DESIGN AND ANALYSIS OF HYSTERESIS CURRENT CONTROL AND SVPWM ON FUZZY LOGIC BASED VECTOR CONTROLLED INDUCTION MOTOR DRIVE

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Submitted by:

TANMAY MISHRA

(2K14/C&I/12)

Under the Joint Supervision of

Prof. Narendra Kumar
&
Mr. Ashish Rajeshwar Kulkarni

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2016

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I, **Tanmay Mishra**, Roll No. 2K14/C&I/12 student of **M. Tech. (Control & Intrumentation)**, hereby declare that the dissertation titled “Design and Analysis of Hysteresis Current Control and SVPWM on Fuzzy Logic Based Vector Controlled Induction Motor Drive” under the joint supervision of Prof. Narendra Kumar Professor, Electrical Engineering Department and Mr. Ashish Rajeshwar kulkarni, Assistant Professor, Electrical Engineering Department, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi

Date: 30.06.2016

TANMAY MISHRA

Mr. Ashish Rajeshwar Kulkarni
Assistant Professor
Department of Electrical Engineering
Delhi Technological University

Prof. Narendra Kumar
Professor
Department of Electrical Engineering
Delhi Technological University

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DEDICATED TO

MY BELOVED FAMILY

ABSTRACT

The induction machine is an important class of electric machines which finds wide applicability as motor in industry and in its single-phase form in several domestic applications. More than 85% of industrial motors in use today are in fact induction motors. In many applications it is required to adjust the speed of Induction Motor (IM) according to load variation. Because of its highly nonlinear dynamic structure with strong dynamic interactions, it requires more complex control schemes than DC machines. The indirect vector control of IM is a control similar to fully compensated DC machine as vector control reduces the coupling effect which is responsible for sluggish response. Traditionally for speed controlling purpose PI controllers are used but it’s hard to tune PI every time with change in parameters. To avoid the effect of parameter variation, fuzzy logic controllers are used. The induction motor is fed from voltage source inverter and to control the output voltage of the inverter different modulation techniques are implemented.

This dissertation presents the performance comparison of Hysteresis Current Control and Space vector pulse width modulation (SVPWM) for generation of pulse width modulation (PWM) signals for voltage source inverter in vector controlled Induction Motor Drive. The dynamic performance of the drive for its speed regulation mode is described using both PWM techniques. Fuzzy Logic Control (FLC) is used for speed controller in both cases. The dynamic performance and ripple content is analyzed using FLC based SVPWM and HCC IM drive and compared at different operating conditions such as change in load torque and speed reversal. A MATLAB /SIMULINK model of FLC based vector controlled IM drive is simulated using hysteresis current controller and SVPWM for PWM signal generation and dynamic performance of these two techniques are compared.

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LIST OF SYMBOLS AND ABBREVIATIONS

IM	Induction Machine
SVPWM	Space vector pulse width modulation
HCC	Hysteresis current control
FLC	Fuzzy logic controller
FIU	Fuzzy inference unit
R_s	Stator resistance
R_r	Rotor resistance
Ψ_{ds}, Ψ_{qs}	$d^e - q^e$ axes stator flux linkage
i_{ds}, i_{qs}	$d^e - q^e$ axes stator current
Ψ_{dr}, Ψ_{qr}	$d^e - q^e$ axes rotor flux linkage
i_{dr}, i_{qr}	$d^e - q^e$ axes rotor current
L_s	Stator self-inductance
L_r	Rotor self-inductance
L_m	Mutual inductance
L_{ls}	Stator leakage inductance
L_{lr}	Rotor leakage inductance
Ψ_{dm}, Ψ_{qm}	$d^e - q^e$ axes magnetising flux linkage
T_L	Load torque
T_e	Electromagnetic Torque produced

ω_m	Mechanical speed of the motor
J	Inertia of the machine rotor
P	Total number of poles of motor

CHAPTER 1
INTRODUCTION

1.1 GENERAL

The drive system consists of electrical machine that convert electrical energy into mechanical energy or vice versa, power converters and Control mechanism. Theses drive systems are highly in demand in industries for various applications like subways, mills, and elevators etc. For high performance of the drive the related engineer must have knowledge about its dynamic model and variation in parameter for different conditions. A constant frequency AC machine is generally used for constant speed application whereas DC machines are used for variable speed. The DC machines have certain advantages like simple control, high starting torque and fast torque response but due to some disadvantages like higher cost, higher rotor inertia, maintenance issues, and due to commutators and brushes the current and speed is limited up to certain value due to these disadvantages now a days for variable speed applications AC machines are used instead of DC machine [1]. Generally used ac machines are induction machine, synchronous machine, reluctance motor, permanent magnet synchronous motor. Second main constituent of drive system is the power converters which are used as supply for the machine. The major power converters are rectifiers, Inverters, cycloconverter, choppers, ac voltage regulators [2]. Controller for a particular control mechanism is necessary for any operation either variable speed or constant speed. The two major steps in designing of a control system is:

1. The mathematical model of the drive system in order to accomplish the analysis and the evaluation of the system.

2. The imposed response of the drive system is obtained through an optimal regulator, when external perturbations are present.

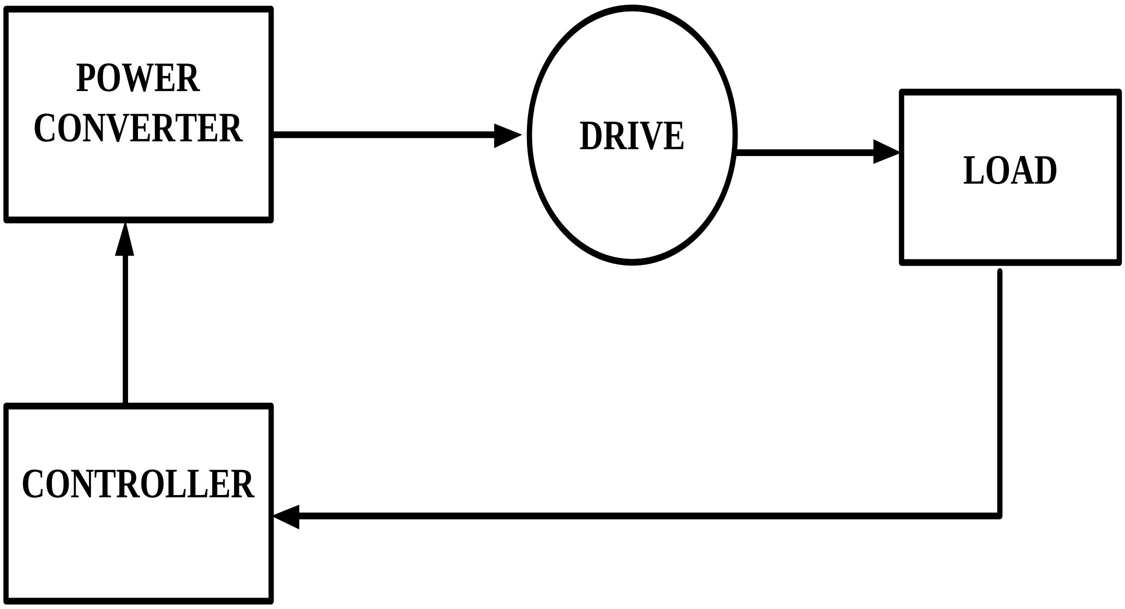

Figure 1.1 Motor drive control drive

1.2. CONTROL TECHNIQUES

In many applications it is required to adjust the speed of Induction Motor (IM) according to load variation. Because of its highly nonlinear dynamic structure with strong dynamic interactions, it requires more complex control schemes than DC machines and the complexity increases as higher performance is needed. The main reason behind this complexity are the requirement of variable frequency , harmonics limitation , complicated dynamic structure of induction machine, parameter variation due load perturbation or temperature variations[38].

There are two basic classes of control schemes:

1. **Analogue**: direct measurement of the machine parameters (mainly the rotor speed), which are compared to the reference signals through closed control loops;

2. **Digital**: estimation of the machine parameters in the sensorlesscontrol schemes (without measuring the rotor speed), with the following implementation methodologies:

a) Slip frequency calculation method;

b) Speed estimation using state equation;

c) Estimation based on slot space harmonic voltages;

d) Flux estimation and flux vector control;

e) Direct control of torque and flux;

f) Observer-based speed sensorlesscontrol;

g) Model reference adaptive systems;
h) Kalman filtering techniques;
i) Sensorlesscontrol with parameter adaptation;
j) Neural network based sensorlesscontrol;
k) Fuzzy-logic based sensorlesscontrol

In 1998, Holtz suggested another classification of control schemes based on the nature of controlled signal:

1. Scalar Control
2. Vector control

1.2.1 SCALAR CONTROL

The scalar control is due to the magnitude variation of control variables only, irrespective of the coupling effect unlike the vector or field oriented control (will be discussed in next section) where magnitude and phase both are taken into account for controlling action. The scalar controlled drives give modest performance but due to easy implementation are widely used in industries. Recently, due to advancement in technology and superior performance by the vector control drives the use of scalar controlled drive is impaired. Before the introduction of the vector control of induction motor, the method which enjoyed wide acceptability in controlling the speed of the induction motor drive are termed as voltage control, frequency control, rotor resistance control, V/f control, flux control, slip control, slip power recovery, etc. All these controls are termed as scalar control of an induction motor [42].

1.2.2 VECTOR CONTROL

The sole idea behind the vector control of an induction motor is to have an electrical drive which must offer superior performance than the widely used separately excited DC motor which has faster dynamic response as compared to the induction motor. The faster dynamic response of the dc motor lies into its being a doubly fed motor along with inherent facility of independent control of torque and flux in the motor. In their efforts to have maintenance free, robust and high performance ac drive, the researcher wanted to realize a separately excited dc motor performance and characteristics with an induction motor with cage rotor. In this direction, Blaschke introduce in 1972 the concept of vector control of an induction motor based on the principle of field orientation to realize dc motor characteristics in an induction motor drive. In vector control, the torque and flux in the motor are controlled independently.

The cage induction motor drive with vector or field oriented control offers a high level of dynamic performance and the closed-loop control associated with this drive provides the long-ter, stability of the system. Despite there being no major difference between scalar and vector controls, the latter has some properties which make it favourable as a control system with high dynamic performance [21].

In a broad sense, control of cage induction motor such that it behaves like a fully compensated separately excited dc motor, is known as its vector. In this case, the stator currents are expressed with reference to the frame of coordinates which rotates in synchronism either with the stator or rotor mmf vector. Stator currents expressed on these coordinates are resolved into two orthogonal components which produc the flux and torque in the motor. These are similar to the dc motor in which torque and flux are controlled by controlling armature and field current independently [22].

To control the torque and flux (thereby speed) independently in induction motor, there is need to control the magnitude and phase of the three stator currents through a inverter. For this purpose, normally a CC-VSI (Current controlled voltage source inverter) is needed. Such a control algorithm would be highly involved. Use is made of three to two-phase transformation. The two-phase currents i_{ds} and i_{qs} being in phase quadrature require the control of the two magnitude and one phase which is carried out by the vector control. Vector control technique is classified as:

1. Direct Vector control
2. Indirect Vector control

In Direct Vector control, the field angle is calculated by using terminal voltages and currents. The field angle is obtained by rotor position estimation and is known as Indirect Vector control. Direct vector control depends on Hall sensors, search coils for sensing the flux. The magnetizing flux linkage space vector is chosen for controlling the torque. A suitable Hall sensor or search coil is used to sense/monitor the magnetizing flux linkage (Ψ_m). The Ψ_m can also be obtained by $\Psi_m = \Psi_s - \Psi_{s\ leakage}$ i.e. from the difference between stator flux linkage and stator leakage flux component [23].

1.3. MOTIVATION

Induction motor is highly used in industries because of its high robustness, reliability, low cost, high efficiency and good self-starting capability. In many applications it is required to adjust the speed of Induction Motor (IM) according to load variation [1]. Because of its highly nonlinear dynamic structure with strong dynamic interactions, it requires more complex control schemes than DC machines [2]. The indirect vector control of IM is a control similar to fully compensated DC machine [3]-[4]. To avoid coupling effect which is responsible for its sluggish response vector control method is used. It is an excellent control strategy of torque and speed control of induction motor [5]-[6]. Traditionally motor controller have fixed gain like proportional-integral (PI) but this fixed gain controllers have certain issues with disturbances in load, change in parameters and they also require the exact mathematical modeling for the IM but due to many reasons including temperature variation, saturation, system disturbances designing exact dynamic model of induction motor is not feasible, to overcome this issue Fuzzy Logic Controller (FLC) is used using certain rule base [31]. FLC is based on plant operator experience and heuristics. It is nonlinear and adaptive control scheme with ease in implementation.

In this control scheme, IM is fed by 3 phase inverter. The input supply to the Motor can be varied by varying the gate pulse to the inverter which requires certain modulation techniques. These modulation techniques can be either voltage control based or current control based. Modulation techniques can be divided into three types of Pulse width Modulation (PWM). First is six steps PWM, second is sinusoidal PWM, and third is SVPWM while current control techniques can be divided into two types HCC and Delta Modulation. The SVPWM and HCC are most commonly used techniques [32]. The HCC is most applied nonlinear control technique due to simple implementation, low software requirement, high reliability, less tracking error and excellent dynamic response. However it also has some drawbacks like uncontrolled operating frequency which gives non-optimum ripples generation, rough operation due to randomness, high switching losses and bad compensation performance at zero crossing and low utilization of DC link. SVPWM is advanced, linear modulation scheme which is computationally intensive with wide range of fundamental voltage. SVPWM also solve the neutral point unbalance problem.

1.4 OBJECTIVE OF THE PROJECT

The main objective of this project is, to simulate MATLAB/SIMULINK model of FLC based vector controlled IM drive using hysteresis current controller and SVPWM for PWM signal generation. Then analyze and compare the dynamic performance of Hysteresis Current Control and SVPWM for generation of PWM signals for voltage source inverter in vector controlled Induction Motor Drive at different operating conditions such as change in load torque and speed reversal.

1.5. OVERVIEW OF THESIS

This thesis describes the performance, control and operation of Induction motor drive. Two modulation techniques viz hysteresis current control and space vector pulse width modulation (SVPWM) for generation of gate pulse have been implemented and demonstrated in fuzzy logic control based induction motor drive and test results is analyzed and studied using MATLAB/Simulink environment. Further, the research work done in this thesis is classified below:

In **Chapter 2: Literature review**, various articles, research papers, books, tutorials are discussed which are related to the study of dynamic modeling of induction machine , generation of rotating magnetic field, various transformation like three-phase to two phase(a, b, c to α, β) transformation, rotating axis (α, β) to stationary axis (d, q) transformation, vector control of induction motor, Indirect vector control scheme ,modulation techniques like hysteresis current control, Space vector pulse width modulation, fuzzy logic and its linguistic variables, fuzzification and defuzzification, interface mechanism, designing of fuzzy logic controller.

The **Chapter 3: Dynamic modelling of Induction machine,** discussed the rotating magnetic field and it's generation, voltage and the flux linkage equations, linear transformations in machine, Three-phase to two phase (a, b, c to α, β) transformation, rotating axis (α, β) to stationary axis (d, q) transformation, dynamic equation of the induction motor as per different reference frames, mathematical modeling of induction machine.

The **Chapter 4: Vector control of Induction motor drive,** discuss about the DC motor analogy, vector control analysis, Vector control principle and algorithm.

Different vector control strategies viz Direct vector control, indirect vector control, Features of vector control.

The **Chapter 5: Fuzzy logic & controller design,** discuss about fuzzy logic and how to design the speed controller using fuzzy logic. In this chapter fuzzy sets, membership functions, Fuzzy inference unit, fuzzification using rule base, rule evaluation, defuzzification are explained briefly. this chapter also provide an inside view of a fuzzy logic controller design for the vector control The fuzzy logic tool box in MATLAB/SIMULINK .

The **Chapter 6: Modulation Techniques** provide the detail about two most popular modulation techniques i.e. Hysteresis current control (HCC) and Space vector pulse width modulation (SPPWM).In this chapter generation of pulse using thes two techniques for Voltage source inverter (VSI) is explained.

The **Chapter 7: Simulation Results and Discussion** includes the proposed model of FLC based vector controlled drive for two modulation techniques HCC and SVPWM. Further the proposed model is designed in MATLAB/SIMULINK environment. The dynamic performance of motor drive is analyzed for step change in torque. Current, speed and torque characteristics are studied and compared for both the modulation techniques. Further dynamic performance is studied for speed reversal and similar characteristics for current, speed and torque is studied and compared.

The **Chapter 8: Conclusion and Future scope** conclude the comparison between two modulating schemes and advantages and drawbacks of these two schemes. The chapter also provides the required improvement to avoid these drawbacks.

1.6 CONCLUSION

The chapter provides the overview of induction motor drive and different controlling techniques for speed control of induction motor drive. Further, objective and motivation of the project is discussed briefly. The overview of thesis is mentioned in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Induction motor drives are suitable for industrial purpose because of their high torque to weight ratio, simple and robust structure, ability to operate in hazardous place and higher reliability. However, their control is a challenging task because rotor quantities are not directly accessible which are responsible for the production of torque. But, with the advancement in power electronics and control strategies in last few decades has mounted the growth in automation of industrial process, which results in efficient operation, higher productivity and product quality. The industry demands for higher standards for high performance motion control applications require, field weakening, minimum torque ripple, four quadrants operation and rapid speed recovery under impact load torque and fast dynamic speed and torque responses. This chapter concludes literature review of the development and research in the field of vector control of induction motor drive and its efficiency optimization control methods and techniques.

2.2 MODELLING AND CONTROL OF INDUCTION MOTOR DRIVE

Induction motor drive has gained its popularity in every industrial automation process due to its versatile performance characteristics. Induction motor is highly used in industries because of its high robustness, reliability, low cost, high efficiency and good self-starting capability. In many applications it is required to adjust the speed of Induction Motor (IM) according to load variation [1]. The dynamic mathematical model of induction motor, frequently used in dynamic studies of motor like drive specifications, motor control, Starting high inertia loads, electrical protection, successive starting, fast and large load changings, locked rotor. The induction motor dynamic model, frequently used in motor dynamic studies, is constituted by four voltage differential equations and one mechanical differential equation being very known among the electrical machine researchers [2]-[5].

2.2.1 CONTROLLING SCHEMES

Improving the dynamic performance of the induction motor drive has been an active area of research in last three decades, various control techniques have been evolved such as open loop and close loop v/f control, sensorless control, and field oriented or vector control and direct torque control for the torque and speed control of induction motor drive.

