_{qr} = 0 \tag{8.4}$$

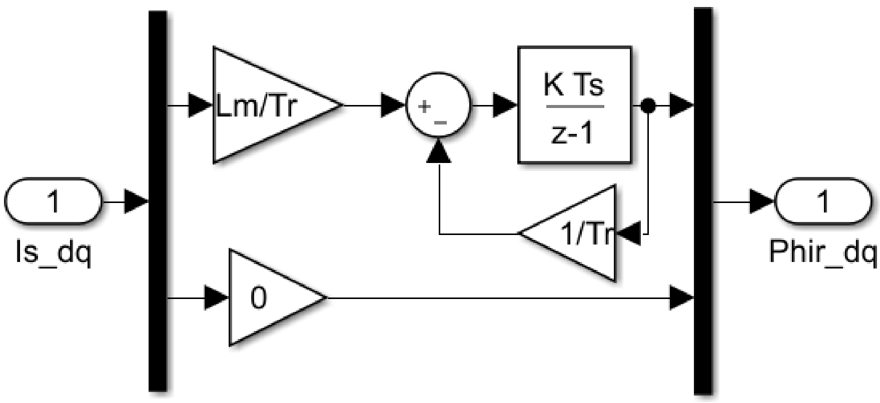

FIGURE 8.5: Current Model

8.1.3 Inverse Park Transformation

$$\psi^i_{\alpha r} = \psi^i_{dr} cos\theta + \psi^i_{qr} sin\theta \tag{8.5}$$

$$\psi^i_{\beta r} = \psi^i_{dr} sin\theta + \psi^i_{qr} cos\theta \tag{8.6}$$

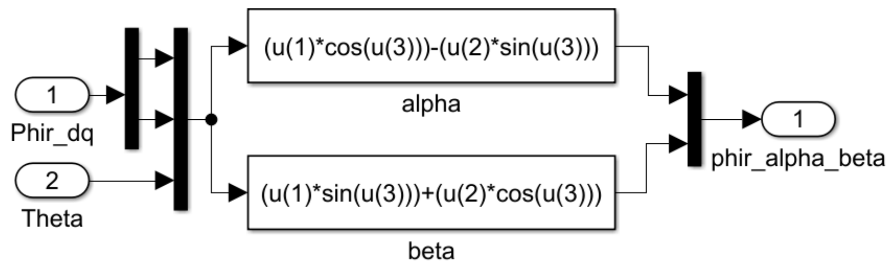

FIGURE 8.6: Inverse Park Transformation

8.1.4 Stator Flux Linkages

$$\psi^i_{\alpha s} = (\frac{L_s L_m - L_r^2}{L_r}) i_{\alpha s} + \frac{L_m}{L_r}\psi^i_{\alpha r} \tag{8.7}$$

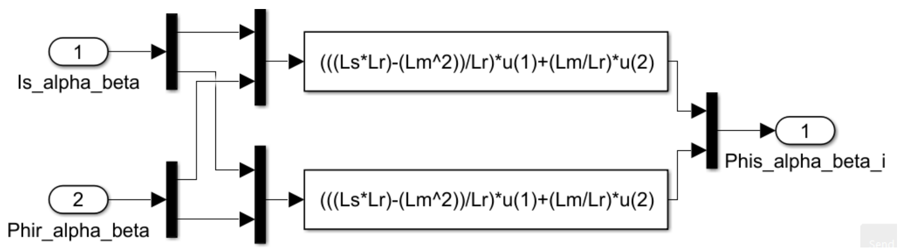

FIGURE 8.7: Stator Flux Linkages

8.1.5 Stator Compensated Voltage

$$v_{comp,\alpha s} = K_p(\psi^v_{\alpha s} - \psi^i_{\alpha s}) + \frac{K_p}{T_I}\int(\psi^v_{\alpha s} - \psi^i_{\alpha s})dt \tag{8.8}$$

$$v_{comp,\beta s} = K_p(\psi^v_{\beta s} - \psi^i_{\beta s}) + \frac{K_p}{T_I}\int(\psi^v_{\beta s} - \psi^i_{\beta s})dt \tag{8.9}$$

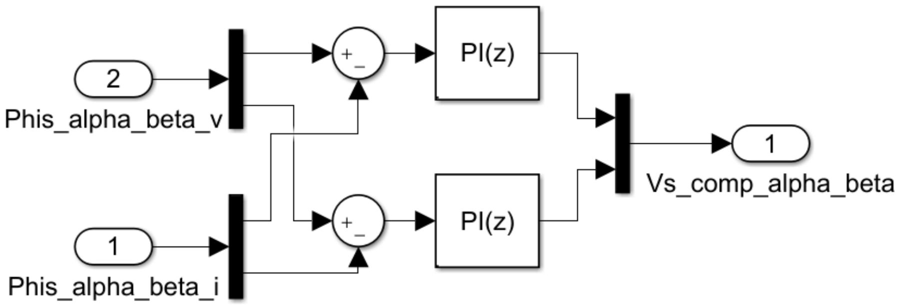

FIGURE 8.8: Stator Compensated Voltage

8.1.6 Stator Flux Linkages Voltage Model

$$\psi^i_{\alpha s} = (\frac{L_s L_r - L_m^2}{L_m}) i_{\alpha s} + \frac{L_m}{L_s} \psi^i_{\alpha r} \tag{8.10}$$

$$\psi^i_{\beta s} = (\frac{L_s L_r - L_m^2}{L_m}) i_{\beta s} + \frac{L_m}{L_r} \psi^i_{\beta r} \tag{8.11}$$

