



Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

**SPACE VECTOR BASED FUZZY CONTROLLED DTC
(DIRECT TORQUE CONTROL) OF THREE PHASE
INDUCTION MOTOR DRIVE**

A thesis submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University in Partial fulfillment for the Degree of Master of Science in Electrical Engineering (Electrical Control Engineering)

By

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

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Date of Submission

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

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Advisor's Name

Signature

Acknowledgement

If there is anything that I consider to have done on my own, it could be written these few lines to express my appreciation to all, without whom the completion of this thesis would have been impossible. At first and most, I would like to thank the almighty of GOD, who gave me strength, patience and courage to complete the thesis successfully.

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Abstract

Induction motors have a wide range of applications due to their well-known advantages, like low costs and robust performances. Among many kinds of modern control strategies for controlling an induction motor, a DTC has gained a huge importance due to its excellent control strategies for torque control. However a conventional DTC of three phase induction motor drive has high ripples in electromagnetic torque, stator flux linkage, stator currents and speed response. In this thesis, a space vector based Fuzzy logic duty ratio controller is designed to reduce the ripples.

In DTC three phase induction motor drive supplied by a voltage source inverter, it is possible to control the stator flux linkage and electromagnetic torque by the selection of the voltage space vector in the inverter. The switching states produce the switching status according to the output of torque and flux comparator and sector judgment. The output of the voltage source inverter is given to the induction motor which is modeled in stationary D and Q axis reference frame. A Fuzzy logic based duty ratio minimizes the ripples by varying the DC link voltage of a voltage source inverter which is limited by the conventional DTC. A comparison is made between a conventional DTC and Fuzzy logic duty ratio based DTC of three phase induction motor drive using MATLAB/Simulink. The use of Fuzzy logic duty ratio controller reduces the ripples by 2.2% and the settling time of the step speed response is 4.122 milliseconds that is better response by 2.713 milliseconds than the conventional DTC. The use of fuzzy logic duty ratio controller also reduces the speed fluctuations at step speed response and at different speed levels when the load torque is applied compared to conventional DTC . The comparison of simulation results are valid by evaluating the performances of the simulation results.

Keywords: Induction Motor, DTC, Space Vector, Fuzzy Logic duty ratio controller, D and Q axis stationary reference frame, MATLAB/Simulink.

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List of Acronyms

FOC	Field Oriented Control
DTC	Direct Torque Control
V/F	Voltage to Frequency Control
AC	Alternate Current
DC	Direct Current
FPGA	Field Programmable Gate Array
VSI	Voltage Source Inverter
PID	Proportional Integrator Derivative
MMF	Magnetomotive Force
EMF	Electromotive Force
IGBT	Insulated Gate Bipolar Transistor
PWM	Pulse Width Modulation
AI	Artificial Intelligence
ANN	Artificial Neural Network
FLC	Fuzzy Logic Controller
D and Q axis	The Direct and Quadrature axis in stationary reference frame
d and q axis	The direct and quadrature axis in arbitrary reference frame
PI	Proportional Integrator
MRAS	Model Reference Adaptive System
KKF	Extended Kalman Filter
SVM-DTC	Space Vector Modulation - Direct Torque Control
THD	Total Harmonic Distortion
FFT	Fast Fourier Transfer

List of Notations

s	Induction motor Slip
ω_e	Synchronously rotating angular velocity
ω_r	Angular velocity of rotor
E_m	Excitation voltage of induction motor
V_s	Phase Voltage
E_r	Induced voltage to the rotor circuit
I_s	Stator phase currents
I_r	Rotor currents
R_s	Stator Resistance
R_r	Rotor Resistance
L_m	Excitation Inductance
L_{ls}	Stator Leakage Inductance
L_{lr}	Rotor Leakage Inductance
X_{ls}	Stator Leakage Reactance
X_{lr}	Rotor Leakage Reactance
V_{abcs}	Vector form of stator voltage
V_{abcr}	Vector form of rotor voltage
λ_{abcs}	Vector form of stator flux linkage
λ_{abcr}	Vector form of rotor flux linkage
L_s	Stator inductance
L_{ss}	Self stator inductance
L_{ms}	Stator mutual inductance
L_{mr}	Rotor mutual inductance
L_{rr}	Self rotor inductance
V_{sD}	Stator voltage D axis in stationary reference frame
ω_m	Actual Motor speed
θ_r	Rotor angular position
i_{rD}	Rotor current D axis in stationary reference frame
i_{sQ}	Stator current Q axis in stationary reference frame