FOC (Field oriented control theory) was invented in Germany in 1968 [6]. *Hasse* proposed indirect vector control and *Blaschke* proposed direct vector control technique. Werner Leonhard further developed FOC techniques [6] [7]. *Abbondanti* and *Brennen* designed a slip calculator in 1975 which was based on the motor processing input quantities such as currents, voltages, and phases [8]. In 1979, *Ishida et al* who followed the work, used rotor slot harmonic voltages in control of slip frequency [9]. *Further, Iwata* and *Ishida* proposed the above technique in improving the speed range [10]. In 1987, *Hammerli et al* presented a method for detecting the speed from 20-100% of its actual speed from rotor slot harmonics, and for the range below 30% of actual speed, an additional signal is given to machine from inverter for the production of rotor slot modulation [11]. *Beck and Naunin* published a conference paper presenting another approach for speed control of a sensorlessdrive or a squirrel cage induction machine [12]. In 1990, scientist *Williams* used rotor slot harmonics in stator current to detect the speed of an induction motor which is fed by an inverter using capacitor filters [13]. *Lorenz* and *Jansen* invented a method in which both rotor speed and rotor position can be detected with the help of extra hardware connected to the system. *Kubota* and *Matsuse* presented a paper [14] revealing the problem of identifying the rotor resistance and speed with the use of adaptive flux observer.

Now-a-days FOC has become so popular that it is commonly used in every application of AC machines. An AC motor can operate similar to a DC motor drive by decoupling of flux control and torque control without affecting the dynamic performance of a machine. Within this plan, a taco-generator (rotational transducer), a resolver or encoder, has fixed with the machine for the machine feedback. Like this, speed can be estimated and the feedback control is also achieved. But these speed sensors may decrease the reliability of the system and with these sensors the implementation become complicate and critical. Now-a-days sensor-less speed control drives are in use for industries.

FOC or vector control gives good performance with the control of speed, torque or position to be attained from an AC drive [1]-[3]. With this it can give an exact performance with an inverter fed drive (induction machine) which we get from the separately excited dc motor. *Marino et al* [15] showed that FOC provides decoupling control of rotor flux and the torque (producing current), with the minimum and maximum change in step torque. The maximum change in torque response can be achieved by calculating and measuring the position of rotor flux and magnitude of rotor flux in the AC machine. In indirect vector control, the calculation of flux position of rotor is depends on the rotor resistance parameters that can be identified through algorithms such as EKF (extended kalman filter), sliding mode, MRAS, leunberger observer can be used for the estimation of the resistance [1] [15]- [17].

Tamai et al. discovered an approach in which [18] the vector control or field oriented reference control is achieved through MRAS (Model Reference Adaptive System). MRAS scheme is used for the estimation of the rotor resistance using two models i.e. reference model and adjustable model that are used to estimate the resistance and the rotor speed. While estimating these two quantities both the systems will behave in different manner, one will be voltage model while other will be current model and the error produced by comparing these models will be minimized to zero using an adaptive controller. The adaptive controller proposed in the system will take the adaptive laws from the dynamic model of the machine which is based on the stator current. *R. Blasco-Gimenez et al.* [19] reported MRAS for the estimation of induction motor speed for measured terminal currents and voltages implemented on induction motor drive.

2.2.2 ADAPTIVE CONTROL

Adaptive systems can use proportional and integral controller, fuzzy logic controller, neural network controller, sliding mode controller or any artificial intelligent controller. The variables used in the adaptation mechanism are constant values in which a system lacks its excitation for steady state operating state, for the tuning of the estimation of resistance the system must be in transient state.

Bhim Singh and *Arunima Dey* presented artificial intelligent technique for three phase induction motor [20]. The controllability of speed and torque in an induction motor without any peak overshoot and less ripples with good steady state and transient response is the main criteria in designing a controller. Although, PI controller is able to achieve this but there exists certain drawbacks. The gain cannot be increased beyond a certain limit so as to have an improved response. It also introduces non linearity in the system making it complex for system and deteriorates the performance of the system. One of the intelligent controllers is the fuzzy logic controller, which uses fuzzy rules to improve the transient and dynamic response of the system and reduce the ripples in various parameters. *B.K. Bose et al*. [1], proposed a Neuro Fuzzy based stator flux oriented sensor-less direct vector controlled induction motor drive that operates at any speed in all four quadrants including the flux weakening region. The performances of fuzzy-logic-based indirect vector control for induction motor drive and it is compared with the conventional PI controller. FLC (Fuzzy Logic Controller) is more robust and, hence, can be replaced by conventional PI controller [21]-[23]. C.C. Lee. Stated to improve the controller's performance fuzzy logic can be used. Fuzzy controller does not need the precise plant model and hence, it is convenient to implement the fuzzy logic to complex process [29]-[30].

Increase in the development of vector control technology previously they had a very small impact on “variable speed” ac drives. Previously, simple voltage-source controlled inverters with adjustable output frequency are used for applications which require very less dynamic control, e.g. fans and pumps but now it has become more common that these machines can work in the closed-loop or in feedback loop with current-control techniques that use vector control systems. Current control is applicable to those voltage-source inverters, where it can reduce the over current tripping and improves inverter performance. In case inverters which are current controlled, more control actions are added to specify the slip frequency and magnitude of the incorporated current vector, and it can control the torque and flux of the motor.

M. Nashir Uddin et al presented the FLC based speed control loop for indirect vector controlled drive. The complete IM drive incorporating the FLC has been successfully implemented in real time using a DSP controller board DS1102 for the prototype 1-hp motor. In order to minimize the real-time computational burden, simple membership functions and rules have been used. Since exact system parameters are not required in the implementation of the proposed controller, the performance of the drive system is robust, stable, and insensitive to parameters and operating condition variations. In order to prove the superiority of the FLC, a conventional PI-controller-based IM drive system has also been simulated and experimentally implemented. The performance has been investigated at different dynamic operating conditions both theoretically and experimentally. It is concluded that the proposed. FLC has shown superior performances over the PI controller [31].

2.2.3 MODULATION TECHNIQUES

Hysteresis current control is preferred for induction motor drive as HCC is more compatible due its nonlinear nature like induction motor while SVPWM is linear and complex to analysis and design. The tutorial by *G. Narayanan* explained basics of SVPWM scheme and the switching sequence of SVPWM for voltage source inverter [32]. Hysteresis current control is widely used in active power filter's current control. *Jurifa Mat Lazi* et al presents the speed responses behavior of Dual Permanent Magnet Synchronous Motor (PMSM) driven base on two different PWM control schemes, which are Space Vector Pulse Width Modulation (SVPWM) and Hysteresis Current Controller. These two techniques are compared for wide range of speed and for variation of load [33]**.** *Yuan Deng-ke et al* explained the principle of novel SVPWM scheme first. Further the deduction, testification and simulation based on the MATLAB are given. Finally the novel SVPWM and the common SVPWM are implemented in the digital signal processor of TMS320LF2407. Simulation and experimental results show that the new SVPWM has less computation work and the same utilization of the dc link voltage as the common SVPWM. Besides the switching frequency of VSI can be easily optimized in the novel SVPWM [36].

O´ scar Lo´pez, et al presented multilevel multiphase space vector pulse width modulation algorithm for voltage source converters with low computational cost has been presented. It can be also used with classical three-phase topologies [41]. *Li Jun et al* stated principle of variable-band hysteresis current control, relationship between compensation capacity of hysteresis and switching frequency are given in this paper. Taking into account the fixed-band hysteresis current control, a control strategy based on command current and current error is proposed which is a variable-band current control strategy based on fuzzy rules and realized by fuzzy controller [42].

2.3 CONCLUSION

Most of the research papers are based on methods to improve the dynamic performance of the drive. Hence, scope of this research work is emphasized on the implementation of vector control scheme on an induction motor drive using two modulation schemes namely, HCC and SVPWM. Both these modulation schemes have some advantages and drawbacks over other.

CHAPTER 3

DYNAMIC MODELLING OF INDUCTION MACHINE

3.1 GENERAL

The induction motor dynamic model, frequently used in motor dynamic studies, is expressed by four voltage differential equations and one mechanical differential equation being very popular among the electrical machine researchers. The main goal of this chapter is to present a more comprehensive three-phase induction motor dynamic mathematical model including the skin effect, the temperature influence on the parameters and allowing for the stator and rotor winding and stator and rotor core average temperature evaluation. This model is useful for any type of motor dynamic studies mainly those including fast motor speed changings, intermittent loading and in case of motors fed from non-sinusoidal voltages contributing to the energy conservation and power quality subjects. To understand the induction machine and and its dynamic equation the knowledge of rotating magnetic field is necessary [1].

3.2 ROTATING MAGNETIC FIELD

The fundamental principle of operation of ac machine is based on the rotating magnetic field. Rotating magnetic field is responsible for the rotor motion according to the speed of rotation of magnetic field. When balanced poly-phase currents flow in balanced poly-phase windings, a rotating magnetic field is produced. In other words, all poly-phase ac machines are associated with rotating magnetic fields in their air-gaps. Consequently, knowledge of rotating magnetic field produced by a poly-phase winding is essential for understanding the poly-phase machine like poly-phase induction machine [2].

For a three-phase machine, the three windings are displaced from each other by 120 electrical space degrees along the air-gap periphery. Figure 3.1 (a) illustrates a 2-pole 3-phase stator winding. Note that each phase is distributed or spread over 60˚ electrical (called phase-spread) under each pole. For convenience, the three-phase winding a, b, c is represented by three full pitched coil aa', bb', cc', as illustrated in Figure 3.1 (b). For this instance, the concentrated full pitched coil aa' represents phase a winding in all respects. A current in phase a winding establishes magnetic flux directed along the magnetic axis of coil aa'. Positive currents are assumed to be flowing as indicated by crosses in coil-sides a', b', c'. It means that when phase a alone carries positive current, the flux produced by this phase is directed horizontally from left to right - if phase a current is negative, the flux produced is directed horizontally from right to left. The three-phase currents flowing in three-phase windings are varying sinusoidally with time. It should be noted that the resultant flux, in the air gap of a 3-phase machine, is due to the combined action of all the three-winding fluxes [3].

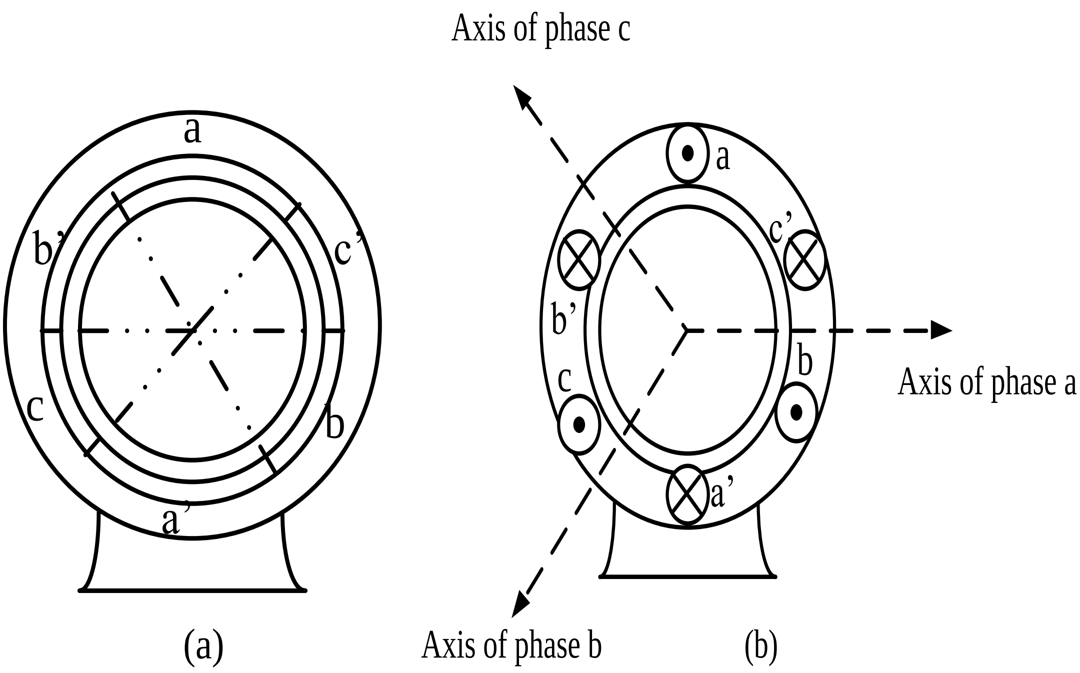

Figure.3.1.(a) 3-phase winding space displaced by 120 degrees electrical from each other, (b) 3-coils aa', bb', cc' represents three-phase winding

The sinusoidal current in any phase of an ac winding produces a pulsating mmf wave in space whose amplitude varies sinusoidally with time. So, three pulsating mmf waves are now set up in the airgap which have a time phase difference of 120° from each other. The resultant mmf is distributed in both space and time i.e. a travelling mmf wave with sinusoidal space distribution whose space phase angle changes linearly with time as ωt. It therefore, rotates in the air-gap at a constant speed of ω rad (elect.)/s.

The conclusion can be drawn from the above discussion as, whenever a balanced 3-phase winding with phases distributed in space so that the relative space angle between them is 120˚ rad(elect.) is fed with balanced 3-phase currents with relative time phase difference of 120˚ rad(elect.), the resultant mmf rotates in the air-gap at a speed of $\omega = 2\pi f$ elect. rad/s. where f is the frequency of currents in Hz. The direction of rotation of the mmf is from the leading phase axis towards lagging phase axis.

3.3 VOLTAGE AND FLUX LINKAGE EQUATION

For the dynamic analysis of the induction machine, the first mathematical model was based on the two real axis reference frame, developed initially by Park (1929) for the synchronous machine. Using the symmetric configuration of the induction machine, Kovacs and Racz (1959) have elaborated the space complex vector theory, and obtained a model for the steady-state analysis of the machine. Both theories are used for modelling the three-phase induction machine. The following assumptions are made when a complete equations system is written to describe the Continuous-time linear model of the induction machine (Krause et al. 1995):

- Symmetrical electrical machine configuration.
- Negligible space harmonics of the stator and rotor magnetic flux.
- Infinitely permeability;
- Sinusoidally distributed in space stator and rotor windings.
- Saliency effects, the slotting effects are neglected;
- Magnetic saturation, anisotropy effect, core loss and skin effect are negligible;
- Windings resistance and reactance do not vary with the temperature;
- Currents and voltages are sinusoidal terms.
- End and fringing effects are neglected

All these assumptions do not alter in a serious way the final result for a wide range of induction machines.

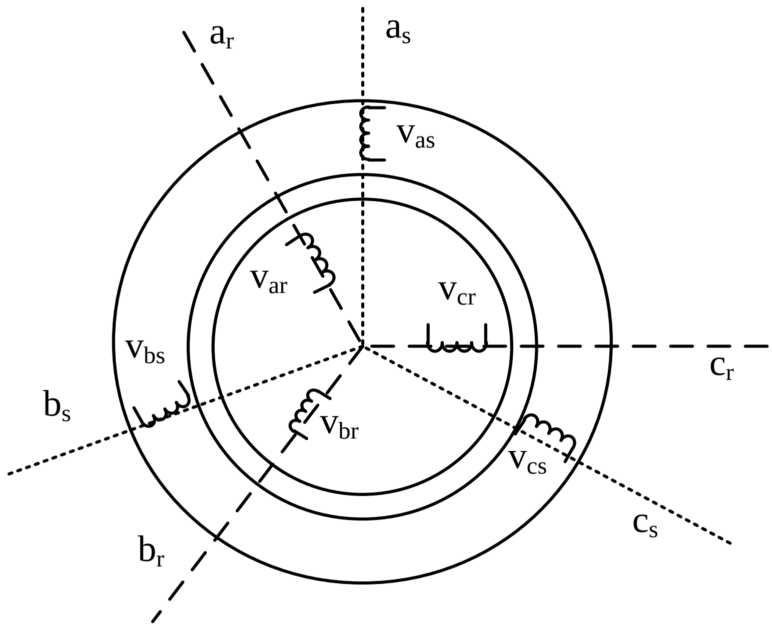

Figure 3.2 Induction motor with stator and rotor windings

Figure 3.2 show three uniformly distributed windings on both rotor and stator. when these three stator windings are excited by the three phase voltage displaced in time by 120˚ as shown by mathematical equations(3.1)- (3.3) as follows:

$$v_a = V_m \cos \omega t \tag{3.1}$$

$$v_b = V_m \cos (\omega t - 2\pi/3) \tag{3.2}$$

$$v_c = V_m \cos (\omega t - 4\pi/3) \tag{3.3}$$

Further these excitation voltages will cause three phase currents with phase difference of ‘Φ’ as follows:

$$i_a = I_m \cos (\omega t - \Phi) \tag{3.4}$$

$$i_b = I_m \cos (\omega t - 2\pi/3 - \Phi) \tag{3.5}$$

$$i_c = I_m \cos (\omega t - 4\pi/3 - \Phi) \tag{3.6}$$

At a particular instant of time as shown in Figure 3.2 where rotor axis is leading stator axis by an angle of θ_r , with consideration that machine is balance machine i.e. phase windings are identical. So, three resistances of stator as well as rotor are same, i.e for stator $r_s = r_{as} = r_{bs} = r_{cs}$ and for rotor $r_r = r_{ar} = r_{br} = r_{cr}$ the equation of induction machines are as follows :

For stator windings,

$$v_{as} = r_s i_{as} + p\Psi_{as} \quad (3.7)$$

$$v_{bs} = r_s i_{bs} + p\Psi_{bs} \quad (3.8)$$

$$v_{cs} = r_s i_{cs} + p\Psi_{cs} \quad (3.9)$$

For rotor windings,

$$v_{ar} = r_r i_{ar} + p\Psi_{ar} \quad (3.10)$$

$$v_{br} = r_r i_{br} + p\Psi_{br} \quad (3.11)$$

$$v_{cr} = r_r i_{cr} + p\Psi_{cr} \quad (3.12)$$

Where 'p' is the differential operator and 'Ψ' is the flux linkage to that particular winding. The flux linkage to the particular phase is arises due to the self-flux and the mutual flux. The self-flux arises due to the current flowing in itself and mutual flux arises due to current flowing in all the other systems present there i.e. all the other phase on stator as well as rotor. self-flux is nothing but the inductance multiply by current flowing through it, i.e. $\Psi_{self} = L_s I$.

For the induction machine the self-flux have two component, one is magnetizing inductance L_{ms} which is created by linkage magnetic flux and second is leakage inductance L_{ls} which is created by leakage magnetic flux. The expression for the mutual inductance can be written for a winding separation angle of δ as :

$$M_s = L_{ms} \cos\delta$$

Here winding is uniformly distributed, hence $\delta = 120^\circ$

$$M_s = -L_{ms}/2$$

So the mutual inductance between any 2 phases can be represented as

$$M_{ab} = M_{bc} = M_{ca} = -L_{ms}/2$$

Now, stator flux linkages can be expressed as

$$\Psi_{as} = L_s i_{as} + M_s i_{bs} + M_s i_{cs} + M_{sr} \cos\theta_r\, i_{ar} + M_{sr} \cos(\theta_r + 2\pi/3)\, i_{br} + M_{sr} (\cos(\theta_r + 2\pi/3)\, i_{cr} \quad (3.13)$$

$$\Psi_{bs} = M_s i_{as} + L_s i_{bs} + M_s i_{cs} + M_{sr} \cos(\theta_r - 2\pi/3)\, i_{ar} + M_{sr} \cos\theta_r\, i_{br} + M_{sr} (\cos(\theta_r + 2\pi/3)\, i_{cr} \quad (3.14)$$

$$\Psi_{cs} = M_s i_{as} + M_s i_{bs} + L_s i_{cs} + M_{sr} \cos(\theta_r + 2\pi/3)\, i_{ar} + M_{sr} (\cos(\theta_r - 2\pi/3)\, i_{br} + M_{sr} \cos\theta_r\, i_{cr} \quad (3.15)$$

Similar equations can be written for the rotor flux.