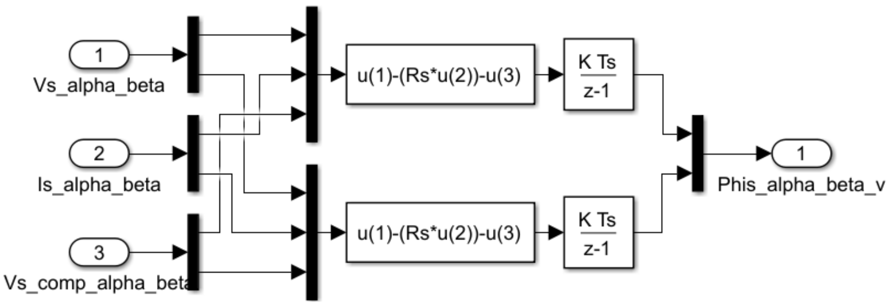

FIGURE 8.9: Stator Flux Linkages Voltage Model

8.1.7 Rotor Flux Linkages Voltage Model

$$\psi^v_{\alpha r} = -(\frac{L_s L_r - L_m^2}{L_m}) i_{\alpha s} + \frac{L_r}{L_m} \psi^v_{\alpha s} \tag{8.12}$$

$$\psi^v_{\beta r} = -(\frac{L_s L_r - L_m^2}{L_m}) i_{\beta s} + \frac{L_r}{L_m} \psi^v_{\beta s} \tag{8.13}$$

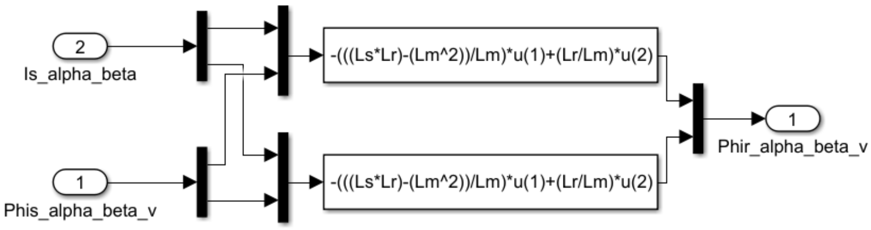

FIGURE 8.10: Rotor Flux Linkages Voltage Model

8.1.8 Rotor Flux Angle

$$\theta_{\psi r} = \arctan \frac{\psi^v_{\beta r}}{\psi^v_{\alpha r}} \tag{8.14}$$

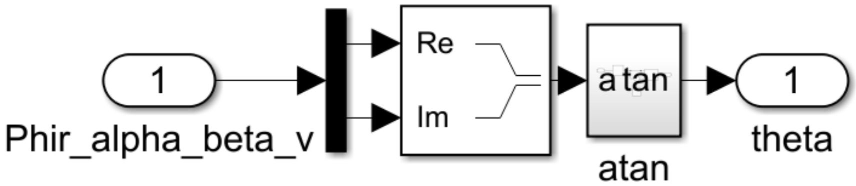

FIGURE 8.11: Rotor Flux Linkages Voltage Model

8.2 Speed Estimation

In this section, a speed observer for the three-phase induction motor is designed mathematically. The estimatorâs accuracy depends mainly on the knowledge of critical motor parameters. The open-loop speed estimator implemented in this FOC structure is a popular method based on a stationary reference frame. The structure of this algorithm is very easy when compared to the advanced estimation techniques.

$$\omega_m = \frac{2}{P}[\frac{d\theta}{dt} - \frac{1}{(\psi^i_r)^2}\frac{L_m}{\tau_r}[\psi^i_{\alpha r} i_{\beta s} - \psi^i_{\beta r} i_{\alpha s}]] \tag{8.15}$$

