Direct Torque Control of Six Phase Induction Motor Supplied With SVPWM Inverter Using Fuzzy Logic Control

Girma Shumi Idae

A Thesis Submitted to

The department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Masters of Science in Electrical Power and Control Engineering

(Specialization in Power system)

Office of Graduate Studies

Adama Science and Technology University

September, 2021

Adama, Ethiopia

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Advisor: Tefera T. Yetayew (PhD)

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DECLARATION

I hereby declare that this Master Thesis entitled "direct torque control of six phase induction motor supplied with svpwm inverter using fuzzy logic control" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Girma Shumi Idea	________________	__________
Name	Signature	Date

RECOMMENDATION

I the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “direct torque control of six phase induction motor supplied with svpwm inverter using fuzzy logic control” prepared under my guidance by Girma Shumi submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Power System Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Tefera T.Yetayew	____________	___________
Advisor	Signature	Date

APPROVAL SHEET

I the advisors of the thesis entitled "direct torque control of six phase induction motor supplied with svpwm inverter using fuzzy logic control" and developed by Girma Shumi, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Tefera T. yetayew	_____________	_____________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Girma Shumi have read and evaluated the thesis entitled "direct torque control of six phase induction motor supplied with svpwm inverter using fuzzy logic control" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Power system.

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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Adama, August, 2021

Girma Shumi

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

SYMBOLS

ω_e	Angular speed
P	Differential operator
R	Resistance
L	Inductance
L_m	Mutual inductance
ψ	Flux
T_e	Electromagnetic Torque
T_L	Load Torque
P_b	Pole pairs
K_p	Proportional gain
K_i	Integral gain
$e(t)$	Error signal
$U(t)$	Actuating signal
$V_{A,}V_B, V_C, V_D, V_{E,}V_F$	Inverter leg voltages
$v_a, v_{b,}v_c, v_d, v_e, v_f$	Phase to neutral voltages
V_{Nn}	Voltage between star point of load and negative rail of dc bus
V_{dc}	DC link voltage
$v_1, v_2, v_3, ….$	Space voltage vectors
T_1, T_2	Time of application of neighboring space vectors

T_o	Time of application of zero space vectors
T_s	Sampling time
L_s	Stator Inductance
L_r	Rotor Inductance
α, β	Relates to alpha and beta axis
V_{ref}	Vector reference

ABBREVIATION

AC	Alternating Current
DC	Direct Current
DSP	Digital Signal Processor
DTC	Direct Torque Control
FLC	Fuzzy logic controller
IM	Induction Motor
MF	Membership function
PI	Proportional Integral
PWM	Pulse Width Modulation
SVM	Space Vector Modulation
SVPWM	Space Vector Pulse Width Modulation
VSI	Voltage Source Inverter

ABSTRACT

In this thesis direct torque control for six-phase IM supplied with svpwm inverter using fuzzy logic control is modeled. Mathematical models of the six-phase induction motor and the six-phase voltage source inverter have been briefly explained. A space vector modulation technique that is used to control a six-phase voltage source inverter had been defined. Six-phase IM drive own several benefits when compared to conventional three-phase IM, in case of the additional degrees of freedom. Some of these advantages include reduction in harmonic currents, lower torque pulsation, and reduced stator current per phase without the need to increase the phase voltage, greater reliability, fault tolerant feature and increased power. The performance of direct torque control of six-phase IM simulation is done for both fuzzy and PI controllers using a matlab/simulik. With fuzzy logic controller harmonic oscillation are less at Transient state and Fuzzy logic controller perform good. Moreover, hardware implementation of this research work, extending this control technique to other types of multiphase motors, and using other soft computing techniques and/or in combination with conventional controllers to enhance the torque performance is recommended as a future work.

Keywords: *six-phase induction motor, Direct Torque control, Space Vector Modulation, Fuzzy logic Controller.*

CHAPTER ONE
INTRODUCTION

1.1. Background

For many years, before the introduction of digital signal processers (DSP), micro-controllers and high switching frequency semiconductor devices, variable speed actuators were dominated by DC motors. Widely they were used in areas where variable speed process. Since the field and armature current can control their flux and torque independently and easily. Particularly, the separately excited DC motor has been used mainly for applications where there was a requirement of fast response and four-quadrant operation with high performance near zero speed. Though, due to the presence of the commutator and the brushes, DC motors have certain difficulty. These are they required frequent maintenance. At the present time these difficulties can be solved by the application of AC induction motors, because of its ruggedness, simplicity, compactness and efficiency.

The advantages of AC induction motor drives compared with DC motor drives are:

- They have high speed operations due to the absence of Commutator and Brushes.
- Induction motors have frequently better efficiency and comparable than the equivalent DC motor.
- A DC motor must be required service regularly to check or replace the brushes and the commutator. But essentially maintenance free in induction motor, except for the bearings.
- Protection of DC motor is difficult than AC motor. For large DC machines protection of a DC circuit breaker is required which are expensive.
- Commonly induction motors have high efficiency and a high overload capability, low weight and inertia.
- Additionally, because of the absence of sparks the motor can work in explosive atmospheres.

Depend on the benefits listed out above, IM are extensively used in commercial, industrial and domestic applications than all the rest of the electric motors. There are two types of control method of induction motor used for high performance applications such as: Scalar control and vector control methods [2]. In scalar control, only the magnitude and frequency, which is based on the steady state model of IM of a space vector variable such as current, voltage and flux linkage, are controlled. The scalar control does not act during the transient position of space vector. In vector controller it is based on relation, which is valid for dynamic states, i.e. not only magnitude and frequency (angular speed) but also instantaneous positions of voltage, current, and flux space vectors are controlled. Thus, the vector control acts on the positions of the space vectors and provides correct orientation for both steady state and transient state. Many methods have been discovered to implement vector control for induction motor. The most popular vector control methods are the FOC (field oriented control) and DTC (direct torque control) [3]. Conventional DTC strategy is quite different from that of the FOC. Because it does not need complicated coordinate transformations and decoupling calculations. DTC technique is introduced for low, medium power application and for high power application [11].

Now a days, Multi-Phase IM such as: six phase, seven phase, nine phase motor and so on, are fast increasing due to their several inherent benefits such as reduction in harmonic currents, lower torque pulsation, greater reliability, reduced stator current per phase without the need to increase the phase voltage, fault tolerant feature and increased power in the same frame as compared to conventional three phase induction motor [20]. Currently the grid power existing is only limited to three-phase so that the supply to multi-phase motors is invariably given from power electronic converters. Various applications such as, electric aircraft drives, electric ship propulsion, locomotive traction, electric/hybrid electric vehicles and high power industrial plants, require high power ratings for both the motor and its converter. However, converter ratings cannot be accordingly increased due to power rating limitations of semiconductor devices [4], [5].

Higher torque density in a multi-phase machine is possible, since apart from the fundamental spatial field harmonic, the space harmonic fields can be used to contribute to the total torque production. In a multi-phase machine, with six or more phases, there are additional degrees of freedom, which can be used to improve the torque production through the injection of higher order current harmonics. Six-phase voltage source inverter (VSI) produces 64 output space vector voltages. The maximum number of output voltage vectors can be reached more precise control in stator flux and electromagnetic torque. This thesis will concentrate on controlling of 6-phase IM supplied with SVPWM inverter.

1.2. Statement of the problem

For several years three-phase IM is one of the most common form of electromechanical drive which is used for commercial, industrial and domestic application due to low weight and inertia, high overload capability, high efficiency, lower cost, simple mechanical construction, more robustness, less proves to any failure at maximum speeds and able to work in explosive environments. But, three phase induction motor has some limitation such as: the over load capability is low and it has only eight space vector voltages that produce high torque ripple, it has only fundamental torque component, the fault tolerance is low and run with high de-rating during phase failure.

To overcome these limitations of three-phase IM drive, DTC of six-phase IM drive has well performance characteristics. Because, six-phase inverter has sixty four possible space vector voltages. So there is a greater flexibility in controlling six-phase drive systems. In case of the additional degrees of freedom, it presents unique characteristics for improving the torque producing capability of the motor. And also they possess many advantages over conventional three-phase drives such as high fault tolerance feature, lower torque pulsation, reliability, lower torque ripple, high efficiency and decreased current per phase without maximizing voltage per phase. Specially, in fault tolerance in six-phase motor if one or two phases fail the motor keeps working which is not possible in conventional three phase motor.

1.3. Objectives of Thesis

1.3.1 General Objectives

The general objective of this thesis work is to design and simulate Direct Torque Control of six-phase induction motor using FLC.

1.3.2 Specific Objectives

The study in this thesis will concentrate on the following specific objectives:

- To develop dynamic model of DTC 6 phase induction motor using SVPWM.
- To design PI torque and flux controller for the 6 phase IM.
- To design Fuzzy logic controller for the 6 phase IM.
- To determine the switching sequence and duty cycle of the inverter circuit using SVPWM technique.
- To simulate the whole integrated DTC of six-phase based space vector modulation (SVM) using matlab/Simulink and evaluate the control performance.

1.4 Significance of studies

Induction Motors are extensively used in commercial, industrial and domestic applications than all the rest of the electric motors. For all these purpose convectional 3 phase IM have been using but conventional 3 phase motor have some limitation so that to solve this limitation currently 3 phase IM substituted by multiphase induction motor. Now days, Multi-Phase IM such as: 6 phase, 7 phase, 9 phase motor and so on, are fast increasing in case of their numerous advantages such as decreasing in harmonic currents, lower torque pulsation, greater reliability, decreased stator current per phase without the need to maximizing the phase voltage, fault tolerant feature

CHAPTER TWO

LITERATURE REVIEW

2.1 Empirical Review

The study of more than 3 phase's electrical machines dates back to the 1910s. The theory of 3, 4 and 6 phase armature windings for a symmetrical multi-phase system was discussed in [14]. In order to decrease the fault current stress on circuit breakers double winding generators were proposed later in [15]. The extension of Park's 2-reaction theory to poly-phase synchronous machines was discussed in [16]. However, there was limited opportunity for application of multiphase machines. One of the reasons for this is the machines had to be supplied from three phase sources as power processing units were yet to come.

Research on multiphase machines with the introduction of power diodes and thyristors started to get more attention in early 1970s. [17] Presented analysis of multiphase induction machines with arbitrary displacements between winding sets. They also indicated that, in a machine with two three phase groups, an arrangement with 30 electrical degree displacements between the two phase groups gives significantly improved torque characteristic. [18] presented a d-q model for a six-phase machine supplied from a current source inverter (CSI). A wide-ranging work including symmetrical component analysis, space harmonics and time harmonics of multiphase induction motors was done by [4]. Experimental work on six- and nine-phase machines was also presented by the same author [19]. A six-phase induction motor voltage driven by a VSI was presented in [20].

[21] introduced the modeling of six-phase IM using VSD. This was an essential work that make easy the modeling and control of 6 phase IM. It simplified the vector control of these machines using space vector and other PWM techniques. Over the last decade research on poly-phase machines has increased. In several of the publications, the furthermost discussed poly-phase machine is a six-phase IM with 30 electrical degree separation between phase groups and with isolated neutral points [5], [6], [20]-[26].

The six-phase IM can be modeled using the method of VSD as demonstrated in [21], [24]-[26]. This technique results in a model of the machine in single six-phase reference frame with three pairs of axes decoupled from one another. A less common modeling method is the dual stator approach mentioned in [23], [24] and [26]. It considers the 6 phase machine as two coupled 3 phase machines, and uses 3 phase transformations.

In several of the publications discussed, only normal operation of 6-phase IM is considered [5] [21] [24] [25]. Power is equally shared in the two stator phase groups of the machine. Moreover, the machine is supplied using a six-phase VSI. The analysis in [26] considered unbalanced current sharing between the two phase groups. Fault tolerance operation of multiphase drives to open circuit in one or some of the phases is discussed in [28] and [29].

2.2 Six-phase Induction Motor

In the environments of industrial drives, the DC motor based drives substituted by Variable speed AC induction motors because of DC motor having the inherent weakness of mechanical brushes and commutator, which experience wear and tear through a time. In past decades the technology opportunities in the area of multi- phase IM undertake a significant evolution.

Industrial drive systems used the 6-phase AC IM at high power [3]-[8]. The main motivations and the list of important advantages behind the study of multi-level inverter fed six phase induction motors are “decreasing harmonic power loss, Improved system reliability, good power distribution per phase, decreasing the rotor harmonic current losses, decreasing the dc-link current harmonics, lowering torque ripples, improved power characteristics and enhance efficiency when compared to that of the conventional 3 phase counterpart” [3], [9]-[12].

Multi-phase IM are obtained by substituting the three-phase windings with additional number of phases [8]. Power supply of three-phase are accessed easily since, conventional 3 phase motors were used for the drive applications. But now a day generation of multi-phase power supply is not difficult, with the advent of inverter technology resulting from power semiconductor switches. Therefore control of multi-phase motors is now easily achievable in high power industrial applications. In a 3 phase machine the conductors are distributed in slots symmetrically for each phase group and the conductors belonging to each individual phase group are connected in series. By splitting the individual 3 phase groups into 2 equal halves we can obtain 6-phase IM [4]-[8].

2.3 PWM Control of Multiphase Induction Motor

Multiphase drives, though known for several decades, have started to charm better attention of researchers and industry wide-reaching recently. Currently multiphase IM are considered as serious contenders for specialized applications, where high consistency and high power ratings are required, such as electric ship propulsion, locomotive traction, industrial high power applications, electric and hybrid-electric vehicles and more-electric aircraft [9].

An increase in interest of multiphase IM had been driven by many advantages of multiphase drive, such as decreasing current without increasing of voltage per phase, high torque density, enhanced reliability, maximized fault tolerance, enhance noise characteristics and better efficiency Many types of multiphase drives had been designed, advanced and studied. They are such as; induction machine and synchronous machine having stator windings with many number of phases where 5, 6 and 7 are the most leading ones. Thus a chance gives to explore many control strategies that are well-matched for a given application. The fast increasing of digital signal processors (DSP) and power electronic component, this combined with the derived comprehensive mathematical models of multiphase drives has empowered implementation and study of several control techniques for multiphase drives [12].

Due to the fact of an AC drives the multiphase drives can be used in industrial application, it is not directly connected to the utility supply, when used in a variable speed drive system. The utility supply and machine are interfaced by using power electronic converter. The converter can easily provide the required number of phase voltages (with the necessary phase difference) that matches the number of machine’s stator winding phases. The converter is most commonly an inverter, and inverter that produces more than 3-phase output is normally referred to as a multiphase inverter.

Before development of PWM and at the beginning of multiphase machines utilization, multiphase inverter was switched at a fundamental frequency. Due to less frequencies torque ripple in 6-step mode of operation of three-phase, at the time the utilization of multiphase machines was considered as one method to solve the problem. A 6-phase IM, built based on asymmetrical stator winding configuration with two isolated neutrals was extensively investigated in order to push the harmonics to higher frequencies. The six-phase supply of the machine was normally obtained by means of two three-phase voltage source inverters (VSI) or by two three-phase current source inverters (CSI) [15].

When the utilization of PWM method started, this benefit become less significant, since the harmonics can be now efficiently controlled by PWM method. However, for very high power applications, in order to maintain low switching losses, this advantage is still relevant due to the limitation of the switching frequency of currently available semiconductors. Studies on PWM method become gradually increased for multiphase inverter, mainly for medium and low power application.

2.3.1 Multiphase machines supplied with two level inverter

Currently the supplies of multiphase variable speed machines are from 2-level multiphase inverters, at which proper PWM method is used for controlling techniques. The carrier-based PWM and SVPWM are the main two groups of PWM techniques.

For SVPWM methods, the set of sinusoidal reference voltages is represented as a reference voltage vector that needs to be generated by the inverter. Different voltage vectors are produced in each switching state combination of inverter legs. By using SVPWM, over one switching period a certain number of space vectors will be used, each with properly calculated dwell time, in order to produce output voltage vector that has an average value equal to the reference.

To carrying out SVPWM, the number of switching state combinations for two-level multi-phase inverter can be calculated as $N_{sw} = 2^n$. Therefore, three-phase inverter have the number of switching states is $2^3 = 8$, the process of selecting the appropriate space vectors and devising SVPWM from, for example, $2^{15} = 32768$ switching state combinations for 15-phase machine is clearly not an easy duty. For a drive with a single neutral point, the other benefit of the SVPWM method, which relates to dc bus voltage utilization, also have low advantage for machines with high number of phases.

2.3.2 Two level Six-phase IM PWM Control

Two level multiphase inverters are mainly supplied to multiphase machines and one of the main two groups of PWM method, either carrier based PWM or SVPWM algorithms are used for controlling. From multiphase induction motor most of the time six phase induction motor are studied by researchers. Six-phase machines selected frequently by researchers because of it can be modified by only the stator winding of an existing 3-phase machine. In other ways, no need to new stator lamination to be designed and manufactured, since the number of slots in 3-phase machines is inevitably appropriate for 6-phase machines as well, as long as there are at least two slots per phase per pole. This is so since six is divisible by three, in contrast to 5 or 7, for example (a five-phase four pole machine asks for a minimum of 20 slots and is regularly constructed using 40 slots; neither of the two is divisible by three and there are no three-phase machines with these slot numbers, so that five phase machine stator lamination need to be designed and manufactured).

Six-phase machine have two main different topologies. The most common one is an asymmetrical, while the other topology is a symmetrical. Stator windings of an asymmetrical six-phase machine consist of two sets of three-phase windings that are spatially shifted by 30°.Coscutive phase are non-equidistant because of this spatial shift. For a symmetrical six-phase machine, stator windings are configured by two sets of three-phase windings that are spatially shifted by 60°, so that spatial displacement between any two consecutive phases is the same and equal to 60°. For both asymmetrical and symmetrical topologies, the two sets of 3-phase stator windings can either share a single neutral connection or may have two isolated neutral points.

There are six supply voltages for six phase machine since it is six dimensional systems. This system can be decomposed into three two-dimensional planes, known as (α-β), (x-y) and (0+-0-). The three planes are mutually orthogonal in the six-dimensional space and the machine can then be described by three pairs of mutually decoupled equations [21]. The electromechanical energy conversion takes place only in the (α-β) plane as long as the machine is designed with sinusoidal flux (magneto-motive force) distribution. The other two planes only contribute to losses, so that current components in these subsystems should be ideally zero (i.e. the drive control needs to minimize them). An induction machine is the most frequently realized type of ac machine, related with a six-phase stator winding.

Currently six-leg two level voltage source inverters are gives supply to stator winding of six-phase machines. Generally, a two-level inverter with n legs produces at the output the number of voltage vectors according to 2^n law, so that 64 voltage vectors are achieved from a six-leg voltage source inverter. These voltage vectors are in essence six-dimensional and they can be projected into three two dimensional planes (α-β), (x-y) and (0+-0-). In the (α-β) and (x-y) planes, these space vectors lay at the vertices of four 12-sided polygons. Voltage vectors on the (0+-0-) space are zero if the two sets of three-phase stator windings have two isolated neutral points. However, if single neutral point is used, there are some nonzero voltage vectors in the (0+-0-) plane [21].

2.4 Asymmetrical Six-phase Drives

One of the commonly stated in the literature among the several multiphase machines is an asymmetrical 6-phase machine. Six phase drives has two sets of 3-phase stator windings that are spatially shifted by 30°. The stator windings can be arranged in two different way neutral points. The first is to form two isolated neutral points by connecting the stator 3-phase winding while the second one is to form a single neutral point by connecting the winding together.

Most commonly the arrangement with two isolated neutral points is used with current research on asymmetrical 6-phase machine. At the beginning of 6-phase variable speed drives studies, six-step mode were used to operate two tow-level 3-phase voltage source inverters and an asymmetrical 6-phase drives supplied from two two-level 3-phase voltage source inverter. Less torque ripple is obtained than n 3-phase drives and frequency ripple maximized to high point [17]. Another significant advantage of using a multiphase drive with two (or more) three-phase windings is that two (or more) 3-phase voltage source inverters can be simply arranged to supply the machine.

The difficulties of less frequency torque ripple in VSI were eliminated with the beginning of PWM control method system. The PWM systems are not only useful for 3-phase drives, but also used for multiphase drives. Many PWM systems for multiphase drives have been established and the most broadly studied are the carrier-based PWM and SVPWM.

If phase shift appropriately introduced between two sets of modulation signal for the two three phase modulator, the six phase drives can be simply modified from three phase system modulation for carrier based PWM. This thought applies to both carrier-based SPWM and carrier-based PWM with zero-sequence injection, which enhance operations of the dc bus voltage without moving into the over-modulation region [13].

In the SVPWM method, a set of sinusoidal reference voltages is represented as a reference voltage vector and certain number of space vectors will be used over one switching period (each with appropriately calculated dwell time) in order to produce output voltage vector that has an average value that is equal to the reference. Since only voltages and currents in the (α-β) plane are related to electromechanical energy conversion, the goal of SVPWM is to synthesize the (α-β) voltage vector that satisfies the machine's torque and flux control requirements. Simultaneously, since references in other planes are zero, it also has to maintain the average volt-seconds in (x-y) and (0+-0-) planes equal to zero during every inverter switching period, since this eliminates low-order harmonics from the output voltage.

Numerous methods of choosing the most suitable voltage vectors have been stated for the execution of SVPWM for an asymmetrical six-phase machine with two isolated neutral points. One option is to use in principle conventional 3-phase SVPWM method. The preferred reference voltage vector is synthesized by using only 3 voltage vectors (two active voltage vectors and one zero voltage vectors), similar to the SVPWM commonly used for 3-phase drives. These two active voltage vectors are selected from the outermost 12-sided polygon (i.e. the largest magnitude space vector) of the (α-β) plane [15]. This selection implies low switching frequency and maximizes dc bus voltage utilization of the inverter. However, since control is only exercised in the (α-β) plane, the voltages in (x-y) plane are not averaged to zero and current harmonics in this plane are left free to flow. As a result, large low-order harmonic currents (especially the fifth and the seventh harmonics), that do not contribute to flux/torque production, flow in the motor phases, hence causing a significant power loss in the machine. The low-order current harmonics can be greatly reduced by using Vector Space Decomposition (VSD) based technique [21]. Harmonic components of the order $6k \pm 1$ ($k = 1, 3, 5...$) can be eliminated in a drive with two isolated neutral points if the reference voltage vector is synthesized by using four neighboring active voltage vectors of the largest magnitude (rather than just two), and one zero voltage vector. The aim of this technique is to achieve on average reference (α-β) components, but at the same time it also intends to minimize the average voltage in the (x-y) plane.