Making use of above inductance equation, the voltage equation can be write which are fairly long and system description is fairly complex with 6 variables on electrical side and one variable on mechanical side, makes it a 7 variable description. In order to simplify the machine description and make it more understandable and easily analytical for simulation purpose, the number of variables must be reduced by certain transforms [4].

3.4 AXES TRANSFORMATION

3.4.1 THREE-PHASE TO TWO-PHASE (a, b, c to α, β, 0) TRANSFORMATION

A symmetrical 3 phase 2-pole, windings on the rotor is represented by three coils A,B, C each of N effective turns and mutually displaced by 120 degrees. Figure 3.3(a) and (b) illustrate the balance 3-phase winding and 2-phase winding. Maximum values of magnetizing force Fa, Fb, Fc are shown along their axis-respective phases. The combined effect of these three mmfs results in a constant magnitude mmf, which rotates at a constant angular speed as mentioned in section 3.2.

In figure 3.3 (a) the three phase currents are written as

$$i_a = I_m \cos(\omega t) \tag{3.16}$$

$$i_b = I_m \cos(\omega t - 2\pi/3) \tag{3.17}$$

$$i_c = I_m \cos(\omega t - 4\pi/3) \tag{3.18}$$

Therefore, the resultant mmf of constant magnitude $3I_mN/2$ rotates with respect to three phase winding at the time frequency. The space phase angle between the windings must comply with the time-phase angle between the currents.

In Figure 3.3(b), balanced two-phase winding (α, β) are orthogonally placed on the rotor. For convenience in transformation, the axes of phase A and α are taken to be coincident. Then the two phase currents are given by

$$i_\alpha = I_m \cos(\omega t) \tag{3.19}$$

$$i_\beta = I_m \cos(\omega t - \pi/2) = I_m \sin(\omega t) \tag{3.20}$$

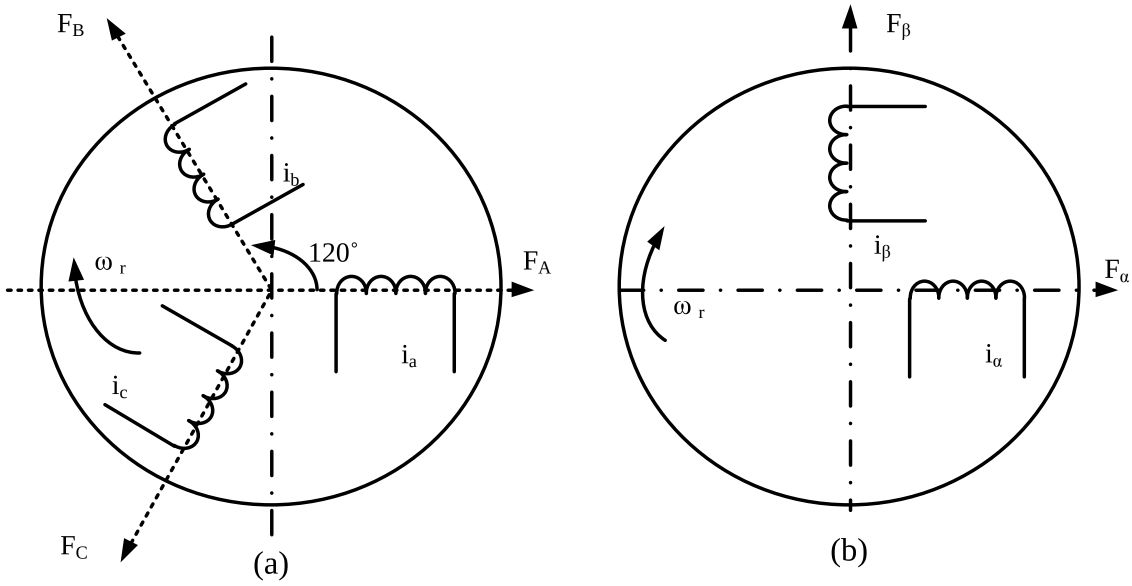

Figure 3.3 (a) Balanced 3-phase winding (b) 2-phase winding of the rotor

It is flowing in two windings, Therefore the resultant mmf of constant magnitude IN rotates with respect to two-phase winding at the time frequency of the phase currents. If the mmfs of three-phase and two-phase system are equal then the following modification can be made.

- By changing the magnitude of two phase currents
- By changing the number of turns of the two phase-phase windings
- BY changing both the magnitude of current and number of turns

The transformation equation giving the new currents i_α and i_β in terms of i_a, i_b and i_c cab be written in a matrix form as follows :

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3.21)$$

In equation (3.21), Transformation matrix consists of constants. Determinant of that constant matrix is a singular, so inverse of singular matrix does not exist. Hence we are introducing another set of constants (third equations) which does not involve energy conversion process in actual system like zero sequence components. So the equation (3.21) can be modified as

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.22}$$

Now the transformation matrix in equation (3.22) is non-singular and the inverse matrix can exist and this transform is known as **CLARKE'S** transform.

3.4.2 ROTATING AXIS (*α, β, 0*) TO STATIONARY AXIS (*d, q, 0*) TRANSFORMATION

When the transformation is carried out from rotating axis to stationary axis, the relative position of rotating axes varies with respect to stationary or fixed axis. In view of this, the matrix giving the transformation from rotating axis to stationary axis and vice versa, must contain coefficients which are functions of the relative position of the moving (*α, β*) and fixed (d,q) axis. The transformation from rotating to stationary axis results in replacing the moving coils by Pseudo-stationary coils shown in figure. 3.4 and this transform is popularly known as **PARK'S** transform [].

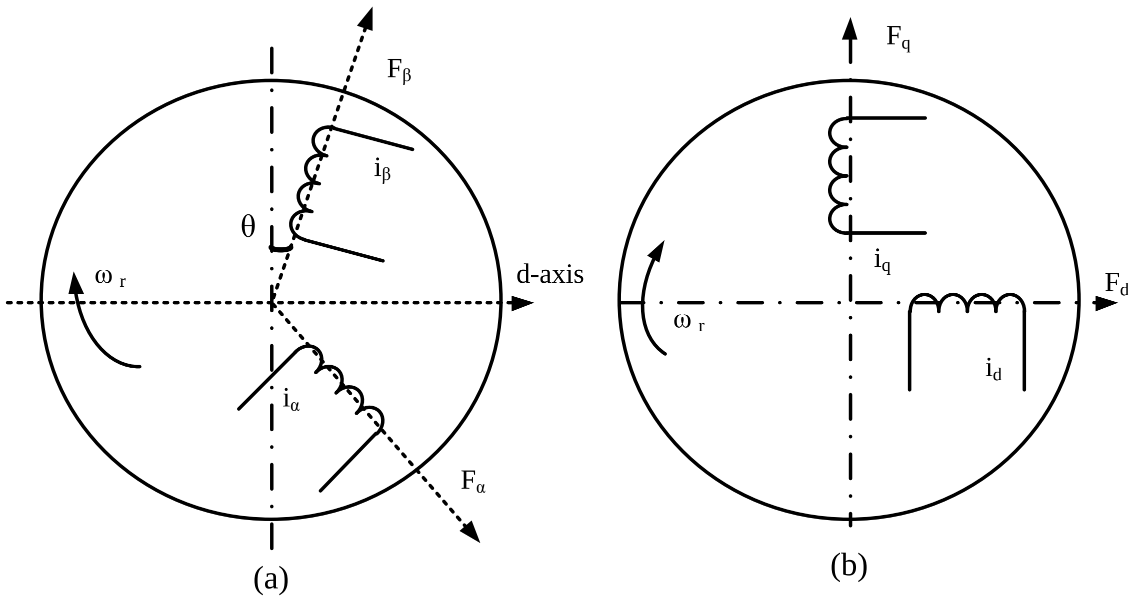

Figure 3.4. (a)Rotating axes *α, β* with rotating space phasors F_α and F_β (b) stationary axes *d,q* with stationary space phasors F_d and F_q

Zero sequence quantities are not transformed and thus the required is only from (*α, β)* to (*d, q)*. This transform can be expressed in matrix form as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.23}$$

If zero sequence current exist matrix can be modified as

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{3.24}$$

Using Eq. (3.22) and Eq. (3.24)

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.25}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos 0 & cos(\theta - 2\pi/3) & cos(\theta - 4\pi/3) \\ sin0 & sin(\theta - 2\pi/3) & sin(\theta - 4\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.26}$$

3.5 DYNAMIC *d-q* MODEL OF INDUCTION MOTOR

The per phase equivalent circuit of induction motor is only valid for steady state performance analysis but in variable speed operation of induction motor there is also need for transient performance. To study the transient performance, the dynamic d-q model of induction motor is used and to understand the vector control or field oriented control (discussed in chapter 4) the knowledge of d-q model is necessary. The dynamic circuit of induction machine is shown in figure 3.5.

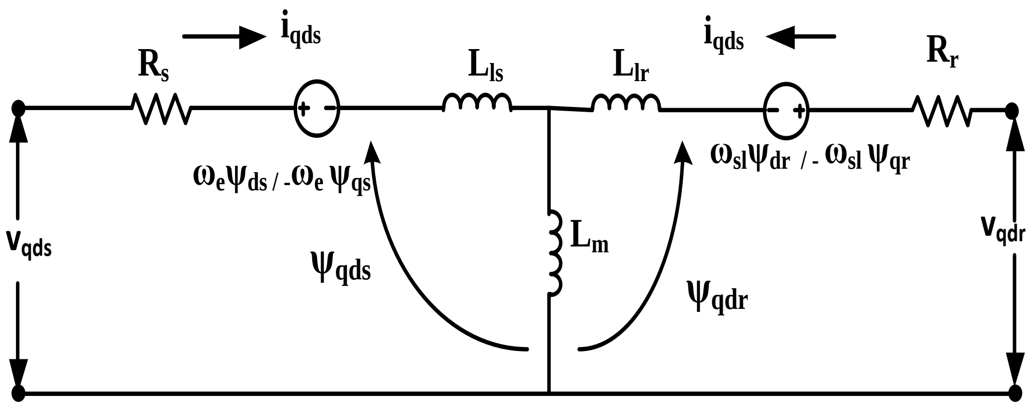

Figure 3.5 Dynamic *d-q* equivalent circuit of induction motor

Here, rotor and stator variables are transformed to synchronously rotating reference frame. Therefore, the stator voltages equations in $d^e - q^e$ frame are:

$$v_{qs} = i_{qs}R_s + \frac{d}{dt}\Psi_{qs} + \omega_e\Psi_{ds} \tag{3.27}$$

$$v_{qs} = i_{ds}R_s + \frac{d}{dt}\Psi_{ds} - \omega_e\Psi_{qs} \tag{3.28}$$

Similarly, rotor voltages equations in $d^e - q^e$ frame are, if rotor is rotating at an angular speed, ω_r, in the direction of rotating magnetic field:

$$v_{qr} = i_{qr}R_r + \frac{d}{dt}\Psi_{qr} + (\omega_e - \omega_r)\Psi_{dr} = 0 \tag{3.29}$$

$$v_{qr} = i_{dr}R_r + \frac{d}{dt}\Psi_{dr} + (\omega_e - \omega_r)\Psi_{qr} = 0 \tag{3.30}$$

The flux linkages can be written in terms of current and inductance:

From equations (3.27) - (3.30)

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & \omega_e L_s & sL_m & \omega_e L_m \\ -\omega_e L_s & R_s + sL_s & -\omega_e L_m & sL_m \\ sL_m & (\omega_e - \omega_r)L_m & R_r + sL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & sL_m & -(\omega_e - \omega_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{3.31}$$

Now, ω_r is a variable and it is related to electromagnetic torque, T_e, given by:

$$T_e - T_L = J\frac{d\omega_m}{dt} \tag{3.32}$$

In terms of electrical speed, the above equation can be given by:

$$T_e - T_L = \frac{2}{P}J\frac{d\omega_r}{dt} \tag{3.33}$$

The electromagnetic torque, T_e developed by the interaction of air gap flux Ψ_m and rotor MMF that is dependent on rotor current, I_r is expressed in vector form:

$$T_e = \frac{3}{2}\frac{P}{2}\bar{\Psi}_m \times \bar{I}_r \tag{3.34}$$

The vector variables can be revolved in $d^e - q^e$ components, according to figure 3.6:

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dm}i_{qr} - \Psi_{qm}i_{dr}\right) \tag{3.35}$$

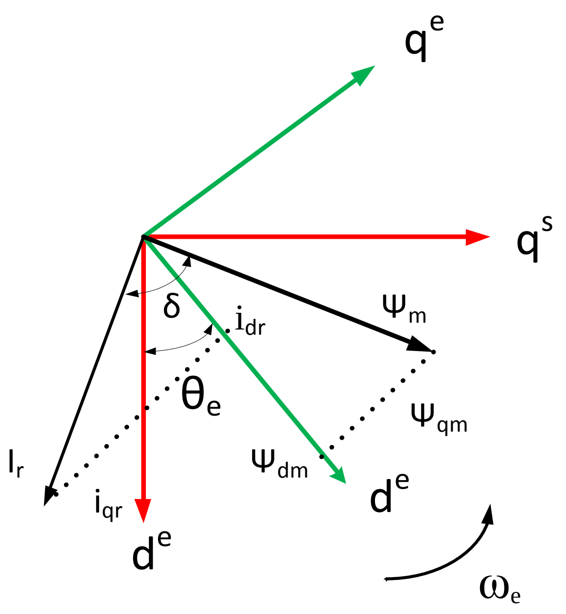

Figure 3.6 d^e-q^e reference frame

Similarly, other torque equations can also easily be derived as,

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dm} i_{qs} - \Psi_{qm} i_{ds}\right) \tag{3.36}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \tag{3.37}$$

$$T_e = \frac{3}{2}\frac{P}{2} L_m\left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{3.38}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\Psi_{dr} i_{qr} - \Psi_{qr} i_{dr}\right) \tag{3.39}$$

3.6 CONCLUSION

In this Chapter, the dynamic modeling of induction machine is discussed in details. In beginning, the discussion is based on the basic of principle of induction machine i.e the rotating magnetic field. This is followed by the different voltage and flux equation for rotor and stator and its complexity for analysis. Further to reduce the complexity Clarke’s and park’s transformation are discussed and finally dynamic d-q model of induction is derived. This will further help in design and analysis the Vector control of induction machine.

CHAPTER 4
VECTOR CONTROL OF INDUCTION MOTOR

4.1 GENERAL

For control induction motor drive numerous control strategies are employed having good steady state response but poor dynamic response due to the deviation of air gap flux linkage from its set value. This deviation is not only in magnitude but also in phase. This deviation of the linkage flux can be controlled by the magnitude and frequency of the rotor and the stator current and their instantaneous phases.

4.2 ANALYSIS OF VECTOR CONTROL

It is assumed that position of rotor flux linkage phasor Ψ is kown at certain field angle θ_s from a stationary frame. The stator currents can be transformed into q and d axis in the synchronous reference frames by using the transformation

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta s & \cos(\theta s - 2\pi/3) & \cos(\theta s - 4\pi/3) \\ \sin\theta s & \sin(\theta s - 2\pi/3) & \sin(\theta s - 4\pi/3) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.1}$$

Now stator current phasor is derived as $I_s = \sqrt{(i_{ds})^2 + (i_{qs})^2}$ and stator phase angle is $\theta_s = \tan^{-1}\left(\frac{I_{qs}}{I_{ds}}\right)$ where I_{qs} and I_{ds} are q and d axis current in synchronous d^e-q^e reference frames that are obtained by projecting the stator current phasor on the q and d axis respectively as shown in Fig 4.1. The current phasor I_s produces rotor flux linkage Ψ and torque. The component of current producing the rotor flux phasor has to be in phase with Ψ. The component I_f is the field producing component and the perpendicular component I_p is torque producing component. Under steady state conditions both I_f and I_p have only dc components because the relative speed with respect to the rotor field is zero. The rotor flux linkage Ψ is oriented towards synchronous reference frame hence flux and torque components are dc quantities. The main advantage of this method is computation and processing the dc sigals is easier [1].

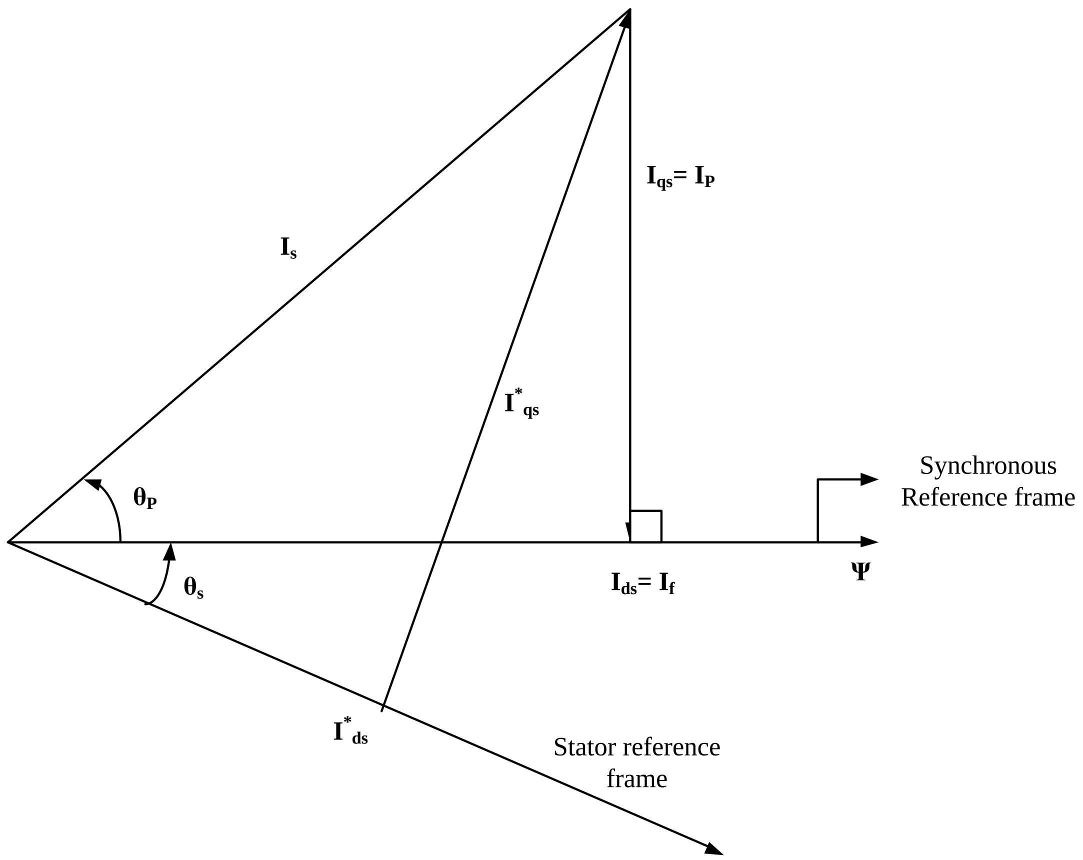

Figure 4.1 Phasor diagram of vector control

4.3 VECTOR CONTROL ALGORITHM

Following are the steps for the vector control algorithm:

1. Obtain the field angle.
2. Calculate the flux producing component of current I_f for a required rotor flux linkage Ψ. The rotor flux linkages are controlled by field current I_f. This is similar to dc machine where field current controls the field flux.
3. The required Torque from the rotor flux linkage Ψ is constant; hence controlling the torque producing component current gives independent control of electromagnetic torque T_e. This similar to field current is maintained constant in separately excited dc machine.
4. Calculate the stator current phasor magnitude I_s from the vector sum of I_p and I_f.
5. Obtain the torque angle from flux and torque producing components of stator current. $\theta_s = \tan^{-1}\left(\frac{I_P}{I_f}\right)$.
6. Add θ_P and θ_f to obtain stator phasor angle θ_s.

