Addis Ababa University

Addis Ababa Institute Of Technology

School Of Electrical & Computer Engineering

Hybrid Fuzzy-PI Speed Control of Five Phase Induction Motor Vector Control

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Approval by Board of Examiners

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Abstract

In this thesis hybrid Fuzzy-PI control speed control of five-phase induction motor vector control is modeled. For modeling purpose five phase squirrel-cage induction motor is selected. This selected motor is analyzed on d-q synchronously rotating reference frame. Also third and fifth harmonics did not considered & fundamental harmonics is taken in to consideration.

In this thesis hybridization technique is applied by connecting both Fuzzy and PI controllers in parallel, giving a common error for both of them from speed comparator output.

The operation sequence first starts from FLC. Then, FLC tunes constants of PI (K_p & K_i), then PI controller produces command torque depending on values of (K_p & K_i) tuned by FLC.

Simulation output results show that the transient response of Fuzzy-PI is better than that of PI transient performances. For this work Matlab/Simulink is used in modeling and verification of models performances.

Keywords: Fuzzy Logic Controller, Induction Motor, d-q Transformation, Space Vector Modulation.

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List of Acronyms

PI	Proportional Integration
PID	Proportional Integral Derivative
FLC	Fuzzy Logic Controller
SVM	Space Vector Modulation
IGBT	Insulated Gate Bipolar Junction Transistor
VSI	Voltage Source Inverter
DC	Direct Current
PWM	Pulse Width Modulation
IM	Induction Motor
IFOC	Indirect Field Oriented Control

List of Symbols

θ	Rotor Flux Angle
T^*	Transformational Matrix
$V_{as}, V_{bs}, V_{cs}, V_{ds}, V_{es}$	Five Phase Stator Voltages
$I_{as}, I_{bs}, I_{cs}, I_{ds}, I_{es}$	Five Phase Stator Currents
w_r	Rotor Speed
w_e	Synchronous Speed
L_s	Stator Flux Linkage
L_r	Rotor Flux Linkage
L_m	Mutual Inductance
T_e	Electromagnetic Torque
T_l	Load Torque
J	Moment of Inertia
P	Poles
K_p, K_i	Proportional and Integral Gain Respectively
L	Inductance
R	Resistance
V_{dc}	DC Voltage
E	Error

w_{ref}	Reference Speed
w_{act}	Actual Speed
T_1, T_2, T_0	Switching Time
f_sw	Sampling Frequency
λ	Flux
w_{sl}	Slip Speed
I_d, I_q	Direct & Quadrature Currents
T_r	$\frac{L_r}{R_r}$
U	Output Signal

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Chapter One

Introduction

1.1 Background

For the past century, induction motor (IM) was widely used in the industry due to its simple and robust construction. Specially, three phase induction motor was widely used over the past years but, recently due to advancement of power electronics, multi-phase induction machine drives are fast increasing, due to their several inherent benefits such as lower torque pulsation, reduction in harmonic currents, reduced stator current per phase without the need to increase the phase voltage, greater reliability, fault tolerant feature and increased power in the same frame as compared to three phase machine [1].

To achieve optimal efficiency of induction motors, several control techniques have been developed to control the induction motor. Few of them are scalar control, vector or field oriented control and direct torque control. Scalar control is one of the first control techniques of induction motors. In this method the ratio of both the amplitude and frequency of the supply voltage is kept constant in order to maintain a constant air gap flux and hence provide maximum torque. Scalar control drives are easy to implement [2].

Over the years, the conventional control such as the proportional plus integral (PI), and proportional plus integral plus derivative (PID) controllers have been used together with vector control methods to better control the speed of induction motors. However, it must be pointed out that conventional controllers have major drawback such as performance sensitivity to variations in system’s parameters, and the fact that when using fixed gains the controller may not provide the required speed performance under variations in the motor parameters and operating conditions. In order to overcome these challenges, fuzzy logic controller has been used for motor speed control. The main advantage of fuzzy logic controller when compared to the conventional controller is that no mathematical model is required for the controller design [3].

Fuzzy logic has been successfully used to control ill-known or complex systems where precise modeling is difficult or impossible. It has been demonstrated that dynamic performance of electric drives as well as robustness with respect to parameter variations can be improved by adopting the nonlinear speed control techniques as in the ones fuzzy control provides and recently, hybrid control techniques based on combination of two or more control methods are proposed to enhance controller's performance. For this thesis the proposed method combine conventional controller with fuzzy logic controller and vector control technique to take advantage of the best attributes of both controllers and eliminate the drawbacks of conventional controller such as oscillation, overshoot, and undershoot[4].

The speed control algorithm is based on the indirect vector control. Specifically, Fuzzy-PI and PI for 5-phase induction motor drive has been designed. The performance of the proposed Fuzzy-PI and PI speed controller are simulated by Matlab/Simulink and tested at different dynamic operating conditions.

1.2 Statement of Problem

For the last many years, induction motor played a great role in industries activity. Even though this type of motor is a backbone of industries, it is not fully efficient due to perfection of the drivers or controlling techniques. For example, the mostly used domestic controlling mechanisms in industries like PI, PD and PID have limitations that affect performance of the motor. Specifically the mentioned controllers have problem of high overshoot and high undershoot in the transient performance analysis. Due to this case the performance of induction motor is reduced. Therefore hybrid way of cascading both fuzzy logic controller and PI controller creates better performance in improving the above limitations in terms of overshoot and undershoot. Because in hybridizing process fuzzy logic controller is flexible and designed easily without need of mathematical model using'' if-then'' approach and simple to cascade with PI controller.

1.3 Objective of Thesis

1.3.1 General Objective

- ✓ The general objective of this thesis work is to model and simulate hybrid Fuzzy-PI speed control of five phase induction motor vector control on Matlab/Simulink software.

1.3.2 Specific Objectives

- ✓ To model five phase induction motor on Matlab/Simulink.
- ✓ To model five phase voltage source inverter.
- ✓ To study dynamic model of IFOC five phase induction motor using space vector modulation.

1.4 Methodology

In this thesis the hybrid Fuzzy-PI speed control of five phase induction motor is modeled using space vector modulation. The SVM is used to generate pulses which are fed to five phase VSI in order to produce five phase voltages. Components of currents which produce torque are aligned with q-axis and components of currents which produce flux are aligned to d-axis.

Generally the summary of above is given by the following bullets:

- ✓ Surveying different literature on areas of speed controlling.
- ✓ Identify problems
- ✓ Model both five phase induction motor and inverter.
- ✓ Model hybrid Fuzzy-PI based indirect field oriented control (IFOC).
- ✓ Compare both PI and Fuzzy-PI controller speed response using Matlab/Simulink.
- ✓ Make conclusion and recommendation.

1.5 Literature Review

As mentioned in previous section, induction motors have been widely used in industry application. Therefore, much attention is given to their control for various applications with different control requirements. In recent years, intelligent control methods such as Fuzzy control, neural network control, and hybrid control have been proposed to enhance the performance of induction motors. Different control methods for speed control of induction motor are reviewed in the following literature survey:

Xu, Toliyat and Petersen [4] proposed five phase induction motor drives with DSP based control system. This paper introduces two kinds of control schemes: vector control and direct torque control (DTC). These control schemes can be extensively applied to the operation of a five-phase induction motor using a fully digital implementation. Direct torque control of the five-phase induction motor reduces the amplitude of the ripples of both the stator flux and the torque, resulting in a more precise flux and torque control. A 32-b floating-point TMS320C32 digital signal processor (DSP) enables these two sophisticated control techniques to be conveniently implemented with high control precision. Experimental results show that an ideal control capability is obtained for both control methods when applied to the five-phase induction motor

Z.M.S. El-Barbary [3] presented Fuzzy logic based controller for five-phase induction motor drive system. The controller is based on indirect rotor field oriented control technique.

The complete control scheme including the fuzzy logic is experimentally implemented using a digital signal processing board for a laboratory five-phase induction motor, the result shows the effectiveness and robustness of fuzzy logic controller as compared with PI.

Gebrihans Yehdego, [5] proposed a direct torque control of five phase induction motor using space Vector modulation. The output results show that the transient response oscillates for 0.03 second with rise time 0.004 second and the steady state value of torque is tracking the load torque with less than 2% error.

Lastly, the authors achieved high performance in terms of precise and fast flux and torque control and a smaller torque and flux ripple for five phase induction machine as compared to three phase induction machine.

An application of rotor field oriented control (RFOC) to a five-phase induction motor with the combined fundamental and third harmonic currents was proposed in [6]. In the proposed technique the complete theory and modeling of RFOC of the five-phase induction motor are established. Specifically, investigation is made to improve power density and output torque of the five-phase induction motor by injecting third harmonic of currents. By the proper dynamical adjustment and steady state compensation, the rotor field oriented control of the five-phase induction motor not only achieves a high drive performance, but also controls the fundamental and third harmonic flux and torque to generate the desired nearly rectangular air-gap flux.

Sharda.Patwa [7] investigated the use of FLC scheme for controlling induction motor parameters such as starting current, flux, torque, and speed. They reported results on two cases: 1) induction motor controlled by PI controller, in which the three phase currents, acceleration curve, and output torque are investigated, and 2) induction motor controlled by FLC, in which the same performance parameters have been investigated. They reported that the performance is improved regarding magnitude of starting currents and also time response of acceleration. For example, with PI controller the amplitude of starting current is 500 A and the rise time is 0.7 sec. While, with FLC the amplitude of starting current is 200 A and the rise time is 0.55 sec. These results show that FLC has improved the rise time with less starting current compared with PI controller.

A detailed comparison between scalar and indirect vector control techniques of induction motor are presented by **Pabitra.K.Bereha [8**]. The performance of PI based scalar control and PI based vector control are evaluated by showing the advantages and disadvantages of each control scheme. The results showed that it is very hard to design the control structure based PI controller because the system is influenced by unpredictable variations in the machine parameters. Robust control techniques were suggested to replace the PI controller to provide better control.

1.6. Thesis Organization

This thesis is totally organized into five chapters. Chapter I give an introduction of overall structure of the thesis. Under this a brief description of five phase induction motor, five phase inverter and types of controllers used are presented. Chapter II gives an introduction of modeling of five phase induction motor, inverter and indirect field oriented control principle. The background and structure of both PI controllers and Fuzzy controllers is presented in chapter III. Also, design of hybrid Fuzzy-PI controller is presented in this chapter.

In chapter IV, the SIMULINK model is presented and simulation results are analyzed and compared under different operating conditions. Finally, the conclusion and recommendations for future work according to the work done are summarized in chapter V.

1.7. Scope

To study how to model five phase induction motor & control it using hybrid Fuzzy- PI using matlab/Simulink.

Chapter Two

Modeling Five Phase Induction Motor

2.1 Introduction

Induction Motors account for more than 85% of all motors used in industry and domestic applications. In the past they have been used as constant-speed motors as traditional speed control methods have been less efficient than speed control methods for DC motors. However, DC Motors require commutators and brushes which are hazardous and require maintenance. Because of this induction motors are preferred.

2.2 Mathematical Model of Five Phase Induction Motor

This chapter details at first the modeling and control of a five-phase VSI. The modeling of five-phase VSI is done for ten-step. A model of a five-phase induction motor is initially developed in phase variable form. In order to simplify the model by removing the time variation of inductance terms, a transformation is applied on model and so-called d-q-x-y-0 model of the machine is designed or constructed [10]. The d-q axis reference frame currents contribute towards torque and flux production, whereas the remaining x-y components plus the zero-sequence components do not. A five-phase induction machine is build using ten phase belts, each of 36 degrees in that phases, along the circumference of the stator. The spatial displacement between phases is therefore $\alpha = 2\pi/N$. Where N is a number of phases

N=5 and 72 degrees phase apart. It is assumed that the rotor winding has already been referred to stator winding, using winding transformation ratio. Equations for pairs of x–y components are completely decoupled from all the other components and stator to rotor coupling does not appear either rotor x-y components are fully decoupled from d-q components and one from the other. Since rotor winding is short-circuited, neither *x–y* nor zero-sequence components can exist, Zero

Sequence component equations for both stator and rotor can be omitted from further consideration due to short circuited rotor winding and star connection of the stator winding [4].
A zero-sequence component does not exist in any star-connected multiphase system without neutral conductor for odd phase numbers, while only zero components can exist if the phase number is even. The equations for x-y components can be omitted from further consideration as well. This means that the model of the five-phase induction machine in an arbitrary reference frame becomes identical to the model of a three phase induction machine [11].

2.3 Expanding DQ0 Transformation to Five Phase Systems

In N phase system, transformation leads to N number of sequences. The first sequence is spaced by $\frac{2\pi}{N}$ and the second is spaced by $2 * \frac{2\pi}{N}$. The final sequence will results in spacing of 2π which means that all phases are in the same direction, this is called the zero sequence.

Thus, a five phase system will result in five sequences these five sequences will be spaced by $\frac{2\pi}{5}, \frac{4\pi}{5}, \frac{6\pi}{5}, \frac{8\pi}{5}\ and\ 2\pi$.

It is clear that sequence 1 and 4 are equivalent; same sequence with opposite direction. The same holds true for sequences 2 and 3.therefore, only sequence 1, 3, and 5 will be used.

2.4 Model Transformation

- ➢ The transformation of axis depend on the following assumptions:

- ✓ Motor winding is purely sinusoidally distributed
- ✓ The stator side of motor is connected by star connection
- ✓ The rotor side of motor is short circuited
- ✓ Zero component is removed because of phase number is odd.
- ✓ X-Y component are fully decoupled from d-q component. Therefore x-y component do not considered further.
- ✓ Only d-q component current is generated

To transform a model we need to have transformation matrix .Therefore transformation matrix is given by:

$$T^{*} = 2/5\begin{bmatrix} \cos(\Theta) & \cos\left(\theta-\frac{2\pi}{5}\right) & \cos\left(\theta-\frac{4\pi}{5}\right) & \cos\left(\theta+\frac{4\pi}{5}\right) & \cos\left(\theta+\frac{2\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta-\frac{2\pi}{5}\right) & \sin\left(\theta-\frac{4\pi}{5}\right) & \sin\left(\theta+\frac{4\pi}{5}\right) & \sin\left(\theta+\frac{2\pi}{5}\right) \\ \cos(\theta) & \cos\left(\theta+\frac{4\pi}{5}\right) & \cos\left(\theta-\frac{2\pi}{5}\right) & \cos\left(\theta+\frac{2\pi}{5}\right) & \cos\left(\theta-\frac{4\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta+\frac{4\pi}{5}\right) & \sin\left(\theta-\frac{2\pi}{5}\right) & \sin\left(\theta+\frac{2\pi}{5}\right) & \sin\left(\theta-\frac{4\pi}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2.1}$$

Where

$$\theta = \omega_e t \tag{2.2}$$

i) Transformation from $\boldsymbol{Vas}, \boldsymbol{Vbs}, \boldsymbol{Vcs}, \boldsymbol{Vds}, \boldsymbol{Ves} \longrightarrow \boldsymbol{V\alpha}, \boldsymbol{V\beta}, \boldsymbol{Vx}, \boldsymbol{Vy}, \boldsymbol{Vo}$

Transformation from five phases $(Vas, Vbs, Vcs, Vds, Ves)\ to\ (V\alpha, V\beta, Vx, Vy, Vo)$ is given by the following:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_x \\ V_y \\ V_0 \end{bmatrix} = 2/5\begin{bmatrix} \cos(\Theta) & \cos\left(\theta-\frac{2\pi}{5}\right) & \cos\left(\theta-\frac{4\pi}{5}\right) & \cos\left(\theta+\frac{4\pi}{5}\right) & \cos\left(\theta+\frac{2\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta-\frac{2\pi}{5}\right) & \sin\left(\theta-\frac{4\pi}{5}\right) & \sin\left(\theta+\frac{4\pi}{5}\right) & \sin\left(\theta+\frac{2\pi}{5}\right) \\ \cos(\theta) & \cos\left(\theta+\frac{4\pi}{5}\right) & \cos\left(\theta-\frac{2\pi}{5}\right) & \cos\left(\theta+\frac{2\pi}{5}\right) & \cos\left(\theta-\frac{4\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta+\frac{4\pi}{5}\right) & \sin\left(\theta-\frac{2\pi}{5}\right) & \sin\left(\theta+\frac{2\pi}{5}\right) & \sin\left(\theta-\frac{4\pi}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} \tag{2.3}$$

ii) Transformation from $\boldsymbol{i_{as}, i_{bs}, i_{cs}, i_{ds}, i_{es} \rightarrow i_{\alpha}, i_{\beta}, i_{x}, i_{y}, i_{0}}$

Transformation of $(ias, ibs, ics, ids, ies)\ to\ (i\alpha, i\beta, ix, iy, io)$ is given below

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_x \\ i_y \\ i_0 \end{bmatrix} = 2/5 \begin{bmatrix} \cos(\Theta) & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) \\ \cos(\theta) & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) \\ \sin(\theta) & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ds} \\ i_{es} \end{bmatrix} \qquad (2.4)$$