2.5 Basics of Fuzzy Logic Theory

When we compare both classical and fuzzy theory it is found that the classical theory focuses on accuracy relatively than simple and effective controlling system. That is hundred percent either true or false (1 or 0). But it found that in fuzzy sets each element have certain degree of membership. That is, fuzzy is all about the relative importance of accuracy.

If-Then Rules:

There are certain rules most significantly required for fuzzy logic which is called rule base. The rule base commonly contains numerous rules of the form If-Then, in which the fuzzy sets and the membership functions are acknowledged first. Then the If-Then rules for the membership functions are decided for the particular control. The output is controlled by these rules on input. For each particular control, the If-Then rules for the membership functions are decided accordingly and hence, the output is controlled by these rules on input.

In a typical If-Then rule of fuzzy there consists of two parts named the antecedent and consequence or conclusion where the If statement is the antecedent and the Then statement is the consequence. That is, If - (Antecedent) and Then - (Consequence).

2.6 Fuzzy Logic Control

Fuzzy logic control is one of the control algorithms that mainly depend up on the rules formed by the linguistic variable which are being resulting from expert knowledge into an automatic control system. Mathematical modeling is not required for fuzzy logic in order to provide exacts the solution for the controlled system and hence, mathematical calculation used to simulate the expert knowledge in fuzzy set is simple, unlike other conventional controllers. Even though it doesn't require any complex mathematical calculation, but fuzzy logic control system perform better. Thus, this control technique is one of the best existing keys for recent broad class of challenging control difficulties.

Fuzzy logic control is based on the fuzzy set theory such that each element has a degree of membership with which it belongs to any particular set. Fuzzy sets can be imagined as classical sets without much sharper boundaries. Mostly, it is taken as an attractive choice when precise mathematical formulations are not possible. That is, it is used when the precision required is moderate.

Fuzzy theory is most successfully applied to practical problem by using fuzzy control systems. If fuzzy systems are used in order to model the process and also if the controllers are designed based on the model, then we call the resulting controllers as fuzzy logic controllers (FLC). There are four main components in a fuzzy logic controller as shown in the Figure 2.1. These are,

1. Fuzzification
2. Inference engine
3. Fuzzy rule base
4. Defuzzification

2.6.1 Fuzzification

In designing of fuzzy controller the most important step to be considered is identifying the state variables that efficiently control the plant and followed by fuzzification of the inputs since fuzzy logic controller works with only the fuzzy inputs. Since, fuzzy rule base block employs rules on only linguistic variables, the measured numerical inputs called crisp inputs must be changed into fuzzy linguistic variables by a block called fuzzifier. The fuzzification process is taken place in this fuzzifier block. Thus, fuzzification is the process of converting a numerical state variable (real number or crisp variable) into a fuzzy input linguistic variable (fuzzy number). System variables, which are generally used are comprises of state error, the rate of change of state error (state error derivative), the area of state error (state error integral) or etc. In this speed control system, speed error and rate of change of speed error are chosen as the input signals.

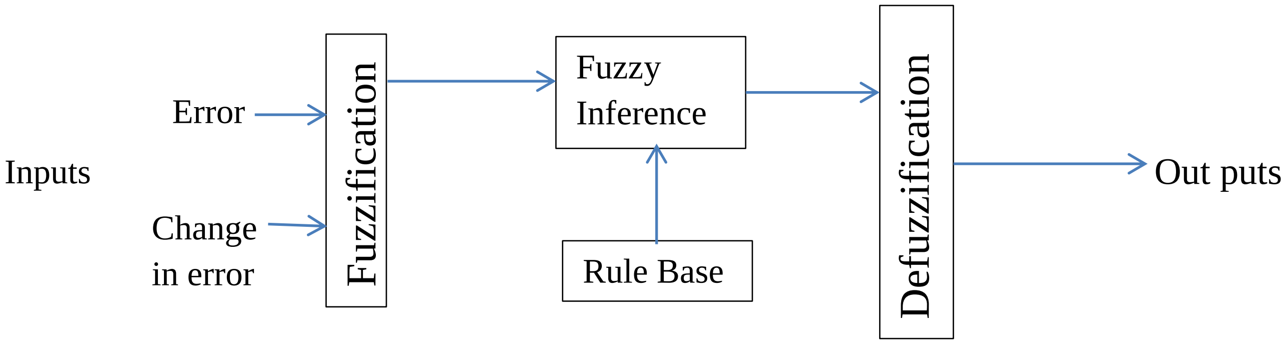


Figure2. 1 FLC structure

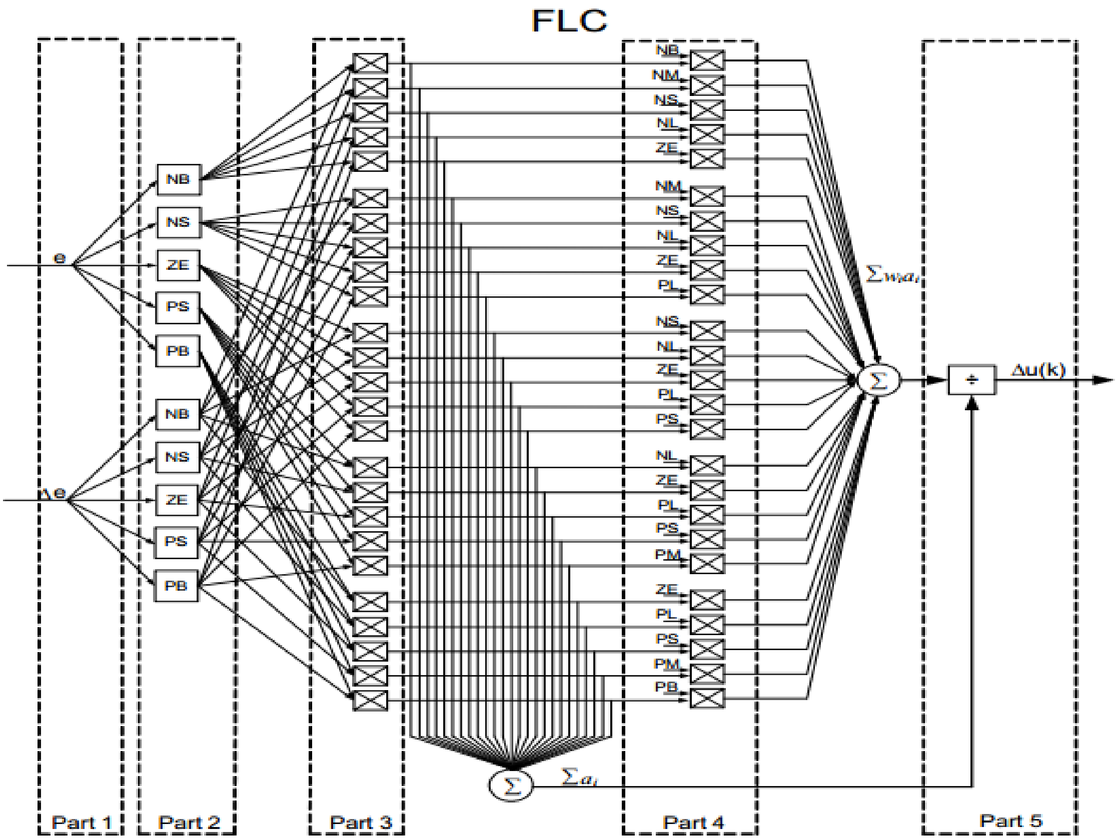


Figure2. 2 The diagram of speed controller with Fuzzy-Logic [15]

The Fuzzy-Logic controller existing in figure 2.2 have 5 portions.

- Part 1 is accountable for determination of two input control signals. The first input signal *e* is the difference between the reference value of the motor speed and the actual value of the motor speed. The second input signal *Δe* is the time derivative of the first input signal.
- Part 2 perfoms fuzzification of the input signals. The triangle-shaped membership functions have been used in this part of Fuzzy-Logic speed controller. The selected triangle-shaped membership functions are presented in

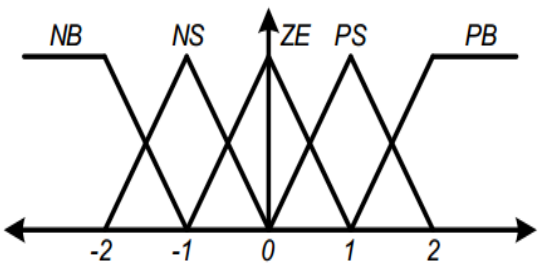


Figure2. 3 The triangle-shaped membership functions [15]

The weight coefficients were chosen as: N (negative), NB (negative big), NM (negative medium), NS (negative small), NL (negative low), ZE (zero), P (positive), PL (positive low), PS (positive small), PM (positive medium), PB (positive big).

- Part 3 responsibility is multiply of the proper output signals from Part 2. The input signals in this part are signals of activation levels of membership functions.
- Part 4 doing multiplication of signals of the activation levels of the rules and weight coefficients.
- Part 5 computes the output signal from the Fuzzy-Logic speed controller.

In fuzzification process the measured input data is conveted into degree of membership functions. That is, the measured data is compared with conditions of rules and determined how well data is matched with rule at particular instance. Thus, here developing a degree of membership function is observed. This fuzzification process is realized with the different kinds of fuzzifiers. Commonly there are three kinds of fuzzifiers. They are;

1. Singleton fuzzifier
2. Gaussian fuzzifier
3. Trapezoidal or Triangular fuzzifier

2.6.2 Fuzzy Rule Base

It is decision making logic that is, simulating a human decision process, inters fuzzy control action from the knowledge of the control rules and linguistic variable definitions. A Rule-base is the collection of rules and these rules are written in Rule-base block according to the control required system. The rules are usually in "If-then" form where the If side is called the conditions and the Then side is called the conclusion.

In this process fuzzy logic operations are more engaged and then results in control action to take place by the inference engine according to the fuzzy inputs on the current process. In this six phase induction motor speed control system, the computer is able to execute the rules and compute a control signal based on the measured input speed error and change in speed error. In such a rule based controller the control strategy is stored in a more or less natural language (human language) and thus it is easy to understand and easy to maintain for non-specialist end user.

2.6.3 Inference Engine

Inference engine is defined as the software code which processes the rules, cases, objects or other type of knowledge and expertise based on the facts of a given situation. In inference engine aggregation is done in which degree of fulfillment is calculated according to the condition specified by a rule. When a problem that involves logic rather than fencing skills is going to be solved, we take a series of inference steps that may include deduction, association, recognition, and decision making. An inference engine can be considered as an information processing system (such as a computer program) that systematically employs inference steps similar to that of a human brain. There are two methods of fuzzy inference system. They are Mamdani and Sugeno and it will be discussed in detail later.

2.6.4 Defuzzification

While using Fuzzy Logic Controller (FLC) it creates an output required in a linguistic variable (fuzzy number) form and as per the requirements of the real world, the linguistic variables should to be changed to a crisp output (real number). Hence, this is done in defuzzification block. Defuzzification block changed resulting fuzzy set into a number that is sent to the system and this number is actually the control signal.

Defuzzification is the process of delivering a quantifiable result in the fuzzy form. It is the method of transforming a fuzzy quantity into a precise quantity. That is why it is said that defuzzification is the reverse of fuzzification. That is, defuzzification is the transformation of a fuzzy linguistic variable into a precise numerical state variable (real number or crisp variable), whereas fuzzification is the conversion of a precise numerical state variable (real number) to a fuzzy linguistic variable.

Generally, we can say a defuzzification process is when all the actions that have been activated are combined and converted into a single non-fuzzy output signal which is the control signal of the system. There are many defuzzification methods but the most widely used methods are as follows:

1. Centre of Gravity Method (COG),
2. Bisector of Area Method (BOA),
3. Mean of Maximum Method (MOM).

In center of gravity (COG) method the crisp control value is the abscissa of the center of gravity of the fuzzy set. That is, it obtains the center of area occupied by the fuzzy set. This method is also best known defuzzification method and utilized as part of this thesis work.

In bisection of area (BOA) defuzzification method, the abscissa of the vertical line is calculated in such a way that divides the area of the resulting membership function into two equal areas.

In mean of maximum (MOM) method the crisp value is chosen as the point with the highest membership and since there may be several points with maximum membership value in the overall implied fuzzy set. Thus, it is common method to calculate the mean value of these maximum points called mean of maximum.

A fuzzy control system has a number of rules that change various variables into a "fuzzy" form, that is, the outcome is shown as membership functions and their degree of membership in fuzzy sets. When dealing with fuzzy set selecting the highest membership belonging may be easiest but not much useful since it results in loss of some data in the process.

2.6.5 Membership Function

In the design of fuzzy logic control system the most important things are the process design of membership function for inputs and outputs, and design of fuzzy if-then rule knowledge base. The membership function is the graphical representation of the degree of belonging (magnitude of participation) of an element to the fuzzy set and illustrates how completely a crisp variable belongs to a fuzzy set (degree of membership, μ). The degree of membership is the degree to which a crisp variable belongs to a fuzzy set. It is expressed either as a fractional value ranging from 0.0 to 1.0 or percentage ranging from 0% to 100%.

The membership functions are determined by using the knowledge of human experts and data collected from various sensors. Designers choose many different shapes based on their preference and experience in order to define fuzzy membership function. There can be different memberships functions associated with each input and output response. There are generally four types of membership functions used as shown in Figure 2.4.

1. Trapezoidal membership function
2. Triangular membership function
3. Gaussian membership function
4. Generalized bell membership function

Among them the common popular shapes are triangular and trapezoidal membership functions because these shapes are easy to represent designer's idea and need low computation time. The quality of control which can be realized using fuzzy controller is determined by the number of membership function .With increase in the number of membership function, the quality (accuracy) of control improves. When the number of linguistic variables increases, the complexity, computational time and required memory also increases.

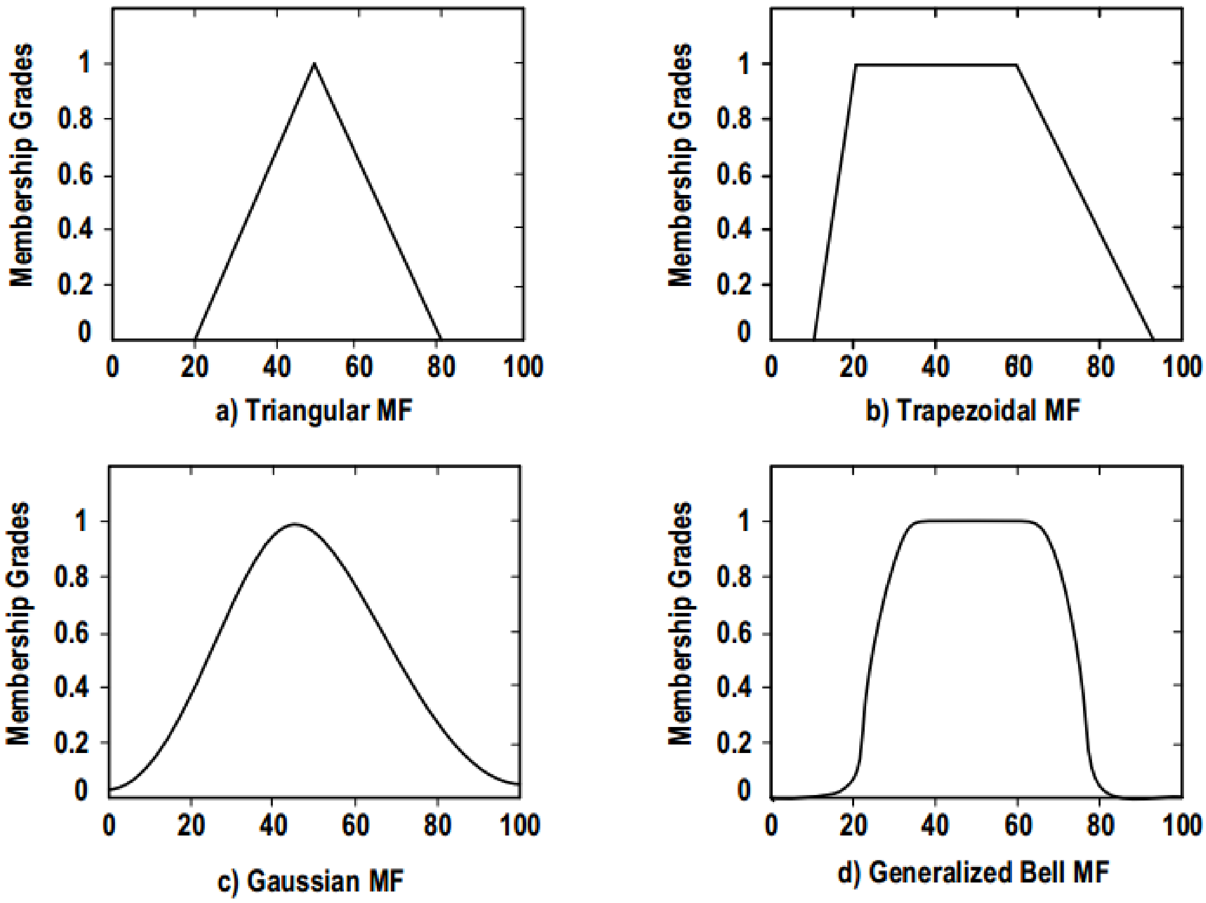


Figure2. 4 different Shapes of MF [6]

2.6.6 Different Fuzzy Control Methods

We can design fuzzy interface systems using two different methods. These are:

- Mamdani fuzzy inference
- Sugeno fuzzy inference

Their outputs vary somewhat in these two methods.

Mamdani Fuzzy Inference

This technique of fuzzy inference is presently the most widely used one. It was among the first control systems built using fuzzy set theory. In Mamdani inference method the output variable is expected to be fuzzy sets. Using a number of fuzzy sets can be tedious in some cases hence it is advantageous to use single membership function of a linguistic variable. This method of using a single linguistic variable in output is known as Singleton output mechanism and it greatly simplifies the computation required by the more general Mamdani method which finds the centroid of the two dimensional function. Thus, Singleton output mechanism enhances the defuzzification process. But in the case of Sugeno type of inference can be used to model any inference system where the output function is either linear or constant.

Sugeno Fuzzy Inference

Sugeno fuzzy inference is similar to the Mamdani fuzzy inference in many aspects. The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between Mamdani and Sugeno is that, the Sugeno output membership functions are either linear or constant whereas it is fuzzy in Mamdani.

If we assume the first input is x and the second input is y, then the output (O_i) is of the linear form $O = Ax + By + C$ and for a zero-order Sugeno model, the output will be a constant ($A = B = 0$). The output level of each rule (O_i) is only weighted by the weightage (W_i) of the rule. That is, the final output of the system is the weighted average of all rule outputs.

2.6.7 Comparison of Mamdani and Sugeno Methods

Both inference systems are the same in many aspects and their main difference arises from the output membership functions which is either linear or constant for Sugeno type and fuzzy for Mamdani one. Sugeno system works well with optimization and adaptive techniques and hence, they are more compact and computationally efficient than a Mamdan isystem. When comparing the performance of both Mamdani and Sugeno models the highest rank is obtained from Sugeno fuzzy inference mode. The following are some final considerations about the two different methods.

Advantages of the Mamdani Method

- It is intuitive. It can be trained in human intuition.
- It has most commonly acceptable.
- It is well suitable to human input.

Advantages of the Sugeno Method

- It is very operative in calculations and controlling.
- It is generally used to enhance the linear techniques.
- It works well with optimization and adaptive techniques.
- It is well suited to mathematical analysis.
- It has guaranteed continuity of the output surface.

In this thesis, Mamdani fuzzy inference type is selected because of its most commonly used one in capturing expert knowledge in more operative way though it sometime slows due to computational burden in defuzzification process. In this speed control case, since mathematical inputs are not available, Sugeno method cannot be used.

2.6.8 Advantages of Fuzzy Logic Control

- Fuzzy controller doesn't need mathematical model of a system and calculation is easy, hence very easily designed.
- It can operate very well even in highly non-linear systems that would be impossible or difficult to model mathematically.
- It is inherently robust since it does not require precise, noise-free inputs and if sensors fail to work properly it can be programmed to turn off safely, instead of keep on working which could be dangerous to the plant.
- Very simple user interface. Easier end-user interpretation when the final user is not an expert.
- Fuzzy logic is flexible. Since the rule base is user defined it can be modified and hence new sensors can easily be incorporated into the system.
- Fuzzy logic is conceptually easy to understand since human knowledge and experience can be implemented to relate input to output in linguistic term.
- Fuzzy logic is a more intuitive approach like a human which gives it the strength to adapt to the difficulties in the control.

- Can achieve less overshoot and oscillation and doesn't require fast processors and it can also control fast processes.
- It requires less data storage in the form of membership functions and rules than conventional look up table for non-linear controllers.

2.6.9 Disadvantages of Fuzzy Logic Control

- Human knowledge is often incomplete and episodic as compared to systematic way.
- If the model is not known then it is impossible to achieve the stability of the controller system.
- Sometime rules are mismatched and non-coherent.
- In complex operation fuzzification and defuzzification take long time.

2.6.10 Implementation of Fuzzy Logic Control

It maps the input to an output in a very efficient way and the mapping can be very easily controlled without much complex knowledge about the process. Steps to be performed in fuzzy control:

- First, study how the rule base system and the operator can be applied to this control.
- Understand the concept of membership functions and linguistic variables.
- Analyze the power system to be controlled and decide the state variables to be considered as inputs to the system.
- Form an understanding as how to control the state variables to get the required control in the plant.
- Now form the Rule base for the linguistic variables of inputs and outputs.
- Try to optimize the membership functions to make the control more efficient.
- Integrate the fuzzy controller into the plant and check the result.