4.4 VECTOR CONTROL SCHEMES

Vector control technique is classified as:

1. Direct Vector control
2. Indirect Vector control

4.4.1 DIRECT VECTOR CONTROL SCHEME

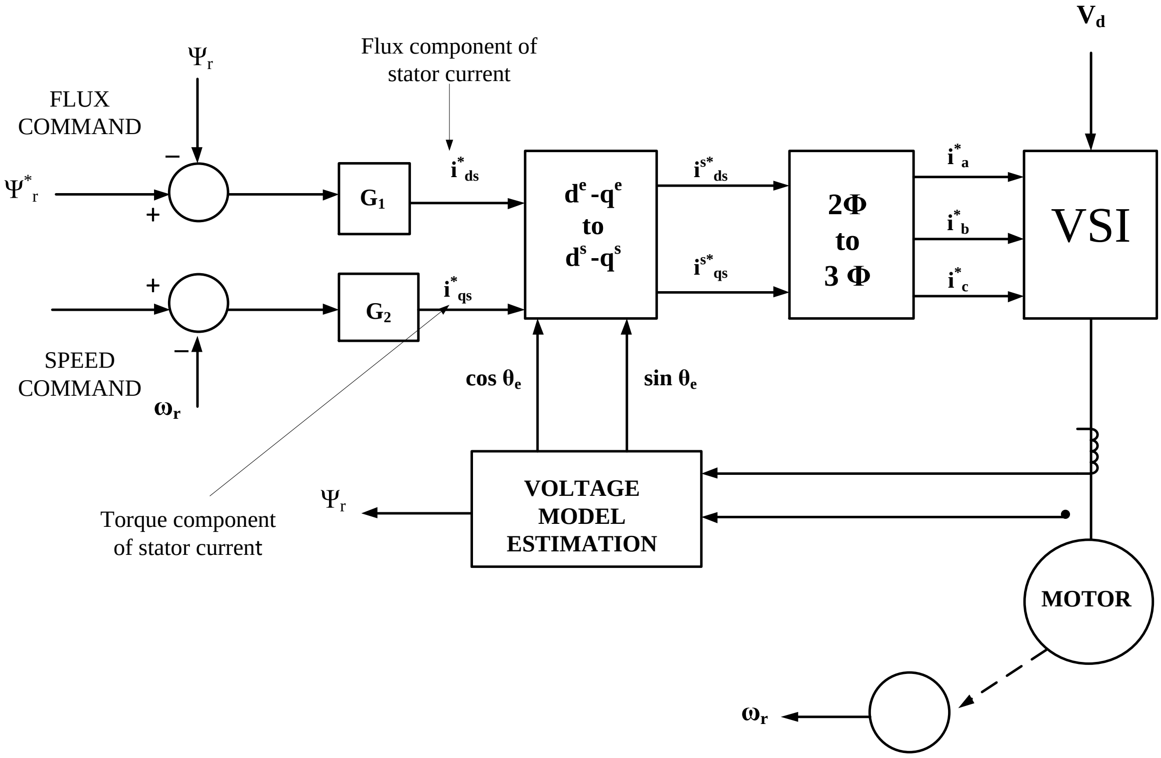

Figure 4.2 Direct vector control function block diagram with rotor flux orientation

The functional block diagram of this scheme with voltage source inverter is shown is Fig.4.2. The controls parameters are i_{ds}^{*} and i_{qs}^{*} which are dc quantities, in synchronously rotating frame and it is converted into stationary frame with vector rotation. With the generated unit vectors from flux signals Ψ_{dr}^{s}andΨ_{qr}^{s}, the resultant of a stationary reference signals are converted into current commands for inverter. Currents are generated from the voltage model of the machine and flux Ψ_{dr}^{s} and Ψ_{qr}^{s} are generated through machine voltage terminals. The current component i_{qs} is produce from speed control loop by a bipolar limiter. The torque component is proportional to current (i_{qs}^{*}) is also bipolar. The current i_{ds} is aligned in the direction of $\widehat{\Psi_r}$ flux and i_{qs} current is perpendicular to flux in vector control. Rotor flux vectors of stationary frame Ψ_{dr}^{s} and Ψ_{qr}^{s} are explained in figure 4.3. The frame d^e-q^e is rotating with synchronous speed ω_e w.r.t. the stationary frame d^s-q^s, the angular angle between the rotating frame and stationary frame is θ_e and θ_e is equal to ω_et. With the voltage model, the flux vector can be estimated from the machine model. Current and voltage can be observed and with that fluxes can be computed from the $d^s - q^s$ stationary frame of referenceThe following equations can be obtained using figure 4.3:

$$\Psi_{dr}^{s} = \widehat{\Psi}_r cos\,\theta_e \tag{4.2}$$

$$\Psi_{qr}^{s} = \widehat{\Psi}_r sin\,\theta_e \tag{4.3}$$

$$cos\,\theta_e = \frac{\Psi_{dr}^{s}}{\widehat{\Psi}_r} \tag{4.4}$$

$$sin\,\theta_e = \frac{\Psi_{qr}^{s}}{\widehat{\Psi}_r} \tag{4.5}$$

$$\widehat{\Psi}_r = \sqrt{{\Psi_{dr}^{s}}^2 + {\Psi_{qr}^{s}}^2} \tag{4.6}$$

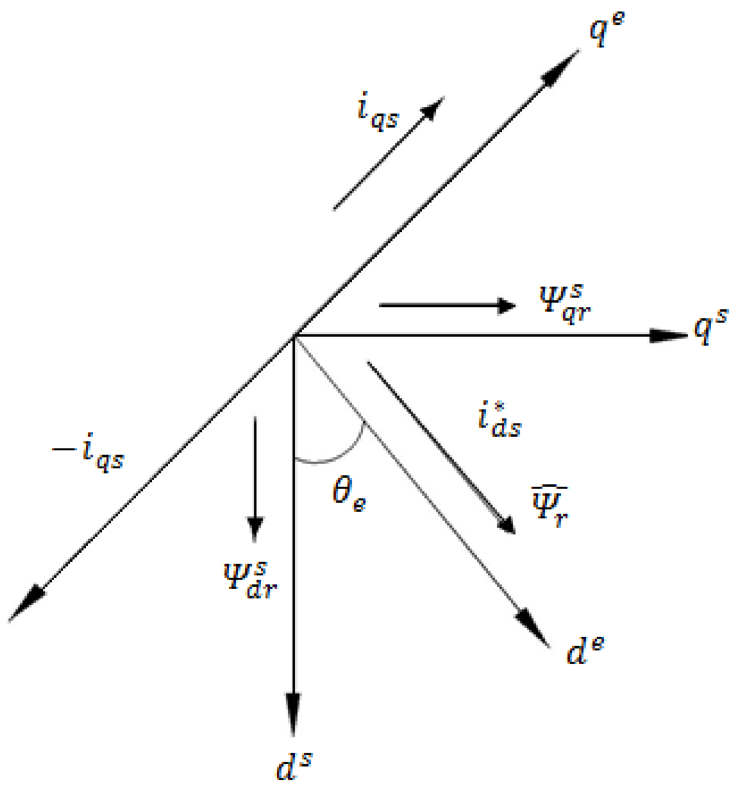

Figure 4.3 Rotor flux orientation in $d^e - q^e$ and $d^s - q^s$ phasors

$$\Psi_{ds}^{s} = \int (v_{ds}^{s} - R_s i_{ds}^{s})\mathrm{dt} \tag{4.9}$$

$$\Psi_{qs}^{s} = \int (v_{qs}^{s} - R_s i_{qs}^{s})\mathrm{dt} \tag{4.10}$$

$$\Psi_{r}^{s2} = \Psi_{dr}^{s\ 2} + \Psi_{dr}^{s\ 2} \tag{4.11}$$

4.4.2 INDIRECT VECTOR CONTROL SCHEME

The indirect vector control is same as direct vector control, the only difference is the unit vectors will be generated in feed forward control. This Indirect vector control is famous in industrial application [3]. The principle of indirect vector control can be explained through phasor diagram which is given below in the figure 4.4:

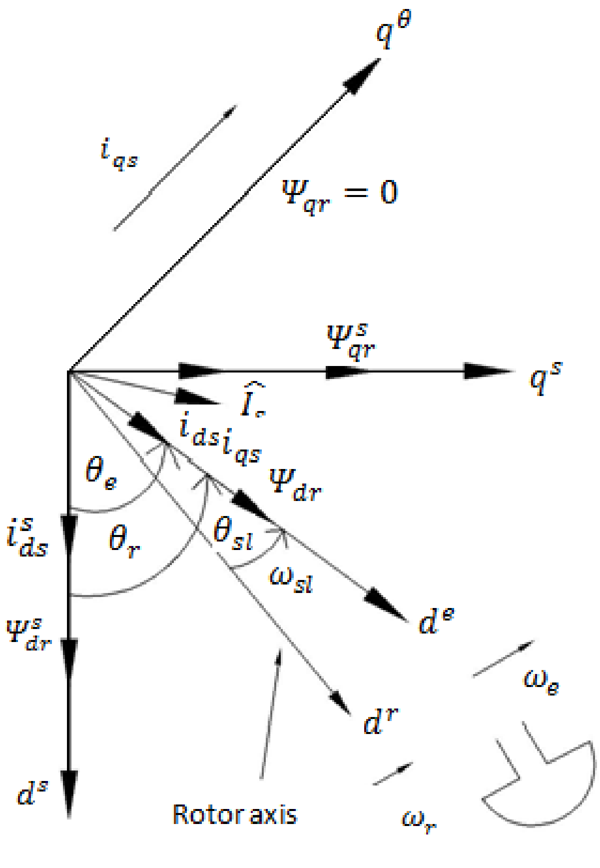

Figure 4.4 Phasor diagram of Indirect Vector Control

The stationary axis (d^{s}–q^{s}) is fixed on the stator terminals, and the rotating axis (d^{r}– q^{r}) is fixed on the rotor terminals and it is rotating at a speed ω_r and is shown in

Figure 44. In Synchronously rotating axes($d^{e}-q^{e}$) leads the rotating axis ($d^{r}-q^{r}$) by positive slip angle(θ_{sl}) analogous to slip frequency (ω_{sl}). Hence, the equation is:

$$\omega_e = \omega_r + \omega_{sl} \tag{4.7}$$

We can also write this equation:

$$\theta_e = \int \omega_e dt = \int \omega_r + \omega_{sl} dt = \theta_r + \theta_{sl} \tag{4.8}$$

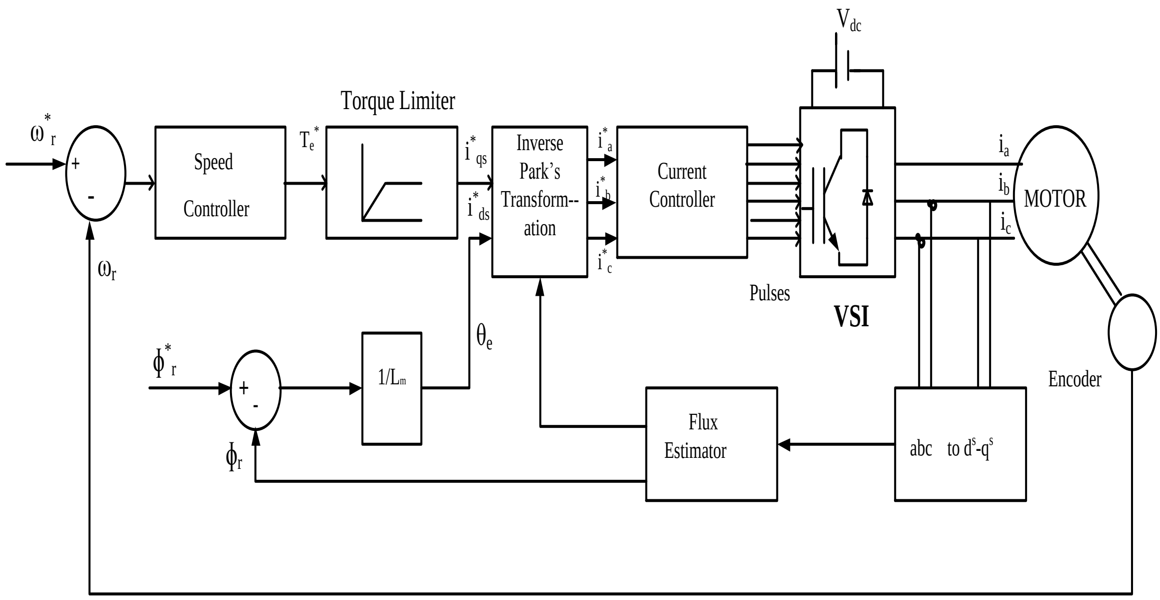

Figure 4.5 Functional block diagram of indirect vector control

The functional block diagram of indirect vector scheme is shown in figure 4.5.the process is similar to that of direct vector control. Flux estimator is used to estimate the actual rotor flux of the machine, from the machine model. Current and voltage can be observed and with that fluxes can be computed from the $d^{s}-q^{s}$ stationary frame of reference. The flux equations are:

$$\Psi^s_{dm} = \Psi^s_{ds} - L_{ls} i^s_{ds} = L_m(i^s_{ds} + i^s_{dr}) \tag{4.12}$$

$$\Psi^s_{qm} = \Psi^s_{qs} - L_{ls} i^s_{qs} = L_m(i^s_{qs} + i^s_{qr}) \tag{4.13}$$

$$\Psi^s_{dr} = L_m\, i^s_{ds} + L_r i^s_{dr} \tag{4.14}$$

$$\Psi^s_{qr} = L_m\, i^s_{qs} + L_r i^s_{qr} \tag{4.15}$$

By eliminating the currents i^s_{dr} and i^s_{qr} from the above equations (4.14) and (4.15) and with equations (4.12) and (4.13) we get:

$$\Psi^s_{dr} = \frac{L_r}{L_m}\Psi^s_{dm}\text{-}L_{lr}i^s_{ds} \tag{4.16}$$

$$\Psi^s_{qr} = \frac{L_r}{L_m}\Psi^s_{qm}\text{-}L_{lr}i^s_{qs} \tag{4.17}$$

We need to derive the control equations of indirect control for decoupling the circuit with the equivalent circuits, and the rotor equations are as follows:

$$\frac{d\Psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\Psi_{qr}=0 \tag{4.18}$$

$$\frac{d\Psi_{qr}}{dt} + R_r i_{qr} + (\omega_e - \omega_r)\Psi_{dr}=0 \tag{4.19}$$

The rotor flux equations are as follows:

$$\Psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds} \tag{4.20}$$

$$\Psi_{qr} = L_r\, i_{qr} + L_m\, i_{qs} \tag{4.21}$$

By arranging the above equation we can find currents:

$$i_{dr} =\frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r}i_{ds} \tag{4.22}$$

$$i_{qr} =\frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r}i_{qs} \tag{4.23}$$

Rotor currents can be eliminated from equations (4.18) and (4.19) using equation (4.22) and (4.23) are as follows:

$$\frac{d\Psi_{dr}}{dt}+\frac{R_r}{L_r}\Psi_{dr} - \frac{L_m}{L_r}R_r i_{ds} - \omega_{sl}\Psi_{qr} = 0 \tag{4.24}$$

$$\frac{d\Psi_{qr}}{dt}+\frac{R_r}{L_r}\Psi_{qr} - \frac{L_m}{L_r}R_r i_{qs} - \omega_{sl}\Psi_{dr} = 0 \tag{4.25}$$

Where $\omega_{sl}= \omega_e - \omega_r$

For decoupling control this condition is desired:

$\Psi_{qr} = 0$ and $\frac{d\Psi_{qr}}{dt} = 0$

Substituting the above conditions we get:

$$\frac{L_r}{R_r}\frac{d\widehat{\Psi}_r}{dt} + \widehat{\Psi_r} = L_m i_{ds} \tag{4.26}$$

$$\omega_{sl} = \frac{L_m R_r}{L_r \widehat{\Psi}_r} i_{qs} \tag{4.27}$$

$\widehat{\Psi_r} = \Psi_{dr}$ is substituted in above equation.

$$\widehat{\Psi_r} = L_m i_{ds} \tag{4.28}$$

This means that rotor flux $\widehat{\Psi_r}$ is directly proportional to i_{ds} current in steady state condition. These above equations are necessary to implement for the vector control implementation. In direct and indirect control, instant inverter current control is mandatory. Hysteresis based current control PWM inverters or Space vector PWM inverters are used.

4.5 FEATURES OF VECTOR CONTROL

1. In vector control the frequency(ω_e) of the machine is controlled not like a scalar control, the frequency and the phase are controlled directly with unit vectors.
2. In vector control, there is no stability problem, like scalar control in which crossing of operating point afar from the breakdown torque T_{em}. To limit the currents in its region it will automatically remain in the stable region.
3. In this it has a fast transient response similar to dc machine because the torque (controlled by i_{qs}) will not affect the flux.
4. Ideal vector control is a myth because of signal processing, variation in parameters and due to delays in the converter.
5. For low frequencies V_{ds}^s and V_{qs}^s voltage signals are low, now due to integrating problem arises in integrator output that dc offset will build up.

Variation in parameters will affect the resistance and inductance that will reduce the accuracy of the system and variation of temperature will dominate the parameters. But for higher voltages we can neglect variation in parameters.

4.6 CONCLUSION

Vector control is the principle of field orientation to realize dc motor characteristics in an induction motor drive. It offers a high level of dynamic performance and the closed-loop control associated with this drive provides the long term stability of the system.

CHAPTER 5

FUZZY LOGIC PRINCIPLE & CONTROLLER DESIGN

5.1` GENERAL

Fuzzy logic is a computing technique with is based on “degree of truth” unlike highly used digital computing Boolean logic which recognize only “true or false” (0 or 1) first .Fuzzy logic was implemented by Dr. Lotfi Zadeh of the University of California at Berkeley in the 1960s.Further fuzzy logic attracted different professional in the field of artificial intelligence as a new domain. Now days, use of Fuzzy logic is increased significantly in various applications. In this chapter we’ll discuss about the fuzzy sets, principle of fuzzy logic, Fuzzy logic tool-box and its use in MATLAB/SIMULINK environment.