The inverse of 2.3 & 2.4 is given by 2.5 & 2.6 respectively

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = 2/5 \begin{bmatrix} \cos(\Theta) & \sin(\theta) & \cos(\theta) & \sin(\theta) & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \cos\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_x \\ V_y \\ V_0 \end{bmatrix} \qquad (2.5)$$

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ds} \\ i_{es} \end{bmatrix} = 2/5 \begin{bmatrix} \cos(\Theta) & \sin(\theta) & \cos(\theta) & \sin(\theta) & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \cos\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_x \\ i_y \\ i_0 \end{bmatrix} \qquad (2.6)$$

Stationary **d-q-0** transformation could be obtained by substituting $\theta = 0$ in equation 2.1 & results the following transformation matrix.

$$T^{*} = 2/5\begin{bmatrix} 1 & \cos\left(-\frac{2\pi}{5}\right) & \cos\left(-\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) \\ 0 & \sin\left(-\frac{2\pi}{5}\right) & \sin\left(-\frac{4\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) \\ 1 & \cos\left(\theta+\frac{4\pi}{5}\right) & \cos\left(-\frac{2\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) & \cos\left(-\frac{4\pi}{5}\right) \\ 0 & \sin\left(\frac{4\pi}{5}\right) & \sin\left(-\frac{2\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) & \sin\left(-\frac{4\pi}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2.7)$$

i) ***abcde equations***

a) Stator voltage is given by

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = R_s \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ds} \\ i_{es} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda_{ds} \\ \lambda_{es} \end{bmatrix} \quad (2.8)$$

Or in vector form:

$$V_s^{abcde} = R_s i_s^{abcde} + \frac{d}{dt}\lambda_s^{abcde} \quad (2.9)$$

b) Rotor voltage is given by

$$\begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \\ V_{dr} \\ V_{er} \end{bmatrix} = R_r \begin{bmatrix} i_{ar} \\ i_{br} \\ i_{cr} \\ i_{dr} \\ i_{er} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_{ar} \\ \lambda_{br} \\ \lambda_{cr} \\ \lambda_{dr} \\ \lambda_{er} \end{bmatrix} \quad (2.10)$$

Or in vector form:

$$V_r^{abcde} = R_r i_r^{abcde} + \frac{d}{dt}\lambda_r^{abcde} \tag{2.11}$$

c) Stator flux linkage

$$\begin{bmatrix}\lambda_{as}\\ \lambda_{bs}\\ \lambda_{cs}\\ \lambda_{ds}\\ \lambda_{es}\end{bmatrix} = L_s \begin{bmatrix}i_{as}\\ i_{bs}\\ i_{cs}\\ i_{ds}\\ i_{es}\end{bmatrix} + L_{sr} \begin{bmatrix}i_{ar}\\ i_{br}\\ i_{cr}\\ i_{dr}\\ i_{er}\end{bmatrix} \tag{2.12}$$

Or in vector form:

$$\lambda_s^{abcde} = L_s i_s^{abcde} + L_{sr} i_r^{abcde} \tag{2.13}$$

d) Rotor flux linkage

$$\begin{bmatrix}\lambda_{ar}\\ \lambda_{br}\\ \lambda_{cr}\\ \lambda_{dr}\\ \lambda_{er}\end{bmatrix} = L_s \begin{bmatrix}i_{ar}\\ i_{br}\\ i_{cr}\\ i_{dr}\\ i_{er}\end{bmatrix} + L_{sr} \begin{bmatrix}i_{as}\\ i_{bs}\\ i_{cs}\\ i_{ds}\\ i_{es}\end{bmatrix} \tag{2.14}$$

Or in vector form:

$$\lambda_r^{abcde} = L_s i_r^{abcde} + L_{sr} i_s^{abcde} \tag{2.15}$$

$$L_s = \begin{bmatrix} L_{aas} & L_{abs} & L_{acs} & L_{ads} & L_{aes}\\ L_{bas} & L_{bbs} & L_{bcs} & L_{bds} & L_{bes}\\ L_{cas} & L_{cbs} & L_{ccs} & L_{cds} & L_{ces}\\ L_{das} & L_{dbs} & L_{dcs} & L_{dds} & L_{des}\\ L_{eas} & L_{ebs} & L_{ecs} & L_{eds} & L_{ees} \end{bmatrix} \tag{2.16}$$

$$L_s = \begin{bmatrix} L_{ls}+M & Mcos\alpha & Mcos\alpha & Mcos2\alpha & Mcos\alpha\\ Mcos\alpha & L_{ls}+M & Mcos\alpha & Mcos2\alpha & Mcos2\alpha\\ Mcos2\alpha & Mcos\alpha & L_{ls}+M & Mcos\alpha & Mcos2\alpha\\ Mcos2\alpha & Mcos2\alpha & Mcos\alpha & L_{ls}+M & Mcos\alpha\\ Mcos\alpha & Mcos2\alpha & Mcos2\alpha & Mcos\alpha & L_{ls}+M \end{bmatrix} \tag{2.17}$$

$$L_r = \begin{bmatrix} L_{aar} & L_{abr} & L_{acr} & L_{adr} & L_{aer} \\ L_{abr} & L_{bbr} & L_{bcr} & L_{bdr} & L_{ber} \\ L_{car} & L_{cbr} & L_{ccr} & L_{cdr} & L_{cer} \\ L_{dar} & L_{dbr} & L_{dcr} & L_{ddr} & L_{der} \\ L_{ear} & L_{ebr} & L_{ecr} & L_{edr} & L_{eer} \end{bmatrix} \tag{2.18}$$

$$L_r = \begin{bmatrix} L_{lr}+M & Mcos\alpha & Mcos\alpha & Mcos2\alpha & Mcos\alpha \\ Mcos\alpha & L_{lr}+M & Mcos\alpha & Mcos2\alpha & Mcos2\alpha \\ Mcos2\alpha & Mcos\alpha & L_{lr}+M & Mcos\alpha & Mcos2\alpha \\ Mcos2\alpha & Mcos2\alpha & Mcos\alpha & L_{lr}+M & Mcos\alpha \\ Mcos\alpha & Mcos2\alpha & Mcos2\alpha & Mcos\alpha & L_{lr}+M \end{bmatrix} \tag{2.19}$$

Mutual inductances between stator and rotor windings are given as:

$$L_{sr} = \begin{bmatrix} cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) \\ \cos(\theta-\alpha) & cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) \\ \cos(\theta-2\alpha) & \cos(\theta-\alpha) & \cos\theta & \cos(\theta+\alpha) & \cos(\theta+2\alpha) \\ \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) & cos\theta & \cos(\theta+\alpha) \\ \cos(\theta+\alpha) & \cos(\theta+2\alpha) & \cos(\theta-2\alpha) & \cos(\theta-\alpha) & cos\theta \end{bmatrix} \tag{2.20}$$

ii*) *dq*0 *equations

a) Stator side

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - w_a \lambda_{qs} \tag{2.21}$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} + w_a \lambda_{ds} \tag{2.22}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \tag{2.23}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \tag{2.24}$$

b) Rotor side

$$V_{dr} = R_r i_{dr} - (w_a - w)\lambda_{qr} + \frac{d}{dt}\lambda_{dr} \tag{2.25}$$

$$V_{qr} = R_r i_{qr} - (w_a - w)\lambda_{dr} + \frac{d}{dt}\lambda_{qr} \tag{2.26}$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) = (L_{lr} + L_m)i_{dr} + L_m i_{ds} \tag{2.27}$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m\left(i_{qs} + i_{qr}\right) = (L_{lr} + L_m)i_{qr} + L_m i_{qs} \tag{2.28}$$

Where

$$L_m = 2.5M \tag{2.29}$$

Electromechanical torque is given by

$$T_e = \frac{5}{2}PM\left[i_{dr} i_{qs} - i_{qr} i_{ds}\right] \; or \;\; PL_m[i_{dr} i_{qs} - i_{qr} i_{ds} \tag{2.30}$$

Motor speed is given by

$$W_r = \int \frac{P}{2J}(T_e - T_l)dt \tag{2.31}$$

2.5 Five Phase Inverter Modeling

2.5.1 Space Vector Representation of a Five Phase VSI

In multiphase inverter we can generate n number of phase, as each leg of the inverter represent the phase, thus by increase the number of leg in the inverter we can increase the number of phases. For the five phases motor we require five leg inverter [12].

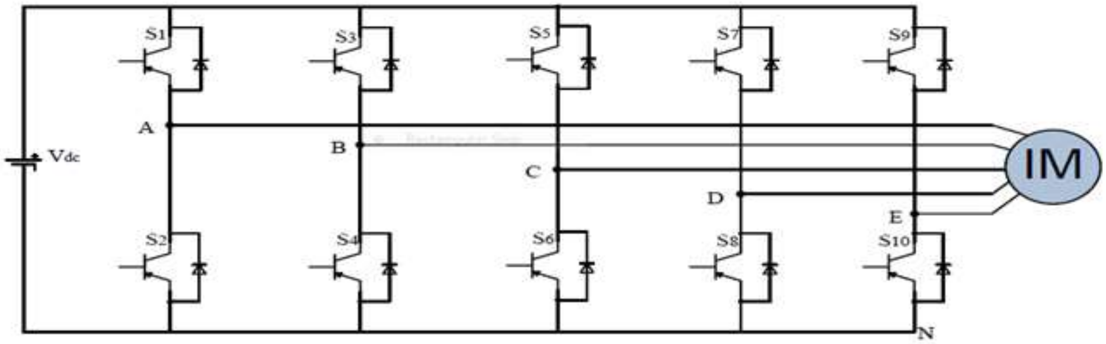


Figure 2.1: Five phase VSI power circuit

Each switch is assumed to conduct for 180°, leading to the operation in the ten-step mode. Phase delay between firing of two switches in any subsequent two phases is equal to 360°/5 = 72°. In five phases ten step inverter three switches from the upper switches and two from the lower switches are turned on at a time and vice versa and each switch is conducting 36° [13]. In five phases ten step inverter three switches from the upper switches and two from the lower switches are turned on at a time and vice versa and each switch is conducting 36°.

The switching sequence & the mode of operation of a five phase inverter are shown below.

Modes	Switches On	Terminal Polarity
1	1,3,6,8,9	A+B+C-D-E+
2	1,3,6,8,10	A+B+C-D-E-
3	1,3,5,8,10	A+B+C+D-E-
4	2,3,5,8,10	A-B+C+D-E-
5	2,3,5,7,10	A+B-C+D-E+
6	2,4,5,7,10	A-B-C+D+E-
7	2,4,5,7,9	A-B-C+D+E+
8	2,4,6,7,9	A-B-C-D+E+
9	1,4,6,7,9	A+B-C-D+E+
10	1,4,6,8,9	A+B-C-D-E+

Table 2.1: Modes of operation for five the phase voltage source inverter

One complete cycle of operation of the inverter can be divided into ten distinct modes indicated in Figure below and summarized in Table above, it follows from Fig and Table that at any instant in time there are five switches that are 'on' and five switches that are 'off'.

Switching Mode	**Switches on**	**Space vector**	**Leg voltage(V_A)**	**Leg voltage(V_B)**	**Leg voltage(V_C)**	**Leg voltage(V_D)**	**Leg voltage(V_E)**
1	1,3,6,8,9	v_1	V_{dc}	V_{dc}	0	0	V_{dc}
2	1,3,6,8,10	v_2	V_{dc}	V_{dc}	0	0	0
3	1,3,5,8,10	v_3	V_{dc}	V_{dc}	V_{dc}	0	0
4	2,3,5,8,10	v_4	0	V_{dc}	V_{dc}	0	0
5	2,3,5,7,10	v_5	0	V_{dc}	V_{dc}	V_{dc}	0
6	2,4,5,7,10	v_6	0	0	V_{dc}	V_{dc}	0
7	2,4,5,7,9	v_7	0	0	V_{dc}	V_{dc}	V_{dc}
8	2,4,6,7,9	v_8	0	0	0	V_{dc}	V_{dc}
9	1,4,6,7,9	v_9	V_{dc}	0	0	V_{dc}	V_{dc}
10	1,4,6,8,9	v_{10}	V_{dc}	0	0	0	V_{dc}

Table 2.2: Leg voltages of five phase VSI

Using the above table space vector leg voltages of inverter is given as follows

First consider, **mode -1** leg voltage

$$v_1 = 2/5(V_{dc} + \alpha V_{dc} + 0 + 0 + \alpha V_{dc}) \tag{2.32}$$

Taking out common V_{dc} out of bracket will result the following

$$v_1 = \frac{2}{5} * V_{dc}\left(1 + \cos\left(\frac{2\pi}{5}\right) + \sin\left(\frac{2\pi}{5}\right) + 0 + 0 + \cos\left(\frac{2\pi}{5}\right) - \sin\left(\frac{2\pi}{5}\right)\right) \tag{2.33}$$

From above equation the following result obtained:

$$v_1 = \frac{2}{5} * V_{dc}\left(1 + \cos\left(\frac{2\pi}{5}\right) + \cos\left(\frac{2\pi}{5}\right)\right) \tag{2.34}$$

Collecting like terms in the above equation results

$$v_1 = \frac{2}{5} * V_{dc} \exp(j0)\left(1 + 2\cos\left(\frac{2\pi}{5}\right)\right) \tag{2.35}$$

Using trigonometric identity

$$v_1 = \frac{2}{5} * V_{dc} 2\left(\cos\left(\frac{\pi}{5}\right)\right) \exp(j0) \tag{2.36}$$

Leg voltage space vectors	
v_1	$2/5V_{dc}2\cos(\pi/5)\exp(j0)$
v_2	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(\frac{\pi}{5}\right)\right)$
v_3	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(2\frac{\pi}{5}\right)\right)$
v_4	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(3\frac{\pi}{5}\right)\right)$
v_5	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(4\frac{\pi}{5}\right)\right)$
v_6	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp(j(\pi))$
v_7	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(6\frac{\pi}{5}\right)\right)$
v_8	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(7\frac{\pi}{5}\right)\right)$
v_9	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(8\frac{\pi}{5}\right)\right)$
v_{10}	$2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(j\left(9\frac{\pi}{5}\right)\right)$

Table 2.3: Leg voltage space vector for five phase VSI

Switching states and phase voltages for five phase inverter is given using the following table

Space vector	On-off	$\boldsymbol{v_a}$	$\boldsymbol{v_b}$	$\boldsymbol{v_c}$	$\boldsymbol{v_d}$	$\boldsymbol{v_e}$	$\boldsymbol{angle\ between\ legs(\theta)}$
v_1	11001	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	0
v_2	11000	$0.6 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	36
v_3	11100	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$-0.6 * V_{dc}$	72
v_4	01100	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	108
v_5	01110	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	144
v_6	00110	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	180
v_7	00111	$-0.6 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	216
v_8	00011	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	V_{dc}	252
v_9	10011	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	288
v_{10}	10001	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	324
v_{11}	10000	$0.8 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	0
v_{12}	11101	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	36
v_{13}	01000	$-0.2 * V_{dc}$	$0.8 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	72
v_{14}	11110	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$-0.8 * V_{dc}$	108
v_{15}	00100	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$0.8 * V_{dc}$	$0.8 * V_{dc}$	$-0.2 * V_{dc}$	144
v_{16}	01111	$-0.8 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	180
v_{17}	00010	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	216
v_{18}	10111	$0.2 * V_{dc}$	$-0.8 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$0.2 * V_{dc}$	252
v_{19}	00001	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$-0.2 * V_{dc}$	$0.8 * V_{dc}$	288
v_{20}	11011	$0.2 * V_{dc}$	$0.2 * V_{dc}$	$-0.8 * V_{dc}$	$-0.8 * V_{dc}$	$0.2 * V_{dc}$	324
v_{21}	01001	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	0
v_{22}	11010	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	36
v_{23}	10100	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	72
v_{24}	01101	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	108
v_{25}	01010	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	144

v_{26}	10110	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	180
v_{27}	00101	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	216
v_{28}	01011	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$0.4 * V_{dc}$	252
v_{29}	10010	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	$-0.4 * V_{dc}$	$0.6 * V_{dc}$	$-0.4 * V_{dc}$	288
v_{30}	10101	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	$-0.6 * V_{dc}$	$0.4 * V_{dc}$	324
v_0	00000	0	0	0	0	0	0
v_{31}	11111	0	0	0	0	0	0

Table 2.4: Switching states and phase voltages for five phase inverter

Phase to-neutral voltages of the star connected load are given by the following relation:

$$\begin{aligned} V_{an} &= V_{as} + V_{nN} \\ V_{bn} &= V_{bs} + V_{nN} \\ V_{cn} &= V_{cs} + V_{nN} \\ V_{dn} &= V_{ds} + V_{nN} \\ V_{en} &= V_{es} + V_{nN} \end{aligned} \tag{2.37}$$

Since the phase voltages in a star connected load sum to zero, summation of the equations yield

$$\begin{aligned} V_{nN} &= \frac{1}{5}(V_{an} + V_{bn} + V_{cn} + V_{dn} + V_{en}) \\ V_{as} &= \frac{4}{5}V_{an} - \frac{1}{5}(V_{bn} + V_{cn} + V_{dn} + V_{en}) \\ V_{bs} &= \frac{4}{5}V_{bn} - \frac{1}{5}(V_{an} + V_{cn} + V_{dn} + V_{en}) \\ V_{cs} &= \frac{4}{5}V_{cn} - \frac{1}{5}(V_{an} + V_{bn} + V_{dn} + V_{en}) \\ V_{ds} &= \frac{4}{5}V_{dn} - \frac{1}{5}(V_{an} + V_{bn} + V_{cn} + V_{en}) \\ V_{es} &= \frac{4}{5}V_{en} - \frac{1}{5}(V_{an} + V_{bn} + V_{cn} + V_{dn}) \end{aligned} \tag{2.38}$$

Where n is negative point of dc link

2.6 FIELD ORIENTED CONTROL

2.6.1 Field Oriented Control Principle

Indirect field oriented control(IFOC) is one of controlling mechanisms that depends up on transformation of five phase to two phases in stationary reference frame and rotating reference frames [2].