2.7 PI Controller

A proportional-integral (PI) controller is a special case of the PID controller in which the derivative (D) term of the error is not used and it is widely used in industrial control systems. PI controller works by calculating error (the speed error in our case), from the processed measured value and the desired reference point. If the system is not clearly known, best results are achieved applying PI controller provided it is tuned properly by keeping parameters of the system according to the nature of the system.

The PI controller depends upon two parameters which are called the proportional (P) and the integral (I) term:

- P determines the reaction to current error. That is, P term is proportional to current value of the error.
- I determine reaction to the sum of recently appeared errors. That is, it accounts for past values of the error and integrates overtime to produce the integral term.

The relation between the control signal u and the error is stated in the Equation (2.3). (Where u is the control signal to the process, e is the error, τ_i is the integral time, K_p and K_i are the proportional and integral gains, s is the Laplace variable).

$$u(t) = K\mathrm{p}e(t) + K\mathrm{i}\int_0^t e(T)dt \tag{2.1}$$

$$\mathrm{u(s)} = Kpe(s) + \frac{Kie(s)}{s} \tag{2.2}$$

$Since\ k_i = {}^{k_p}/_{\tau_i}$

$$\text{Transfer function} = \frac{u(s)}{e(s)} = Kp(1 + \frac{1}{\tau\mathrm{i}s}) \tag{2.3}$$

In controlling a speed of motor drives a simple proportional gain in the speed loop may not be sufficient enough since it may results in a high overshoot and also an undesirable steady state error in the speed. Hence, another compensation technique is required to improve the performance of the drive. That is, PI (proportional plus integral) control which is most commonly used compensation method for AC motor drives.

A proportional controller will reduce the rise time and will reduce, but never eliminate, the steady-state error. The integral term contribution is proportional to both the magnitude of the error and the duration of the error. Thus, it accelerates the movement of the process towards the set point and eliminates the residual steady-state error that occurs with a pure proportional controller.

The PI controller can be summarized as follows:

1. The integrative action will eliminate also the disturbance effects to the process output.
2. More complex in control design than P-controller and require complex tuning (selecting of the K_p and K_i gain).
3. Complexity in algorithm of implementation when using microcontrollers (embedded system).
4. Increasing the K_i coefficient makes the system more responsive and hence increasing performance. Though increasing the K_i to high values may cause the system to oscillate and become unstable.
5. The integrative action has a negative effect on the speed of the response.

2.7.1 Advantages of PI Controller

- Due to presence of the integral term, steady state error in speed is zero, making the system quite accurate.
- It is not necessary to use such high gains as required in proportional gain controller.
- The scheme has found to be quite robust and satisfactory.

2.7.2 Disadvantages of PI Controller

- If a very fast response is desired, the penalty paid is a higher overshoot in speed, which is not desirable.
- This can be designed without any overshoot but the response to a load change becomes very slow.
- A very high gain cannot be used, because that wills result higher overshoots.

CHAPTER THREE

METHODOLOGY

3.1. Overview of the Chapter

In this chapter the methods and alternatives that had been used from the starting to the end of this thesis work are stated. It includes mathematical modeling of six phase induction motor, mathematical modeling of voltage source inverter, Fuzzy logic controller design, PI controller design, six-phase space vector PWM technique.

3.2. Procedures of the Study

To attain the objective of the study, the following procedures are undertaken:

- Literature Survey: Different literatures which are related to this thesis work have studied and different concepts are adopted.
- System Modeling and Design: modeling of the system and designing an appropriate fuzzy logic and PI controller for the system.
- Simulation: the modeled and designed systems will be tested and simulated using Matlab/Simulink tools.
- Validation: Validation of results obtained from simulation of both Fuzzy and PI controllers with that of expected one.

3.3 Dynamic Modeling of DTC Six-Phase Induction Motor

Direct torque control is a controller method that used to control the stator flux and the torque directly and independently by selecting the appropriate inverter switching state. It has been gaining more popularity since its introduction due to its exceptional dynamic response and less dependence on machine parameters. DTC with a lookup table is more used in controlling the induction motor because it is considered a simple and robust method. The common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Recently, to overcome this problem many researchers are doing to replace the lookup table DTC with the DTC space vector modulation in the six-phase IM drive. This type of control further reduces the torque ripple because it can produce the voltage reference which accurately compensates the differences between the commanded torque and flux values and their actual values from measurement and estimation [20].

The main features of direct torque control are given as follows:

- Direct control of flux and torque.
- Indirect control of stator currents and voltages.
- Completely a motion-sensor less control method.
- Not sensitive for rotor parameters because its need only stator flux and torque estimator.
- High dynamic performance even at locked rotor.

3.3.1 Comparison of Conventional DTC and SVM DTC Method

The principle behind direct torque control of induction motor drive is to control the flux linkage and electromagnetic torque directly by the selecting proper inverter switching state with the help of lookup table or SVM. The conventional DTC includes two level and three level hysteresis controllers, three level for torque and two level for flux linkage. Even though it has many advantages like no feedback control, no traditional PWM algorithm, no vector transformation, it has some drawbacks like variable switching frequency, difficult to control flux and torque at low speed, current and torque distortion during the change of the sector, a high sampling frequency needed for digital implementation of hysteresis controllers, inherent steady state torque and flux ripple. Due to hysteresis band controller, steady state torque and flux ripple is more in direct torque control of induction motor which is undesirable from smooth response point of view. In the journal paper [12], Direct Flux and Torque Control with Space Vector Modulation (DTCSVM) schemes are proposed in order to overcome the drawbacks of the classical DTC of Induction motor. The DTC-SVM strategy operates at a constant switching frequency is shown in figure 3.1

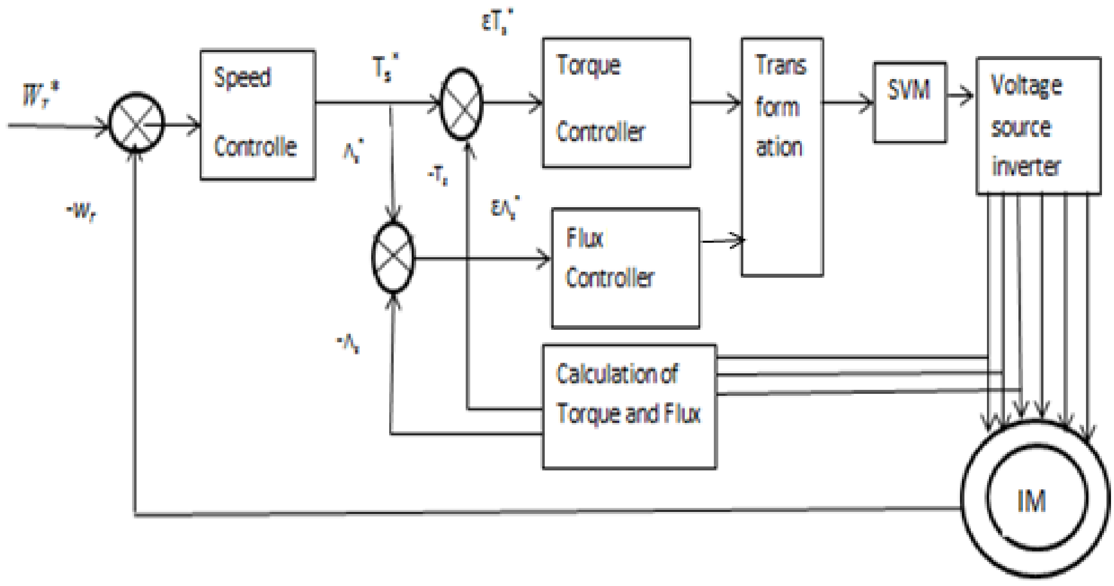


Figure3. 1 Direct Torque Control with SVM [4]

Compared with the steady-state performance of lookup table DTC, DTC-SVM results in much lower torque ripple. Because; it uses the zero-vector instead of backward active vectors to reduce torque ripple. The control algorithm in DTC-SVM methods are based on averaged values whereas the switching signals for the inverter are calculated by space vector modulator. The objective of this DTC-SVM scheme is to estimate a reference stator voltage vector V_{ref} and modulate it by SVM technique in order to drive the power gates of the inverter with a constant switching frequency.

Mathematical Modeling of Six Phase Induction Motor

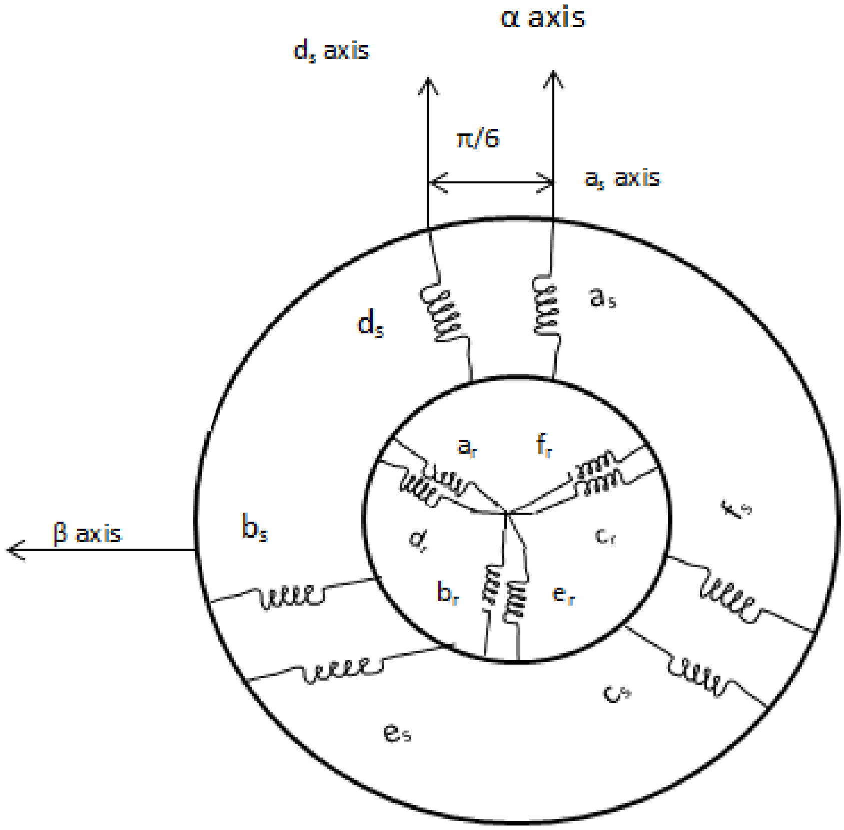


Figure3. 2 the physical model of six phase asymmetrical induction motor [11]

The six-phase induction machine is a six-dimensional system. The voltage equations in the original phase coordinates can be described as follows [9] [10].

$$[V_s] = [R_s].[i_s] + p[\psi_s]$$

$$= [R_s].[i_s] + P([L_{ss}].[i_s] + [L_{sr}].[i_r]) \quad (3.1)$$

$$[0] = [R_r].[i_r] + p[\psi_s]$$

$$= [R_r].[i_r] + P([L_{rr}].[i_r] + [L_{rs}].[i_s]) \quad (3.2)$$

Where, L_{ss}, L_{rr} is stator and rotor inductance matrix respectively, L_{sr}, $L_{rs,}$ is stator and rotor mutual inductance matrix respectively, $p = d/dt$.

According to VSD (vector space decomposition) the original six dimensional system of the machine can be decomposed into three orthogonal sub-spaces (α, β) (x, y) and (Z_1, Z_2)

introducing a 6x6 transformation matrix [T_6] [10] having the following properties. Using the vector space decomposition model the machine phase variables (λ_k) are related to the stationary frame variables $[\lambda_{\alpha\beta xy}]$ via decoupling transformation $[T]$

$$[\lambda_{\alpha\beta xy}] = [T].[\lambda_k] \quad (3.3)$$

where

$$[\lambda_k] = [\lambda_a \quad \lambda_b \quad \lambda_c \quad \lambda_d \quad \lambda_e \quad \lambda_f]^T \quad (3.4)$$

$$[\lambda_{\alpha\beta xy}] = [\lambda_\alpha \quad \lambda_\beta \quad \lambda_x \quad \lambda_y \quad \lambda_{z1} \quad \lambda_{z2}]^T \quad (3.5)$$

Where λ representing arbitrary machine variables (voltage (v), current (i) or flux (ψ)).

$$[T6] = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & \frac{-1}{2} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

1) The fundamental components of the machine variables and the harmonics order K = 12n $\pm$ 1, (n = 1, 2, 3…) are mapped in the (α, β) sub-space. These components contribute to the air-gap flux.

2) The harmonics of order $k = 6n \pm 1$, (n = 1, 3, 5,”) are transformed in the ($x_, y$) subspace. These harmonics do not contribute to the air-gap flux; will increase current loss of stator.

3) The zero-sequence components are mapped in the (Z_1, Z_2) subspace. When the motor has two sets stator windings with isolated neutral points, it can be demonstrated that no current components flow in the subspace (Z_1, Z_2). So the machine model only need decompose to (α, β) and ($x_, y$) subspace.

In the (α, β) sub-space, the state equations of six-phase induction motor are

$$\begin{cases} \overline{V}_s = R_s.\bar{i}_s + P.\overline{\psi}_s \\ 0 = R_r.\bar{i}_r + P.\overline{\psi}_r - j\omega_r.\overline{\psi}_r \end{cases} \quad (3.6)$$

$$\begin{cases} \overline{\psi}_s = L_s.\bar{i}_s + L_m.\bar{i}_r \\ \overline{\psi}_r = L_r.\bar{i}_r + L_m.i_s \end{cases} \quad (3.7)$$

$$\begin{cases} \overline{V}_s = V_{s\alpha} + jV_{s\beta} & \overline{\psi}_s = \psi_{s\alpha} + j\psi_{s\beta} \\ \bar{i}_s = i_{s\alpha} + ji_{s\beta} & \\ \bar{i}_r = i_{r\alpha} + ji_{r\beta} & \overline{\psi}_r = \psi_{r\alpha} + j\psi_{r\beta} \end{cases} \quad (3.8)$$

Where ψ_r and ψ_s are rotor and stator flux respectively, L_r and L_s are rotor and stator inductance respectively, ω_r is rotor speed and $p = d/dt$.

Electromagnetic torque is

$$T_e = 3.\frac{P_b}{2}.\left(\psi_{s\alpha}.i_{s\beta}.i_{s\alpha}\right) = 3.\frac{P_b}{2}.(\bar{\psi}_s \otimes i_s) \quad (3.9)$$

Where, P_b is the number of pole pairs.

Mechanical motion equation $T_e.T_m = \frac{j_m}{p_b}.p\omega_e$

Where, T_e is electromagnetic torque, ω_e the electrical angular speed of the motor;

T_m is load torque, j_m is the motion inertia of the drive system; p_b is p is number of pole pairs, p= d/dt

3.3.2. Flux and Torque control

The voltage space vector of multiphase is:

$$\left\{V_s = \frac{1}{m}U_d\left[1 \quad e^{j2\pi/m} \quad e^{j4\pi/m} \quad \ldots \quad e^{j(m-1)\pi/m}\right]XS_k\right. \quad (3.10)$$

Where, m is the phase of multiphase motor, U_d is DC bus-bar voltage of inverter, V_s is space voltage vector of stator, S_k is switching function of inverter.

The relationship between stator voltage vector and flux linkage vector is:

$$\frac{d}{dt}\psi_s = U_s - r_s i_s \approx U_s \quad (3.11)$$

The (9) can be written:

$$\Delta\psi_s = U_s.\Delta t \quad (3.12)$$

Where Δt is the operation time of (U_s).

Where L_σ is very small in the stationary state, the variable value of torque in adjacent on-off state is:

$$\Delta T_e = \frac{p.\psi_s \otimes U_s}{L_\sigma}\Delta t \quad (3.13)$$

Where $L_\sigma = (L_s L_r - L_m^2)/L_m$.

Where, L_σ is leakage inductance.

From (3.10), and (3.11), the angle between voltage vector and flux linkage depend on the alternation of torque and flux linkage when the amplitude of nonzero voltage vector is determined. Torque will increase when voltage vector of stator flux linkage is in advance. As for flux linkage, the angle between voltage vector and flux linkage will decrease when the errors of flux linkage are increasing.

3.4 Space Vector PWM of Six phase Voltage Source Inverter

When three phase supply is given to the stator of the induction machine a three phase rotating magnetic field is produced. Due to this field flux, a three phase rotating voltage vector is generated which lags the flux by 90^0. This field can also be realized by a logical combination of the inverter switching which is the basic concept of SVPWM [10]. Space vector pulse width modulation has become one of the most popular PWM techniques because of its easier digital implementation and better dc bus utilization, when compared to the ramp-comparison sinusoidal PWM method. There is a lot of flexibility available in choosing the proper space vector combination for an effective control of multi-phase VSIs because of large numbers of space vectors. With reference to six-phase VSI, there are a very few journal papers found in the literature. In this research the large space vector of SVPWM schemes for six-phase VSI are formulated and elaborated [15].

SVPWM is one of the preferred real-time modulation techniques and is widely used for digital control of VSI. The SVPWM is unconventional and computation-severe PWM method. Space- vector PWM is very different from the rest of PWM techniques and modulation is achieved by inverters switch state. The advantage of the SVPWM than the sine-triangle PWM is that it gives nearly 15% more output voltage [27].

The SVPWM method has been implemented for the control of six-phase VSI with the six-phase induction motor. Due to the great number of VSI there are some differences in application of the SVM algorithm for six-phase VSI in comparison with modulation for conventional three-phase VSI [22].

3.4.1 Voltage Source Inverter

The process of converting DC to AC power is called inversion. Inverter is an electronic device which creates the variable frequency from the fixed DC source in order to drive an induction motor at a variable speed. Depending on the type of DC source supplying the inverter; it can be classified as voltage source inverters (VSI) and current source inverters (CSI). The DC source is usually rectified from the three phase input power. There is a DC link connected between the rectifier and the inverter. A capacitive-output DC link is used for a VSI and an inductive output link is employed in CSI and an inductive output link is employed in CSI. The circuit diagram for a two-level voltage source inverter for power applications is shown in figure 3.2-1. The power circuit topology of a two-level six-phase VSI supplying an asymmetrical machine with two isolated neutral points is shown in Fig. 3.2.1. It consists of two three-phase inverters sharing a common dc bus voltage, V_{dc}, while the machine's stator windings are connected in star with isolated neutrals, n1 and n2. A lower case symbol (a, b, c, d, e, f) denotes the machine output phases, while an upper case symbol (A, B, C, D, E, F) denotes the inverter legs. The dc bus voltage is assumed to be constant, and the negative rail of the dc bus is denoted by N. There are two switches for each inverter leg, where an upper switch and a lower switch work complementarily.

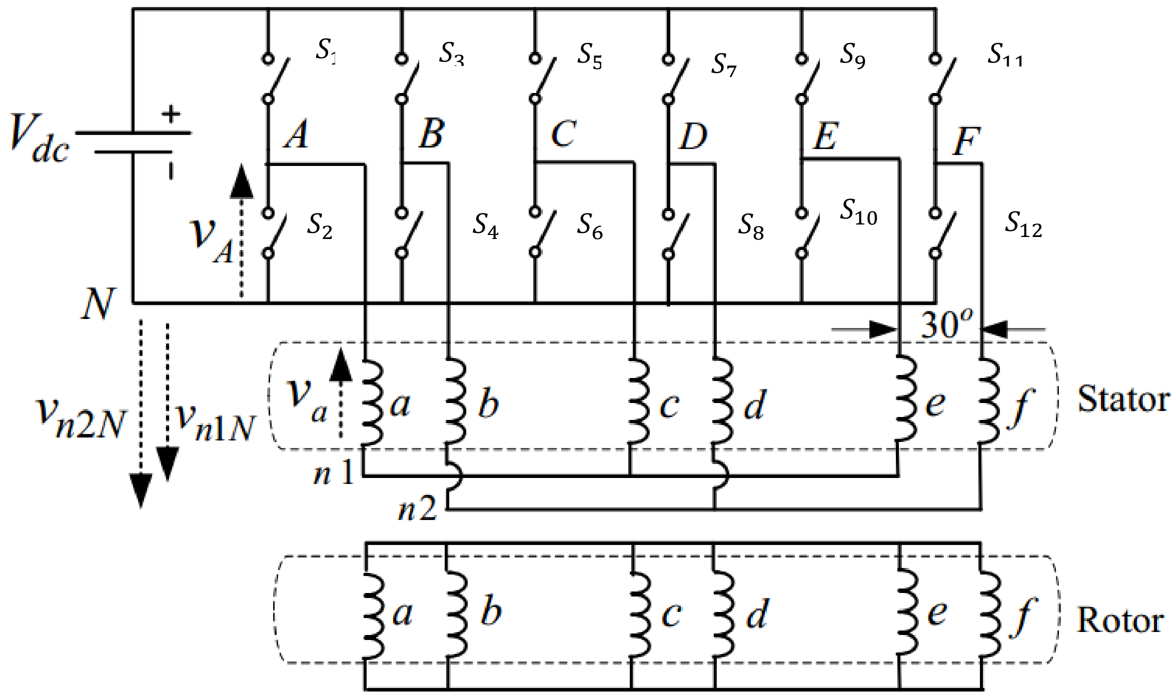


Figure3. 3 Power circuit topology of two-level six-phase VSI supplying asymmetrical machine with two isolated neutral points [17]

In total there are six inverter legs; therefore switching state combination of inverter are 2^6 = 64; which in turn determine space vectors. Depend on the SV theory, the switching states lead to 64 voltage space vectors. The space vector model of the inverter is developed with an assumption that the switches have an ideal commutation and zero forward voltage drop.

3.4.2 Switching States of Voltage Source Inverter

The principle and implementation of Space vector modulation for the six phase two-level inverter.