V_{rQ}	Rotor Voltage Q axis in stationary reference frame
V_{sQ}	Stator voltage Q axis in stationary reference frame
λ_{sD}	Stator flux D axis in stationary reference frame
λ_{rD}	Rotor flux D axis in stationary reference frame
λ_{sQ}	Stator flux Q axis in stationary reference frame
P	Number of Pole
B	Viscous friction constant
J	Moment of Inertia
T_e	Electromagnetic Torque
V_{dc}	Inverter DC link Voltage
δ	duty ratio

CHAPTER 1

Introduction

1.1 Background

High performance drive refers to the drive systems ability to offer precise control, in addition to a rapid dynamic response and a good steady-state response [18]. Variable DC drives have been used to control DC motors speed and torque for decades. It is simple that controlling of the armature and field winding voltages separately. The cost, size of the machine and the poor dynamic performances are main DC drive disadvantages. Due to the less maintenance requirement the wide range of variable speed control, good dynamic performances and etc. nowadays AC drives are used widely in many applications. The controlling parameters of the AC drives are voltage and frequency of the applied voltage /current to the motor. The grid supplies fixed magnitude and frequency voltage/ currents, and are thus not suitable for obtaining controlled operation of machines [17]. Hence, power electronic converters, mainly DC-AC converters are used as an interface between the grid supply and the electric motors.

Induction motor is very popular in variable speed drives due to its well known advantages of simple construction, ruggedness and inexpensive and available at all power ratings. The control of AC machines can be broadly classified into scalar and vector controls. Scalar controls are the type of induction motor drive controllers, that are easy to implement and offer a relatively a good steady state response, even though their dynamic performances are poor. On the other hand, vector control induction motor drive techniques are used to obtain high precision and good dynamic performances, as well as a steady-state response.

One of the methods for controlling the induction motors torque and speed is direct torque control, which was introduced in 1985 by Japanese and German researchers Takahashi and Noguchi and nowadays it is an industrial standard for induction

motor drive [9]. In DTC, torque and flux are directly controlled by using the selection of optimum voltage vectors. DTC makes direct use of physical interactions that take place within the integrated system of the machine and its supply.

The main advantages of DTC are absence of co-ordinate transformation; current regulator and absence of separate voltage modulation block [28]. Although the conventional DTC has some drawbacks, such as the torque and flux ripples thus, the use of Fuzzy logic duty ratio controller reduces the ripples.

1.2 Literature Review

To start this thesis, many prior research papers have been read about DTC (Direct Torque Control) of three phase induction motor drive. The various control strategies for the control of the inverted-fed induction motor have provided good steady state but poor dynamic response. From the traces of the dynamic response, the cause of such poor dynamic response is found to be that the air gap flux linkages deviate from their set values. The deviation is not only magnitude but also in phase. The variations in the flux linkages have to be controlled by the magnitude and frequency of the stator and rotor phase currents and their instantaneous phases.

Paper [21] is presented on the design and simulation of a direct torque controlled induction motor drive system based on space vector modulation technique for electromagnetic torque ripple reduction. The basis of the SVM-DTC methodology is the calculation required voltage space vector to compensate the flux and torque errors and its generation using the SVM at each sample period.

Paper [26] is investigated on DTC problems of at low speed operation. The induction motor variables and parameters estimation is performed using a recursive nonlinear observer known as EKF. This observer is used to estimate the stator currents, the rotor flux linkages, the rotor speed and the stator resistance. The main drawback of the EKF in this case is that the load dynamics has to be known which is not usually possible. Therefore, a new method based on the Model Reference Adaptive System (MRAS) is used to estimate the rotor speed. The two different

nonlinear observers applied to sensorless DTC of induction motor; are discussed and compared each other.

Paper [29] is presented on the very low flux, torque ripples and almost fixed switching frequency. It is based on the compensation of the error flux linkage vector by means of space vector modulation.