Generally the block diagram representation of indirect field oriented looks the following.

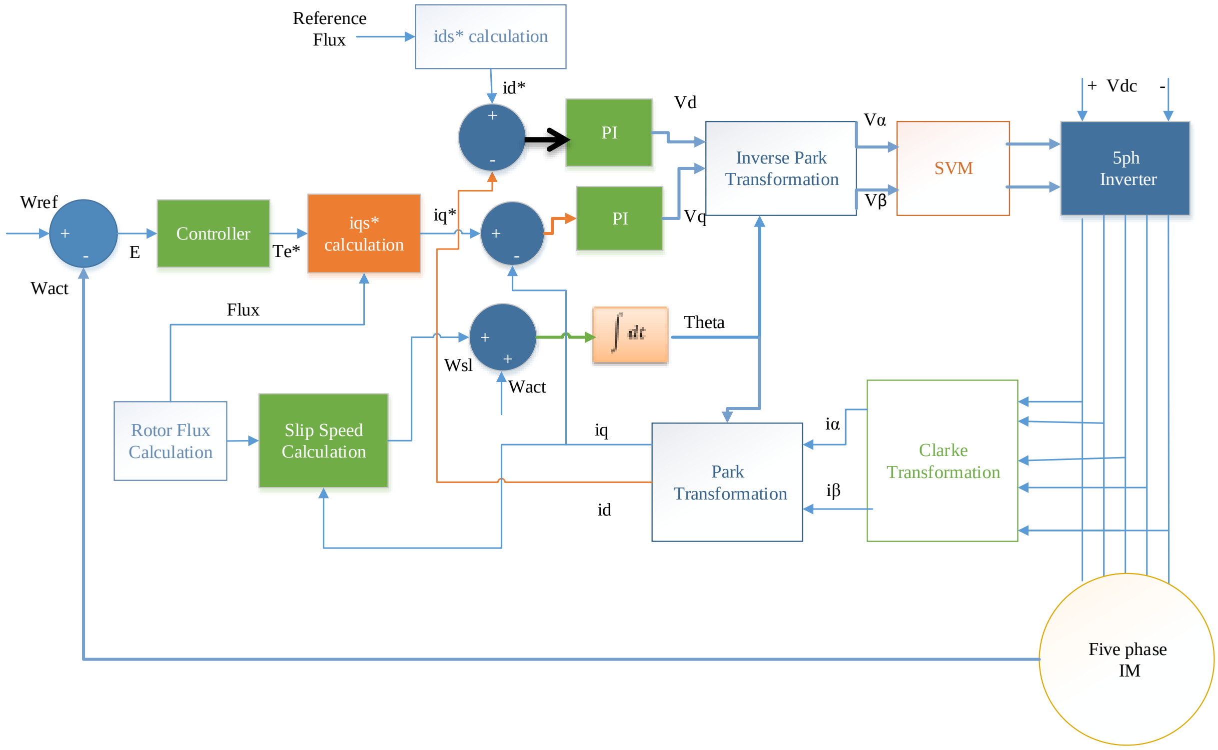


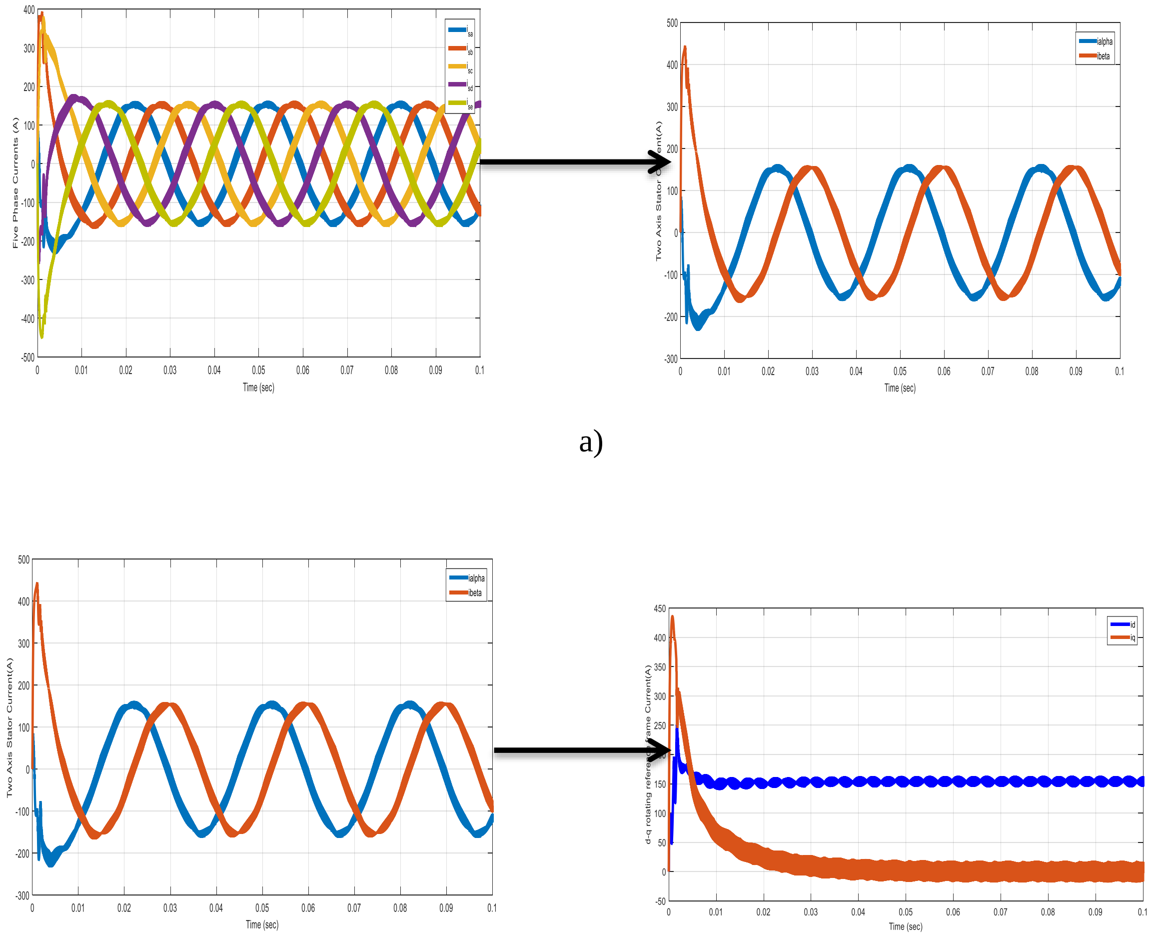
Figure 2.2: Indirect field oriented control scheme

2.6.2 Indirect Field Oriented Control Algorithm

Indirect field oriented control have the following steps to implement

Step-1 Measure the stator currents and apply it to Clarke transformation to have two phase stationary reference frames.

Step-2 Apply park transformation to convert two phase stationary reference frames to rotating frames.



a)

b)

Figure 2.3: a) Clarke transformation b) Park transformation

Step-3 Compute rotor angle

Rotor angle is computed by

$$\theta = \int w_e \, dt \tag{2.39}$$

Where $w_e = w_{sl} + w_{act}$ (2.40)

$$w_{sl} = \frac{M}{Lr} * \frac{Rr}{\psi} * i_q \tag{2.41}$$

Step-4 Calculate quadrature stator current

$$I_q^* = \frac{2}{5} * \frac{2}{p} * \frac{Lr}{M} * \frac{T_e^*}{\psi} \tag{2.42}$$

Step-5 Calculate direct stator current

$$I_d^* = \frac{reference\ flux(\psi^*)}{M} \tag{2.43}$$

Step-6 Apply inverse of both Clarke and park transformation.

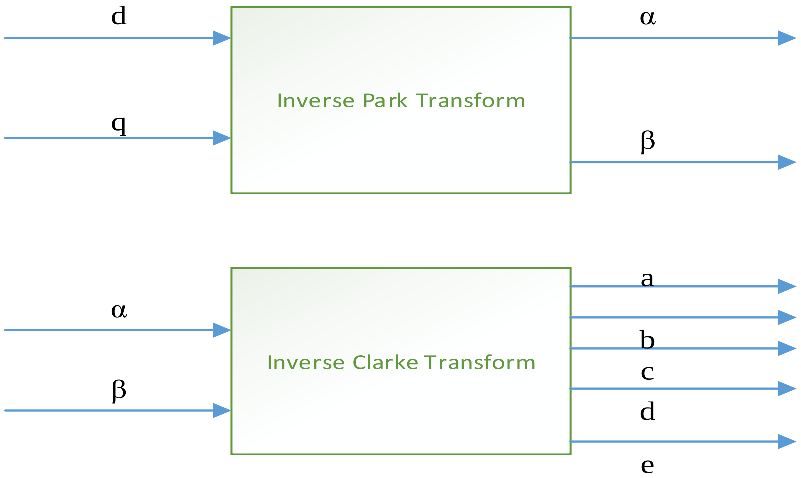


Figure 2.4 Inverse park transformation & Inverse Clarke transformation

Generally, IFOC undergoes the following transformations:

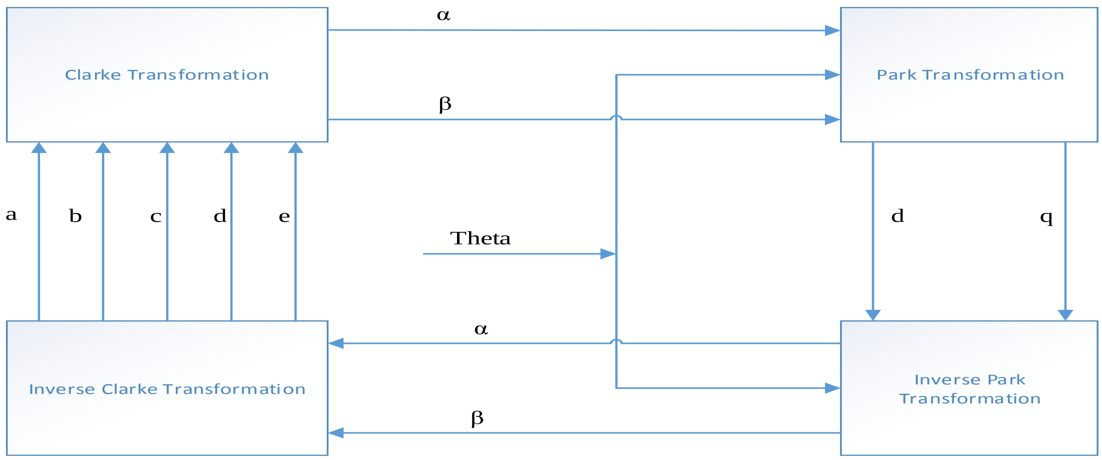


Figure 2.5: Basic transformations in indirect field oriented control

2.6.3 Realization of Space Vector PWM

Space vector realization has the following steps [14].

1. Determine $V_\alpha, V_\beta, V_{ref}\ and\ angle(\theta)$
2. Determine time duration T_1, T_2, T_0
3. Determine switching time of each transistor ($S_1\ through\ S_{10}$)

Step-1 Determine $\boldsymbol{V_\alpha, V_\beta, V_{ref}\ and\ angle(\theta)}$

To obtain the parameters of step-1, consider the following transformation

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{2.44}$$

$$|V_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \tag{2.45}$$

$$\alpha = \tan^{-1}\frac{V_\beta}{V_\alpha} \tag{2.46}$$

Step-2 Determine time duration T_1, T_2, T_0

Time duration for sector-1 is calculated using the figure below as follows

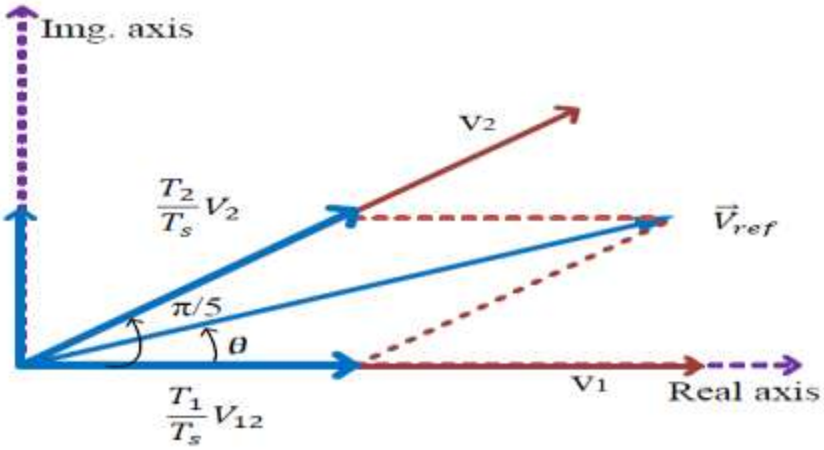


Figure 2.6 space vector realization for sector-1

As shown from the fig 3.3, $\vec{V}_{ref}$ is adjacent to $\vec{V}_1$ and$\vec{V}_2$. Therefore we express $\vec{V}_{ref}$ in terms of these adjacent voltages as follows

$$\int_0^{T_s} \vec{V}_{ref}\, dt = \int_{T_0}^{T_1} \vec{V}_1\, dt + \int_{T_1}^{T_1+T_2} \vec{V}_2\, dt + \int_{T_1+T_2}^{T_s} \vec{V}_0\, dt \tag{2.47}$$

From the integration we obtain

$$T_s\vec{V}_{ref} = T_1\vec{V}_1 + T_2\vec{V}_2 \tag{2.48}$$

$$T_s = T_1 + T_2 + T_0 \tag{2.49}$$

Where

$$\vec{V}_{ref} = V_{ref}e^{j\alpha} \tag{2.50}$$

$$\vec{V}_1 = 2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp(j0) \tag{2.51}$$

$$\vec{V}_2 = 2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(\frac{j\pi}{5}\right) \tag{2.52}$$

$$\vec{V}_0 = 0 \tag{2.53}$$

Then this can be simplified as

$$T_s|V_{ref}|\begin{bmatrix}\cos(\alpha)\\ \sin(\alpha)\end{bmatrix} = T_1 2/5V_{dc}2\cos(\pi/5)\begin{bmatrix}1\\ 0\end{bmatrix} + T_2 2/5V_{dc}2\cos(\pi/5)\begin{bmatrix}\cos\left(\frac{\pi}{5}\right)\\ \sin\left(\frac{\pi}{5}\right)\end{bmatrix} \tag{2.54}$$

By collecting the same terms of the equation 3.18, will result the following

$$\begin{cases} real\ part\ T_sV_{ref}\cos(\alpha) = T_1 2/5V_{dc}2\cos(\pi/5) + T_2 2/5V_{dc}2\cos(\pi/5)\cos(\pi/5) \\ imaginary\ part\ T_sV_{ref}\sin(\alpha) = T_2 2/5V_{dc}2\cos(\pi/5)\sin(\pi/5) \end{cases} \tag{2.55}$$