- **Switching state 'P' denotes** that the upper switch in an inverter leg is on and the inverter terminal voltage (V_{AN}, V_{BN}, $V_{CN,}V_{DN},V_{EN}$ *or* V_{FN}) *is positive (+Vd) while*
- ***Switching state 'O'*** *indicates that the inverter terminal* voltage is zero due to the conduction of the lower switch.

There are 64 possible combinations of switching states in the six phase two-level inverter as listed in Table below. For example the switching state [PPOOOO], corresponds to the conduction of S_1 S_3 S_6 S_8 S_{10} S_{12} *in the inverter legs ABCDEF respectively*.

Table3. 1 switching state definition [1]

Switching state	Leg A			Leg B			Leg C			Leg D			Leg E			Leg F		
	S_1	S_2	V_{AN}	S_3	S_4	V_{BN}	S_5	S_6	V_{CN}	S_7	S_8	V_{DN}	S_9	S_{10}	V_{EN}	S_{11}	S_{12}	V_{FN}
P	on	off	V_d	on	off	V_d	on	off	V_d	on	off	V_d	on	off	V_d	on	off	V_d
O	off	on	0	off	on	0	off	on	0	off	on	0	off	on	0	off	on	0

Table3. 2 Space Vectors, Switching States, and On-State Switches [1]

Space vector		Switching State	On-state switch	Vector definition
Zero Vector	V_O	OOOOOO	S_2 S_4 S_6 S_8 S_{10} S_{12}	0
	V_{63}	PPPPPP	S_1 S_3 S_5 S_7 S_9 S_{11}	0
Active Vector	V_1	POOOOO	S_1 S_4 S_6 S_8 S_{10} S_{12}	$\frac{1}{3}V_{dc}$
	V_2	OPOOOO	S_2 S_3 S_6 S_8 S_{10} S_{12}	$\frac{1}{3}V_{dc}e^{j\pi/6}$
	V_3	PPOOOO	S_1 S_3 S_6 S_8 S_{10} S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j5\pi/12}$
	V_4	OOPOOO	S_2 S_4 S_5 S_8 S_{10} S_{12}	$\frac{1}{3}V_{dc}e^{j3\pi/6}$
	V_5	POPOOO	S_1 S_4 S_5 S_8 S_{10} S_{12}	$\frac{1}{3}V_{dc}e^{j4\pi/6}$
	V_6	OPPOOO	S_2 S_3 S_5 S_8 S_{10} S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j11\pi/12}$
	V_7	PPPOOO	S_1 S_3 S_5 S_8 S_{10} S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j13\pi/12}$
	V_8	OOOPOO	S_2 S_4 S_6 S_7 S_{10} S_{12}	$\frac{1}{3}V_{dc}e^{j\pi}$
	V_9	POOPOO	S_1 S_4 S_6 S_7 S_{10} S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j17\pi/12}$
	V_{10}	OPOPOO	S_2 S_3 S_6 S_7 S_{10} S_{12}	$\frac{1}{3}V_{dc}e^{j9\pi/6}$
	V_{11}	PPOPOO	S_1 S_3 S_6 S_7 S_{10} S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j21\pi/12}$
	V_{12}	OOPPOO	S_2 S_4 S_5 S_7 S_{10} S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j23\pi/12}$
	V_{13}	POPPOO	S_1 S_4 S_5 S_7 S_{10} S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j25\pi/12}$
	V_{14}	OPPPOO	S_2 S_3 S_5 S_7 S_{10} S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j27\pi/12}$

V_{15}	PPPPOO	S_1 S_3 S_5 S_7 S_{10} S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j29\pi/12}$
V_{16}	OOOOPO	S_2 S_4 S_6 S_8 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j15\pi/6}$
V_{17}	POOOPO	S_1 S_4 S_6 S_8 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j16\pi/6}$
V_{18}	OPOOPO	S_2 S_3 S_6 S_8 S_9 S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j35\pi/12}$
V_{19}	PPOOPO	S_1 S_3 S_6 S_8 S_9 S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j37\pi/12}$
V_{20}	OOPOPO	S_2 S_4 S_5 S_8 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j19\pi/6}$
V_{21}	POPOPO	S_1 S_4 S_5 S_8 S_9 S_{12}	0
V_{22}	OPPOPO	S_2 S_3 S_5 S_8 S_9 S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j43\pi/12}$
V_{23}	PPPOPO	S_1 S_3 S_5 S_8 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j22\pi/6}$
V_{24}	OOOPPO	S_2 S_4 S_6 S_7 S_9 S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j47\pi/12}$
V_{25}	POOPPO	S_1 S_4 S_6 S_7 S_9 S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j49\pi/12}$
V_{26}	OPOPPO	S_2 S_3 S_6 S_7 S_9 S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j51\pi/12}$
V_{27}	PPOPPO	S_1 S_3 S_6 S_7 S_9 S_{12}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j53\pi/12}$
V_{28}	OOPPPO	S_2 S_4 S_5 S_7 S_9 S_{12}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j55\pi/12}$
V_{29}	POPPPO	S_1 S_4 S_5 S_7 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j28\pi/6}$
V_{30}	OPPPPO	S_2 S_3 S_5 S_7 S_9 S_{12}	$\frac{\sqrt{2}}{3}V_{dc}e^{j59\pi/12}$
V_{31}	PPPPPO	S_1 S_3 S_5 S_7 S_9 S_{12}	$\frac{1}{3}V_{dc}e^{j30\pi/6}$
V_{32}	OOOOOP	S_2 S_4 S_6 S_8 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j31\pi/6}$
V_{33}	POOOOP	S_1 S_4 S_6 S_8 S_{10} S_{11}	$\frac{\sqrt{2}}{3}V_{dc}e^{j55\pi/12}$
V_{34}	OPOOOP	S_2 S_3 S_6 S_8 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j33\pi/6}$
V_{35}	PPOOOP	S_1 S_3 S_6 S_8 S_{10} S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j69\pi/12}$

V_{36}	OOPOOP	S_2 S_4 S_5 S_8 S_{10} S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j71\pi/12}$
V_{37}	POPOOP	S_1 S_4 S_5 S_8 S_{10} S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j73\pi/12}$
V_{38}	OPPOOP	S_2 S_3 S_5 S_8 S_{10} S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j75\pi/12}$
V_{39}	PPPOOP	S_1 S_3 S_5 S_8 S_{10} S_{11}	$\frac{\sqrt{2}}{3}V_{dc}e^{j77\pi/12}$
V_{40}	OOOPOP	S_2 S_4 S_6 S_7 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j39\pi/6}$
V_{41}	POOPOP	S_1 S_4 S_6 S_7 S_{10} S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j81\pi/12}$
V_{42}	OPOPOP	S_2 S_3 S_6 S_7 S_{10} S_{11}	0
V_{43}	PPOPOP	S_1 S_3 S_6 S_7 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j42\pi/6}$
V_{44}	OOPPOP	S_2 S_4 S_5 S_7 S_{10} S_{11}	$\frac{\sqrt{2}}{3}V_{dc}e^{j87\pi/12}$
V_{45}	POPPOP	S_1 S_4 S_5 S_7 S_{10} S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j89\pi/12}$
V_{46}	OPPPOP	S_2 S_3 S_5 S_7 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j45\pi/6}$
V_{47}	PPPPOP	S_1 S_3 S_5 S_7 S_{10} S_{11}	$\frac{1}{3}V_{dc}e^{j46\pi/6}$
V_{48}	OOOOPP	S_2 S_4 S_6 S_8 S_9 S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j95\pi/12}$
V_{49}	POOOPP	S_1 S_4 S_6 S_8 S_9 S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j97\pi/12}$
V_{50}	OPOOPP	S_2 S_3 S_6 S_8 S_9 S_{11}	$\frac{\sqrt{2}}{3}V_{dc}e^{j99\pi/12}$
V_{51}	PPOOPP	S_1 S_3 S_6 S_8 S_9 S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3}V_{dc}e^{j101\pi/12}$
V_{52}	OOPOPP	S_2 S_4 S_5 S_8 S_9 S_{11}	$\frac{\sqrt{2}}{3}V_{dc}e^{j103\pi/12}$
V_{53}	POPOPP	S_1 S_4 S_5 S_8 S_9 S_{11}	$\frac{1}{3}V_{dc}e^{j52\pi/6}$
V_{54}	OPPOPP	S_2 S_3 S_5 S_8 S_9 S_{11}	$\frac{\sqrt{2}-\sqrt{3}}{3}V_{dc}e^{j107\pi/12}$
V_{55}	PPPOPP	S_1 S_3 S_5 S_8 S_9 S_{11}	$\frac{1}{3}V_{dc}e^{j54\pi/6}$

	V_{56}	OOOPPP	S_2 S_4 S_6 S_7 S_9 S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3} V_{dc} e^{j111\pi/12}$
	V_{57}	POOPPP	S_1 S_4 S_6 S_7 S_9 S_{11}	$\frac{\sqrt{2}}{3} V_{dc} e^{j113\pi/12}$
	V_{58}	OPOPPP	S_2 S_3 S_6 S_7 S_9 S_{11}	$\frac{1}{3} V_{dc} e^{j57\pi/6}$
	V_{59}	PPOPPP	S_1 S_3 S_6 S_7 S_9 S_{11}	$\frac{1}{3} V_{dc} e^{j58\pi/6}$
	V_{60}	OOPPPP	S_2 S_4 S_5 S_7 S_9 S_{11}	$\frac{\sqrt{2+\sqrt{3}}}{3} V_{dc} e^{j119\pi/12}$
	V_{61}	POPPPP	S_1 S_4 S_5 S_7 S_9 S_{11}	$\frac{1}{3} V_{dc} e^{j60\pi/6}$
	V_{62}	OPPPPP	S_2 S_3 S_5 S_7 S_9 S_{11}	$\frac{1}{3} V_{dc} e^{j61\pi/6}$

The relationship between phase voltages and leg voltages of the inverter can be given as follows:

$$\begin{cases} V_A = V_a + V_{nN} & V_D = V_d + V_{nN} \\ V_B = V_b + V_{nN} & V_E = V_e + V_{nN} \\ V_C = V_C + V_{nN} & V_F = V_f + V_{nN} \end{cases} \quad (3.14)$$

Phases are star connected with isolated neutral points, so

$$V_a + V_b + V_c = 0 \qquad V_d + V_e + V_f = 0 \quad (3.15)$$

And summation of (3.12) becomes:

$$\begin{cases} V_{n1N} = (1/3)\,(V_A + V_C + V_E) \\ V_{n2N} = (1/3)\,(V_B + V_D + V_F) \end{cases} \quad (3.16)$$

We can obtain the relationship between the phase voltages of the machine and leg voltages of the inverter by substituting (3.16) into (3.14). And result is as follows:

$$
\begin{cases}
V_a = (2/3)\,V_A-(1/3)\,(V_c+ V_E) & V_b = (2/3)\,V_B-(1/3)\,(V_D+ V_F) \\
V_c = (2/3)\,V_C-(1/3)\,(V_A+ V_E) & V_d = (2/3)\,V_D-(1/3)\,(V_B+ V_F) \\
V_e = (2/3)\,V_E-(1/3)\,(V_A+ V_C) & V_f = (2/3)\,V_F-(1/3)\,(V_B+ V_D)
\end{cases} \qquad (3.17)
$$

The space vectors of the phase voltages can be projected into two orthogonal two-dimensional planes, known as (α-β) and (x-y), and a pair of zero-sequence components (0+-0-). By using power variant transformation, the space vectors in the stationary reference frame and zero-sequence components can be defined as follows [10]:

$$
\begin{cases}
\underline{v}_{\alpha\beta} = v_\alpha + jv_\beta = 2/6\,(v_a + \underline{\alpha}^4 v_c + \underline{\alpha}^8 v_e + \underline{\alpha}\, v_b + \underline{\alpha}^5 v_d + \underline{\alpha}^9 v_f) \\
\underline{v}_{xy} = v_x + jv_y = 2/6\,(v_a + \underline{\alpha}^8 vc + \underline{\alpha}^{16} v_e + \underline{\alpha}^5\, v_b + \underline{\alpha} v_d + \underline{\alpha}^9 v_f)
\end{cases} \qquad (3.18)
$$

$$
\begin{cases}
v_{o+} = 2/6\,(v_a+v_b+v_e) \\
v_{o-} = 2/6\,(v_b+v_d+v_f)
\end{cases} \qquad (3.19
$$

where $\underline{\alpha}$ = exp(jπ/6).

The mapping of the phase voltage space vectors into the (α-β) and (x-y) planes are shown in Fig. 3.3.1, where the value of V_{dc} has been taken as 1 p.u. Because of the isolated neutrals the zero-sequence components in the (0+-0-) axes are equal to zero for all switching state combinations. The space vectors are labeled with decimal numbers, if converted into binary code, the numbers correspond to the state of an inverter leg in the sequence of (A, B, C, D, E, and F). "**P**" indicates that an upper switch in a particular leg is in "on" state, while "**O**" indicates lower switch is in "off" state.

In the (α-β) and (x-y) planes in total, there are 48 distinct active space vectors. Based on their magnitude, the active space vectors in the (α-β) and (x-y) planes can be categorized into four (4) different groups, which are largest $v_{l(k)}$, second largest $v_{2l(k)}$, third largest $v_{3l(k)}$, shortest $v_{sh(k)}$, and zero v_0 space vectors where index k denotes the k^{th} space vector for each group of space vectors. The groupings of space vectors are shown in Fig. 3.1 and can be expressed using equations presented in Table 3.3.3. Each group contains twelve distinct space vectors. The third largest space vectors have redundancy, each being produced by two switching state combinations. On the other hand, the zero space vectors is produced by four switching state combinations, which are V_0, V_{63}, V_{21}, and V_{42}.The largest space vectors in the (α-β) plane are mapped as the shortest space vectors in the (x-y) plane and vice versa. In the (α-β) and (x-y) planes, all redundant active space vectors have magnitude of the third largest space vectors [15].

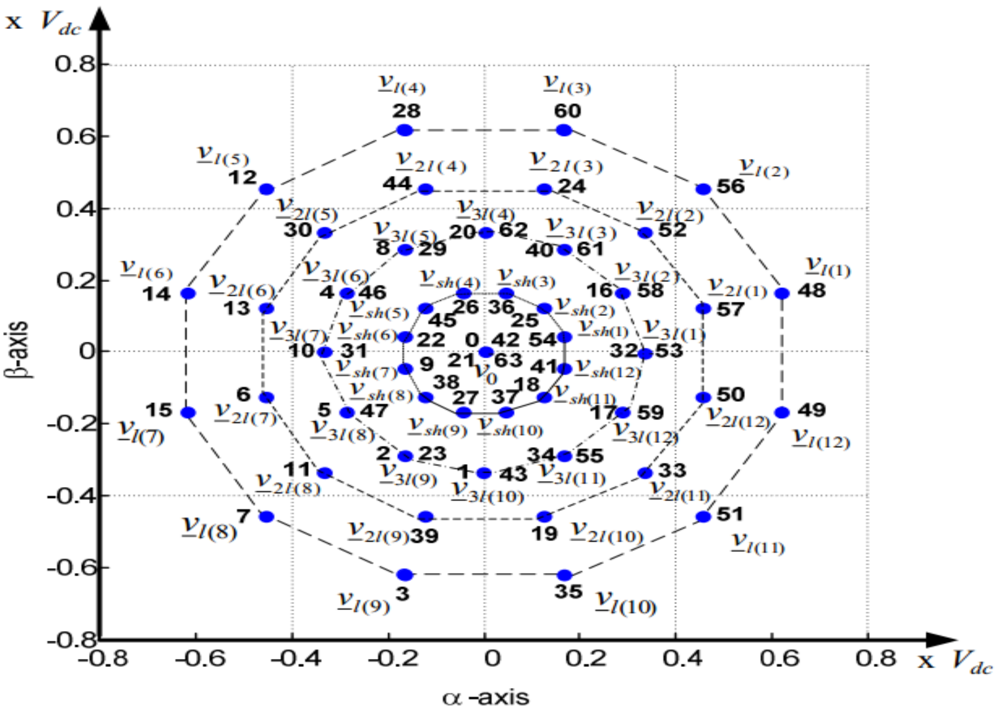


Figure3. 4 phase voltage space vectors for 2 level 6-phase VSI supplying asymmetrical machine in (α-β) plane [15]

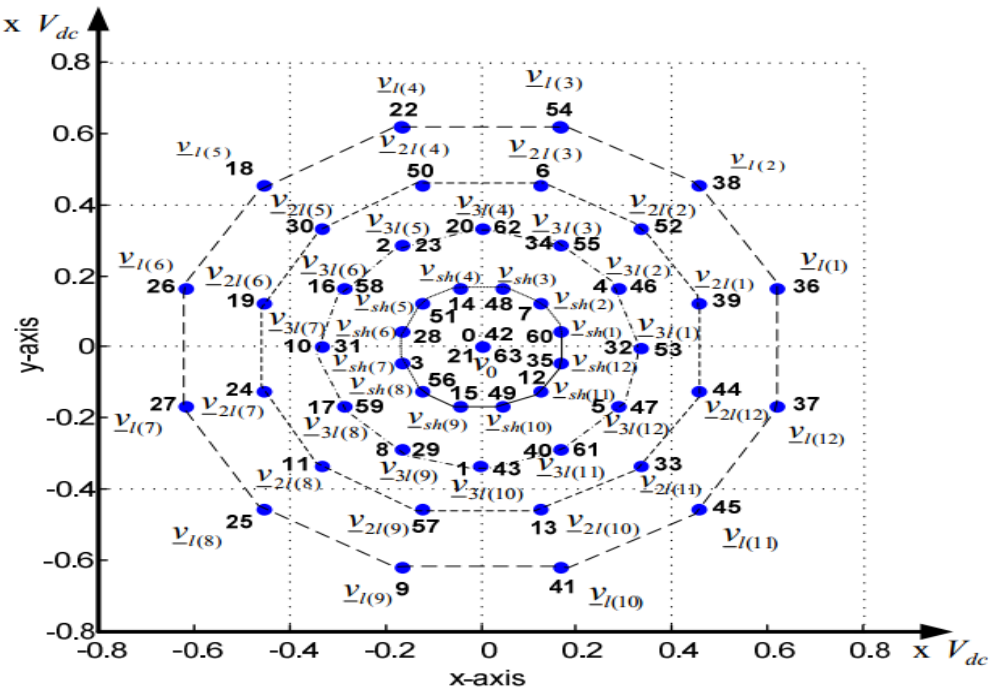


Figure3. 5 phase voltage space vectors for 2 level 6-phase VSI supplying asymmetrical machine: in (x,y) plane [15]

Table3. 3 table of Space vectors of 2-level 6-phase VSI supplying asymmetrical machine in (α-β) and (x-y) planes [15]

Space Vectors	Values Of Space Vectors
Largest($\underline{v}_{l(k)}$)	$\frac{\sqrt{2+\sqrt{3}}}{3} v_{dc} e^{j(2k-1)\pi/12}$ For K=1,2,3,......,12
Second Largest($\underline{v}_{2l(k)}$)	$\frac{\sqrt{2}}{3} v_{dc} e^{j(2k-1)\pi/12}$ For K=1,2,3,......,12
Third Largest($\underline{v}_{3l(k)}$)	$\frac{1}{3} v_{dc} e^{j(k-1)\pi/6}$ For K=1,2,3,......,12
Shortest($\underline{v}_{sh(k)}$)	$\frac{\sqrt{2-\sqrt{3}}}{3} v_{dc} e^{j(2k-1)\pi/12}$ For K=1,2,3,......,12
Zero($\underline{v}_o$)	0

3.4.3 Realization of Space Vector PWM

Space vector PWM can be realized based on three steps:

1. Determine V_α , V_β $V_{ref}(\underline{V}^*)$ and angle (α)
2. Determine time duration T_1 , T_2 , T_o
3. Determine the switching time of each transistor (S_1 to S_{12})

SVPWM is a control algorithm where a reference signal, which is in the (α-β) plane, is synthesized by using combination of active and zero space vectors. The space vectors are properly selected and applied for a fraction of time (called dwell time) of a switching period. The space vectors can be selected and applied in many ways, but the target is to select the space vectors that produce the highest fundamental component amplitude in the (α-β) plane, while minimizing (or zeroing, ideally) all harmonic components in the other plane(s). In this way, losses generated by harmonics will be minimized, while at the same time the utilization of dc bus voltage can be maximized [12].

SVPWM For a six-phase inverter feeding an asymmetrical machine with two isolated neutrals points, two of the utilized vectors are active space vectors with the largest amplitude, while the third is one of the four switching state combinations of the zero space vector [15].The choice of the voltage vectors is based on space vector drawing in (α-β) plane. Here, the (α-β) plane is equally divided into twelve 30^o sectors (I to XII), as shown in Fig. 3.4 The carefully chosen active space vectors for sector I are indicated by heavy arrows.