5.2 FUZZY LOGIC

The fuzzy system is defined by using certain membership function having value between 0 to1. Where o indicated completely false statement while 1 indicate completely true statement and in between values describe the degree of trueness. However both fuzzy logic and probability operate between same range i.e. between 0 to 1 but there is difference between fuzzy logic and probabilistic approach. Probability tells about the chances of correctness of any statement or event while fuzzy logic yield the degree of membership in particular set.

5.3 FUZZY INFERENACING

The process of building a system using fuzzy logic is called fuzzy inferenacing. Fuzzy interfacing consists three major steps as shown in Figure.5.1 are as follows

1. Fuzzification
2. Rule evaluation
3. Defuzzification

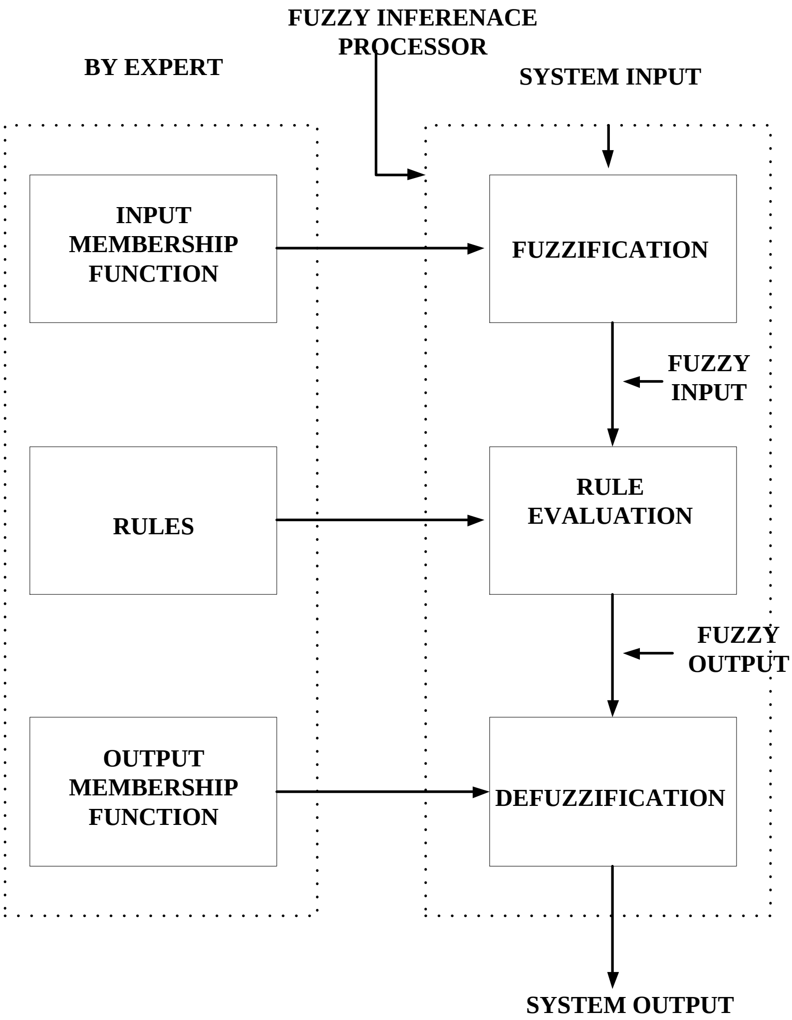

Figure 5.1 Fuzzy inference unit

5.3.1 FUZZIFICATION

The first step of fuzzy inferencing is fuzzification in which crisp inputs are transformed into corresponding fuzzy inputs using different membership functions. The crisp input is exact input measured using sensors and passed into control unit for further processing. Examples of crisp inputs are speed, pressure, temperature etc. Each crisp input that is to be processed by the FIU has its own group of membership functions or sets to which they are transformed. This group of membership functions exists within a universe of discourse that holds all relevant values that the crisp input can possess. The membership function structure within universe of discourse is consisting of following terms:

1. *Degree of membership*: it is also known as fuzzy input and it describes the trueness having range in between 0 to 1.
2. *Membership function*: It is defined by mapping crisp input into a fuzzy set according to the degree of membership.
3. *Crisp input* : it is exact measured input from the system e.g. speed=1400 rpm.
4. *Label*: To identify the membership function, certain names are used they are known as labels.it must be indicated initially for every membership function.
5. *Scope:* It describes the width of the membership function. It is also known as domain.
6. *Universe of discourse:* it defines all possible values in a set.

A variable is represented in fuzzy system by the shape of the membership function as per available computing resource. If the shape of shape of membership function is too complex then it requires large look up table or complex equations for description. Few shapes are shown in Figure. 5.2.

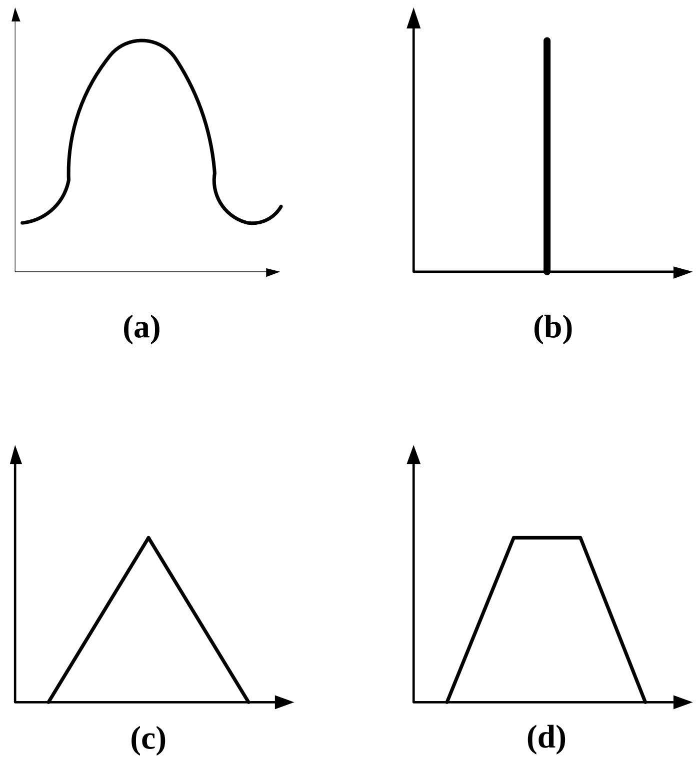

Figure 5.2 Different shapes of membership functions (a) Bell (b) Single-tone (c) Triangular (d) Trapizoidal

The number of membership function to define certain fuzzy system should be optimum. Fewer membership functions make system a bit sluggish and oscillatory while the higher number of membership function will cause the system instability due to large change in out for small input change.

There should be some overlap between membership function else it will be like a Boolean function. Every input point on the universe of discourse should belong to the scope of at least one but no more than two membership functions. No two membership functions should have the same point of maximum truth, When two membership functions overlap, the sum of truths or grades for any point within the overlap should be less than or equal to 1. Overlap should not cross the point of maximal truth of either membership function. Quantitatively, overlap of membership function can be described by two indices as proposed by *Marsh*. These are overlap ratio and overlap robustness.

Overlap Ratio = (Overlap scope) / (Adjacent MF Scope)

Overlap Robustness = (area of summed overlap / (maximum area of summed overlap)

$$= \frac{\int_{L}^{U} (\mu_1 + \mu_2)\, dx}{2(U - L)}$$

5.3.2 RULE EVALUATION

Rule evaluation is the process to apply the input to a set consisting of IF-THEN rule.e.g.

IF temperature is very cool *THEN* turn off the air conditioner.

In general syntax for these rules are as follows:

IF antecedent-1 *ZADEH OPERATOR* antecedent-2 THEN consequent-1 *ZADEH OPERATOR* consequent-2.

The antecedent consists of input variable while the consequent consist of output variable. Zadeh operator act as a connecting link between two antecedent or two consequent. There are three main types of Zadeh operator AND, OR, NOT.

AND represents the intersection between the two sets. It is expressed as:

$$\mu_{A\cap B} = \min [\mu_A (x), \mu_B (x)]$$

OR represents the union between the two sets. It is expressed as:

$$\mu_{AUB} = \max [\mu_A (x), \mu_B (x)]$$

NOT represents the compliment of a set. It is expressed as:

$$\mu_A{'} = [1-\mu_A (x)]$$

5.3.3 DEFUZZIFICATION

Defuzzification involves transforming the fuzzy output into the crisp or the system output. There are many method for defuzzification. Some of the defuzzification techniques are as following.

- AI (adaptive integration)
- BADD (basic defuzzification distributions)
- BOA (bisector of area)
- CDD (constraint decision defuzzification)
- COA (center of area)
- COG (center of gravity)
- ECOA (extended center of area)
- EQM (extended quality method)
- FCD (fuzzy clustering defuzzification)
- FM (fuzzy mean)
- FOM (first of maximum)
- GLSD (generalized level set defuzzification)
- ICOG (indexed center of gravity)
- IV (influence value)
- LOM (last of maximum)
- MeOM (mean of maxima)
- MOM (middle of maximum)
- QM (quality method)

- RCOM (random choice of maximum)
- SLIDE (semi-linear defuzzification)
- WFM (weighted fuzzy mean)

In this thesis for controller design only center of gravity is used. So, here discussion is limited to center of gravity only. The center of gravity method is averaging method in which centroid of sets are calculated. Mathematically crisp output can be transformed from the fuzzy output using equation 5.1.

$$\text{Crisp output [Y]} = \frac{\sum(fuzzy\ output)\ X\ (weight\ of\ membeship\ function\ )}{\sum(fuzzy\ output)} \tag{5.1}$$

5.4 DESIGN OF FUZZY LOGIC CONTROLLER

Traditionally motor controller have fixed gain like proportional-integral (PI) but this fixed gain controllers have certain issues with disturbances in load, change in parameters and they also require the exact mathematical modeling for the IM but due to many reasons including temperature variation, saturation, system disturbances designing exact dynamic model of induction motor is not feasible, to overcome this issue Fuzzy Logic Controller (FLC) is used using certain rule base. FLC is based on plant operator experience and heuristics. It is nonlinear and adaptive control scheme with ease in implementation.

In the FLC there are two input linguistic variables one is change in speed error e= ω_r^*- ω_r and second is rate of change in speed error C_e = $\frac{de}{dt}$ and reference toque producing component of current i_q^* as its output. Where ω_r^* is reference rotor speed in rad/sec. Figure 5.3 show the internal structure of FLC.

Where these input linguistic variables undergo fuzzification and defuzzification according to the rule base and mamdani-type fuzzy interface mechanism. FLC tracks the reference speed which generates the suitable i_q^* depending upon operating conditions. To restrict the linguistic variable within -1 to +1 range, scaling factors are used depending upon the reference speed and rated current. After selecting the suitable scaling factors, membership functions are created as shown in igure 5.4. For avoiding complex computation only trapezoidal and triangular membership functions are used.

In this study, For FLC based IM drive certain rules are defined which are created by trial and error to get the optimum performance of machine. Based on these rules the fuzzy-rule-base-matrix is designed shown in Table 5.1. For defuzzification center of gravity method is used.

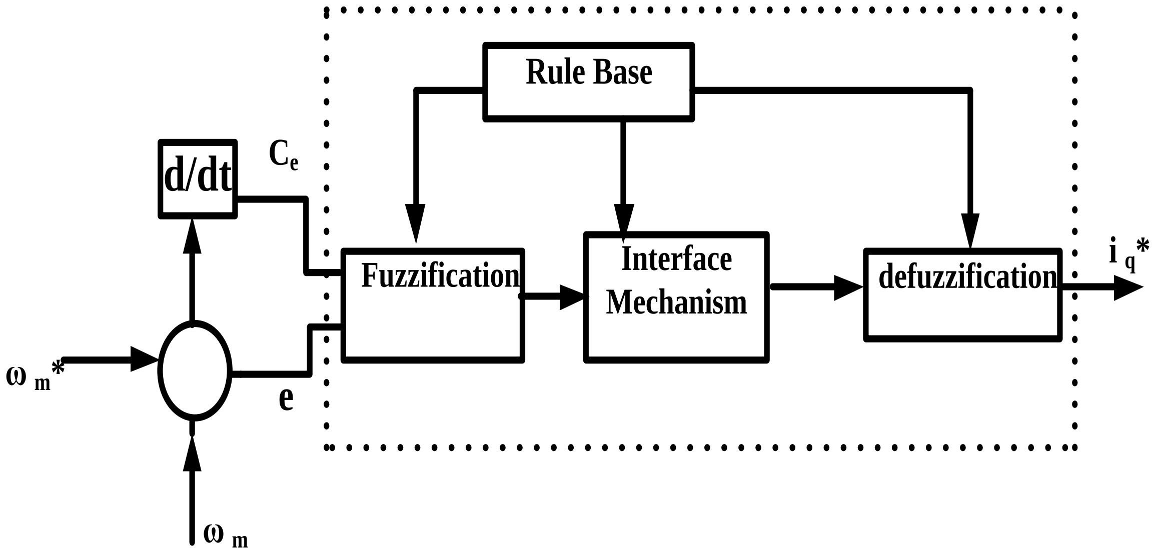

Figure.5.3. Fuzzy logic controller internal structure

RULE BASE :

1. If δ is PH then I_{qref} is PH
2. If ω is PL then I_{qref} is PM
3. If ω is zero and δω is PE then I_{qref} is PL
4. If ω is zero and δω is NE then I_{qref} is NC
5. If ω is zero and δω is zero then I_{qref} is NC
6. If ω is NL then Iqref is NL
7. If ω is NH then I_{qref} is NH

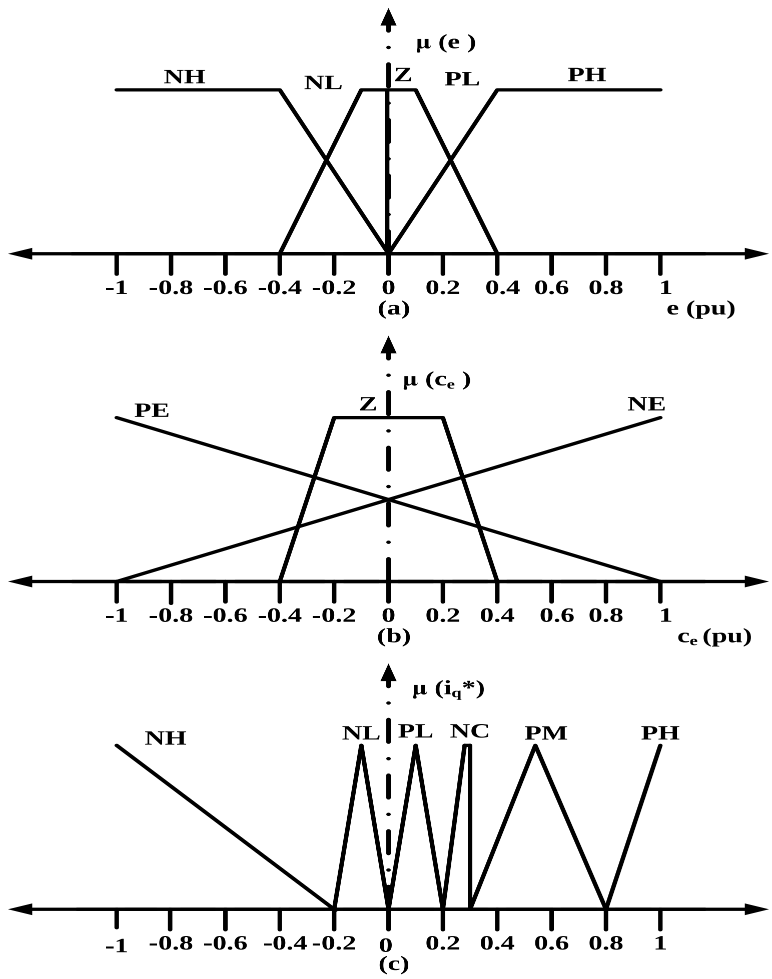

Figure.5.4. Membership function of fuzzy variable (a) speed error μ (Ce) (b) Change in speed error (c) q-axis reference current i_q^*

Table 5.1 Fuzzy rule base matrix

E / C_e	**NH**	**NL**	**Z**	**PL**	**PH**
NE	NH	NL	NC	PM	PH
Z	NH	NL	NC	PM	PH
PE	NH	NL	PL	PM	PH

To design fuzzy logic controller (FLC) as a speed controller in MATLAB/SIMULINK, GUI based fuzzy logic toolbox is used.For implementation of FLC block fuzzy inference system (FIS) is used in Simulink as shown in Figure 5.5.

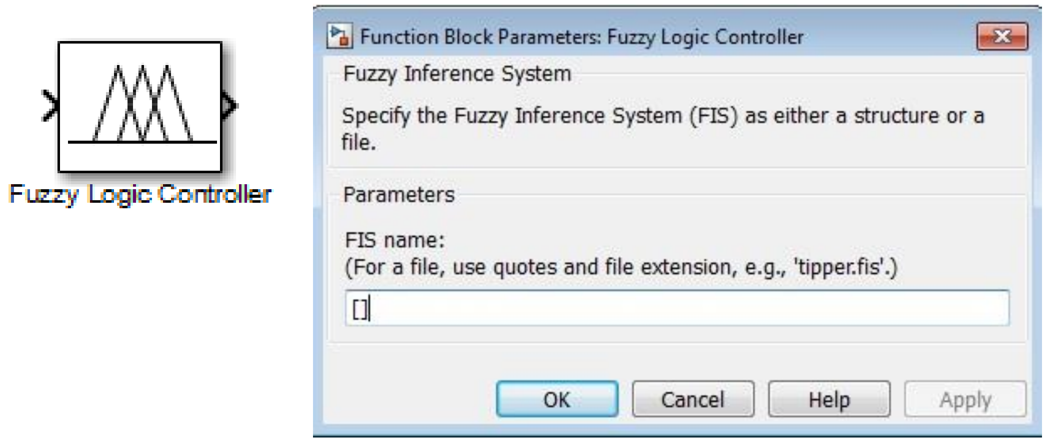

Figure 5.5 MATLAB Fuzzy inference system

FIS name

Specify the FIS as one of the following:

- Structure — Specify the name of the FIS structure variable. For example, fismat.
- File — Specify the file name in quotes and include the file extension. For example, ‘indirect.fis' .

The file contains the rules for particular fuzzy system (in our case its for speed control).as mentioned above The need to export from its location to the workspace before using it in FIS. Rules can also viewed in the MATLAB. Figure 5.6 show the rule base for fuzzy logic speed controller as mentioned in this thesis.