By solving the above

$$T_1 = \frac{T_sV_{ref}\sin\left(\frac{\pi}{5} - \alpha\right)}{V_1\sin\left(\frac{\pi}{5}\right)} \tag{2.56}$$

$$T_2 = \frac{T_sV_{ref}\sin(\alpha)}{V_2\sin\left(\frac{\pi}{5}\right)} \tag{2.57}$$

$$T_0 = T_s - T_1 - T_2 \tag{2.58}$$

Where $V_1 = |\vec{V}_1| = V_2 = |\vec{V}_2| = 4/5V_{dc}\cos\left(\frac{\pi}{5}\right)$ (2.59)

$$V_{ref} = |\vec{V}_{ref}|, \qquad 0 \le \alpha \le 36° \tag{2.60}$$

Switching time duration at any sector is given by

$$\int_0^{T_s}\vec{V}_{ref}\,dt = \int_0^{T_n}\vec{V}_n\,dt + \int_{T_n}^{T_n+T_{n+1}}\vec{V}_{n+1}\,dt + \int_{T_n+T_{n+1}}^{T_s}\vec{V}_0\,dt \tag{2.61}$$

$$T_s\vec{V}_{ref} = T_n\vec{V}_n + T_{n+1}\vec{V}_{n+1} \tag{2.62}$$

Where $T_n, T_{n+1}\ and\ T_0$ is switching time for space vector V_n, V_{n+1}, V_0

$$\vec{V}_{ref} = V_{ref}e^{j(\alpha-(\frac{n-1}{5}\pi))} \tag{2.63}$$

$$\vec{V}_n = 2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(\frac{j(n-1)}{5}\pi\right) \tag{2.64}$$

$$\vec{V}_{n+1} = 2/5V_{dc}2\cos\left(\frac{\pi}{5}\right)\exp\left(\frac{j(n)}{5}\pi\right) \tag{2.65}$$

$$T_s\left|V_{ref}\right|\begin{bmatrix}\cos\left(\alpha-\frac{n-1}{5}\pi\right)\\ \sin(\alpha-\frac{n-1}{5}\pi)\end{bmatrix} = 2/5V_{dc}2\cos(\pi/5)\left\{\begin{bmatrix}\cos\left(\frac{n-1}{5}\pi\right)\\ \sin\left(\frac{n-1}{5}\pi\right)\end{bmatrix} + \begin{bmatrix}\cos\left(\frac{\pi}{5}n\right)\\ \sin\left(\frac{n\pi}{5}\right)\end{bmatrix}\right\} \tag{2.66}$$

By extracting real part and imaginary parts of the above equation we have

$$\left[T_sV_{ref}\cos\left(\alpha-\frac{n-1}{5}\right)\right] = \begin{bmatrix}2/5V_{dc}2\cos(\pi/5)\cos(\frac{n-1}{5}\pi\\ 2/5V_{dc}2\cos(\pi/5)\cos(n\pi/5)\end{bmatrix}\begin{bmatrix}T_n\\ T_{n+1}\end{bmatrix} \tag{2.67}$$

$$\left[T_sV_{ref}\sin\left(\alpha-\frac{n-1}{5}\right)\right] = \begin{bmatrix}2/5V_{dc}2\cos(\pi/5)\sin(\frac{n-1}{5}\pi\\ 2/5V_{dc}2\cos(\pi/5)\sin(n\pi/5)\end{bmatrix}\begin{bmatrix}T_n\\ T_{n+1}\end{bmatrix} \qquad (2.68$$

By solving the above equation the following results obtained

$$T_n = \frac{T_sV_{ref}\sin\left(\frac{n\pi}{5}-\alpha\right)}{V_n\sin\left(\frac{\pi}{5}\right)} \tag{2.69}$$

$$T_{n+1} = T_sV_{ref}\sin\left(\alpha-\frac{n-1}{5}\pi\right) \tag{2.70}$$

$$T_0 = T_s - T_n - T_{n+1} \tag{2.71}$$

$$V_n = \left|\vec{V_n}\right| = 4/5V_{dc}\cos\left(\frac{\pi}{5}\right) \tag{2.72}$$

Where n is the number of sector from 1 to 10.

Switching time sequence for sector 1 through 10

Sector	T_1	T_2	T_0
1	$T_s * a * sin(\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha)$	$T_s - T_1 - T_2$
2	$T_s * a * sin(2\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{\pi}{5}))$	$T_s - T_1 - T_2$
3	$T_s * a * sin(3\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{2\pi}{5}))$	$T_s - T_1 - T_2$
4	$T_s * a * sin(4\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{3\pi}{5}))$	$T_s - T_1 - T_2$
5	$T_s * a * sin(\pi - \alpha)$	$T_s * a * sin(\alpha - (\frac{4\pi}{5}))$	$T_s - T_1 - T_2$
6	$T_s * a * sin(6\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\pi))$	$T_s - T_1 - T_2$
7	$T_s * a * sin(7\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{6\pi}{5}))$	$T_s - T_1 - T_2$
8	$T_s * a * sin(8\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{7\pi}{5}))$	$T_s - T_1 - T_2$
9	$T_s * a * sin(9\frac{\pi}{5} - \alpha)$	$T_s * a * sin(\alpha - (\frac{8\pi}{5}))$	$T_s - T_1 - T_2$
10	$T_s * a * sin(2\pi - \alpha)$	$T_s * a * sin(\alpha - (\frac{9\pi}{5}))$	$T_s - T_1 - T_2$

Table 2.5: Switching time sequence

Step-3. Determine switching time of each sector

Switching time of each transistor is given by the following table

Sector	Upper switches	Lower switches
1	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_0/2$ $S_7 = T_0/2$ $S_9 = T_1 + T_0/2$	$S_2 = T_0/2$ $S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_8 = T_1+T_2+T_0/2$ $S_{10} = T_2 + T_0/2$
2	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_2+T_0/2$ $S_7 = T_0/2$ $S_9 = T_0/2$	$S_2 = T_0/2$ $S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_8 = T_1+T_2+T_0/2$ $S_{10} = T_1+T_2+T_0/2$
3	$S_1 = T_1 + T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_1+T_2+T_0/2$ $S_7 = T_0/2$ $S_9 = T_0/2$	$S_2 = T_2 + T_0/2$ $S_4 = T_0/2$ $S_6 = T_0/2$ $S_8 = T_1+T_2+T_0/2$ $S_{10} = T_1+T_2+T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1+T_2+T_0/2$ $S_5 = T_1+T_2+T_0/2$ $S_7 = T_2+T_0/2$ $S_9 = T_0/2$	$S_2 = T_1+T_2+T_0/2$ $S_4 = T_0/2$ $S_6 = T_0/2$ $S_8 = T_1 + T_0/2$ $S_{10} = T_1+T_2+T_0/2$

5	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1+T_2+T_0/2$ $S_7 = T_1+T_2+T_0/2$ $S_9 = T_0/2$	$S_2 = T_1+T_2+T_0/2$ $S_4 = T_2+T_0/2$ $S_6 = T_0/2$ $S_8 = T_0/2$ $S_{10} = T_1+T_2+T_0/2$
6	$S_1 = T_0/2$ $S_3 = T_0/2$ $S_5 = T_1+T_2+T_0/2$ $S_7 = T_1+T_2+T_0/2$ $S_9 = T_2+T_0/2$	$S_2 = T_1+T_2+T_0/2$ $S_4 = T_1+T_2+T_0/2$ $S_6 = T_0/2$ $S_8 = T_0/2$ $S_{10} = T_1 + T_0/2$
7	$S_1 = T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$ $S_7 = T_1+T_2+T_0/2$ $S_9 = T_1+T_2+T_0/2$	$S_2 = T_1+T_2+T_0/2$ $S_4 = T_1+T_2+T_0/2$ $S_6 = T_2 + T_0/2$ $S_8 = T_0/2$ $S_{10} = T_0/2$
8	$S_1 = T_2+T_0/2$ $S_3 = T_0/2$ $S_5 = T_0/2$ $S_7 = T_1+T_2+T_0/2$ $S_9 = T_1+T_2+T_0/2$	$S_2 = T_1 + T_0/2$ $S_4 = T_1+T_2+T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_8 = T_0/2$ $S_{10} = T_0/2$
9	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_0/2$ $S_5 = T_0/2$ $S_7 = T_1 + T_0/2$ $S_9 = T_1+T_2+T_0/2$	$S_2 = T_0/2$ $S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_8 = T_1+T_2+T_0/2$ $S_{10} = T_2 + T_0/2$

10	$S_1 = T_1+T_2+T_0/2$ $S_3 = T_2+T_0/2$ $S_5 = T_0/2$ $S_7 = T_0/2$ $S_9 = T_1+T_2+T_0/2$	$S_2 = T_0/2$ $S_4 = T_1 + T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_8 = T_1+T_2+T_0/2$ $S_{10} = T_0/2$

Table: 2.6: Switching time for each transistor

Chapter Three

Hybrid Fuzzy-PI Controller Design

3.1 Introduction

The dynamic d-q model of an AC motor is complex and nonlinear. However, vector control or field oriented control can overcome this problem, but accurate vector control is nearly impossible. To combat this problem, classical control and hybrid fuzzy-PI controller are combined with indirect field oriented control to solve this problem.

3.2 PI Controller Design

Proportional-Integral (PI) controller is most widely adopted in industrial application due to its simple structure, easy to design and low cost. PI controller produces an output signal consist of a sum of error and the integral of that error. The error represents the difference between the desired motor speed and the actual motor speed and it is expressed as:

$$E = w_{ref} - w_{act} \tag{3.1}$$

Where $w_{ref} = reference\ speed\ , w_{act} = actual\ speed$ & $E = error$

- ✓ In time domain PI controller is modeled as:

$$K_p e(t) + K_i \int e(t)\, dt \tag{3.2}$$

Equation (3.2) in transfer function form is given by:

$$\frac{U(s)}{E(s)} = G(s) = K_p + \frac{K_i}{s} \tag{3.3}$$

Where K_p is the proportional gain, K_i is the integral gain, and U(s) is the output control.
The characteristics equation from (3.3) is given as:

$$1 + G(s)H(s) = 0 \tag{3.4}$$

Selected parameters are:

$\in = 0.5, J = 0.002, P = 4, f = 10HZ$

$w_0 = 2\pi * f = 6.28 * 10 = 62.8$

Characteristics equation of PI controller systems obtained by plugging the above parameters looks like the following:

$$S^2 + 2000K_pS + 2000K_i = 0 \tag{3.5}$$

Standard second order characteristics equation

$$S^2 + 2 \in w_0S + {w_0}^2 = 0 \tag{3.6}$$

Comparing equation 3.5 & 3.6 will give the following results

$$K_p = \frac{62.8}{2000} = 0.0314$$

$$K_i = \frac{62.8^2}{2000} = 2.32562$$

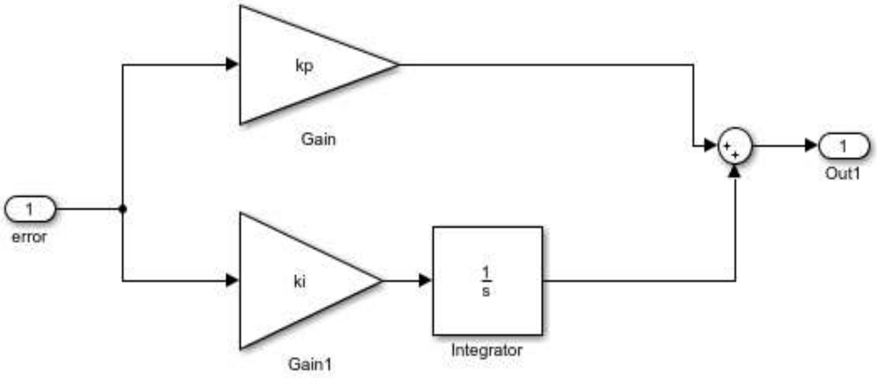


Figure 3.1: Simulink model of PI controller

Overall PI controller based indirect vector control is given by the following block diagram

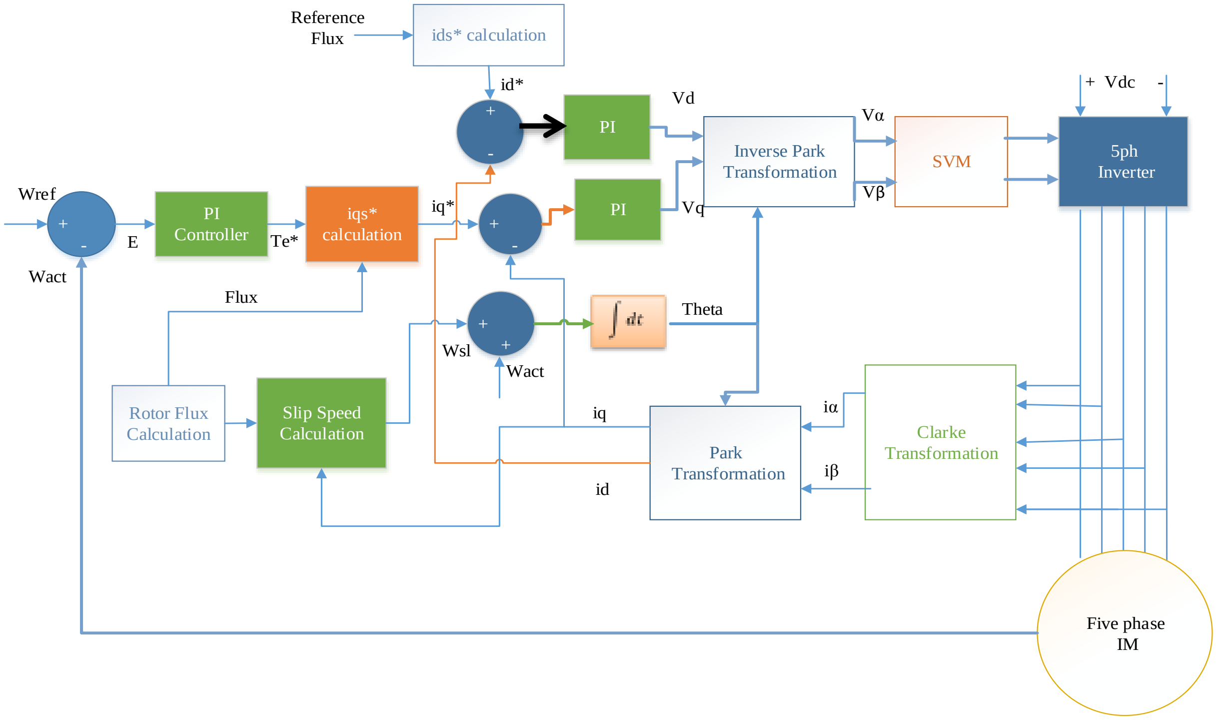


Figure 3.2: Block diagram of PI speed controller

3.3 Fuzzy Logic Controller Design

Fuzzy logic is a convenient way to map an input to an output. Fuzzy logic is conceptually easy to understand & a control algorithm based on a linguistic control strategy which tries to account the human's knowledge about how to control a system without requiring a mathematical model. Generally Fuzzy logic controller consists of three steps:

- ✓ The first step is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions.
- ✓ In second step, once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule.

- ✓ In third step the input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number crispness recovered from fuzziness at last [14].

3.3.1 Structures of FLC

FLC is made of the following four structures

1. **Knowledge base**

The Knowledge base is composed of data base and rule base. Data base consist of input and output membership functions that provides information for appropriate fuzzification and defuzzification operations.

2. **Fuzzification**

Fuzzification is the process in which the crisp input value is converted into fuzzy number by using the input membership function.

3. **Inference engine**

Fuzzy inference engine is the process that relates input fuzzy sets to output fuzzy sets using if then rules and fuzzy operators to drive a reasonable output fuzzy value. There are number of inference systems like Mamdani, Lusing Larson, and Sugeno.

4. **Defuzzification**

Defuzzification converts the fuzzified output value to crisp control value using the output membership function. The most famous defuzzification methods are center of area, height, mean of maxima, and sugeno.

Overall fuzzy logic controller structure is shown as below:

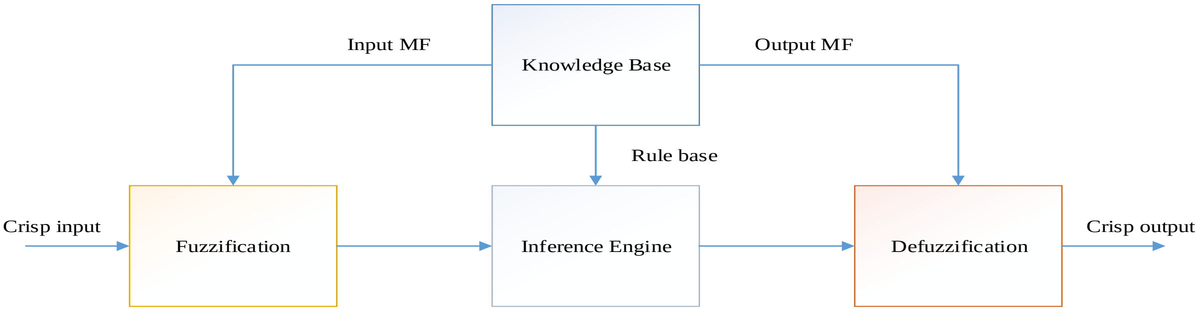


Figure 3.3 Basic structure of fuzzy logic controller

3.3.2 Working principle of fuzzy logic control

Fuzzy controller block diagram is shown in figure 3.5. There are two input signal to the fuzzy controller, the error signal E and the derivative of error which represents the change in error signal (CE). The controller output is electromagnetic torque ($\boldsymbol{T_e^*}$). The controller observes the loop error signal and correspondingly changes the output, so that the actual output signal matches the reference or commanded signal [3].

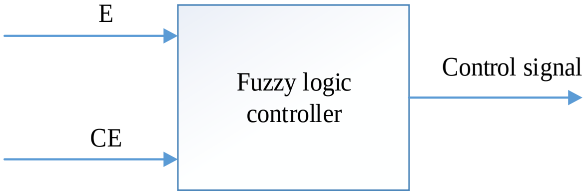


Figure 3.4: Fuzzy logic controller scheme

3.4 Hybrid Fuzzy-PI Speed Controller

To combine the advantages of both fuzzy logic controller and conventional controllers, a hybridization of fuzzy logic and conventional controllers is proposed. The hybrid system work as a single controller with the utilization of indirect field oriented control to control the speed of squirrel cage induction motor.