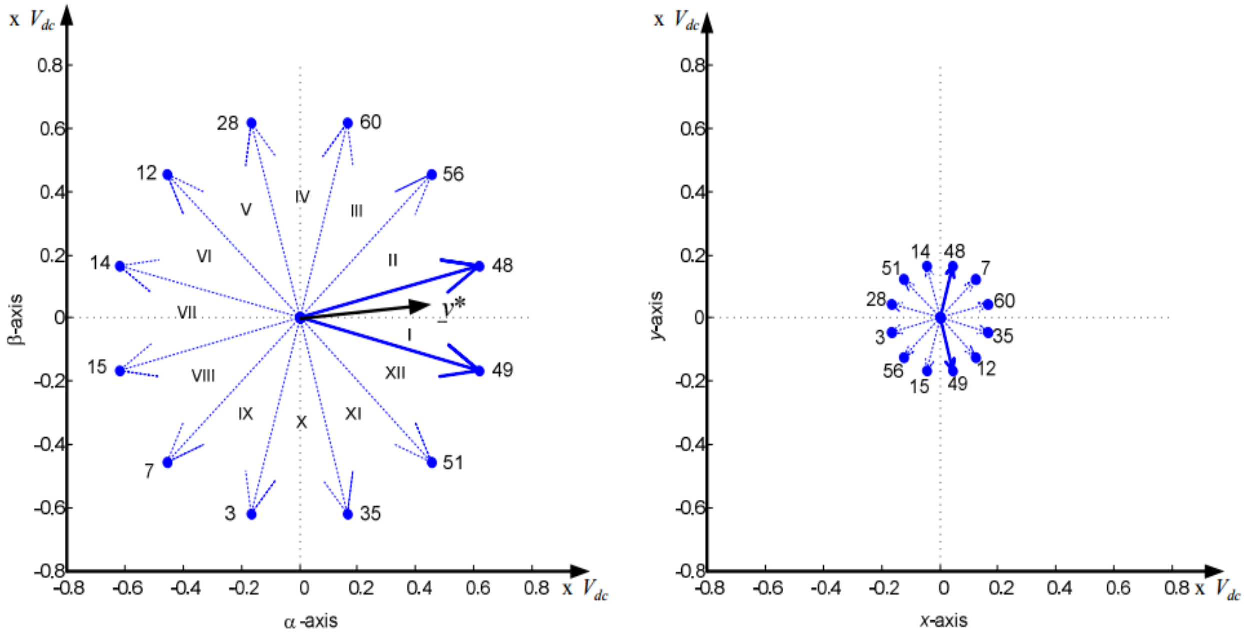


Figure3. 6 mapping of Space vector selection for sector I SVPWM method in (α-β) plane and in (x-y) plane [15]

The dwell time's calculation done for selected space Vectors based on fig. 3.4.2. V_1 and V_2 are represented the two active space vectors. During a switching period T_s, the reference vector $\underline{V}$* is synthesized by means of V_1 , V_2 and zero voltage vector, applied for time intervals T_1, T_2 and T_0 respectively.

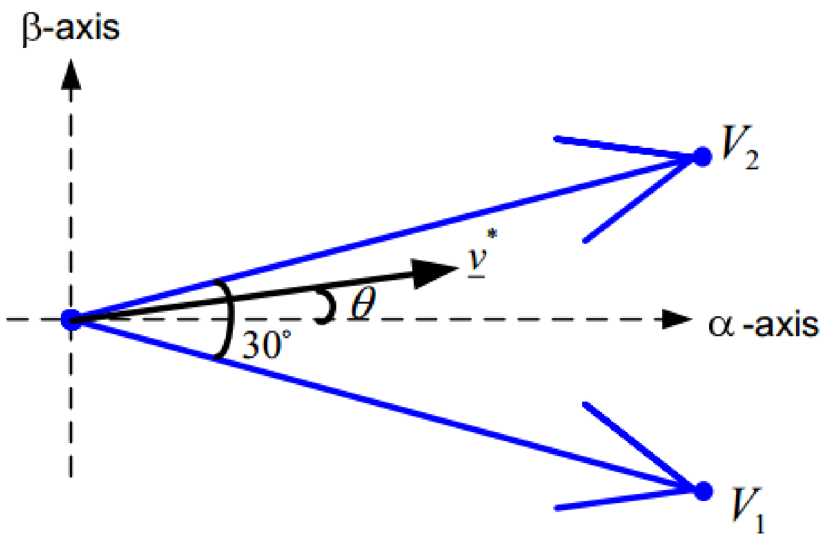


Figure3. 7 Dwell time calculation principle for SVPWM technique [15]

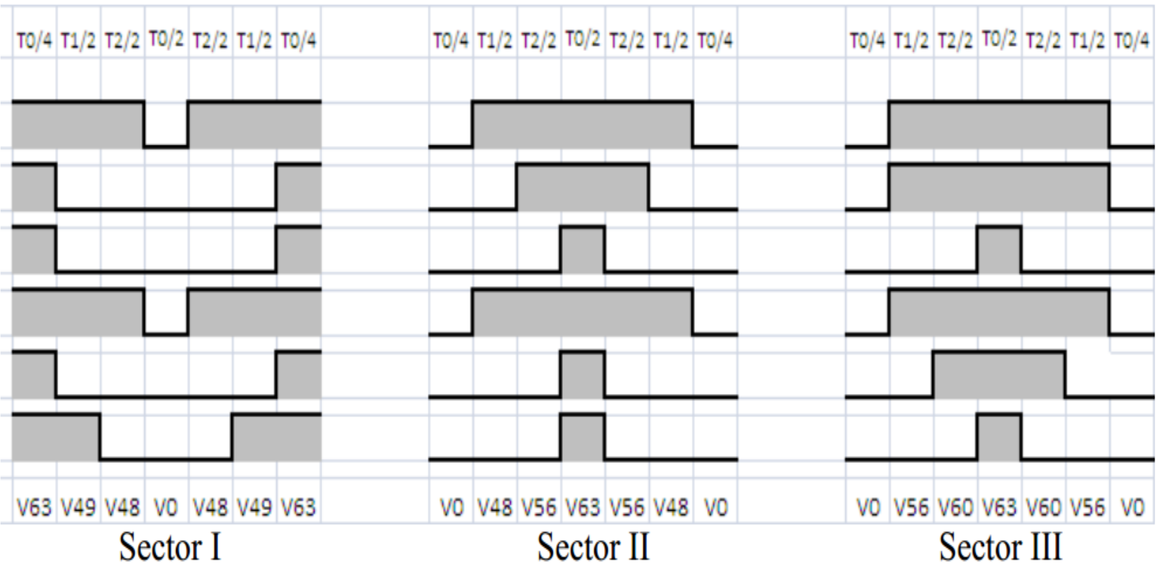
The dwell time corresponding to each space vector can be expressed as follows based on the volt-second balance principle:

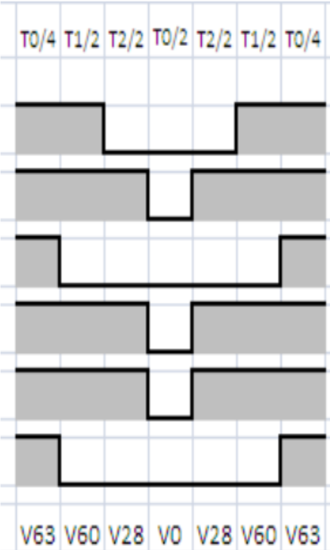
$$\begin{cases} T_1 V_{1\alpha} + T_2 V_{2\alpha} = V^*_{\alpha} T_s \\ T_1 V_{1\beta} + T_2 V_{2\beta} = V^*_{\beta} T_s \\ T_1 + T_2 + T_o = T_s \end{cases} \qquad (3.19)$$

T1 and T2 can be calculated as follows, where α-β subscripts indicate that (α-β) components of the space vector.

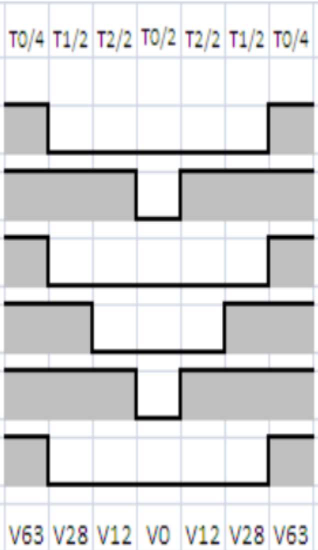
$$\begin{cases} T_1 = 2\frac{|v^*|}{|V|} T_s \sin(30^0 - \theta) \\ T_2 = 2\frac{|v^*|}{|V|} T_s \sin\theta \end{cases} \qquad (3.20)$$

|V| is the amplitude of V_1 and V_2 (i.e. the magnitude of the large space vector) and θ is angular position of the reference. The switching sequences of inverter legs for all twelve sectors are shown as following in Fig. 3.4.4. The selected space vectors for each sector are also listed. During the switching period each switch is being switched on and off once only because of the four switching state combinations of the zero space vector are used alternately.

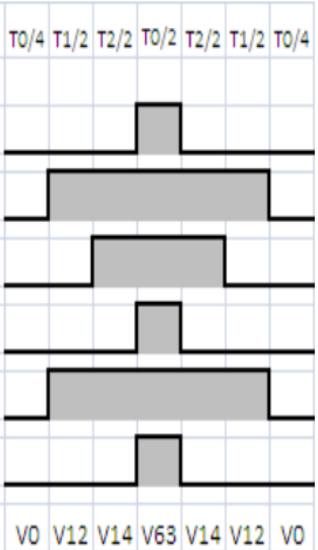




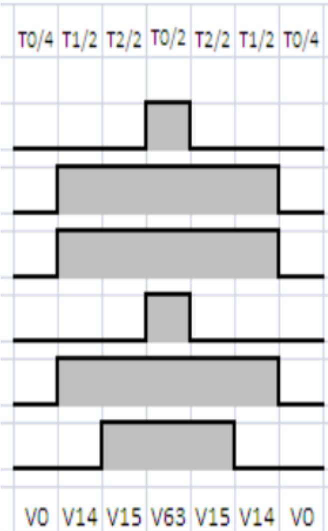
Sector IV



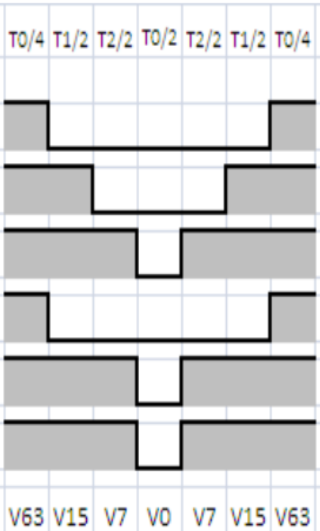
Sector V



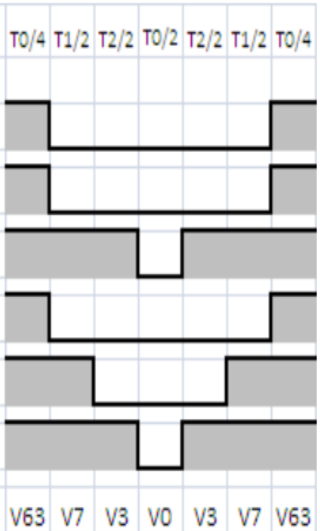
Sector VI



Sector VII



Sector VIII



Sector IX

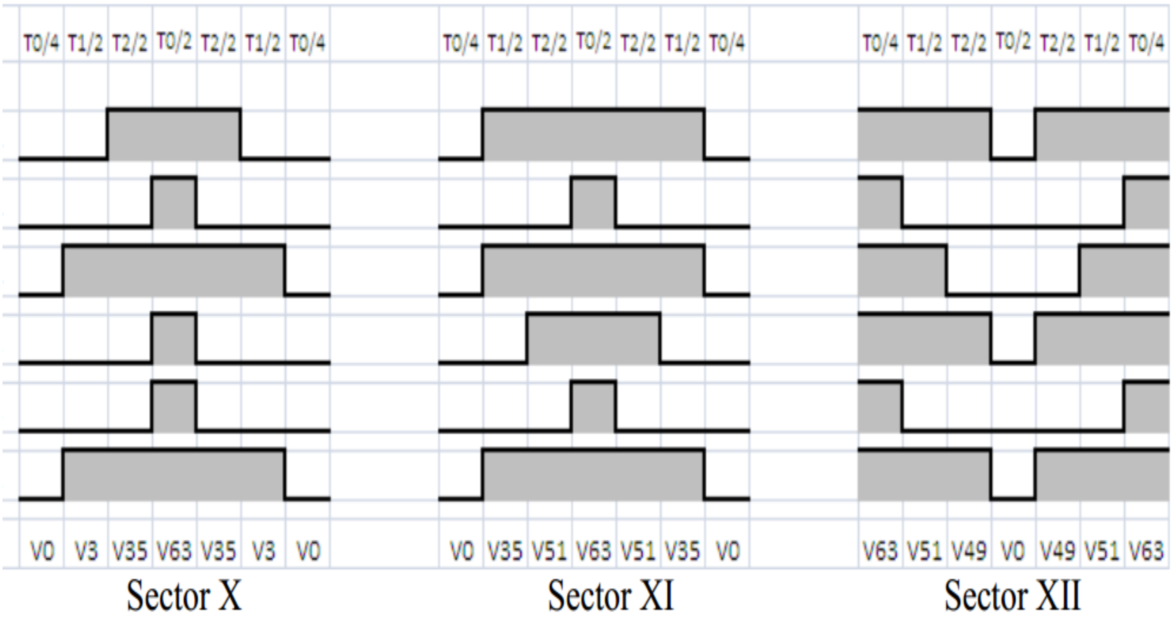


Figure3. 8 Switching sequences of inverter legs for SVPWM technique [22]

Based on figure 3.8 the switching time at each sector is summarized in table 3.4. As follows:

Table3. 4 the switching time at each sector [15]

Sector	Upper Switch	Lower Switch
I	$S_1=T_o/4 + T_1/2 + T_2/2$ $S_3=T_o/4$ $S_5=T_o/4$ $S_7=T_o/4 + T_1/2 + T_2/2$ $S_9=T_o/4$ $S_{11}=T_o/4 + T_1/2$	$S_2= T_o/2 + T_o/2$ $S_4= T_1/2 + T_2/2$ $S_6= T_1/2 + T_2/2 + T_o/2$ $S_8= T_o/2$ $S_{10}= T_1/2 + T_2/2 + T_o/2$ $S_{12}= T_2/2 + T_o/2$
II	$S_1= T_1/2 + T_2/2 + T_o/2$ $S_3=T_2/2 + T_o/2$ $S_5=T_o/2$ $S_7= T_1/2 + T_2/2 + T_o/2$ $S_9=T_o/2$ $S_{11}=T_o/2$	$S_2=T_o/4$ $S_4= T_o/4 + T_1 /2$ $S_6= T_o/4 + T_1/2 + T_2/2$ $S_8= T_o/4$ $S_{10}= T_o/4 +T_1/2 + T_2/2$ $S_{12}= T_o/4 + T_1/2 + T_2/2$
III	$S_1= T_1/2 + T_2/2 + T_o/2$ $S_3= T_1/2 + T_2/2 + T_o/2$ $S_5=T_o/2$	$S_2=T_o/4$ $S_4= T_o/4$ $S_6= T_o/4 + T_1/2 + T_2/2$

	S_7= T_1/2 + T_2/2 + T_o/2 S_9= T_2/2 + T_o/2 S_{11}=T_o/2	S_8= T_o/4 S_{10}= T_o/4 + T_1/2 S_{12}= T_o/4 + T_1/2 + T_2/2
IV	S_1= T_o/4 + T_1/2 S_3= T_o/4 + T_1/2 + T_2/2 S_5=T_o/4 S_7= T_o/4 + T_1/2 + T_2/2 S_9= T_o/4 + T_1/2 + T_2/2 S_{11}=T_o/4	S_2= T_2/2 + T_o/2 S_4= T_o/4 S_6= T_o/4 + T_1/2 + T_2/2 S_8= T_o/2 S_{10}= T_o/2 S_{12}= T_o/4 + T_1/2 + T_2/2
V	S_1= T_o/4 S_3= T_o/4 + T_1/2 + T_2/2 S_5=T_o/4 S_7= T_o/4 + T_1/2 S_9= T_o/4 + T_1/2 + T_2/2 S_{11}=T_o/4	S_2= T_1/2 +T_2/2 + T_o/2 S_4= T_o/2 S_6= T_1/2 + T_2/2 + T_o/2 S_8= T_2/2 + T_o/2 S_{10}= T_o/2 S_{12}= T_1/2 + T_2/2 + T_o/2
VI	S_1= T_o/2 S_3= T_1/2 + T_2/2 + T_o/2 S_5= T_2/2 + T_o/2 S_7= T_o/2 S_9= T_1/2 + T_2/2 + T_o/2 S_{11}=T_o/2	S_2= T_o/4 + T_1/2 + T_2/2 S_4= T_o/4 S_6= T_o/4 + T_1/2 S_8= T_o/4 + T_1/2 + T_2/2 S_{10}= T_o/4 S_{12}= T_o/4 + T_1/2 + T_2/2
VII	S_1= T_o/2 S_3= T_1/2 + T_2/2 + T_o/2 S_5= T_1/2 + T_2/2 + T_o/2 S_7= T_o/2 S_9= T_1/2 + T_2/2 + T_o/2 S_{11}= T_2/2 + T_o/2	S_2= T_o/4 + T_1/2 + T_2/2 S_4= T_o/4 S_6= T_o/4 S_8= T_o/4 + T_1/2 + T_2/2 S_{10}= T_o/4 S_{12}= T_o/4 + T_1/2
VIII	S_1= T_o/4 S_3= T_o/4 + T_1/2 S_5= T_o/4 + T_1/2 + T_2/2 S_7= T_o/4 S_9= T_o/4 + T_1/2 + T_2/2 S_{11}= T_o/4 + T_1/2 + T_2/2	S_2= T_1/2 + T_2/2 + T_o/2 S_4= T_2/2 + T_o/2 S_6= T_o/2 S_8= T_1/2 + T_2/2 + T_o/2 S_{10}= T_o/2 S_{12}= T_o/2

IX	$S_1= T_o/4$ $S_3= T_o/4$ $S_5= T_o/4 + T_1/2 + T_2/2$ $S_7= T_o/4$ $S_9= T_o/4 + T_1/2$ $S_{11}= T_o/4 + T_1/2 + T_2/2$	$S_2= T_1/2 + T_2/2 + T_o/2$ $S_4= T_1/2 + T_2/2 + T_o/2$ $S_6= T_o/2$ $S_8= T_1/2 + T_2/2 + T_o/2$ $S_{10}= T_2/2 + T_o/2$ $S_{12}= T_o/2$
X	$S_1= T_2/2 + T_o/2$ $S_3= T_o/2$ $S_5= T_1/2 + T_2/2 + T_o/2$ $S_7= T_o/2$ $S_9= T_o/2$ $S_{11}= T_1/2 + T_2/2 + T_o/2$	$S_2= T_o/4 + T_1/2$ $S_4= T_o/4 + T_1/2 + T_2/2$ $S_6= T_o/4$ $S_8= T_o/4 + T_1/2 + T_2/2$ $S_{10}= T_o/4 + T_1/2 + T_2/2$ $S_{12}= T_o/4$
XI	$S_1= T_1/2 + T_2/2 + T_o/2$ $S_3= T_o/2$ $S_5= T_1/2 + T_2/2 + T_o/2$ $S_7= T_2/2 + T_o/2$ $S_9= T_o/2$ $S_{11}= T_1/2 + T_2/2 + T_o/2$	$S_2= T_o/4$ $S_4= T_o/4 + T_1/2 + T_2/2$ $S_6= T_o/4$ $S_8= T_o/4 + T_1/2$ $S_{10}= T_o/4 + T_1/2 + T_2/2$ $S_{12}= T_o/4$
XII	$S_1= T_o/4 + T_1/2 + T_2/2$ $S_3= T_o/4$ $S_5= T_o/4 + T_1/2$ $S_7= T_o/4 + T_1/2 + T_2/2$ $S_9= T_o/4$ $S_{11}= T_o/4 + T_1/2 + T_2/2$	$S_2= T_o/2$ $S_4= T_1/2 + T_2/2 + T_o/2$ $S_6= T_1/2 + T_o/2$ $S_8= T_o/2$ $S_{10}= T_1/2 + T_2/2 + T_o/2$ $S_{12}= T_o/2$

3.5 PI controller

In control system of closed loop, control is required to modify the behavior of a system so that it behaves in a specific desirable manner over time. PI controllers are the most broadly used controllers in industries today. P stands for Proportional term in the controller and I stand for the Integral term in the controller. PI controller is applied in speed, torque, current and position control.