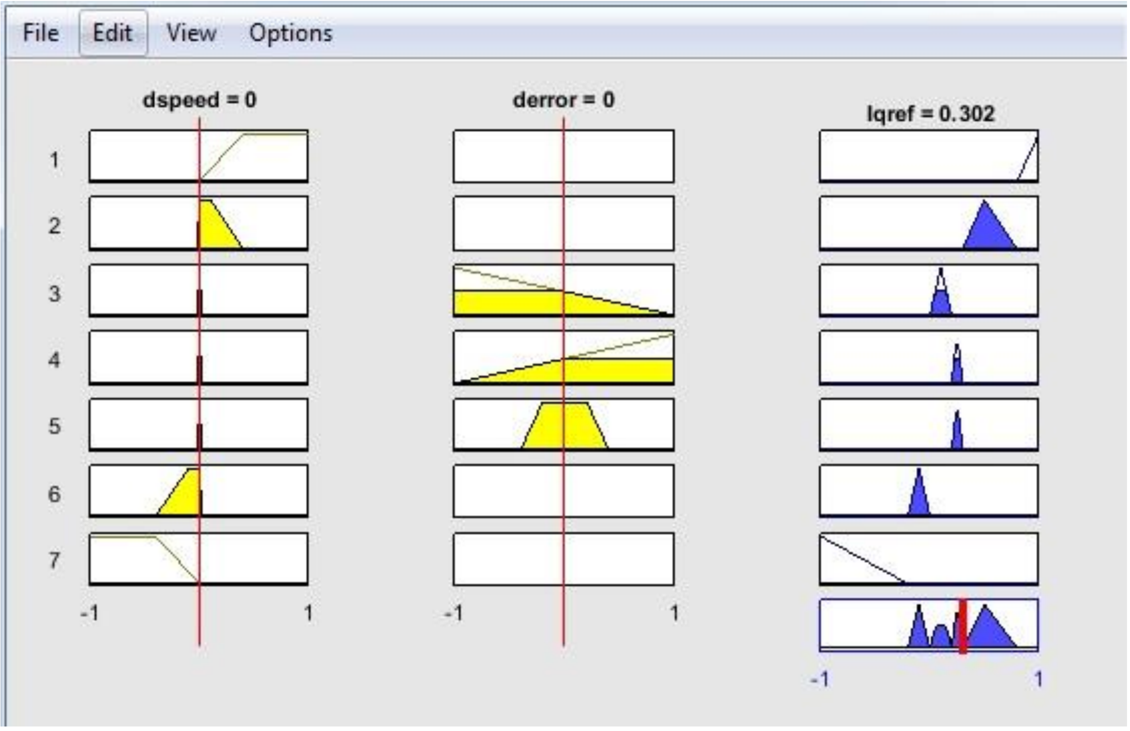

Figure 5.6 Fuzzy logic rule base in MATLAB/SIMULINK

5.5 CONCLUSION

This chapter broadly discusses the fuzzy logic principle and its application as fuzzy logic controller. The analogy and the difference between boolean and fuzzy logic is explained briefly. The principle steps of fuzzy inference system were explained mainly related to its operation. To avoid the effect of parameter variation fuzzy logic controller is used. By using fuzzy logic tool box in MATLAB/SIMULINK environment fuzzy logic controller is designed for vector controlled induction motor drive.

CHAPTER 6

MODULATION TECHNIQUES

6.1 GENERAL

In order to generate gate pulses for DC voltage fed three phase voltage source inverter (VSI) modulation techniques are used. These modulation techniques are also used control the output voltage of the inverter varying the gate pulse to the inverter according to desirable inverter output voltage. These modulation techniques can be either voltage control based or current control based. Voltage control techniques can be divided into three types of Pulse width Modulation (PWM). First is six steps PWM, second is sinusoidal PWM, and third is SVPWM while current control techniques can be divided into two types HCC and Delta Modulation. The SVPWM and HCC are most commonly used techniques. The HCC is most applied nonlinear control technique due to simple implementation, low software requirement, high reliability, less tracking error and excellent dynamic response. However it also has some drawbacks like uncontrolled operating frequency which gives non-optimum ripples generation, rough operation due to randomness, high switching losses and bad compensation performance at zero crossing and low utilization of DC link. SVPWM is advanced, linear modulation scheme which is computationally intensive with wide range of fundamental voltage. SVPWM also solve the neutral point unbalance problem.

6.2 HYSTERESIS CURRENT CONTROLLER

Hysteresis current control is implemented by comparing reference current (i*) and actual current (i) and then the actual current wave form is forced to follow the reference current and accordingly the gate pulse are generated and the inverter switches are updated shown in Figure 6.1.This process is applied simultaneously on all the three phases and each three phase reference currents (i_{abc}*) are compared with actual supply current i_{abc} to generated the six gate pulses. Error between two will be pass through comparator with suitable hysteresis band to restrict the current as close as possible to the actual value. The hysteresis band decides the peak to peak current ripple and the switching frequency. Figure 6.1 shows the block diagram for instantaneous current control. As the current exceeded the prescribed hysteresis band value the upper switch turns off and lower switch turns on during fall time t_f. Due to this output voltage falls to lower saturation value from the upper saturation value which results in decay in current. To avoid the shoot through fault at every transition there is provision for lock out time t_d which led to track the actual sinusoidal current waveform within hysteresis band (HB). HB is defined mathematically as

$$HB = V(R_1/R_1+R_2) \tag{6.1}$$

Where V is comparator biased voltage. Figure 6.2 shows the switching conditions as follows:

If (i*- i) > HB : Upper switch turn on

If (i*- i) < HB : Lower switch turn on

For optimum dynamic performance there must be balance between switching frequency and the current ripples e.g. for smaller hysteresis band switching frequency is high and lower current ripples.

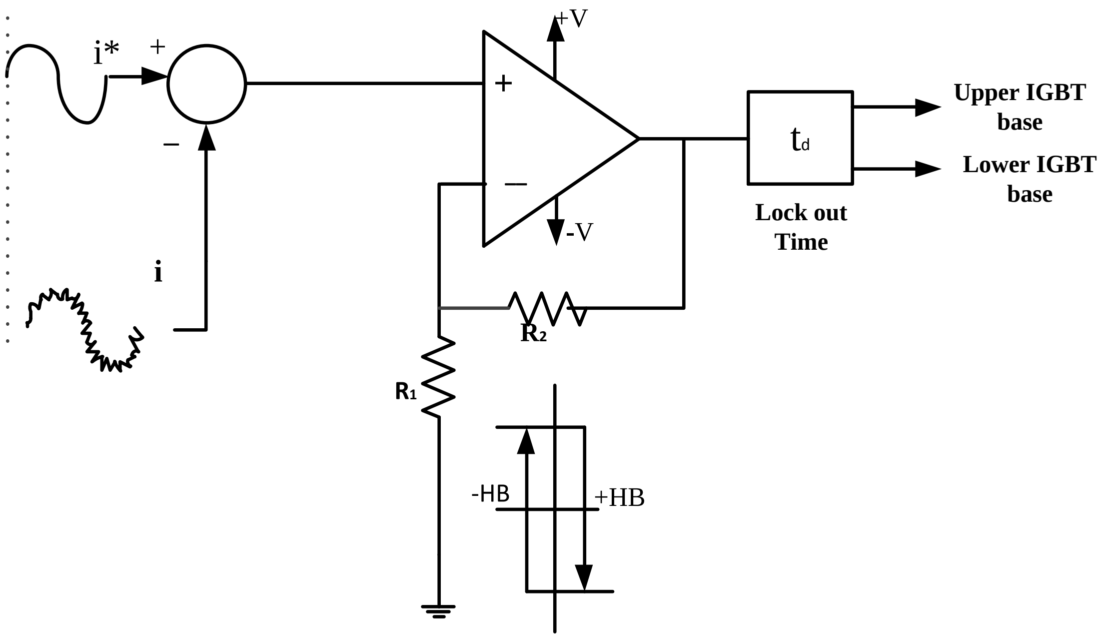

Figure 6.1 Block diagram for instantaneous hysteresis current control

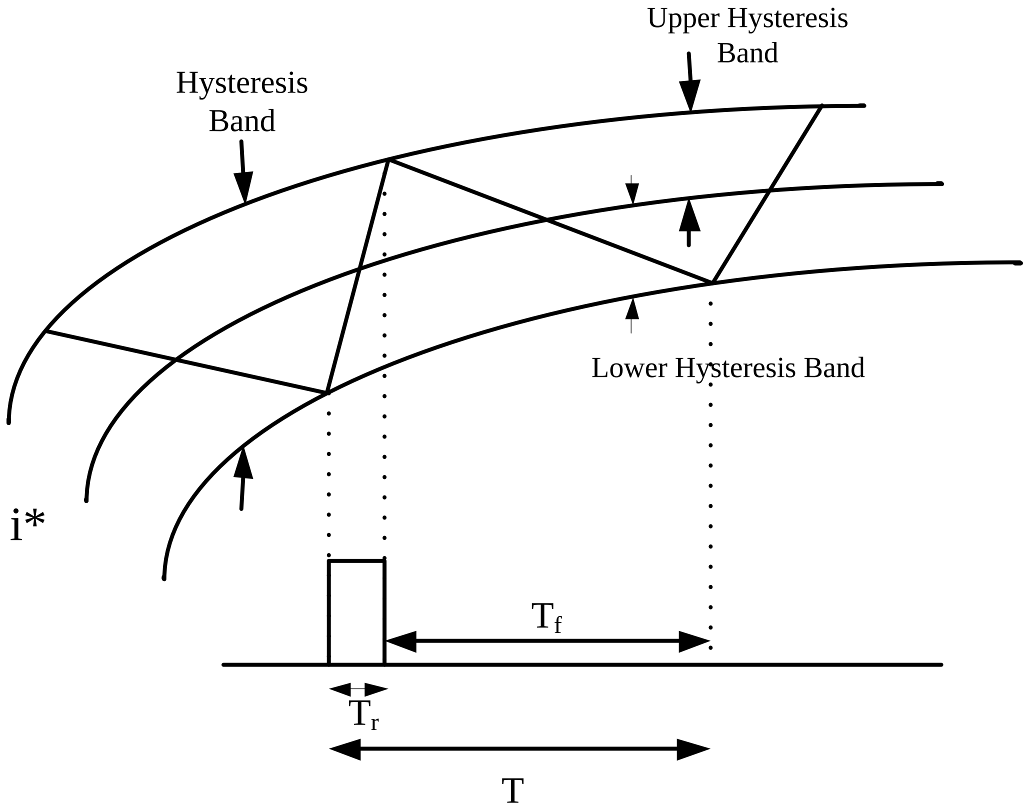

Figure 6.2 Principle of hysteresis-band current control

6.3 SPACE VECTOR PULSE WIDTH MODULATION (SVPWM)

When the three phase sinusoidal voltages fed to three phase winding the revolving mmf is produced, this revolving mmf is an example of a space vector. As mmf is in single plane then it can be resolve in two perpendicular components along with α-β axis. Similarly the three phase voltages can be resolve into two phase voltage using space vector transform.

For the implementation of SVM algorithm some rules are implemented such as:

1. The output voltage lies in the trajectory which should be circular.
2. There should be only one switching per transition.
3. Only three switching's are allowed in single modulation period.
4. The output of one sample must be input of next sample.

Number of switching states will be in limit with these rules. Hence, there will be reduction in switching losses. They keep symmetry in switching signals at the inverter output to attain the low Total Harmonic Distortion (THD). The SVM algorithm, with these switching rules is known as Conventional SVM.

The SVM approach consists of these steps shown below:

1. Sector identification
2. Space vector decays into directions of base vectors.
3. Estimation of PWM duty cycle

For balanced star connected load it can be shown mathematically as : ,

$$V_{\alpha} = V_{RN} + V_{YN}\cos 30^{\circ} + V_{BN}\cos 240^{\circ} = \frac{3}{2} V_{RN} \qquad (6.2)$$

$$V_{\beta} = V_{YN}\cos 30^{\circ} + V_{BN}\cos 150^{\circ} = \frac{\sqrt{3}}{2}(V_{YN} - V_{BN}) \qquad (6.3)$$

Where V_{RN}, V_{YN}, V_{BN} are phase to neutral voltage of RYB phase respectively. The pole voltages V_{RO},V_{YO},V_{BO} are given as +0.5Vdc and -0.5 V_{dc} depending upon upper and lower switch positions respectively. The voltage vectors can be represented in term of pole voltage as

$$V_{\alpha} = \frac{1}{2}(2V_{RO} - V_{YO} - V_{BO}) \qquad (6.4)$$

$$V_{\beta} = \frac{\sqrt{3}}{2}(V_{YO} - V_{BO}) \qquad (6.5)$$

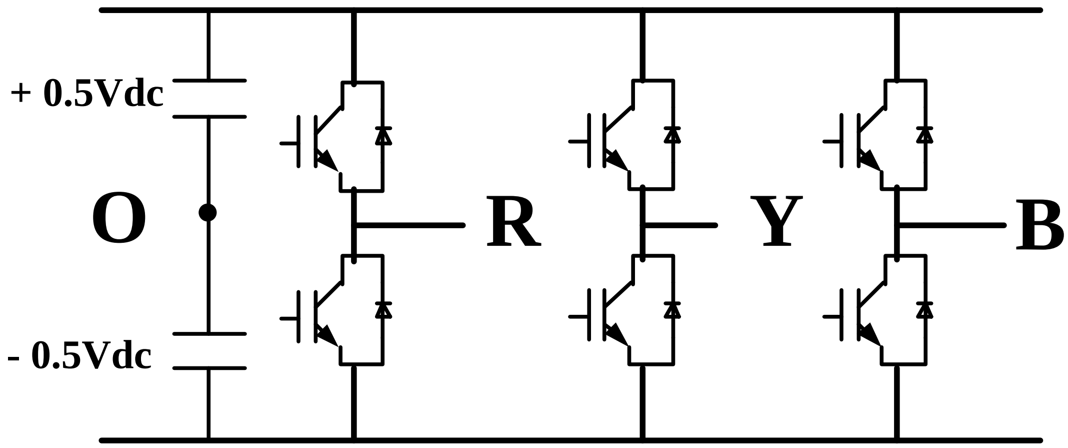

Figure 6.3 Circuit diagram of three phase voltage source inverter

It produces six different vectors, known as active states as shown in figure 6.4. it also produce two cases where vector produce is a null vector when either all the upper switches are ON or all the lower switches are ON in the figure 6.3.

Three phase sinusoidal voltage modulating signal get transformed into revolving voltage vector with a constants magnitude and angular frequency. In SVPWM, a revolving voltage vector is used as reference voltage V_{REF}, sampled at every sub cycle T_s. Further vector space can be divided into 6 sectors I to VI. Let the reference voltage vector is in sector I shown in figure 6.5 The following mathematical equations are used to calculate the dwell times T_1,T_2,T_Z for which two active vectors and null vectors are applied.

$$V_{REF}\,T_s = V_1\,T_1 + V_2\,T_2 + V_Z\,T_Z \tag{6.6}$$

$$Ts = T1 + T_2 + T_Z \tag{6.7}$$

$$T_1 = \frac{V_{REF}\ \sin(60^\circ - \theta)}{Vdc\,\sin(60^\circ)}\,Ts \tag{6.8}$$

$$T_2 = \frac{V_{REF}\ \sin(\theta)}{Vdc\,\sin(60^\circ)}\,Ts \tag{6.9}$$

$$T_Z = Ts - T1 - T_2 \tag{6.10}$$

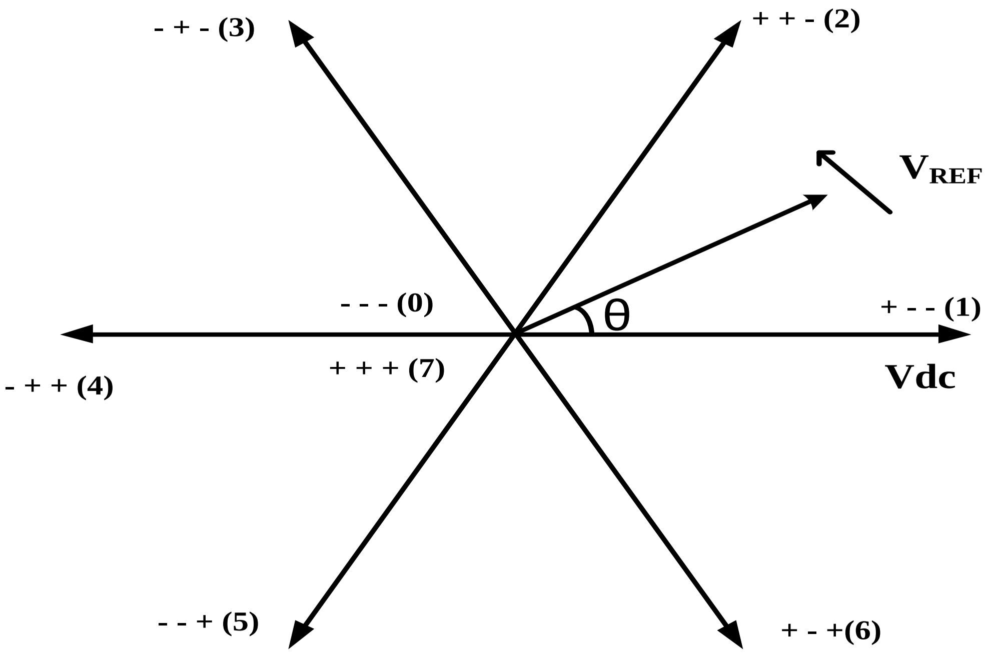

Figure 6.4 Space vector orientations

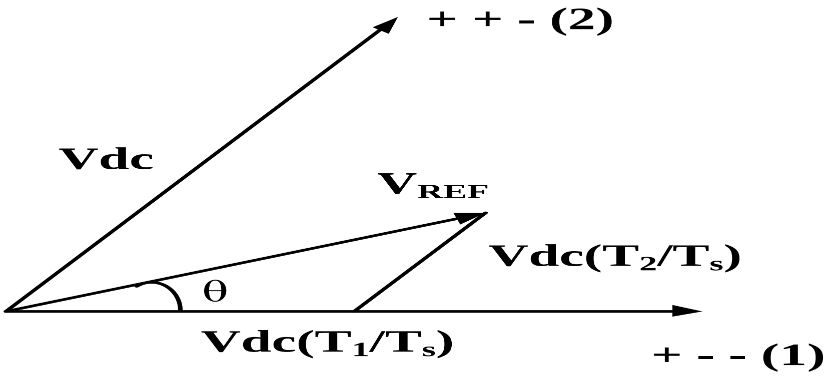

Figure 6.5 Sector I vector space

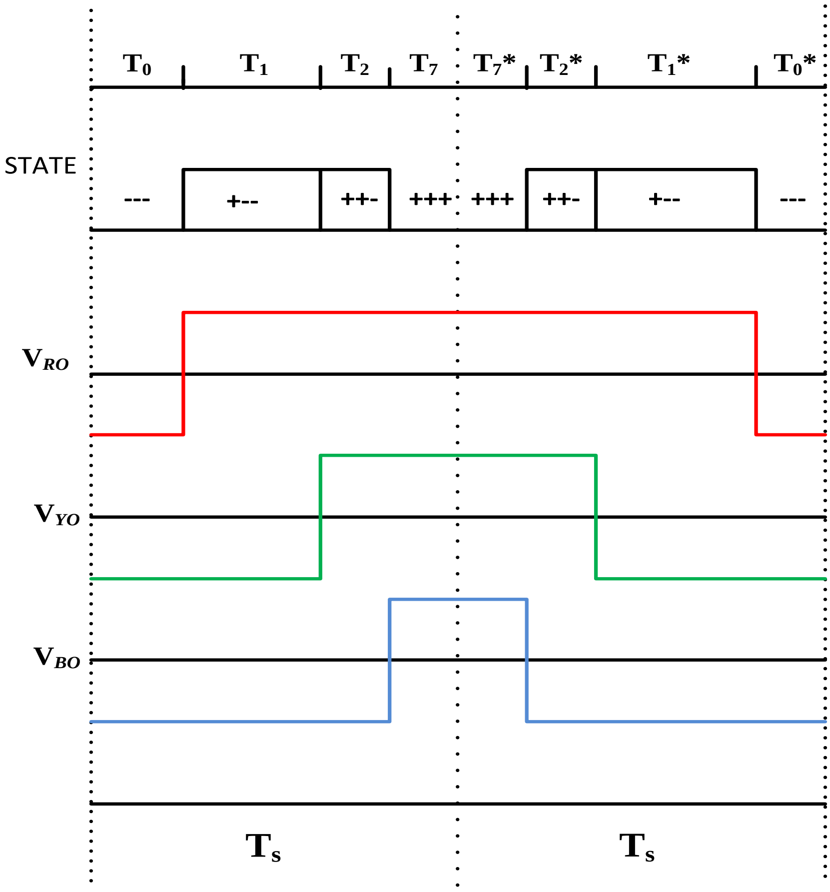

Figure 6.6 Timing diagram of inverter state for sector I

T_0 and T_7 are of equal duration that is of 0.5 T_Z accordingly figure 6.6 show the inverter state with respect to time. In the proposed model of FLC based IM drive with HCC and SVPWM control schemes as shown in figure 7.1 both the models FLC is used as speed control with output as i_q* and d-axis reference current i_d* can be calculated from the rotor flux. In HCC scheme current is transformed from d^e-q^e to abc before passing through hysteresis current controller with suitable hysteresis band while in SVPWM scheme, reference and actual d^e-q^e axis are compared and errors are fed to PI controller to generate respective d^e-q^e axis voltage using inverse park transform these voltage are transform into corresponding αβ voltage before giving to the SVPWM controller.