There is one input signal to the fuzzy controller, the error signal E. FLC tunes Kp and Ki constants of PI controller.

3.4.1 Design Methodology

1. Identify the input and output variables of fuzzy control system.
2. Define the universe of discourse of the input and output variables.
3. Formulate the fuzzy sets and select the corresponding MF shape of each.
4. Build the fuzzy rules table.
5. Define the gain values of conventional controllers.
6. Simulate the system and iterate the gain values, fuzzy sets and rule table until the performance is optimized.

3.4.2 Proposed Model for Induction Motor Speed Controller

The block diagram of proposed hybrid speed controller system for a vector control drive system is shown in figure 3.5. The speed error is expressed as follow

$$E = w_{ref} - w_{act} \tag{3.7}$$

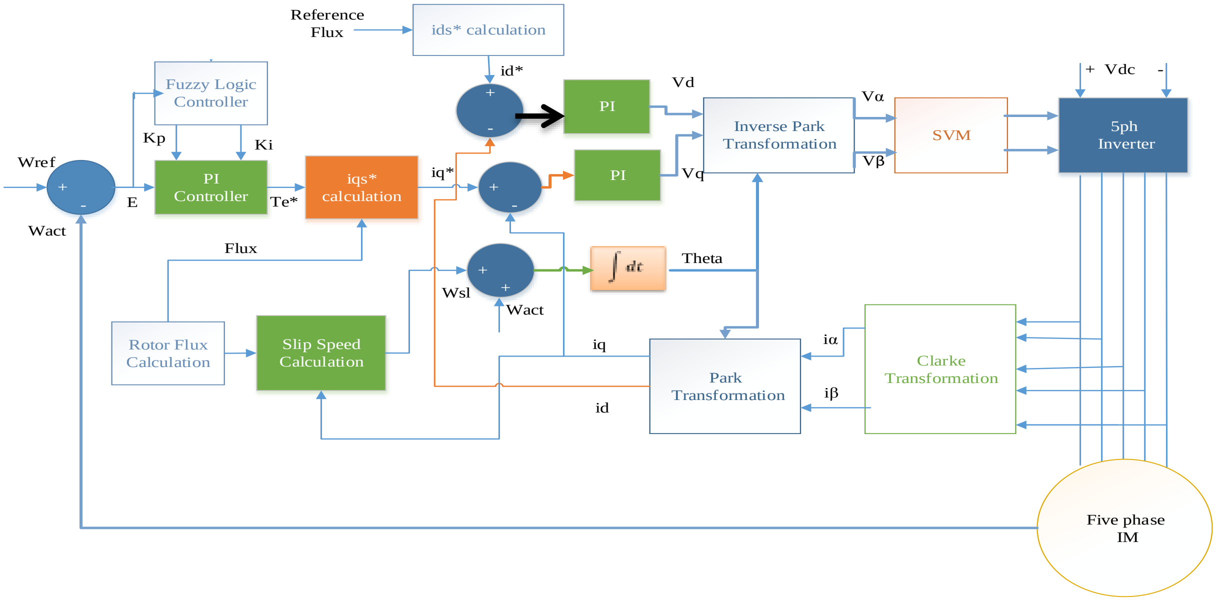


Figure 3.5: Block diagram of hybrid fuzzy-PI speed controller

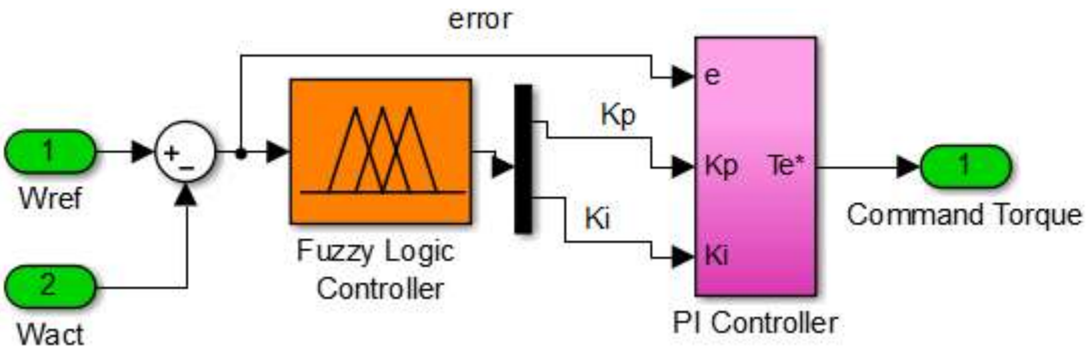


Figure 3.6: Simulink model of self-tuned Fuzzy-PI controller

3.4.3 Designing Rule Base

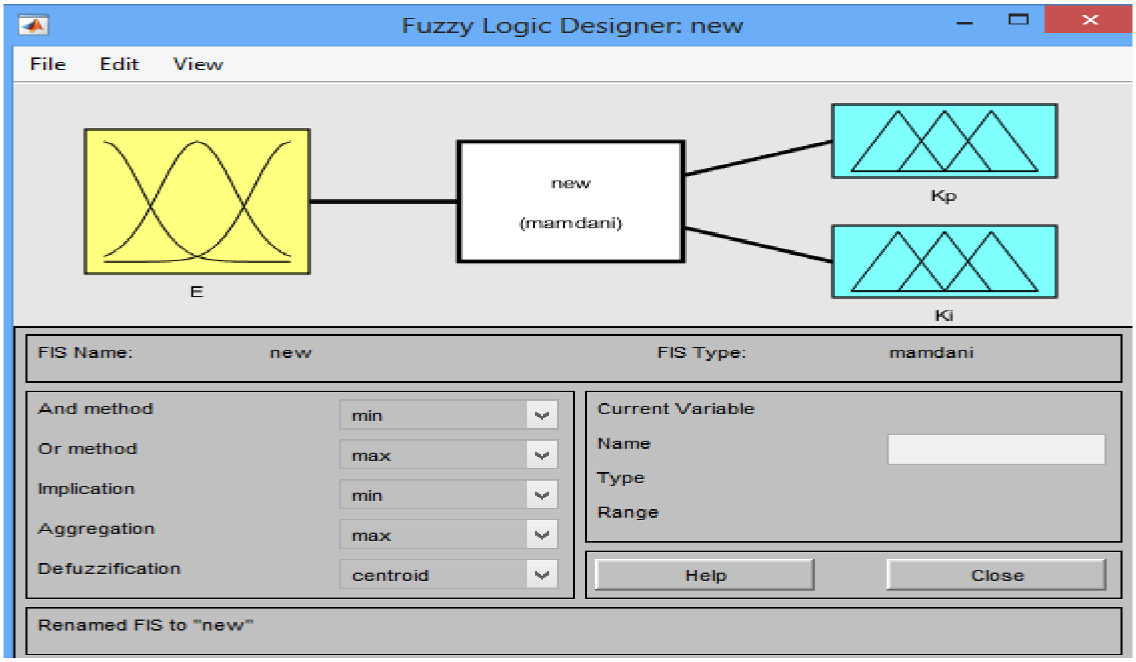
The most important step in designing fuzzy system is the design of the rule base. It consists of a number of fuzzy IF-THEN rules that define the behavior of the system.

$if\ error(E) is\ high\ \left(K_p\right)\ is\ N\ \&\ (K_i)\ is\ P$

$if\ error(E) is\ medium\ \left(K_p\right)\ is\ Z\ \&\ (K_i)\ is\ Z$

$if\ error(E) is\ low\ \left(K_p\right)\ is\ P\ \&\ (K_i)\ is\ N$

Where: N-Negative, P-Positive, Z-Zero



FIS Name: new

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name

Type

Range

Renamed FIS to "new"

Figure 3.7 Fuzzy logic controller design

Here as shown from figure above there are one input (error) and two outputs (Kp & Ki) and Fuzzy rules are designed in accordance to tune PI constants Kp and Ki based on single input error (E).

Chapter Four

Simulation Model and Results

4.1 Simulation Model

Among several simulation software packages, SIMULINK is one of the most powerful techniques for simulating dynamic systems due to its graphical interface and simplicity. Matlab/Simulink 2015 version is software used to model, simulate and analyze overall the system response. The mathematical equations mentioned in chapter two and three are used to model five phase induction motor in Matlab/Simulink 2015 environment.

Figure 4.1 shows overall Simulink model of hybrid fuzzy-PI speed control of five phase induction motor.

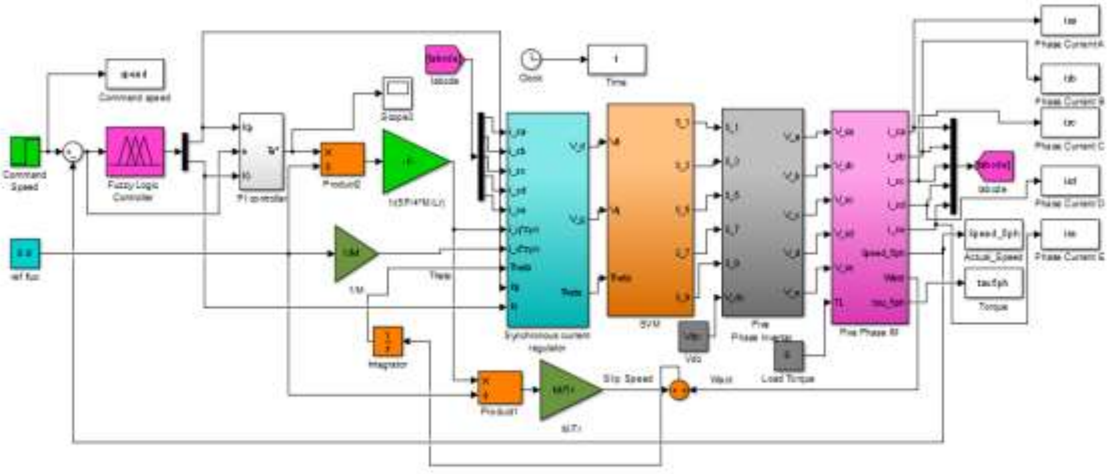


Figure 4.1: Fuzzy-PI control overall Simulink block

The above, complete Simulink model includes sub-functional models such as: PI speed control, VSI, SVM, Coordinate Transformations, IM modeling block and sub functional blocks & the word hybrid indicates that both fuzzy and PI controller act as a single controller. Sequentially, PI controller comes after fuzzy controller; because fuzzy controller reduces disadvantages occurred due to PI controller. Mainly few of the disadvantages are overshoot while starting, undershoot while load application. Then, output of PI controller is electromagnetic torque. This torque controls the quadrature current for further process.

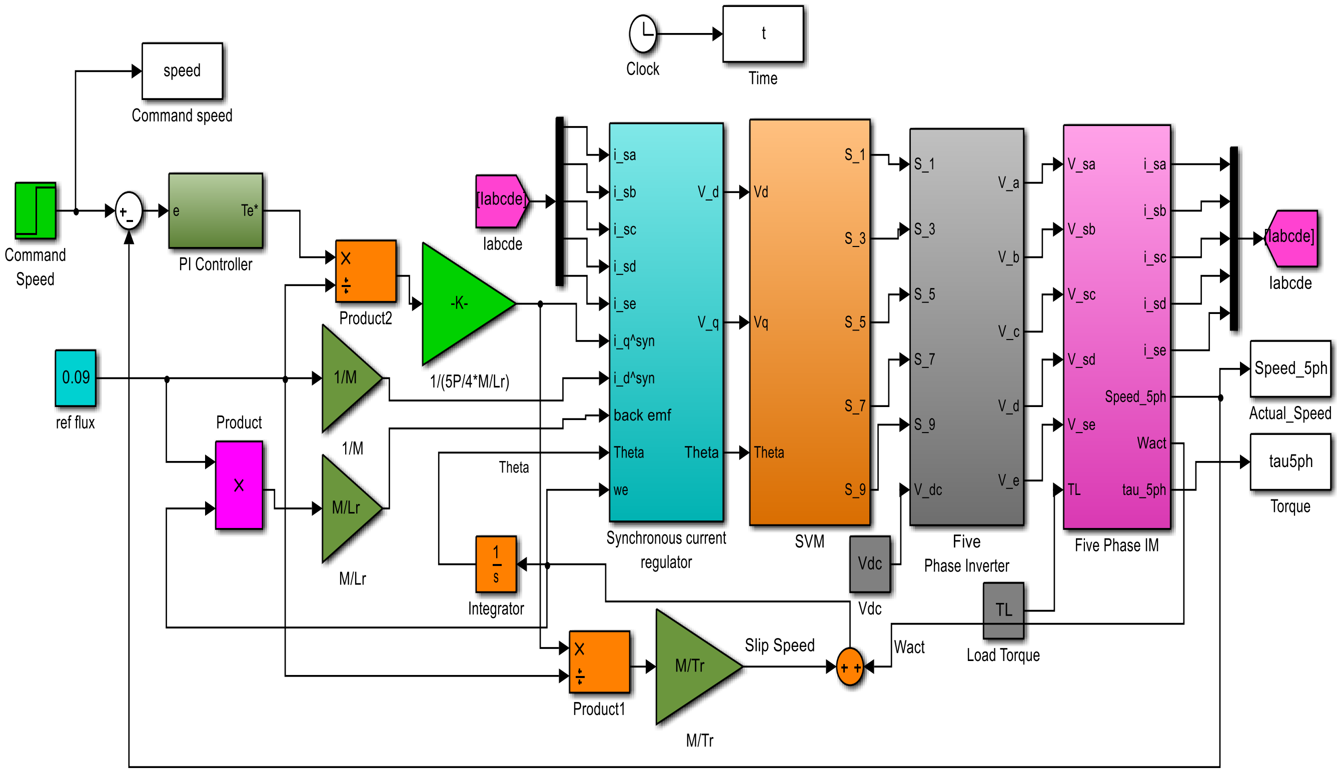


Figure 4.2: PI control Simulink block

In the above figure of 4.2 PI controller used to observe speed response. Here the difference between reference speed and actual speed is an error. This error act as input to the PI controller and electromagnetic torque is output from this controller.

Voltage Source Inverter block

The VSI block is used to generate five phase voltages from the DC voltage by triggering the switching states that are generated in SVM techniques. The phase voltage output of VSI feds to induction motor and also that used to estimate the actual flux and actual torque.

SVM Simulink block

Space vector modulation is an important functional block that produces appropriate duty cycle which controls working condition of VSI. Also for high dynamic response, interactions among current, fluxes, and speed must be taken into account in determining appropriate control strategies. One these strategies is space vector modulation.

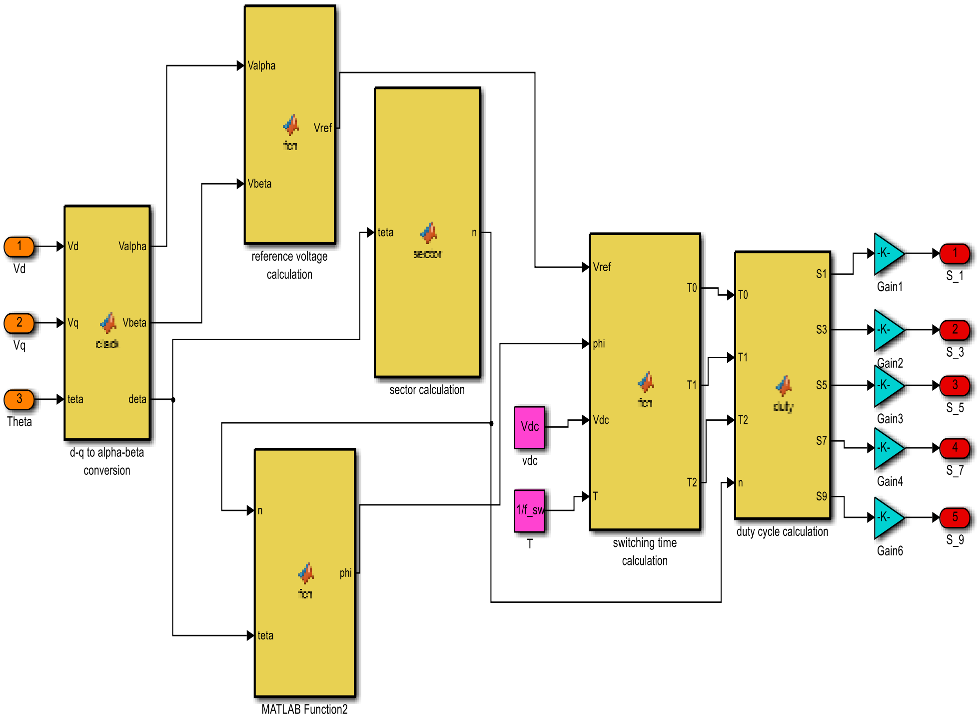


Figure 4.3: Simulink model of SVM

Coordinate Transformation blocks

The different coordinate transformations such as: Clark transformation, park transformation, Clark-inverse transformation and park-inverse transformation are written in MATLAB source code and embedded in simulation blocks. The source codes are shown in the appendix

IM simulation model

In this chapter, the mathematical model of induction motor based on space vector theory and the principle of indirect FOC are presented. The simulation model of the induction motor drive is developed using the principle of indirect FOC. The Simulink blocks are based on rotating and stationary reference frames.