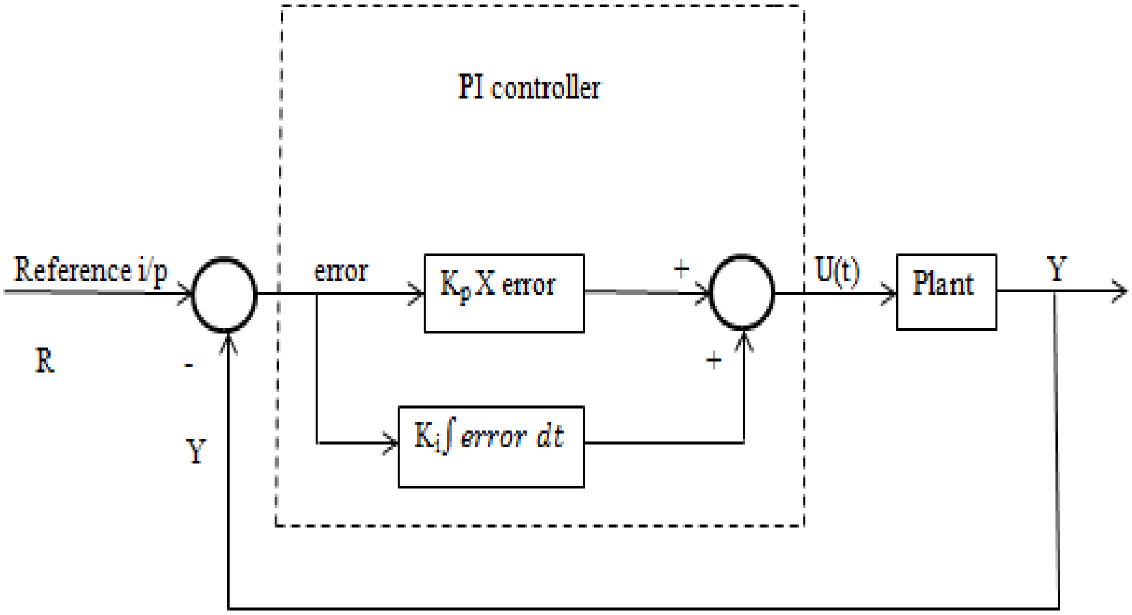


Figure3. 9 PI controller [10]

PI control in time domain can be expressed as follows:

$$U(t) = k_p[R(t) - Y(t)] + k_i \int_0^t [R(t) - Y(t)]dt$$

$$U(t) = k_p e(t) + k_i \int_0^t e(t)dt \tag{3.20}$$

Where: $U(t)$ is the controller's output signal

$e(t)$ is the controller's input error signal

K_p is the proportional control gain

K_i is the integral control gain

The Laplace transform of equation (1) and the structure of PI controller will be given as follows:

$$\begin{cases} U(s) = k_p E(s) + \frac{k_i}{s} E(s) = E(s)(k_p + \frac{k_i}{s} \\ D(s) = \frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} = \frac{k_p s + k_i}{s} \end{cases} \tag{3.21}$$

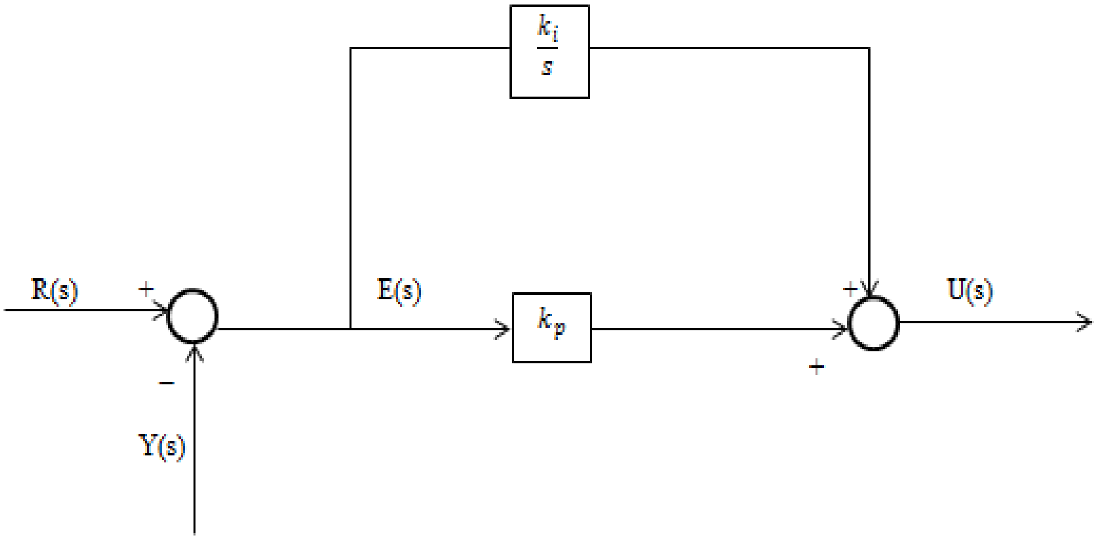


Figure3. 10 Structure of PI control [10]

A proportional controller (k_p) will have the effect of reducing the rise time and will reduce, but never eliminate the steady state error. If k_p is increasing the steady state error will be decreased but may cause the controller signal to be large which may lead to saturation or limiting problems with the system actuator. An integral control (k_i) will have the effect of eliminating the steady state error, but it may make the transient response worse [20].

PI controller is a type of state-feedback controller and in general, for the system with first-order dynamics the PI control is sufficient, and the D is not needed [24]. The direct synthesis technique is used to calculate the controller parameters based on the knowledge of the process model. It simply attempts to find a controller that gives desired closed loop transfer function.

The continuous time domain

PI controllers are in most cases analyzed and tuned in the continuous time domain. The corresponding transfer function is given as:

$$U(s) = \left(K_p + \frac{K_i}{s}\right).I(s) \tag{3.22}$$

I and U denote the input error signal and the controller's output, respectively, S is the Laplace variable and K_p and K_i are the two parameters of the PI controller associated with the proportional (P) and integral (I) part. However, tuning a PI controller is not very intuitive when specifying these two parameters. The equation above may be rewritten as follows [10]:

$$U(s) = K_p.\left(1 + \frac{K_I}{K_p}.\frac{1}{s}\right).I(s) = K_p.\omega_{PI}\left(\frac{\frac{s}{\omega_{PI}}+1}{s}\right).I(s) \qquad (3.23)$$

Where $\omega_{PI} = \frac{K_I}{K_P}$ (expressed in [rad/s]).

3.5.1 Integral with First Order Hold (FOH)

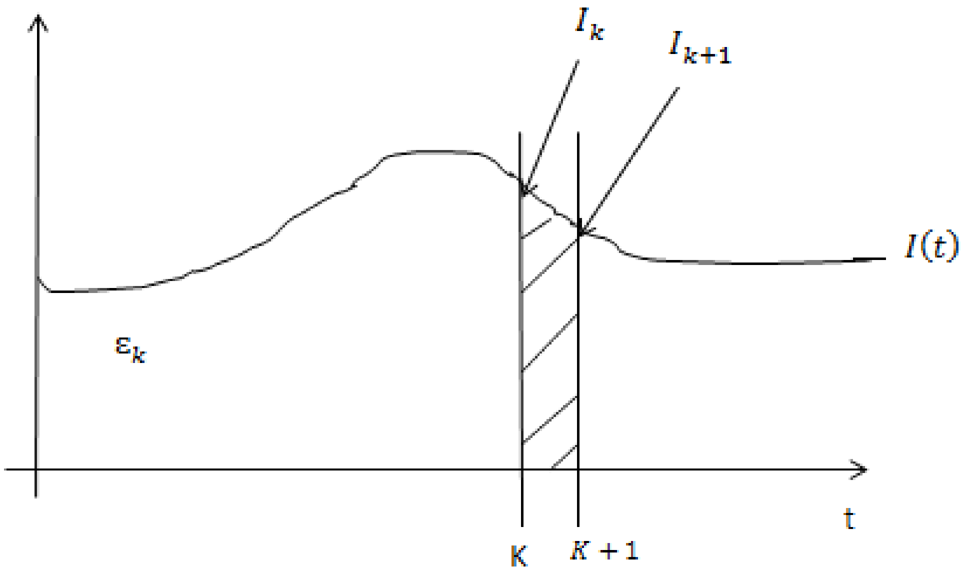


Figure3. 11 Integral with FOH Approximation [10]

The integral operation is approximated by accumulating the trapezoidal areas. Denoting the sum at instant k with $\sum_k$, the signal at instant k with I_k and the sample time with T_{sample} the "integration" is achieved by:

$$\textstyle\sum_{k+1} = \sum_k \frac{I_k + I_{k+1}}{2}.T_{sample} \qquad (3.24)$$

where the last term is derived from the known formula for the area of a trapezoid. Following a similar procedure as in the previous section, this may be expressed in the z-domain by:

$$Z\textstyle\sum(Z) = \sum(Z) + I(Z).\frac{1+Z}{2}.T_{sample} \qquad (3.25)$$

Which results in:

$$\sum(Z) = \frac{T_{sample}}{2} . \frac{Z+1}{Z-1} . I(Z) \qquad (3.26)$$

The continuous integration $\frac{1}{s}$ in equation (23) is replaced by the whole factor preceding$I(z)$. The transfer function in the discrete domain is obtained from (3.23) and (3.27) as:

$$U(z) = K_p . \left(1 + \omega_{PI} . \frac{T_{sample}}{2} \frac{z+1}{z-1}\right) I(z) = \frac{K_p\left(\frac{\omega_{PI} . T_{sample}+1}{2}\right) z + K_p . \left(\frac{\omega_{PI} . T_{sample}-1}{2}\right)}{z-1} I(Z) \qquad (3.27)$$

This corresponds to the following difference equation:

$$U_{k+1} = K_p \left(\frac{\omega_{PI} . T_{sample}}{2} + 1\right) . I_{k+1} + k_p \left(\frac{\omega_{PI} . T_{sample}}{2} - 1\right) . I_k + U_k \qquad (3.28)$$

$K_p = 16.216$ $\qquad$ $K_I = 2.8096$ $\qquad$ $K = 0.8$

3.6 Fuzzy Controller

In the design of fuzzy logic controller there are three main linguistic variables: Error, Change in Error and Control (Output) has to be defined based on the problem statement specified.

Table3. 5 Linguistic Rule table

		Derivative of Control error (Δe)				
		NB	NS	ZE	PS	PB
Control error (e)	NB	NB	NM	NS	NL	ZE
	NS	NM	NS	NL	ZE	PL
	ZE	NS	NL	ZE	PL	PS
	PS	NL	ZE	PL	PS	PM
	PB	ZE	PL	PS	PM	PB

Where, N (negative), NB (negative big), NM (negative medium), NS (negative small), NL (negative low), ZE (zero), P (positive), PL (positive low), PS (positive small), PM (positive medium), PB (positive big).

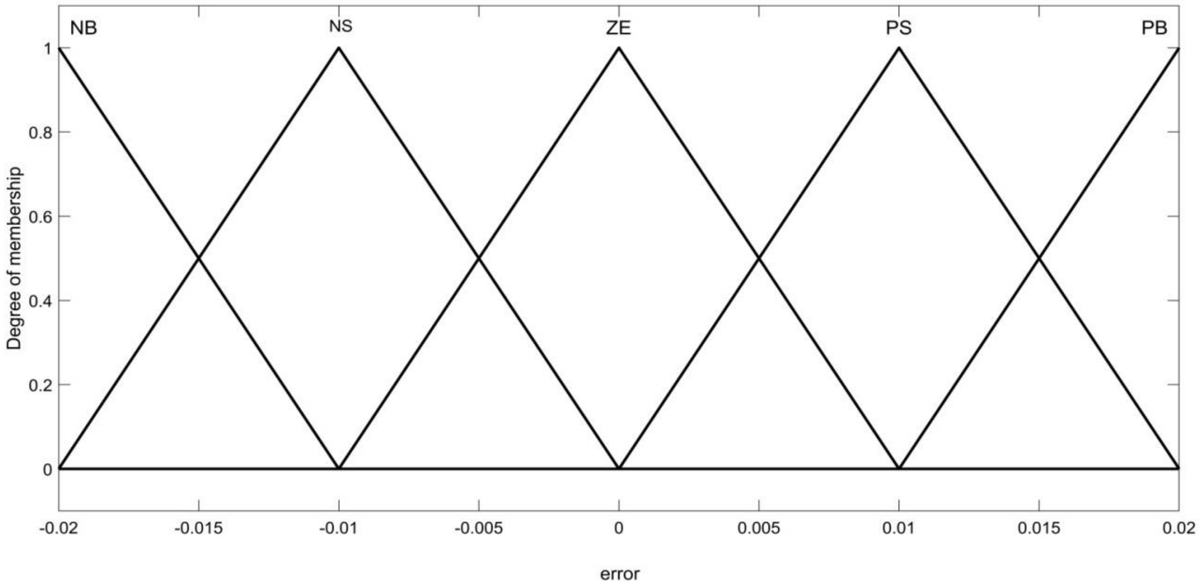


Figure3. 12 MF plots for input variable error

Figure 3.12 shows the same types of membership functions for input Error with their respective ranges. In input Error five linguistic values are considered with all of them are triangular membership functions.

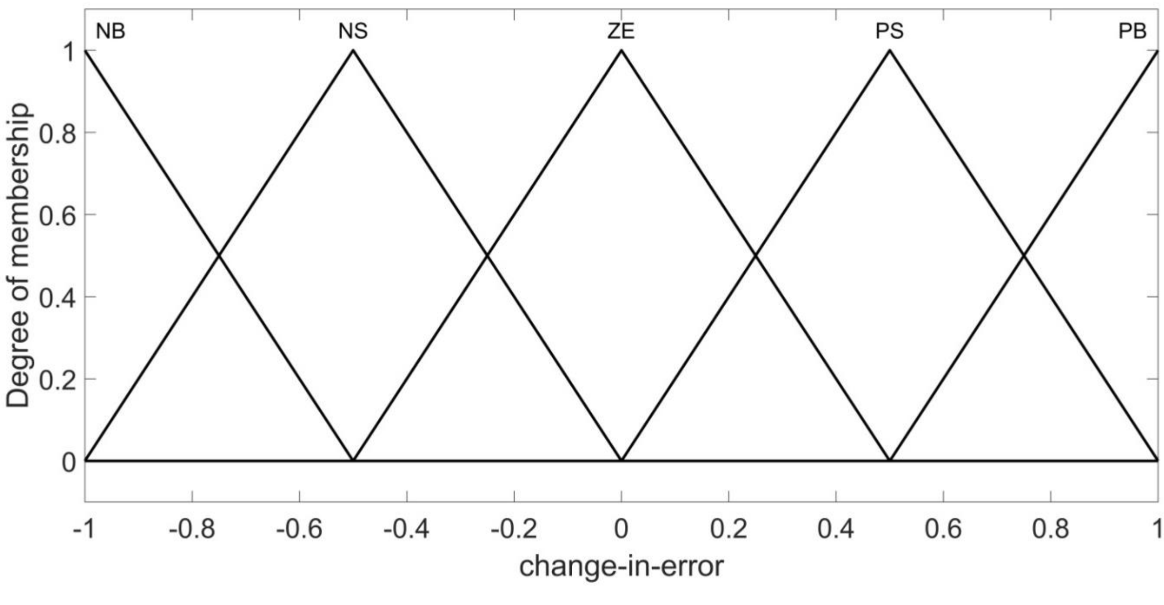


Figure3. 13 MF plots for input variable change in error

Figure 3.13 shows the same types of membership functions for input variable change in error with their respective ranges. In input Error five linguistic values are considered with all of them are triangular membership functions.

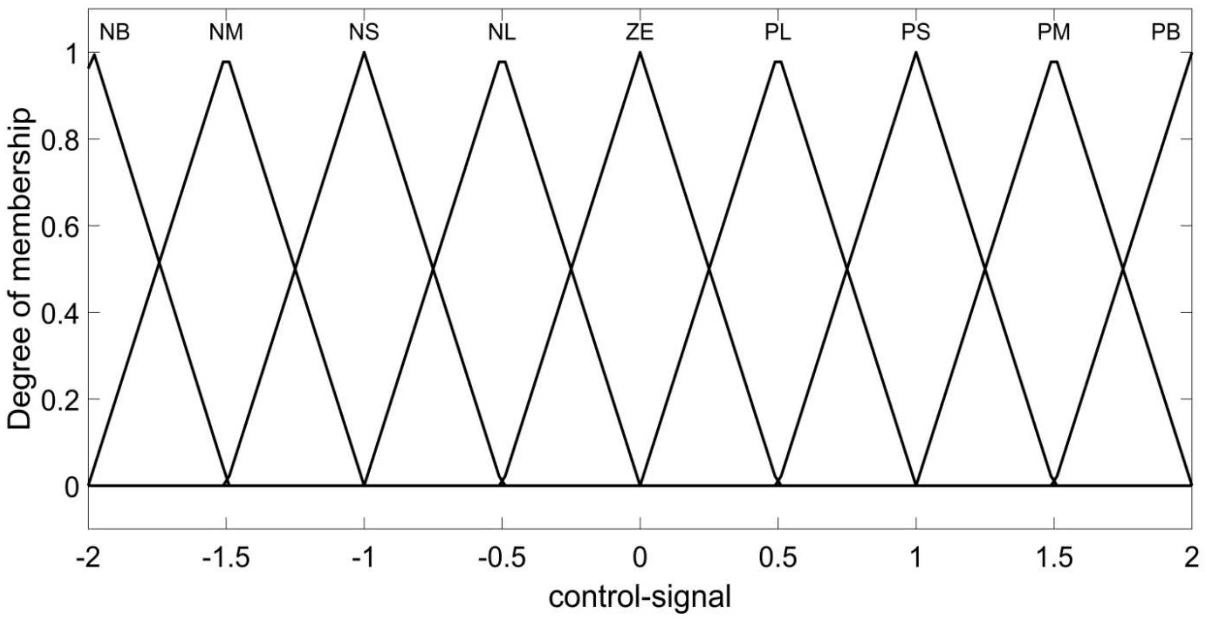


Figure3. 14 MF plots for (output variable) control signal

Figure 3.14 shows the same types of membership functions for output Control with their respective ranges and notations. In output Control nine linguistic values are considered and all of them are with triangular membership functions.

3.6.1 Rules

When designing fuzzy logic speed controller, the general rules are defined as, if the measured motor speed is less than the desired reference speed then speed up the motor and if the measured motor speed is more than the reference speed then slow down its speed. There are five linguistic variables of Error, five linguistic variables of Change in Error and nine linguistic variables of Control from which 25 rules in fuzzy controller are written.

The 25 corresponding fuzzy rules are defined as follows.

1. If (error is NB) and (change in error is NB) then (control signal is NB)
2. If (error is NB) and (change in error is NS) then (control signal is NM)
3. If (error is NB) and (change in error is ZE) then (control signal is NS)
4. If (error is NB) and (change in error is PS) then (control signal is NL)
5. If (error is NB) and (change in error is PB) then (control signal is ZE)
6. If (error is NS) and (change in error is NB) then (control signal is NM)
7. If (error is NS) and (change in error is NS) then (control signal is NS)
8. If (error is NS) and (change in error is ZE) then (control signal is NL)
9. If (error is NS) and (change in error is PS) then (control signal is ZE)
10. If (error is NS) and (change in error is PB) then (control signal is PL)
11. If (error is ZE) and (change in error is NB) then (control signal is NS)
12. If (error is ZE) and (change in error is NS) then (control signal is NL)
13. If (error is ZE) and (change in error is ZE) then (control signal is ZE)
14. If (error is ZE) and (change in error is PS) then (control signal is PL)
15. If (error is ZE) and (change in error is PB) then (control signal is PS)
16. If (error is PS) and (change in error is NB) then (control signal is NL)
17. If (error is PS) and (change in error is NS) then (control signal is ZE)
18. If (error is PS) and (change in error is ZE) then (control signal is PL)
19. If (error is PS) and (change in error is PS) then (control signal is PS)
20. If (error is PS) and (change in error is PB) then (control signal is PM)
21. If (error is PB) and (change in error is NB) then (control signal is ZE)
22. If (error is PB) and (change in error is NS) then (control signal is PL)
23. If (error is PB) and (change in error is ZE) then (control signal is PS)
24. If (error is PB) and (change in error is PS) then (control signal is PM)
25. If (error is PB) and (change in error is PB) then (control signal is PB)

CHAPTER FOUR
RESULT AND DISCUSSION

4.1 System Model

MATLAB/Simulink is software which is used to model, simulate, and analyze of dynamic systems. The mathematical equations presented in chapter three are used to model the six phase induction motor in Matlab/Simulink R2018b environment. Figure 4.1 represents the complete Simulink model of DTC of six phase induction motor.

The general system simulation block contains different sub-functional blocks such as: SVPWM block, VSI block and IM modeling block are sub functional blocks.

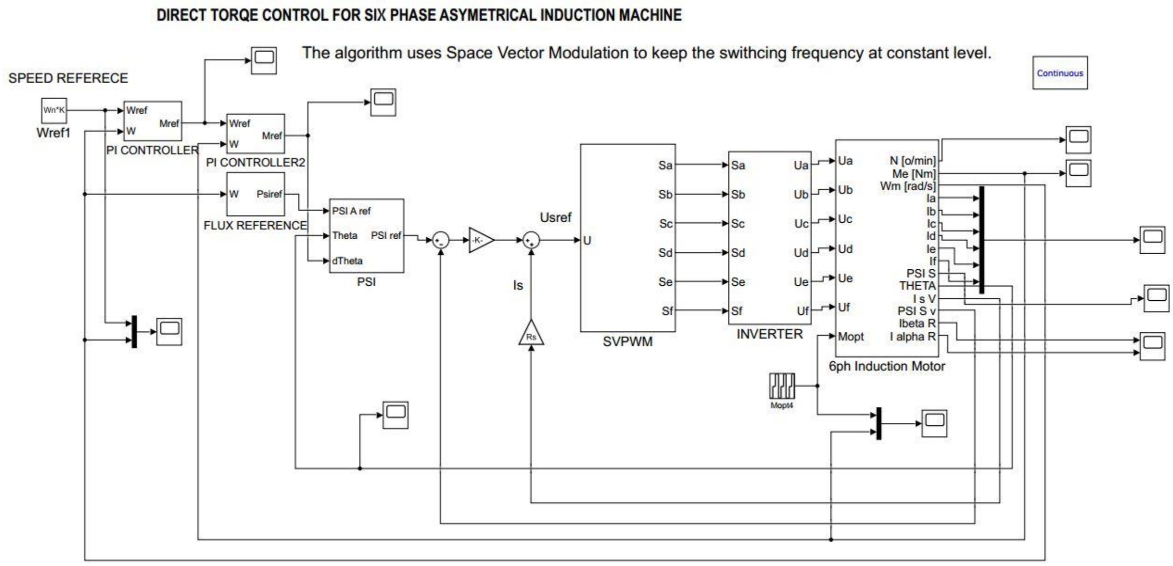


Figure4. 1 DTC of Six-Phase Asymmetrical IM with PI controller

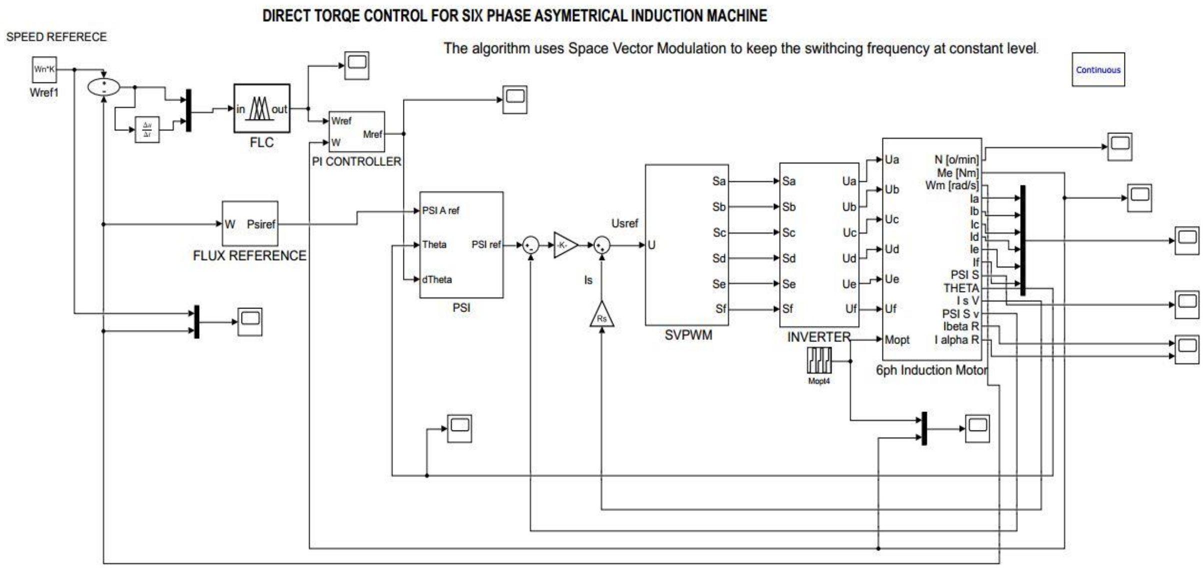


Figure4. 2 DTC of Six-Phase Asymmetrical IM with FLC controller

The PI controller blocks are used to minimize the torque errors. The PI torque output is theta (angle) and the flux reference output is flux controller calculation. And then this output is fed to modified SVPWM sub-blocks.