$$\psi^i_r = \sqrt{{\psi^i_{\alpha r}}^2 + {\psi^i_{\beta r}}^2} \tag{8.16}$$

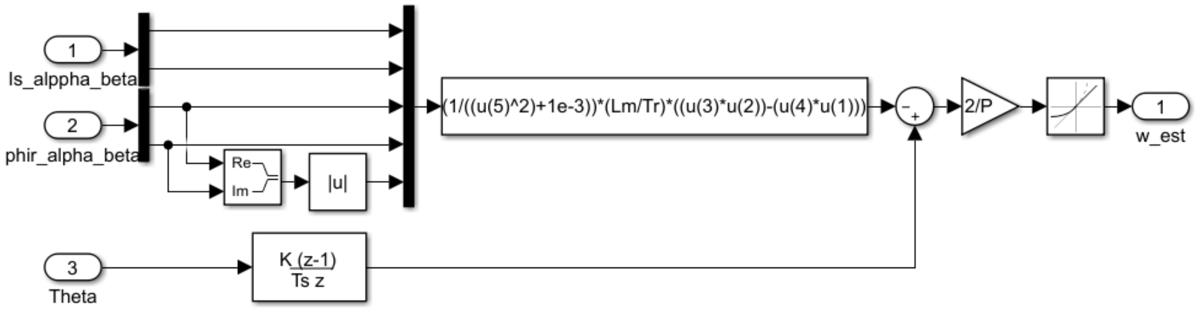

FIGURE 8.12: Block Diagram for FOC Implementation

8.3 Resutlt

This is the graph of output speed of Sensorless field oriented control implemented induction motor chasing reference speed, which is almost same ae

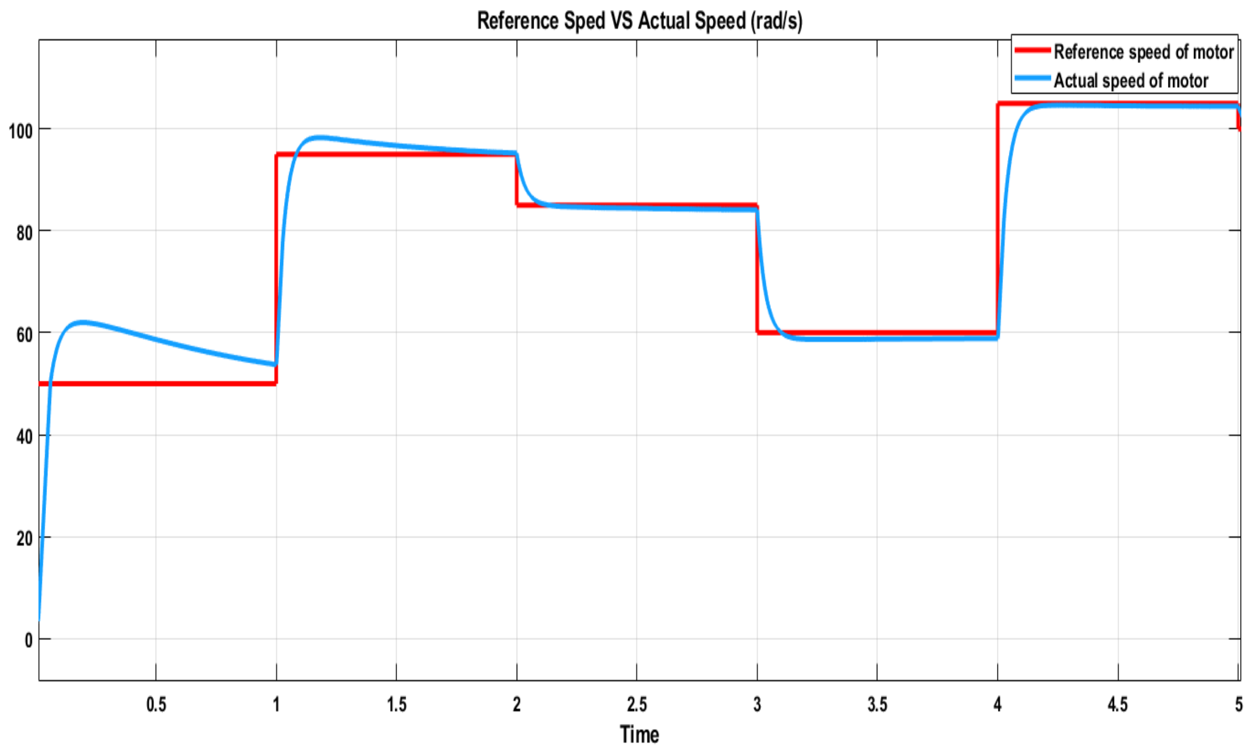

FIGURE 8.13: Complete Model of Sensor-less FOC implemented on Induction Motor

Chapter 9

Conclusion and Future Works

This project endeavors to the improvisation of both sensored and sensor-less field-oriented control (FOC) for the induction motor. PI feedback controllers are used to maintain the parameters at desired values. We implemented Space Vector PWM Technique to generate a gate signal for the inverter from the correction voltages generated by the PI controller. Future Works can be listed as;

1. implement controller and feedback techniques like fuzzy logic or Particle Swarm Optimization (PSO).

2. The machine parameters and the rotor time constant can be estimated and it can be used in the flux estimator model and can be improved by closed-loop control.

3. Implementation of neurologic based FOC drives

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