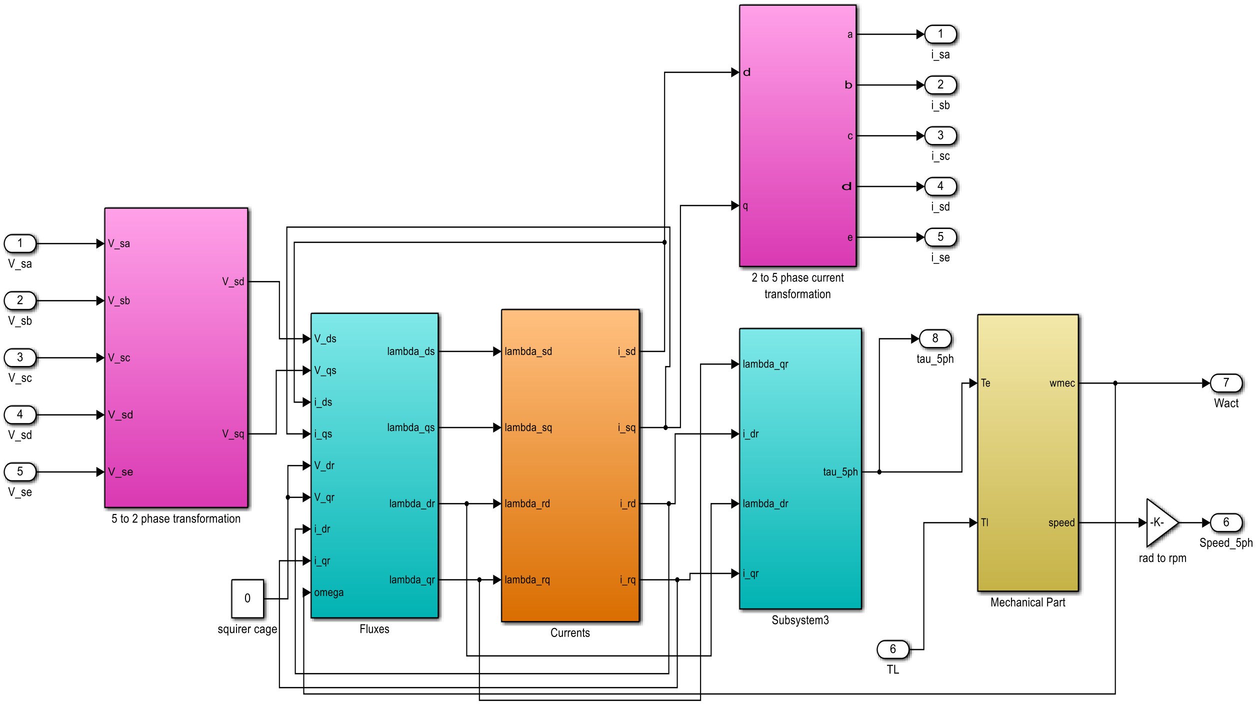


Figure: 4.4 Simulink model of five phase IM

4.2 Simulation Results of PI controller

4.2.1 Simulation Results of IM

This part mainly focuses on simulation results of five phase induction motor drive system. The motor parameters used in the simulation results are given by table 4.1 as shown below. These parameters are obtained from matlab Simulink documentation.

Motor and VSI parameter

Name	Symbol	Value	Unit
Stator resistance	R_s	0.1	Ω
Rotor resistance	R_r	0.5	Ω
Stator inductance	L_s	5.25e-3	H
Rotor inductance	L_r	5.23e-3	H
Mutual inductance	M	5.2e-3	H
DC-Voltage	V_{dc}	1000	V
Moment of inertia	J	0.002	Kg.m^2
Poles	P	4	-

Table 4.1: Motor and VSI parameters

The simulation is carried out for different load torque applications (no load, 2.5Nm & 5Nm.

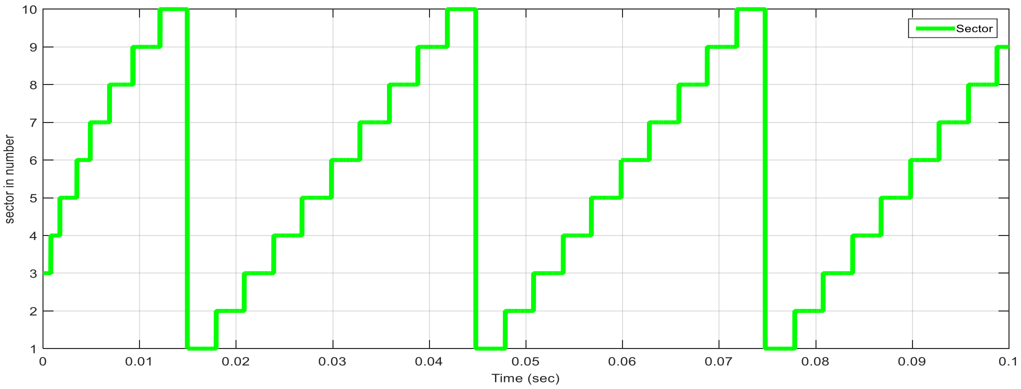


Figure 4.5: PI based simulation result of sectors in number

Figure 4.5 shows the sector number for five phase system. As it shown from the figure there are ten sectors. This indicates that five phase system have ten sectors which is quite right.

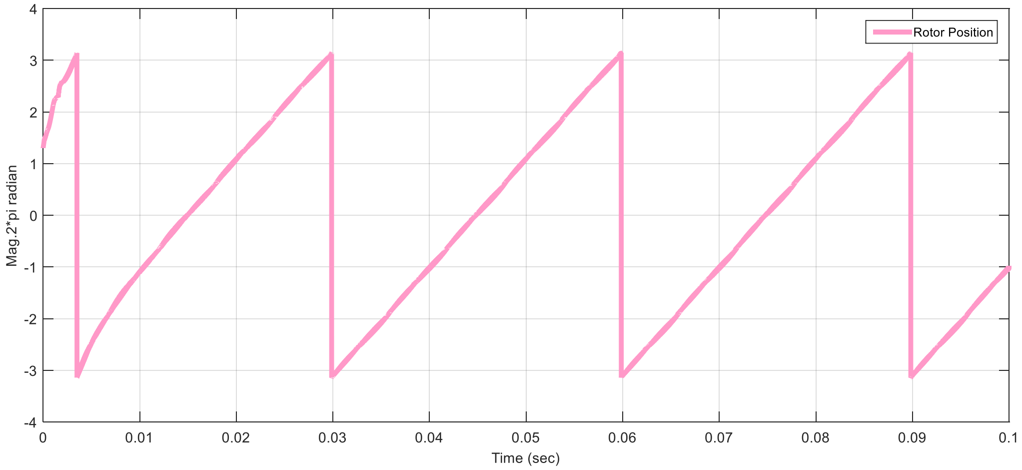


Figure 4.6: PI based simulation result of rotor position

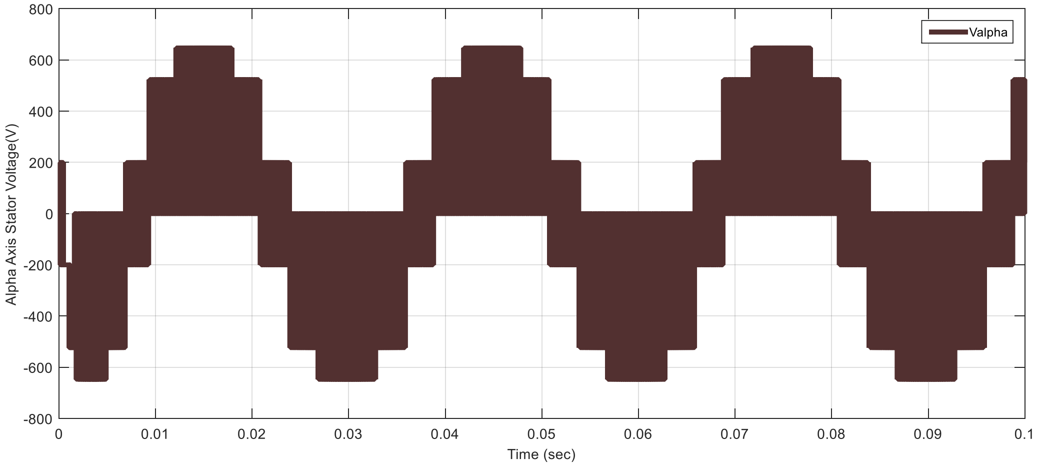


Figure 4.7: PI based alpha axis stator voltage

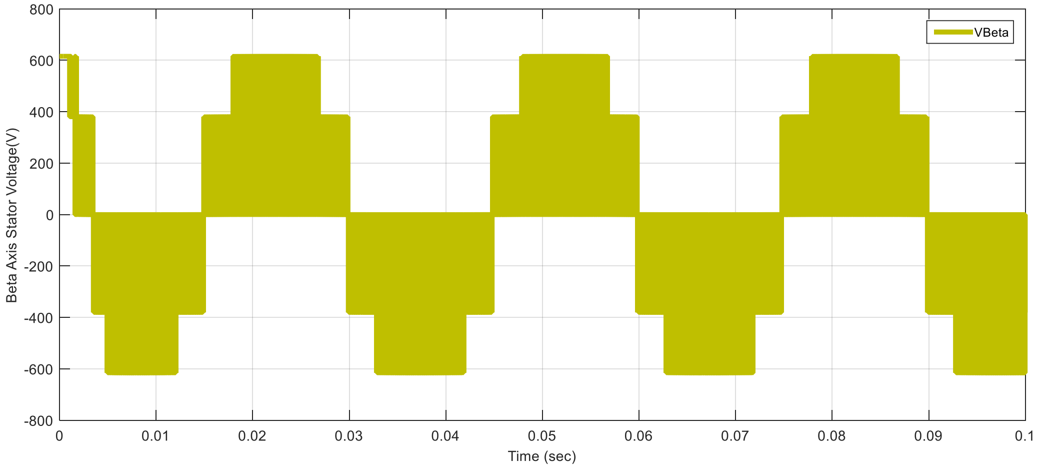


Figure 4.8: PI based beta axis stator voltage

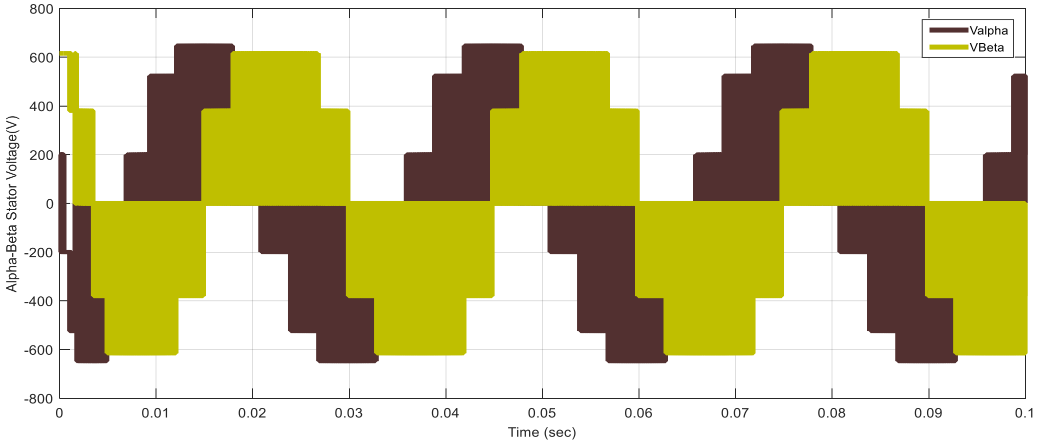


Figure 4.9: PI based two axis alpha-beta stator voltages

Figure 4.9 shows two phase alpha-axis and beta-axis stator voltages. They are obtained by Clark transformations in the orthogonal fixed reference frame. It can be observed that these quantities are sinusoidal and have phase difference of 90°.

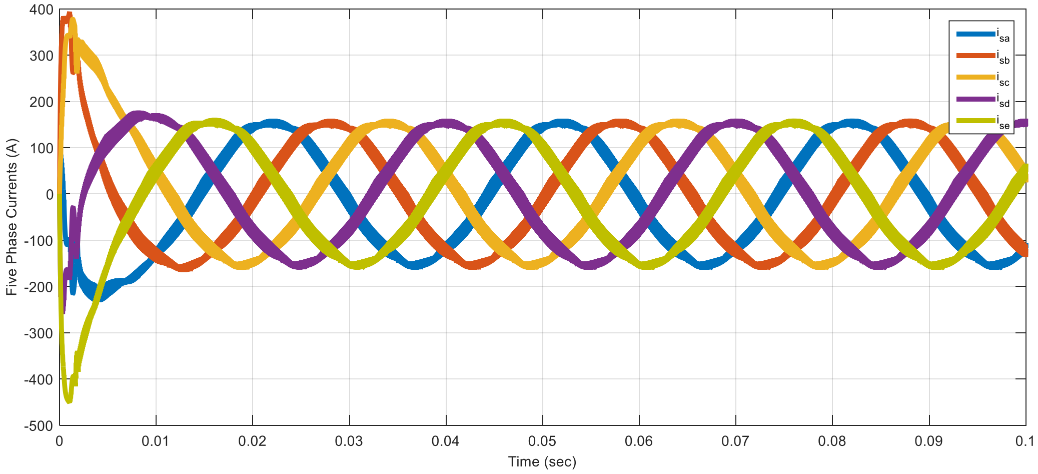


Figure 4.10: PI based five phase currents

Here these currents obtained by applying inverse Clarke transformation of figure 4.9 and they are 72° phase apart.

4.2.2 Speed and Torque Performance Simulation Results

Here figure 4.11, 4.13 & 4.15 shows PI control speed control of five phase induction motor under different load conditions. For example it is tested under no load, 2.5NM & 5NM. Accordingly the result shows as the load torque increases from no load to 5NM the speed of the motor decreases sequentially.