SVPWM Simulink block

The SVPWM simulation block, shown in figure 4.2, is used to determine the switching sequence and duration of the power transistors of six-phase voltage source inverters. SVPWM algorithm is used to keep the switching frequency at constant level. SVPWM is a control algorithm where a reference signal, which is in the (α-β) plane, is synthesized by using combination of active and zero space vectors. The space vectors are properly selected and applied for a fraction of time (called dwell time) of a switching period. The space vectors can be selected and applied in many ways, but the target is to select the space vectors that produce the highest fundamental component amplitude in the (α-β) plane, while minimizing (or zeroing, ideally) all harmonic components in the other plane(s). In this way, losses generated by harmonics will be minimized, while at the same time the utilization of dc bus voltage can be maximized.

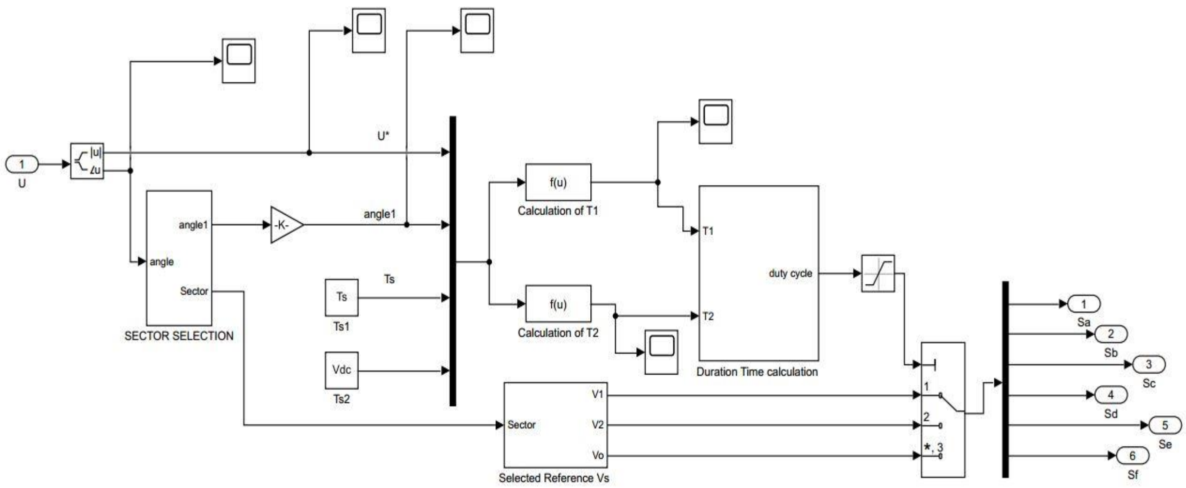


Figure4. 3 The subsystem block of SVPWM

Voltage Source Inverter Block

The VSI block is used to develop 6-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.

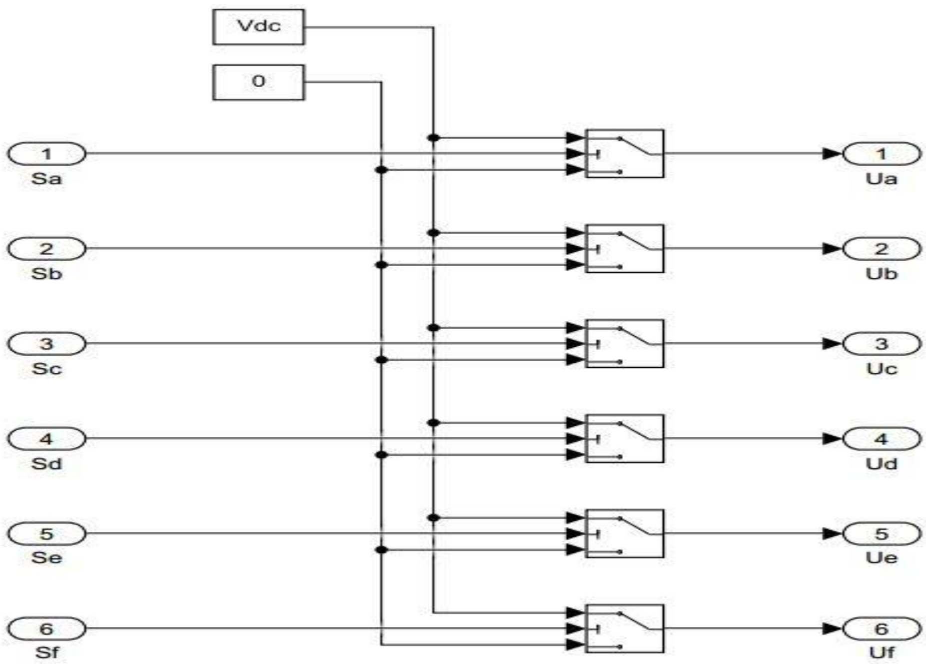


Figure4. 4 The subsystem block of VSI

Six-phase Simulation Model

The simulation design of 6-phase IM is not accessible in the Simulink library. However, it is designed using the rotor resistance, stator resistance, rotor inductance, stator inductance, mutual inductance and moment of inertia as shown in figure 4.4. The 6-phase VSI output voltages are transforming into α-axis voltage and β-axis voltage. From these voltages will be determine the actual stator flux and the rotor flux. Then, α-axis and β-axis currents are calculated from α and β-axis voltage and flux variables. After that, the electromagnetic torque is developed from the interaction of stator flux's and stator currents that is taken as actual torque. The rotor speed can be calculated from the mechanical torque calculation and torque load.

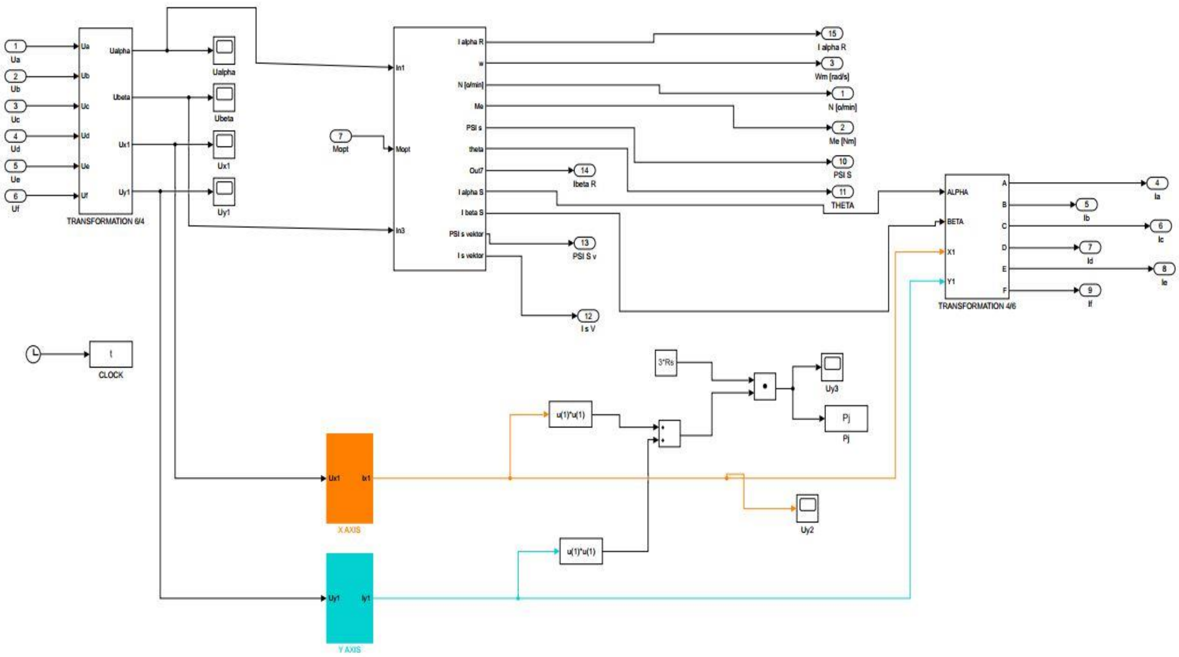


Figure4. 5 The subsystem block of six phase IM

4.2 Simulation Results of six-Phase IM

Table4. 1 IM and six-phase voltage source inverter parameter

Dc link voltage	$V_{dc} = 514.6$V
Stator resistance	$R_s = 11.6ohm$
Rotor resistance	$R_r = 10.4ohm$
Stator inductance	$L_s = 0.579mH$
Rotor inductance	$L_r = 0.579mH$
Mutual inductance	$L_m = 0.557H$
Moment of inertia	$J = 0.002kg.m^2$
Number of pole pairs	$P = 2$

The simulation results are taking into account different reference torques by varying loading circumstances. The steps of varying load torque is (there is no load at t=0 and the steps of varying load is, as 0, 2, 4.5 and 0, 0.33, 0.65 second respectively) and the corresponding variations in stator current, torque, and speed are observed. Had been observed that as load increases, stator current and motor torque is increasing while speed is decreasing. The transient oscillations of the torque for a load variation from zero loads to varied load, torque condition are observed by PI and FLC controllers.

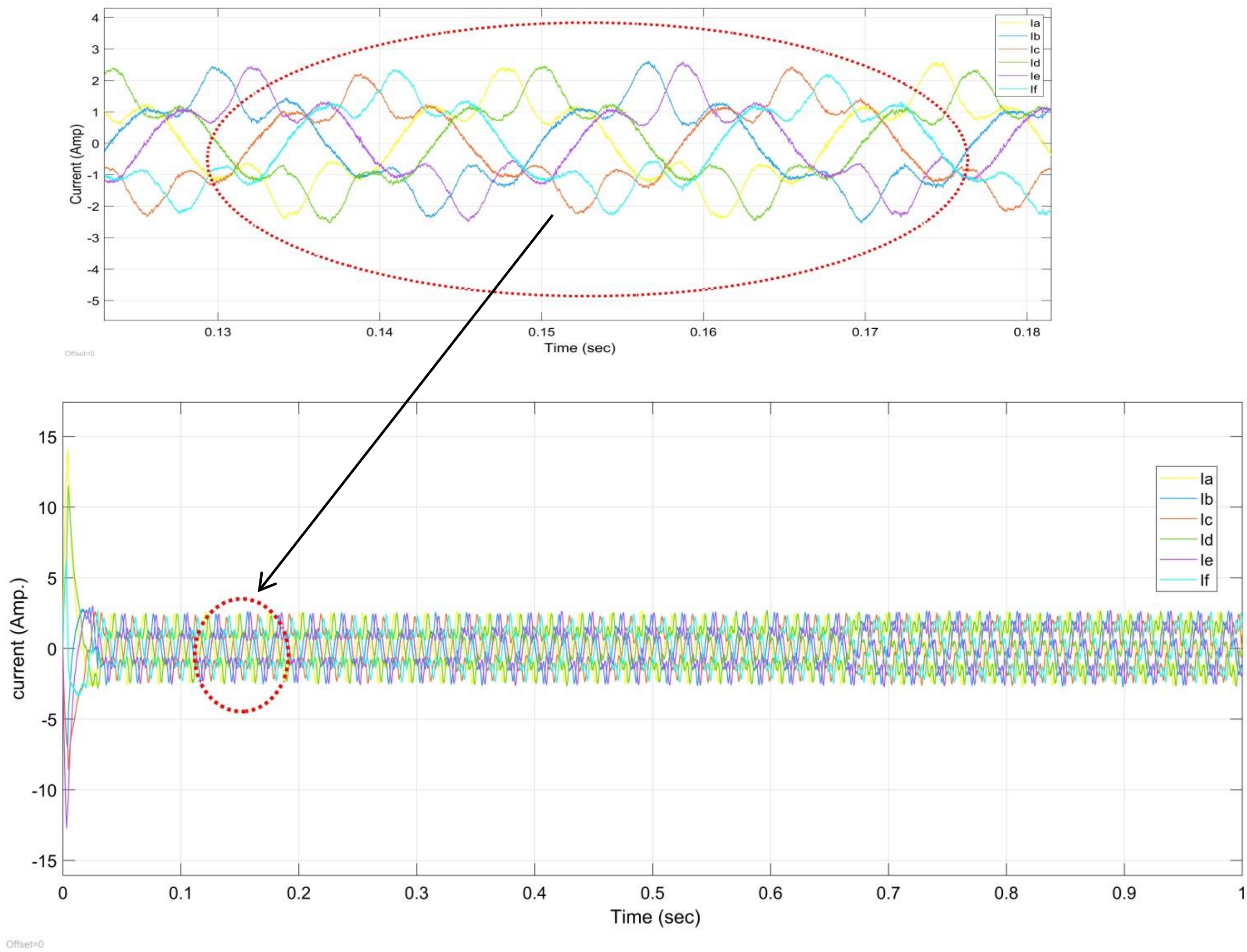


Figure4. 6 six-phase current with PI controller

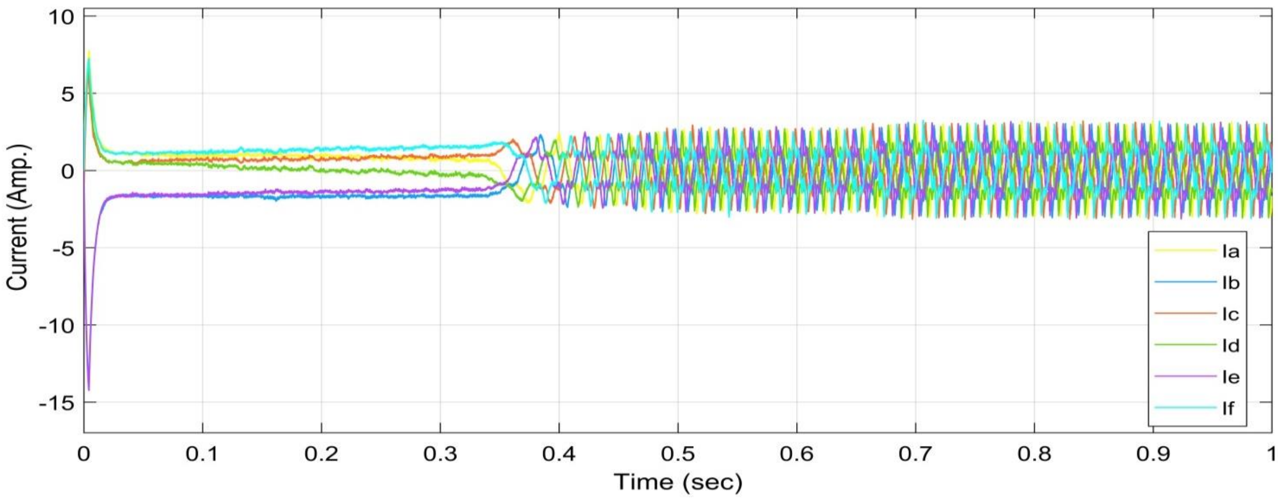


Figure4. 7 Six-phase current with FLC

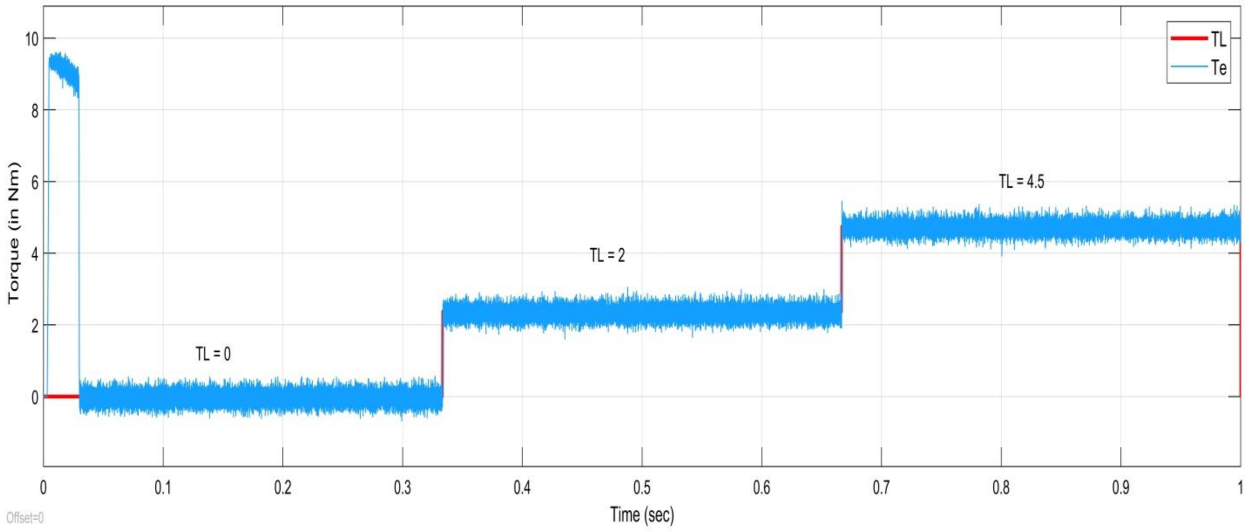


Figure4. 8 Electromagnetic torque and Load torque

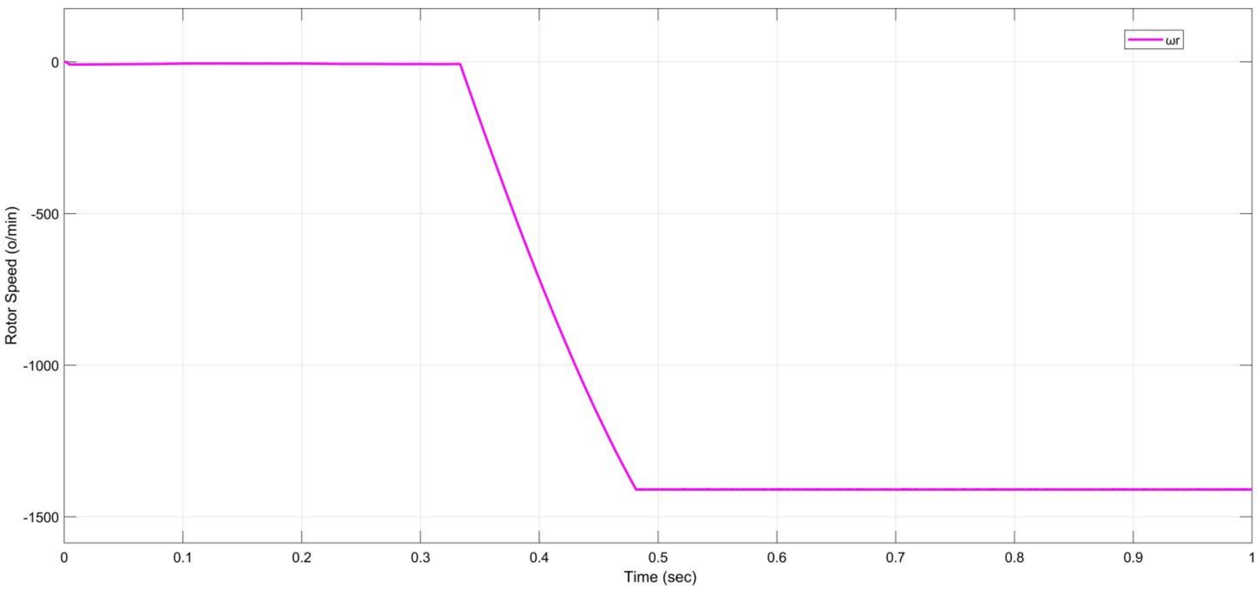


Figure4. 9 Rotor speed

In general, the Figure4.6, Figure4.7, Figure4.8 and Figure4.9, electromagnet torque, rotor speed and Stator phase currents respectively shows that the system at different load condition have good transient and steady state response. The starting torque is high at the transient response that oscillates for 0.02 seconds. As load increases, Motor torque and stator current increases while rotor speed decrease.