6.4 CONCLUSION

In this chapter two modulation techniques for generating the gate pulse for the voltage source inverter is discussed .Current control based HCC and voltage control SVPWM are two modulating schemes which are simulated and compared. In HCC actual current follow the desired current within a band and SVPWM controls the switching of VSI according to the position of revolving reference voltage. HCC have variable PWM frequency but faster response and compatible to induction motor drive as both have nonlinear characteristic while SVPWM is linear and its analysis is complex but have less chattering.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 GENERAL

This Chapter presents the performance comparison of Hysteresis Current Control and SVPWM for generation of PWM signals for voltage source inverter in vector controlled Induction Motor Drive. The dynamic performance of the drive for its speed regulation mode is described using both PWM techniques. Fuzzy Logic Control (FLC) is used for speed controller in both cases. The dynamic performance and ripple content is analyzed using FLC based SVPWM and HCC IM drive and compared at different operating conditions such as change in load torque and speed reversal. A MATLAB /SIMULINK model of FLC based vector controlled IM drive is simulated using hysteresis current controller and SVPWM for PWM signal generation and dynamic performance of these two techniques are compared.

7.2 PROPOSED MODEL

The simulation have been configured based on the proposed model shown in Figure.7.1 to analysis and compare dynamics response of HCC and SVPWM schemes with IM drive having parameter mentioned in Table A.1. In proposed model a 3-phase cage motor is fed by 3-phase VSI. The two modulation scheme shown for pulse generation to control the output of the inverter .The switch is used to change the modulation scheme from hysteresis current controller to SVPWM or vice-versa. FLC is used as a speed control which generate the desired torque component of current i^*_q. Desired flux component of current i^*_d can be calculated from the rated flux it self.

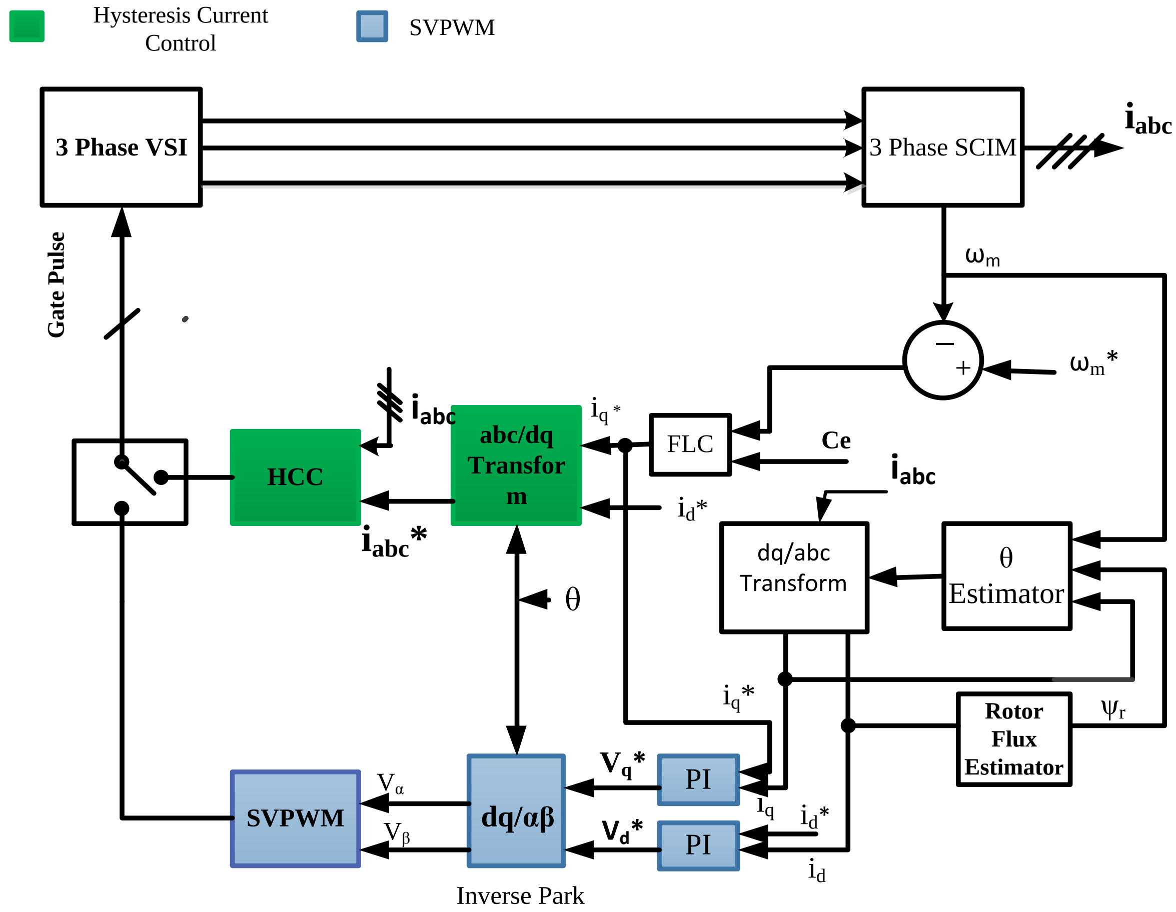

Figure 7.1 Proposed FLC based IM drive model

7.3 DYNAMIC PERFORMANCE ANALYSIS FOR STEP CHANGE IN LOAD

In simulation reference speed is taken as 120 rad/sec and load torque of 5N-m (55% of full load) is applied from 0.4 sec to 0.8 sec. Figure.7.2 and Figure. 7.3 show the dynamic response of hysteresis current controller and SVPWM on FLC based IM-drive. The result show there is very less overshoot in both the cases with SVPWM have lesser overshoot, almost same rise time with HCC have slightly faster response. SVPWM have lesser chattering in torque and better stator current quality than HCC.

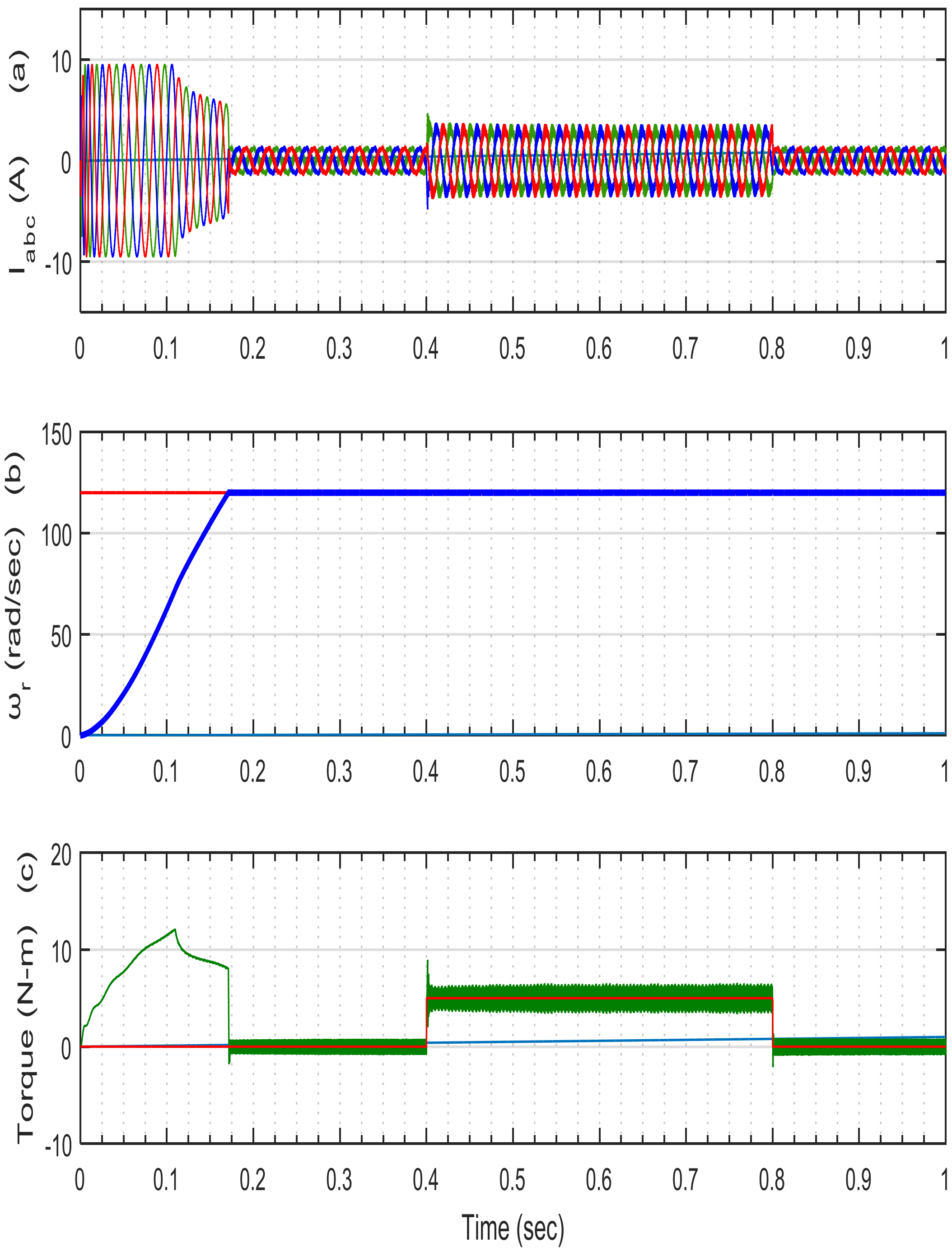

Figure 7.2 Hysteresis current controlled based dynamic response of induction motor on step change in load (a) stator current I_{abc} [A] (b) rotor speed ω_r [rad/s] (c) electromagnetic torque Te [N-m]

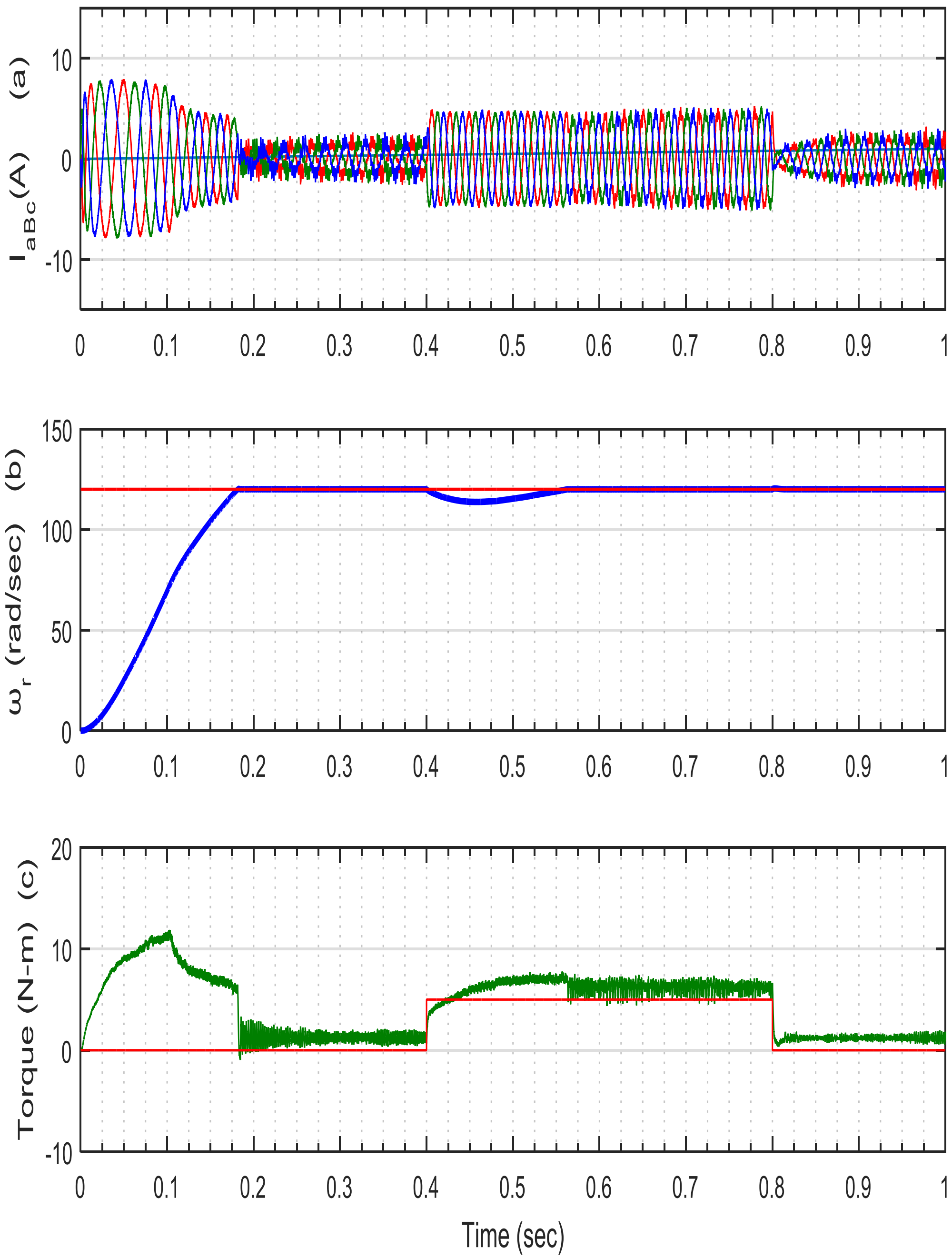

Figure 7.3 SVPWM based dynamic response of induction motor on step change in load (a) stator current I_{abc} [A] (b) rotor speed ω_r [rad/s] (c) electromagnetic torque Te [N-m]

7.4 DYNAMIC RESPONSE ANALYSIS FOR SPEED REVERSAL

Figure.7.4 and Figure.7.5 shows the dynamic response of hysteresis current controller and SVPWM during speed reversal from 120 rad/sec to -120 rad/sec at time t=0.4 sec. on sudden change in speed the phase reversal of current when the phase reversal of current is completed speed reversal start proceeding. For complete speed reversal HCC takes 0.24 sec while the SVPWM takes 0.44 sec. Overall comparison between HCC and SVPWM is summarized in TABLE II.