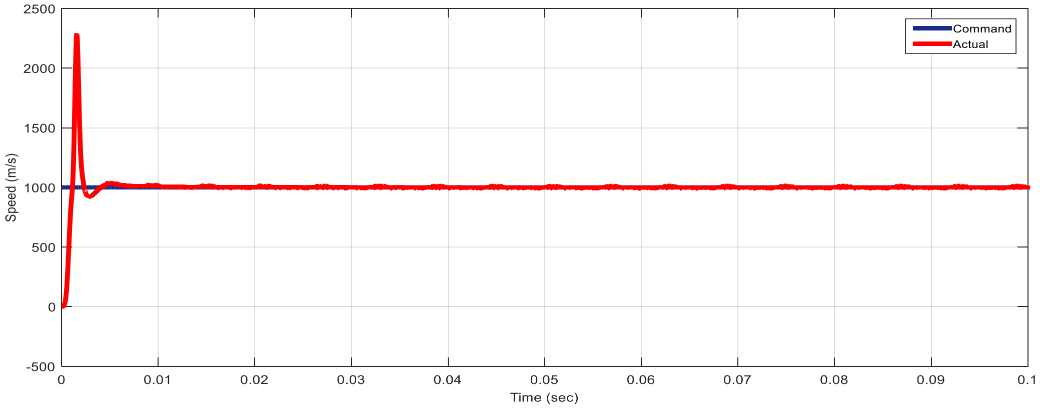


Figure 4.11: PI based speed response at no load

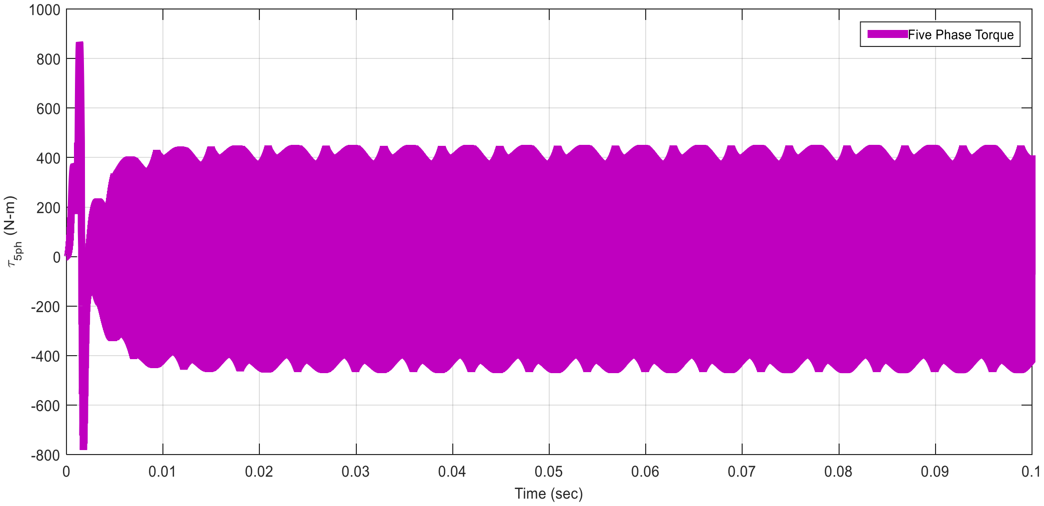


Figure 4.12: PI based torque response at no load

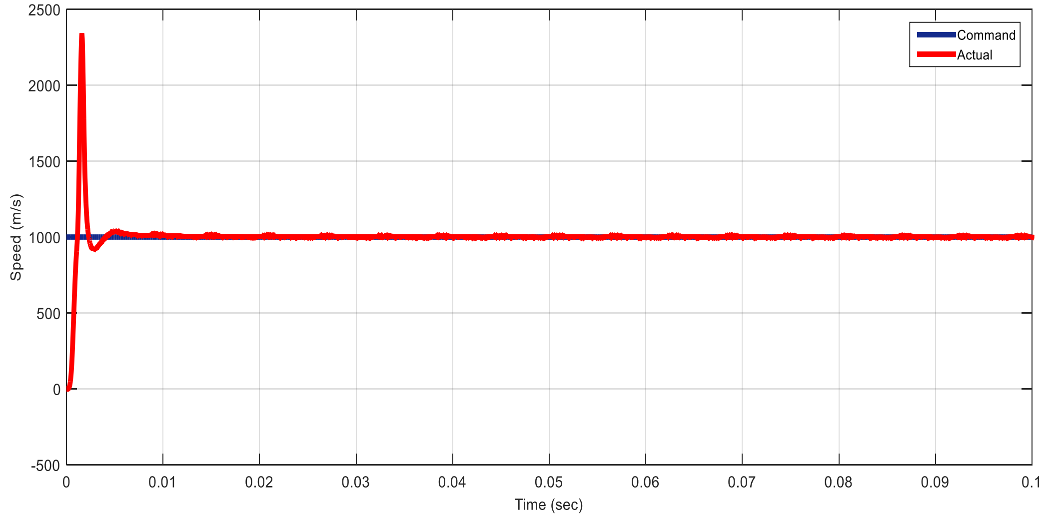


Figure 4.13: PI based speed response for 2.5N.M load

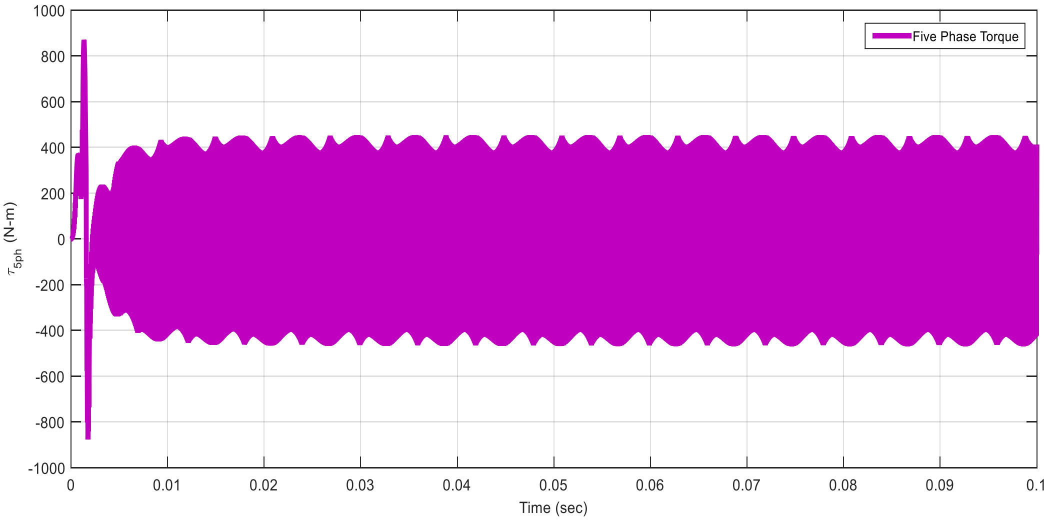


Figure 4.14: PI based torque response at 2.5N.M load

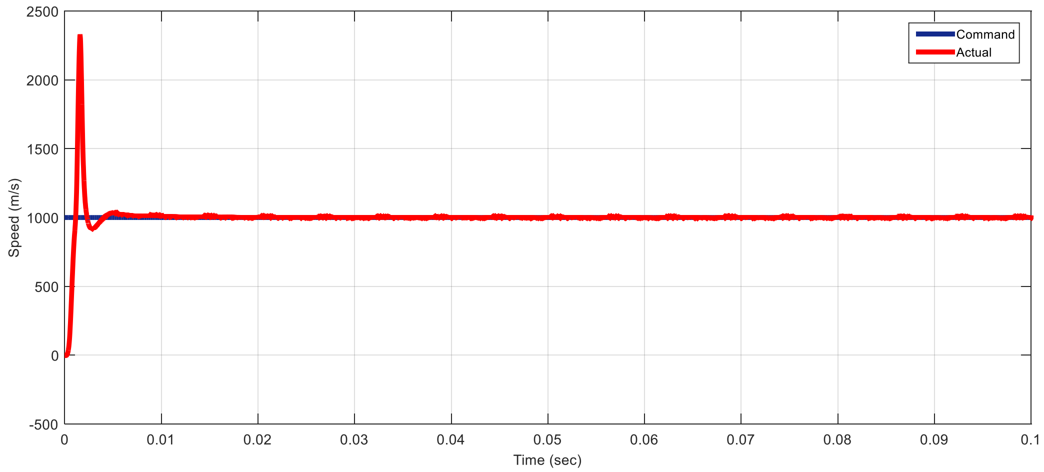


Figure 4.15: PI based speed response for 5N.M load

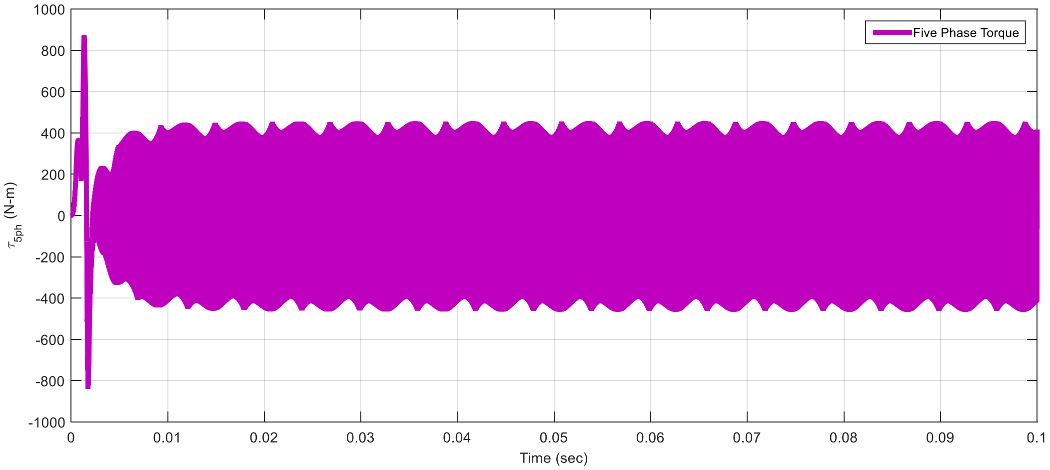


Figure 4.16: PI based torque response at 5N.M load

It is observed from Fig. 4.11, 4.13 & 4.15 that the motor achieve rated speed of 1000 rpm at around 0.01sec and also achieve steady state speed for different load with approximate zero steady state error. The speed of five-phase induction motor is 1000 rpm for the entire load.

The variations in transient as well as steady state current are less with the change in load torque of five-phase induction motor.