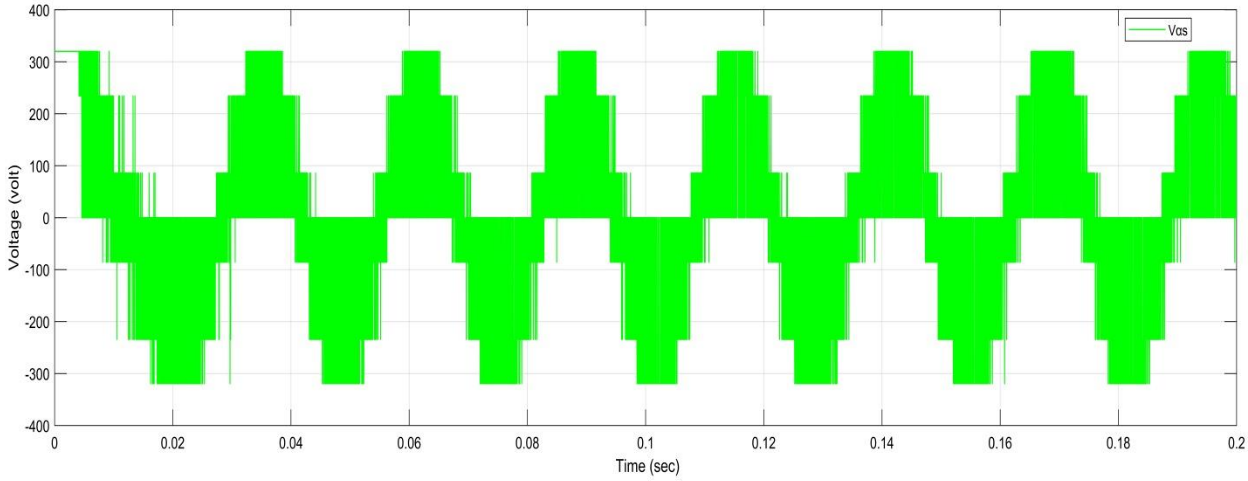


Figure4. 10 Alpha axis Stator Voltage

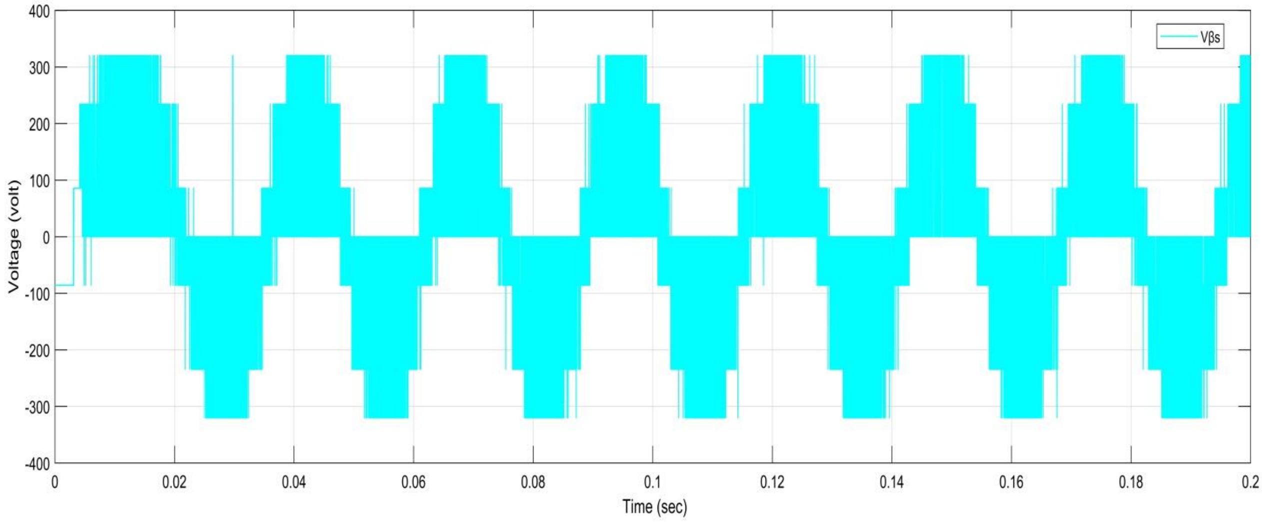


Figure4. 11 Alpha axis Stator Voltage

Figure 4.10 and Figure 4.11 shows that two phases alpha-axis and beta-axis stator voltages. It can be observed that these quantities are sinusoidal and have phase difference of 90^0.

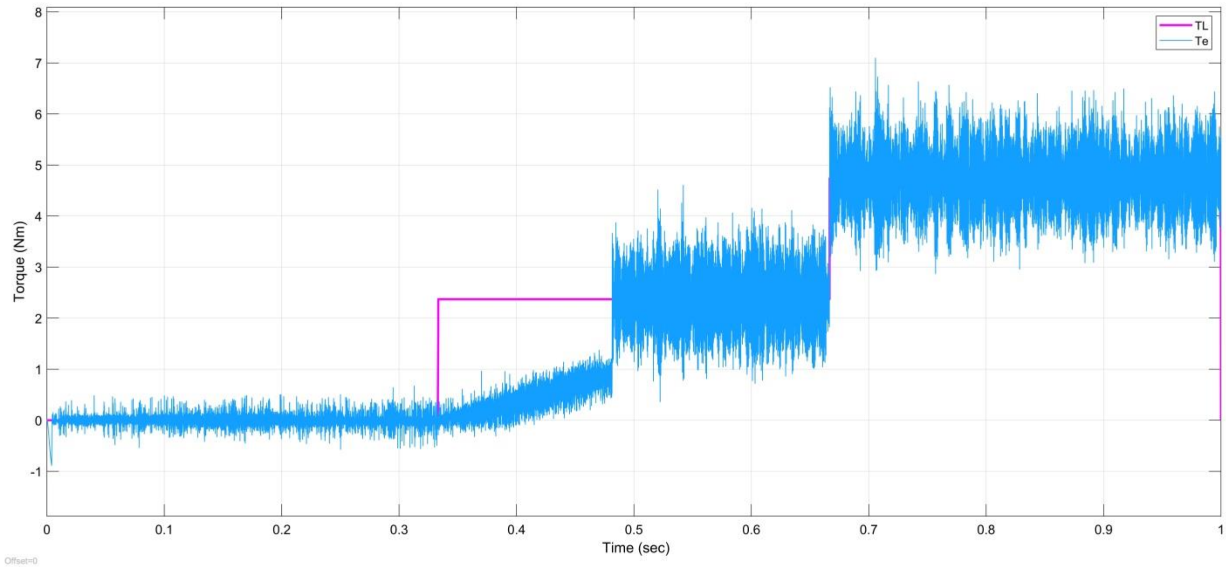


Figure4. 12 Electromagnetic Torque and Load torque with FLC

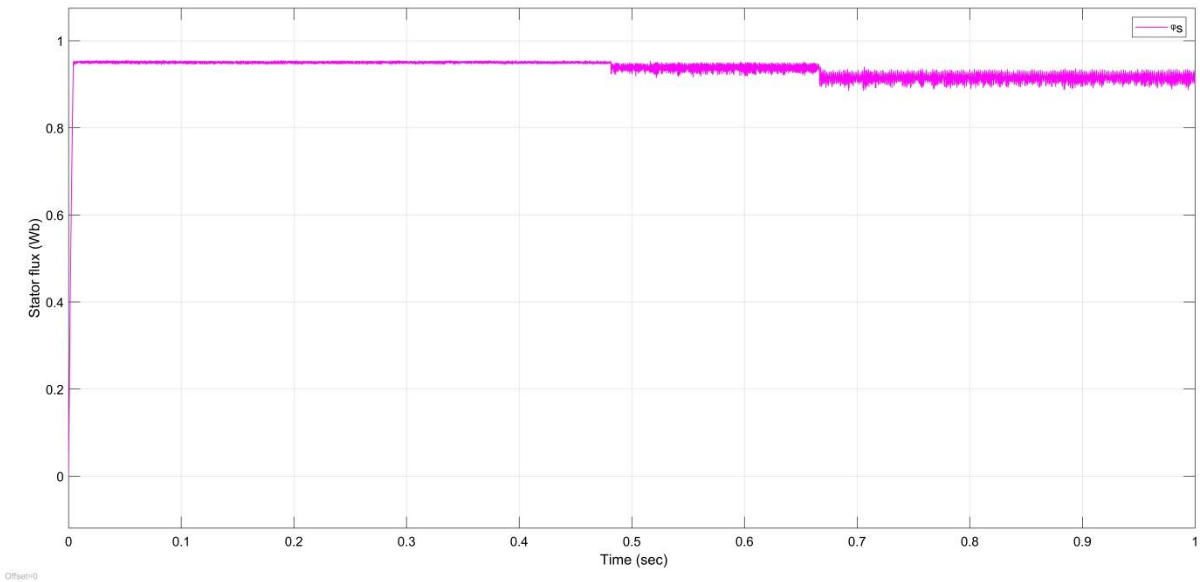


Figure4. 13 Stator Flux

Figure 4.12 shows that Electromagnetic torque of the system at different load condition have good transient and steady state response in FLC than PI controller and Figure 13 shows that stator flux is varying with load condition.

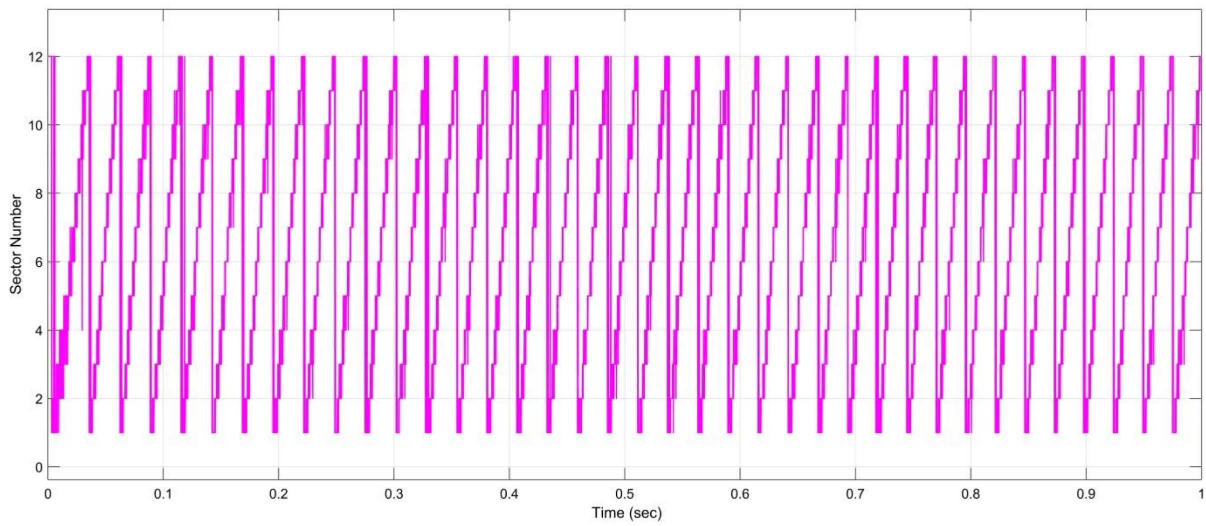


Figure4. 14 Sector number

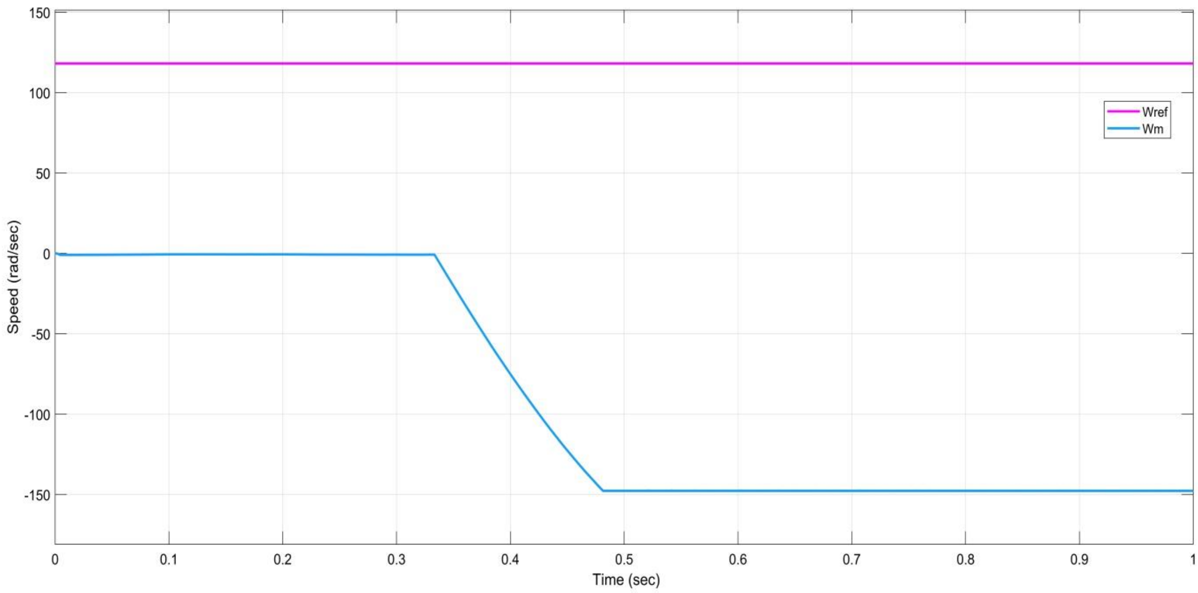


Figure4. 15 measured and reference speed

Figure 4.15 shows that measured and reference speed, the reference speed is 120 rad/sec and the measured speed is varying with load condition which is decrease, as load torque or electromagnetic torque is increase.

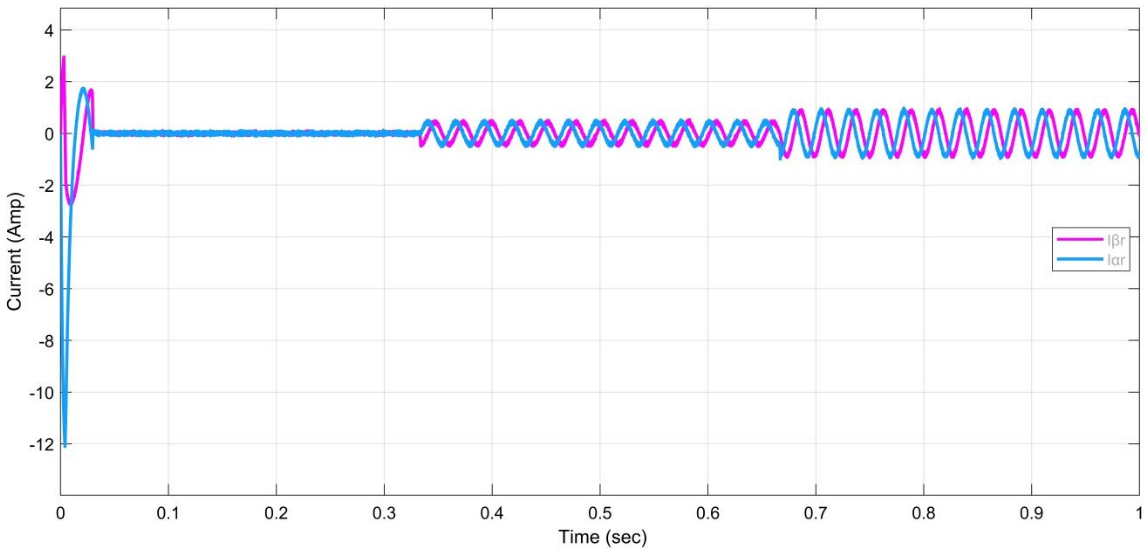


Figure4. 16 Alpha and Beta axis Rotor current with PI controller

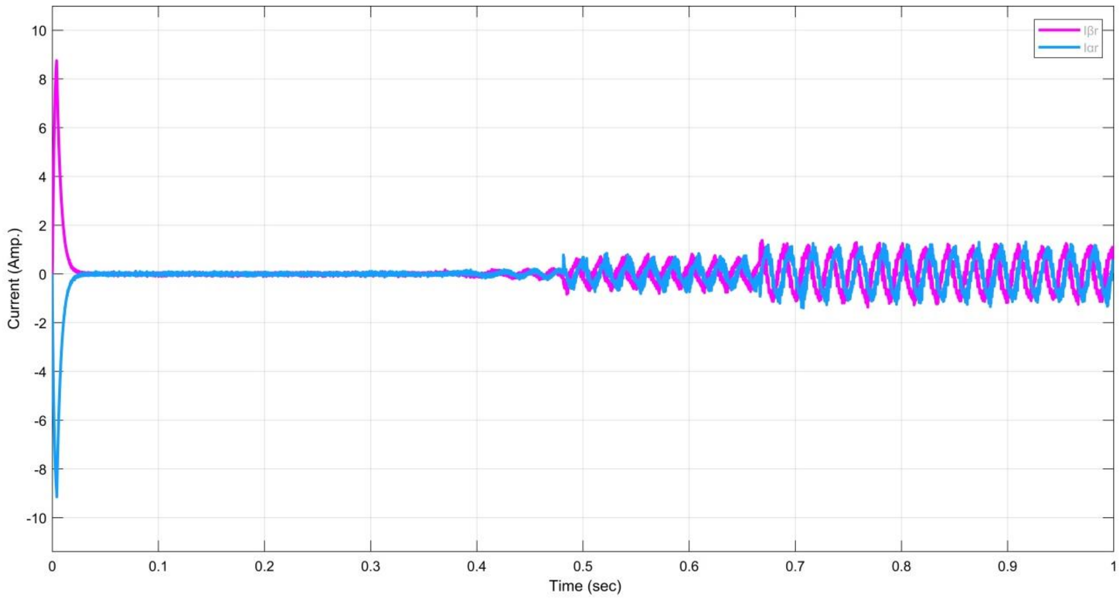


Figure4. 17 Alpha and Beta axis Rotor current with FLC

Figure 4.16 and Figure 4.17 shows that Alpha and Beta axis stator current. The transient response oscillation stays only for 0.02 second and transient response oscillation is less in FLC.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Direct torque control of 6-phase IM supplied with SVPWM inverter using fuzzy logic control had been studied. Based on estimates of the sudden errors in stator flux magnitude and PI and torque, fuzzy logic controller outputs, a voltage vectors are selected. The developed SVPWM algorithm utilized for generates the triggering signal of the VSI. In case of the added degrees of freedom, the 6-phase induction motor machine presents distinctive characteristics for improving the torque generating ability of the induction motor. The principle of DTC and flux estimation technique of IM are also elaborated and the overall model results have been analyzed with the help of MATLAB/SIMULINK. Both PI and fuzzy logic controllers are applied to the system. From the simulation results of better responses are obtained with fuzzy logic controller than PI controller. There is lower oscillation at steady state (which stay for about 0.02sec) with FLC.

5.2. Recommendation

In this thesis, direct torque control of 6-phase IM supplied with SVPWM inverter using fuzzy logic control had been done. Hence, from this research work the following points are recommended for further studies.

- Enhance motor Torque performance using various soft computing techniques such as GA, ANN, and PSO and/or in combination with conventional controllers.
- VSI with multilevel converters are preferable than two level converters.
- Evaluate the effect of number of MF of input Change in Error and output Control on the performance of the Torque control.
- Extend this control technique to other types of multi-phase motors.

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APPENDICES

Appendix A: fuzzy matlab code

```
[System]
Name='Girma'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=25
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='error'
Range=[-0.02 0.02]
NumMFs=5
MF1='NB':'trimf',[-0.03 -0.02 -0.01]
MF2='NS':'trimf',[-0.02 -0.01 0]
MF3='ZE':'trimf',[-0.01 0 0.01]
MF4='PS':'trimf',[0 0.01 0.02]
MF5='PB':'trimf',[0.01 0.02 0.03]
[Input2]
Name='change-in-error'
Range=[-1 1]
NumMFs=5
MF1='NB':'trimf',[-1.5 -1 -0.5]
MF2='NS':'trimf',[-1 -0.5 0]
MF3='ZE':'trimf',[-0.5 0 0.5]
MF4='PS':'trimf',[0 0.5 1]
MF5='PB':'trimf',[0.5 1 1.5]
[Output1]
Name='control-signal'
Range=[-2 2]
NumMFs=9
MF1='NB':'trimf',[-2.5 -1.98049837486457 -1.49]
MF2='NM':'trimf',[-2 -1.5 -1]
MF3='NS':'trimf',[-1.5 -1 -0.5]
MF4='NL':'trimf',[-1 -0.5 0]
MF5='ZE':'trimf',[-0.5 0 0.5]
MF6='PL':'trimf',[0 0.5 1]
MF7='PS':'trimf',[0.5 1 1.5]
MF8='PM':'trimf',[1 1.5 2]
MF9='PB':'trimf',[1.5 2 2.5]
```

Appendix B: parameters of a six phase IM

```
PARAMETERS OF A SIX PHASE IM

K=0.8; %REFERENCE SPEED [r.j.]!
Rs= 11; %[Ohm]  STATOR RESISTANCE
Rr= 10; %[Ohm]  ROTOR RESISTANCE
Ls= 0.6; %[H] STATOR INDUCTIVITY
Lr= 0.6; %[H] ROTOR INDUCTIVITY
Lm= 0.56; %[H] MUTUAL INDUCTIVITY
J= 0.02; %[kgm^2] INERCIA
p= 2; % POLES
f= 50; % [Hz] NOMINAL FREQUENCY
Pn= 750; % [W] NONOMINAL POWER
Nn= 1410; % [o/min] NOMINAL SPEED
Ufn= 220; % [V] NOMINAL PHASE VOLTAGE

PARAMETER CALCULATION

Ws= 2*pi*f/p; %[rad/s] SYNCHRONOUS SPEED
Wn= Nn*(2*pi/60); %[rad/s]
sn= (Ws-Wn)/Wn; % NOMINAL SLIP
Mn=(3*p*(Ufn*Ufn/Ws)*(Rr/sn))/((Rs+(Rr/sn))^2+(Ws*Ws)*(Ls+Lr)^2); % [Nm] NOMINAL TORQUE
sigma= Ls*Lr-Lm*Lm; % COEFICIJENT

DTC PARAMETERS

Vdc=3*sqrt(3)*220*sqrt(2)/pi;
Ts=4e-5;
Ts1=Ts; %SIMULATION SEMPLING TIME

PI REGULATOR FOR SPEED

T=0.5e-4;
Kp= 0.2027*(2*J/T)
Ki= 0.03512*(2*J/T)

PI REGULATOR FOR ANGLE OF STATOR FLUX LINKAGE VECTOR

T1=12e-4;
Kp1d= 0.2027*(2*J/T1)
Ki1d= 0.03512*(2*J/T1)
```