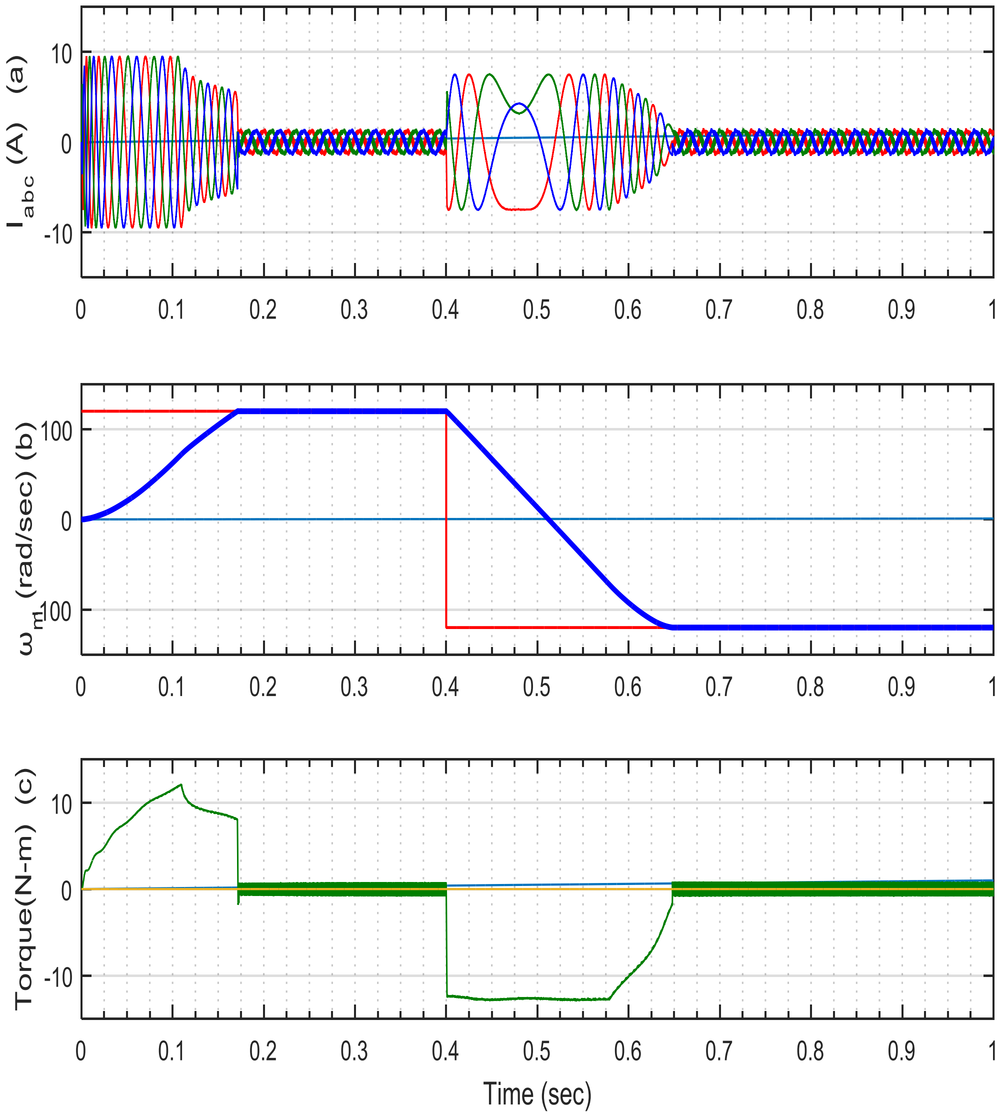

Figure 7.4 Hysteresis current controlled based dynamic response of induction motor on speed reversal (a) stator current I_{abc} [A] (b) rotor speed ω_r [rad/s] (c) electromagnetic torque Te [N-m]

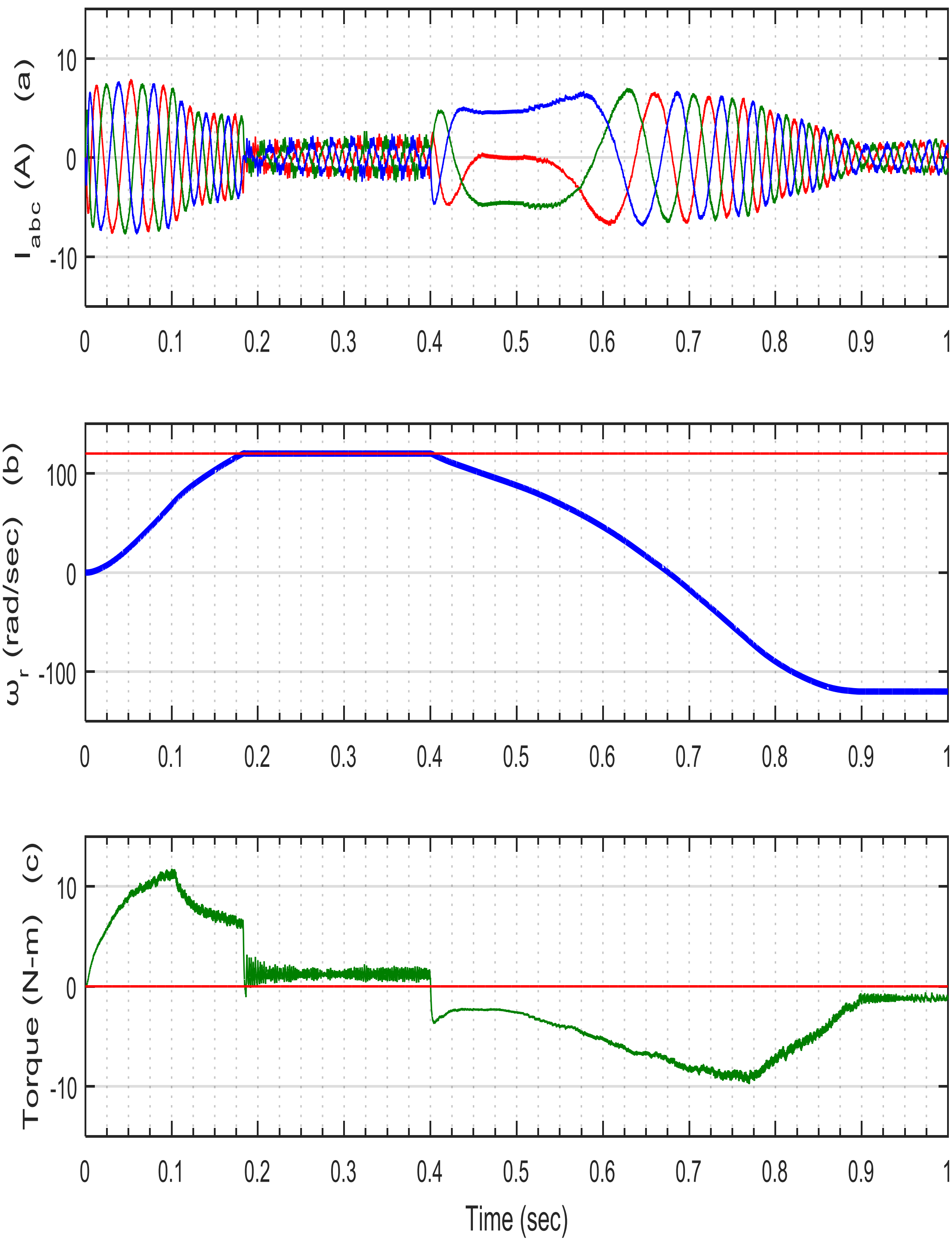

Figure.7.5. SVPWM based dynamic response of induction motor on speed reversal (a) stator current I_{abc} [A] (b) rotor speed ω_r [rad/s] (c) electromagnetic torque Te [N-m].

Table 7.1 comparison between dynamic performance of HCC and SVPWM

	rise time t_r (sec)	settling time t_s (sec)	% peak overshoot	speed reversal time (sec)	undershoot in speed on load perturbation	overshoot in speed on load removal
FLC - HCC	0.171	0.173	0.125	0.24	0.16%	0.1%
FLC - SVPWM	0.181	0.182	0.0833	0.44	3.91 %	0.21 %

CHAPTER 8
CONCLUSION AND FUTURE SCOPE

8.1 CONCLUSION

The comparison between HCC and SVPWM controller is presented for FLC based indirect vector controlled three phase IM drive. Both these schemes show satisfactory performance of IM drive for wide range of speed either with no load or with load. Although hysteresis current control scheme have faster response as compared to SVPWM technique but high chattering in torque as compared to SVPWM. For variable loads both schemes manage to stabilize the system with acceptable duration. Dynamic response for speed reversal of hysteresis current controller is faster than the SVPWM scheme.

8.2 FUTURE SCOPE

In Hysteresis current control scheme the PWM frequency is not constant and continuously changes within the band. As a result undesired harmonic ripples are generated in the machine. This issue can be rectify be using adaptive hysteresis band. It also resolves the issues related to phase deviations at higher frequency. SVPWM technique is complex to implement. So, the PWM switching is limited in case of SVPWM. To increase the PWM frequency artificial neural network (ANN) based SVPWM scheme can be used. For better controlling speed of sliding mode controller or the model referring adaptive control (MRAC) scheme can be used.

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APPENDIX –I

Table A.1 System Parameters

Rated Power	1.47	Hp
Rated Voltage	415	V
Frequency	50	Hz
Stator Resistance	6.03	Ω
Rotor Resistance	6.085	Ω
Stator Inductance	0.0299	H
Rotor Inductance	0.0299	H
Mutual Inductance	0.4893	H
Rotor Inertia	0.011	Kg-m^2
Rotor friction co-efficient	0.01	
Pole Pairs	2	

APPENDIX – II

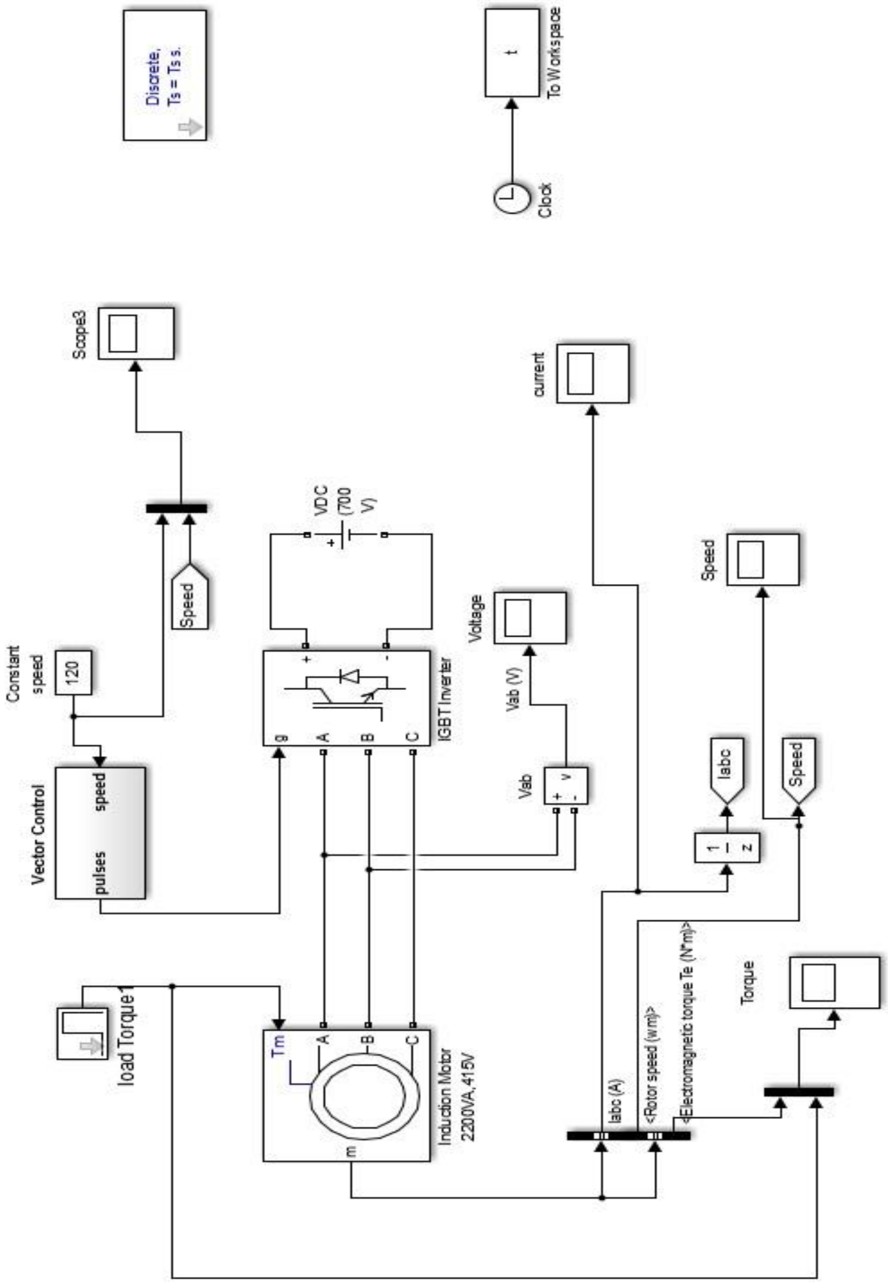

Figure A.1 SIMULINK model of FLC based vector controlled IM drive using Hysteresis current control

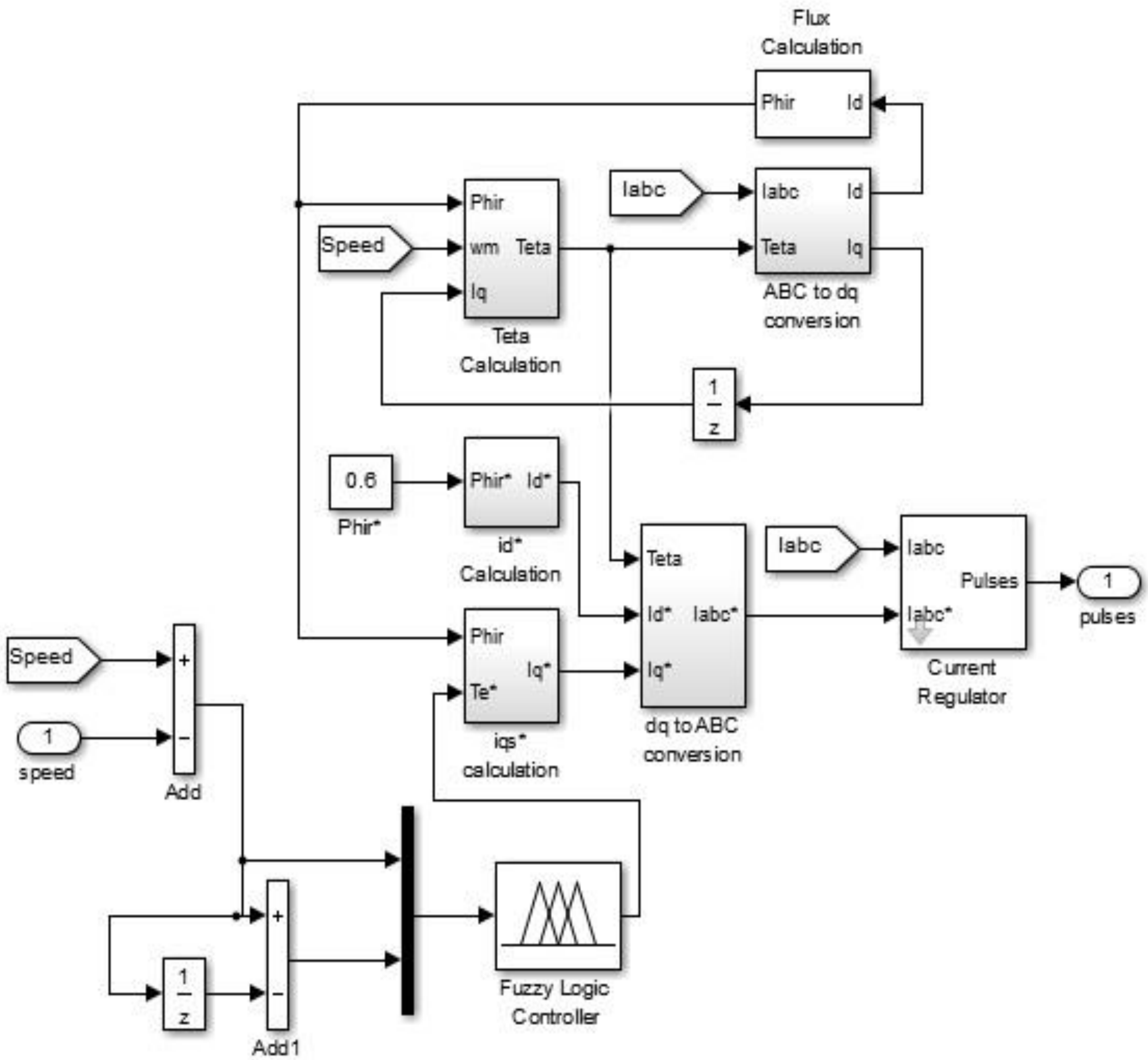

Figure A.2 Siulink model of indirect vector control

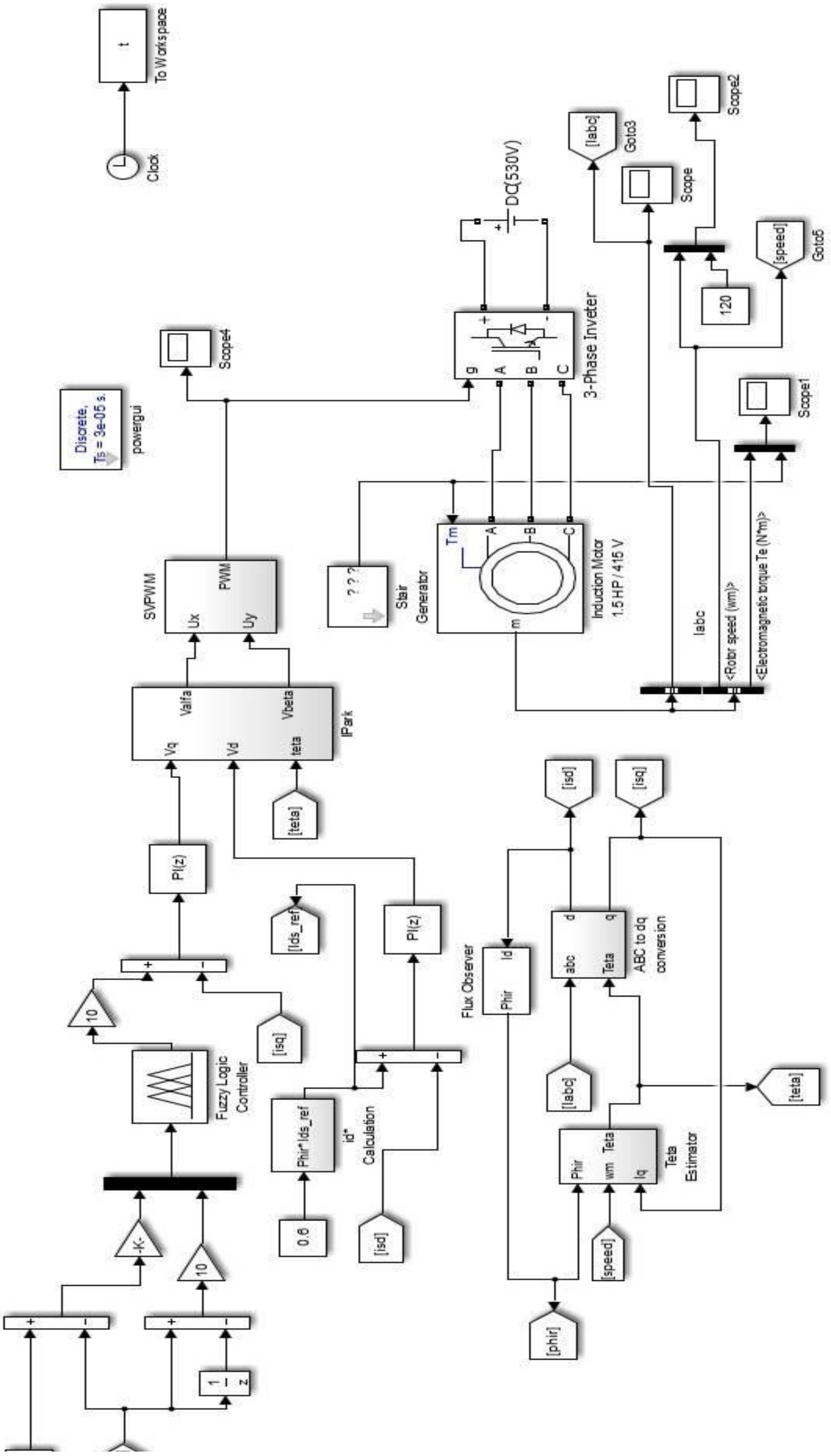

Figure A.3 SIMULINK model of FLC based vector controlled IM drive using SVPWM

List of Publication of the candidate's work:

[1] Tanmay Mishra, Ambrish Devanshu, Narendra Kumar, Ashish R Kulkarni "Comparative Analysis of Hysteresis Current Control and SVPWM on Fuzzy Logic Based Vector Controlled Induction Motor Drive", *IEEE International Conference on Power Electronics, Intelligent control and Energy system (ICPEICES 2016, DTU, Delhi 4-6 July, 2016.*