4.3 Simulation Results of Fuzzy-PI Controller

4.3.1 Simulation Results of IM

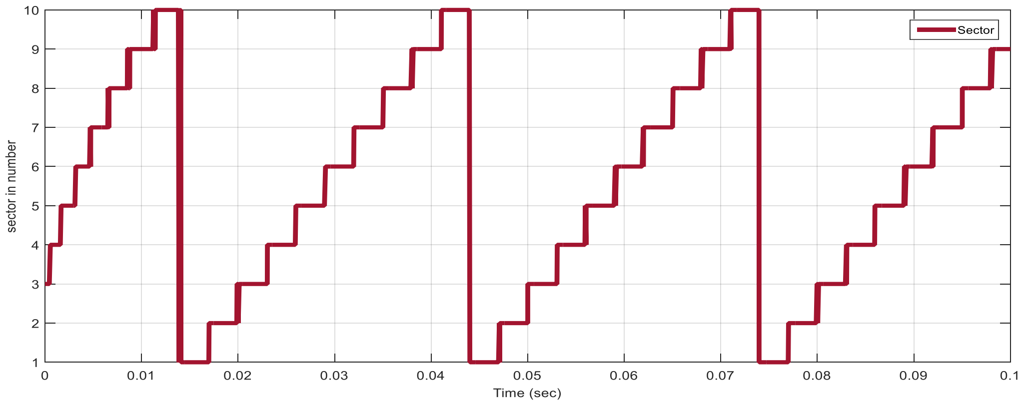


Figure 4.17: Fuzzy-PI based simulation result of sectors in number

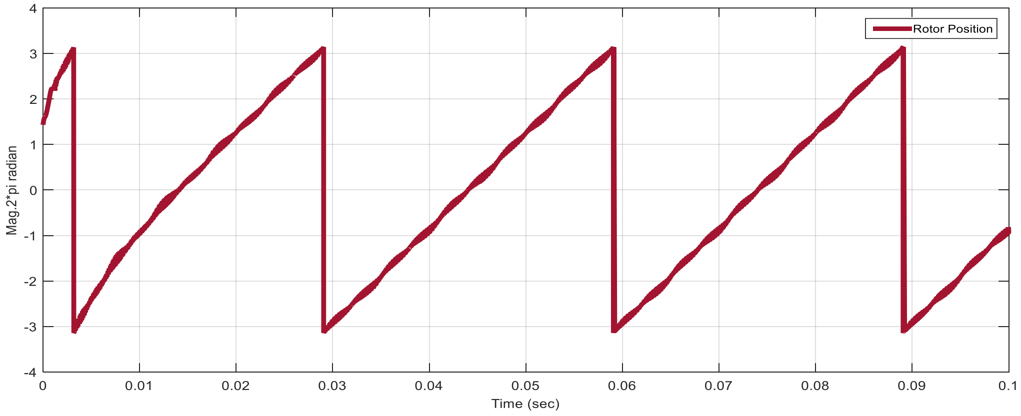


Figure 4.6: Fuzzy- PI based simulation result of rotor position

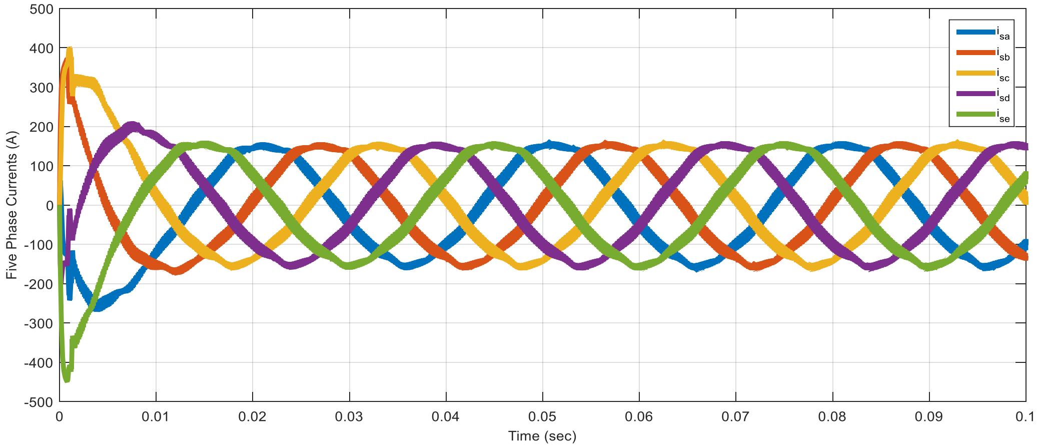


Figure 4.19: Fuzzy-PI based five phase currents

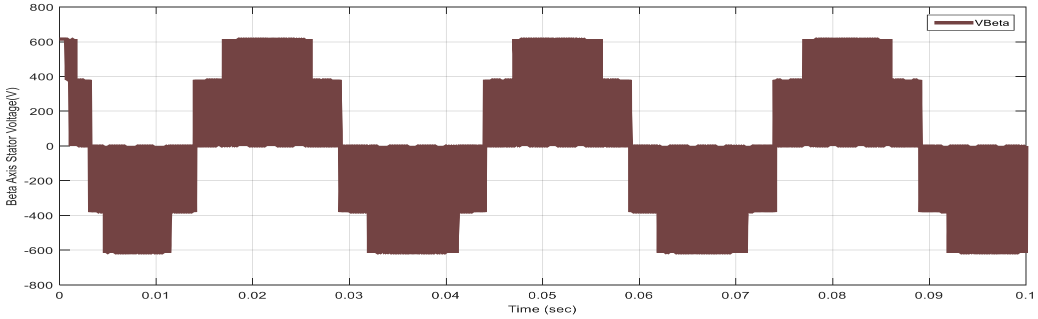


Figure 4.20: Beta axis voltage

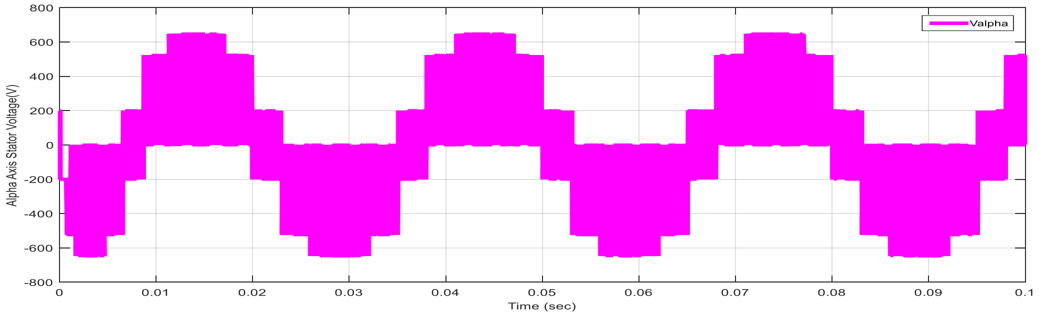


Figure 4.21 : Alpha axis voltage

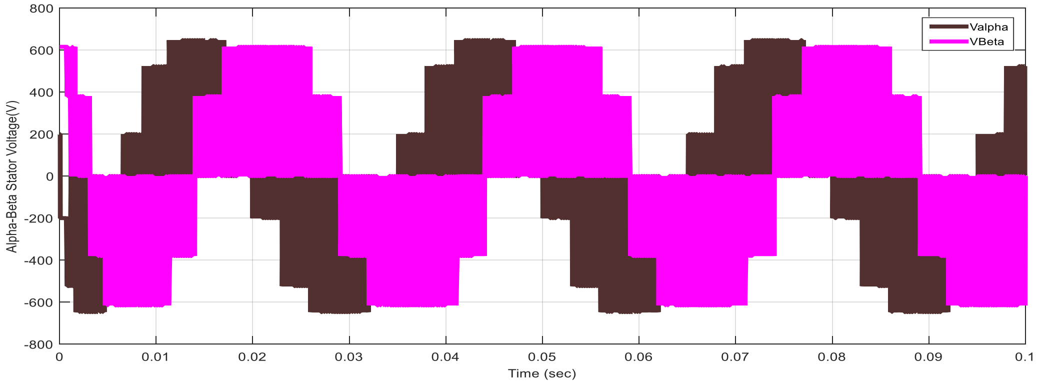


Figure 4.22: Beta -Alpha axis voltages

4.3.2 Simulation Result of Speed and Torque Performance

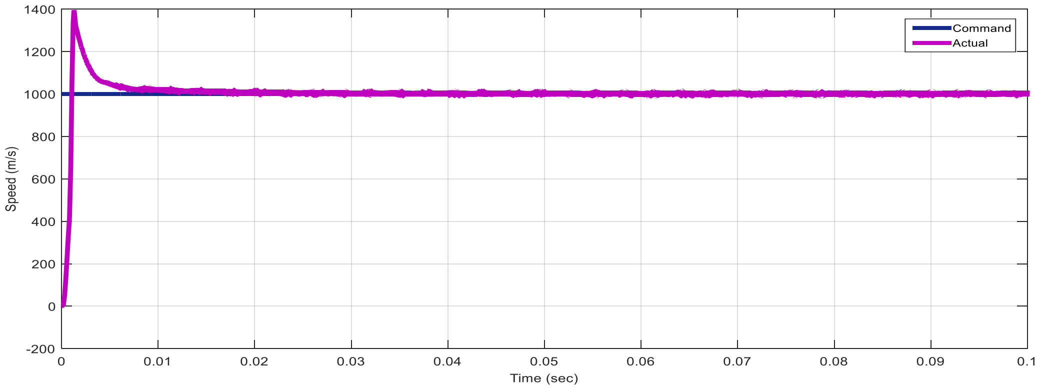


Figure 4.23: Speed response at no load

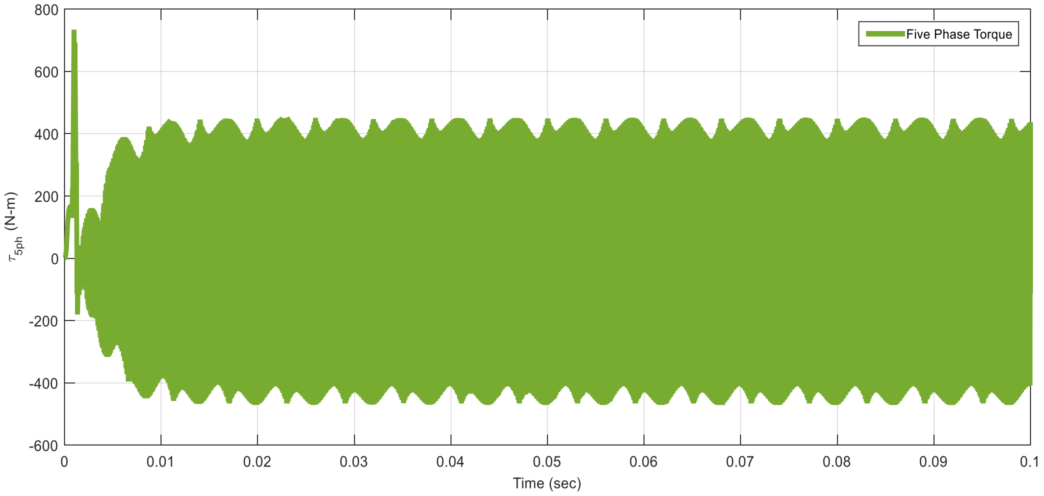


Figure 4.24: Fuzzy-PI based torque response at no load

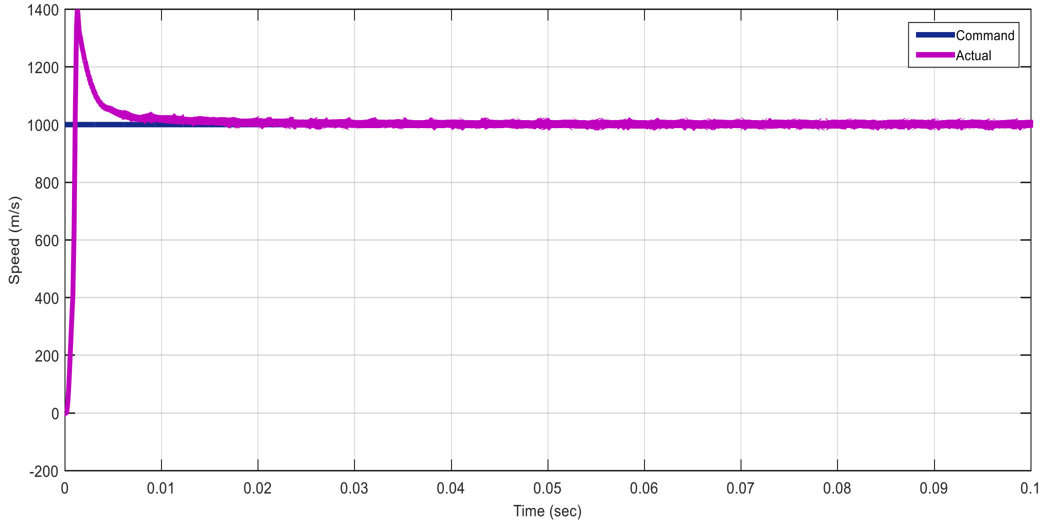


Figure 4.25: Speed response at 2.5 Nm load

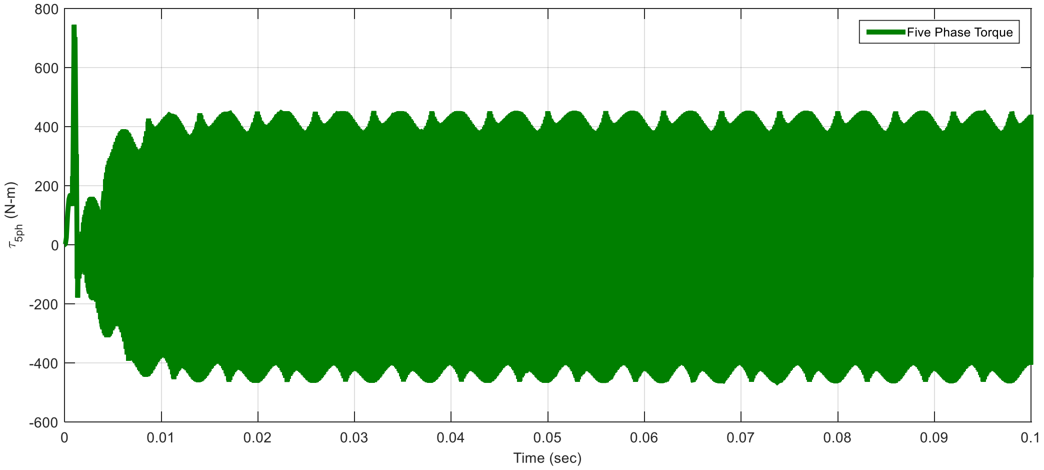


Figure 4.26: Fuzzy-PI based torque response at 2.5 Nm load

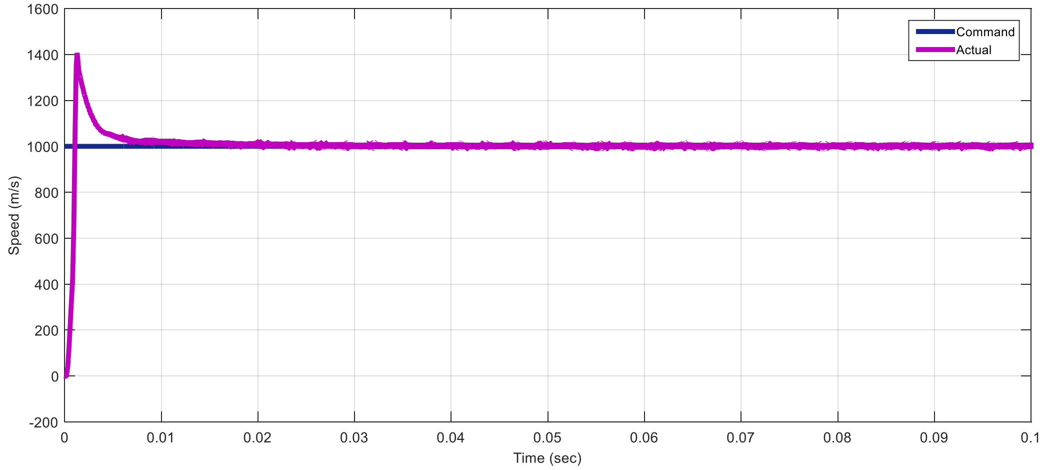


Figure 4.27: Fuzzy-PI based speed response at 5NM

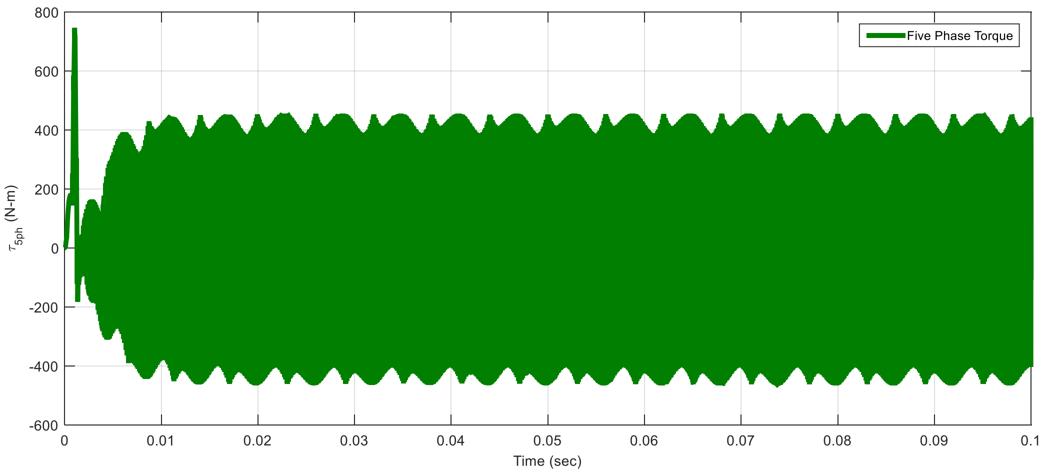


Figure 4.28: Fuzzy-PI based torque response at 5NM

Chapter Five

Conclusion & Recommendation

5.1 Conclusion

This thesis has successfully presented a hybrid Fuzzy-PI system for controlling a five-phase induction motor. The word hybridization indicates that both fuzzy logic and conventional PI speed controller act as a single controller. Additionally, indirect field oriented control space vector controlling techniques utilized to solve instability of induction motor. In this thesis both PI and fuzzy-PI were designed and simulated in MATLAB/Simulink.

The performance and robustness of this PI and fuzzy-PI controllers have been tested under different operating conditions. For example the speed response for different load torques i.e. (no load, 2.5N.M & 5N.M) is considered. Furthermore, a comparative study of both controllers has been completed using the performance measures such overshoot and undershoot. Based on simulation results verification, it is concluded that dynamic response characteristics with the hybrid Fuzzy-PI controller take less overshoot and undershoot, when compared with the PI conventional controller. Also, the hybrid controller shows better robustness during the transient period and during the sudden load changes compared with PI controller. In conclusion, I showed that the proposed hybrid Fuzzy-PI speed controller for closed loop operation of the induction motor drive system has improved performance over the PI conventional controller and that it gives better speed response and shows higher levels of robustness and effectiveness.

The transient performance of both controllers summarized as below

Load (N.M)	**Controller**	t_d**(sec)**	t_r**(sec)**	t_p**(sec)**	M_p	$T_{max}(Nm)$
0	PI	0.00081	0.0011	0.00123	1286	865.7
	Fuzzy-PI	0.00075	0.0008	0.00082	395	733.7
2.5	PI	0.000841	0.00131	0.00132	1341	869.4
	Fuzzy-PI	0.00078	0.00081	0.00083	399	744.9
5	PI	0.00086	0.0014	0.00141	1343	872.1
	Fuzzy-PI	0.00081	0.000831	0.00084	407	746.4

Table 5.1: Comparative analysis of PI & Fuzzy-PI controllers

5.2 Recommendation

Future work should include applying the proposed method to real time system and conduct full analysis of other power quality issues such as harmonic distortion, voltage imbalance, and power factor improvements. Additionally, system protection should take into consideration both under and over voltage conditions. Finally, it is essential to comment on the fact that induction motor working at rated flux will give optimum transient response, however, at lighter loads, excessive core loss can occur resulting in a very low efficiency. Therefore, future work should improve the motor efficiency by controlling the flux and thus allow for obtaining a balance between the copper and iron.

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Appendix

1. DUTY CYCLE CALCULATION

```
        $function[S_1,S_3,S_5,S_7,S_9] = duty(T_0,T_1,T_2,n)$
        $S_1 = 0;$
        $S_3 = 0;$
        $S_5 = 0;$
        $S_7 = 0;$
        $S_9 = 0;$
        $if(n == 1)$
$S_1 = T_1+T_2+T_0/2;$

$S_3 = T_1+T_2+T_0/2;$

$S_5 = T_0/2;$

$S_7 = T_0/2;$

$S_9 = T_1 + T_0/2;$

        $end;$
        $if(n == 2)$
$S_1 = T_1+T_2+T_0/2;$

$S_3 = T_1+T_2+T_0/2;$

$S_5 = T_2+T_0/2;$

$S_7 = T_0/2;$

$S_9 = T_0/2;$
```

```
        $end;$

        $if(n == 3)$
$S_1 = T_1 + T_0/2;$

$S_3 = T_1 + T_2 + T_0/2;$

$S_5 = T_1 + T_2 + T_0/2;$

$S_7 = T_0/2;$

$S_9 = T_0/2;$

        $end;$
        $if(n == 4)$
$S_1 = T_0/2;$

$S_3 = T_1 + T_2 + T_0/2;$

$S_5 = T_1 + T_2 + T_0/2;$

$S_7 = T_2 + T_0/2;$

$S_9 = T_0/2;$

$end;$

        $if(n == 5)$
$S_1 = T_0/2;$

$S_3 = T_1 + T_0/2;$

$S_5 = T_1 + T_2 + T_0/2;$

$S_7 = T_1 + T_2 + T_0/2;$
```

```
$S_9 = T_0/2;$

$end;$

        $if(n == 6)$
$S_1 = T_0/2;$

$S_3 = T_0/2;$

$S_5 = T_1+T_2+T_0/2;$

$S_7 = T_1+T_2+T_0/2;$

$S_9 = T_2+T_0/2;$

$end;$

        $if(n == 7)$
$S_1 = T_0/2;$

$S_3 = T_0/2;$

$S_5 = T_1 + T_0/2;$

$S_7 = T_1+T_2+T_0/2;$

$S_9 = T_1+T_2+T_0/2;$

$end;$

        $if(n == 8)$
$S_1 = T_2+T_0/2;$

$S_3 = T_0/2;$

$S_5 = T_0/2;$
```

```
$S_7 = T_1 + T_2 + T_0/2;$
$S_9 = T_1 + T_2 + T_0/2;$
$end;$
        $if (n == 9)$
$S_1 = T_1 + T_2 + T_0/2;$
$S_3 = T_0/2;$
$S_5 = T_0/2;$
$S_7 = T_1 + T_0/2;$
$S_9 = T_1 + T_2 + T_0/2;$
$end;$
        $if (n == 10)$
$S_1 = T_1 + T_2 + T_0/2;$
$S_3 = T_2 + T_0/2;$
$S_5 = T_0/2;$
$S_7 = T_0/2;$
$S_9 = T_1 + T_2 + T_0/2;$
$end;$
```

1. REFERENCE VOLTAGE CALCULATION

$function\, V_{ref} = fcn(V_{alpha}, V_{beta})$

$V_{ref} = sqrt(V_{alpha}^2 + V_{beta}^2)$

2. SECTOR CALCULATION

```
function n = sector(teta)
n = 0;
if(teta >= 0)&&(teta < pi/5)
n = 1;
end
if(teta >= pi/5)&&(teta < 2 * pi/5)
n = 2;
end
if(teta >= 2 * pi/5)&&(teta < 3 * pi/5)
n = 3;
end
if(teta >= 3 * pi/5)&&(teta < 4 * pi/5)
n = 4;
end
if(teta >= 4 * pi/5)&&(teta < pi)
n = 5;
end
if(teta >= −pi/5)&&(teta < 0)
n = 10;
end
if(teta >= −2 * pi/5)&&(teta < −pi/5)
n = 9;
```

```
end
if(teta >= −3 ∗ pi/5)&&(teta < −2 ∗ pi/5)
n = 8;
end
if(teta >= −4 ∗ pi/5)&&(teta < −3 ∗ pi/5)
n = 7;
end
if(teta >= −pi)&&(teta < −4 ∗ pi/5)
n = 6;
end
```

3. ALPHA CALCULATION

```
function phi  =  fcn(n, teta)
phi = 0;
if(n == 1)
phi = teta;
end
if(n == 2)
phi = teta − pi/5;
end
if(n == 3)
phi = teta − 2 ∗ pi/5;
end
if(n == 4)
phi = teta − 3 ∗ pi/5;
end;
if(n == 5)
phi = teta − 4 ∗ pi/5;
end
```

```
if(n == 10)
phi = teta + pi/5;
end
if(n == 9)

phi = 2 * pi/5 + teta;
end
if(n == 8)
phi = 3 * pi/5 + teta;
end
if(n == 7)
phi = 4 * pi/5 + teta;
end
if(n == 6)
phi = pi + teta;
end
```

5. SWITCHING TIME CALCULATION

```
function [T0,T1,T2] = fcn(Vref,phi,Vdc,T)
a = Vref/(4/5) * Vdc * cos(pi/5);
T1 = T * a * sin(pi/5 - phi)/sin(pi/5);
T2 = T * a * sin(phi)/sin(pi/5);
T0 = T - T1 - T2;
```

Declaration

I declare that this thesis is organized and written by my own. The work included in this paper has not been submitted and presented for any qualification.

Abera Assebe ____________________

Name Signature

Addis Ababa, Ethiopia ____________________

Place Date of Submission

This thesis has been submitted for examination with my approval as a university advisor.

Dr.Mengesha Mamo ____________________

Advisor's Name Signature