Paper [30] is presented on the speed control of three phase induction motor using Artificial Neural Network (ANN) controller. The ANN controller will be programmed to control the speed of three phase induction motor at certain speed level. This paper introduces proportional Integral (PI) for speed control and the ANN is used in place of switching vector selector of conventional DTC.

Paper [31] is presented on the reduction of stator current and electromagnetic torque pulsations. The fuzzy controller is used instead of switching vector selector of the conventional DTC. The implementation of the applied fuzzy controller is used for the pulsation of the torque twice lower, the stator current, flux and the maximum overshoots were lowered.

1.3 Direct Torque Control

Direct Torque Control (DTC) is one method used in variable frequency drives to control the torque and thus finally the speed of Induction motor. In principle, the motor terminal voltages and currents are sampled and used to estimate the motor flux and torque .They can be controlled directly and independently by selecting optimum inverter switching modes. Based on estimates of the flux position, the instantaneous errors in torque and stator flux magnitude, a voltage vector is selected to restrict the torque and flux errors within their respective torque and hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant [1].

1.3.1 Features of Direct Torque Control

The main features of DTC are as follows:-

1. Direct control of flux and torque
2. Indirect control of stator currents and voltages

3. Very simple control scheme and low computational time
4. Reduced parameter sensitivity

Advantages of Direct Torque control

- Absence of co-ordinate transform
- Absence of voltage modulator block, as well as other controllers such as PID for motor flux and torque.
- Minimum torque response time.

Disadvantages of Direct Torque Control

- Difficulty to control torque and flux at very low speed.
- High current and torque ripple.
- Requirement of torque and flux estimators, implying the consequent parameters identification.

1.4 Statement of the Problem

In Direct Torque controlled induction motor drives, it is possible to control directly the stator flux linkage and the electromagnetic torque by selection of an optimum inverter switching state. The selection of the switching state is made to restrict the flux and the torque errors within their respective hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. Direct Torque control is simpler than field-oriented control and less dependent on the motor model, since the stator resistance value is the only machine parameter used to estimate the stator flux.

High ripples in torque, stator flux linkage, stator currents and sluggish speed response and requirement of torque and flux estimators are the main disadvantages of DTC. The use of Artificial Intelligence technique, Fuzzy logic duty ratio controllers reduces the ripples compared to the conventional DTC induction motor drive. This enables the induction motor for high performance applications like electric Vehicles and drives.

Space Vector Based Fuzzy Controlled DTC of three phase induction Motor Drive

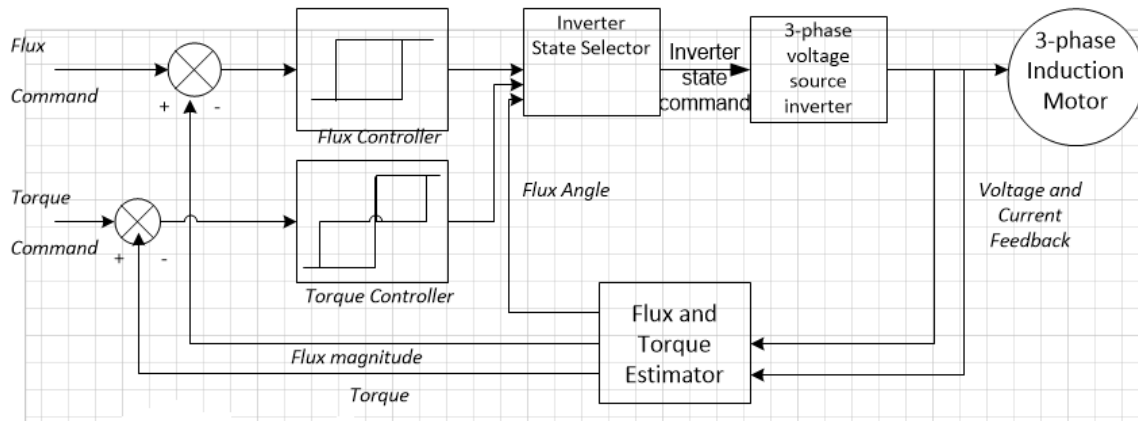


Figure 1.1 Block diagram of DTC scheme

The state selector selects the optimum switching states of the voltage source inverter by taking command signals from flux linkages error, electromagnetic errors and angle of flux linkages. For the conventional DTC, the flux angle is divided into six sectors of 60° .

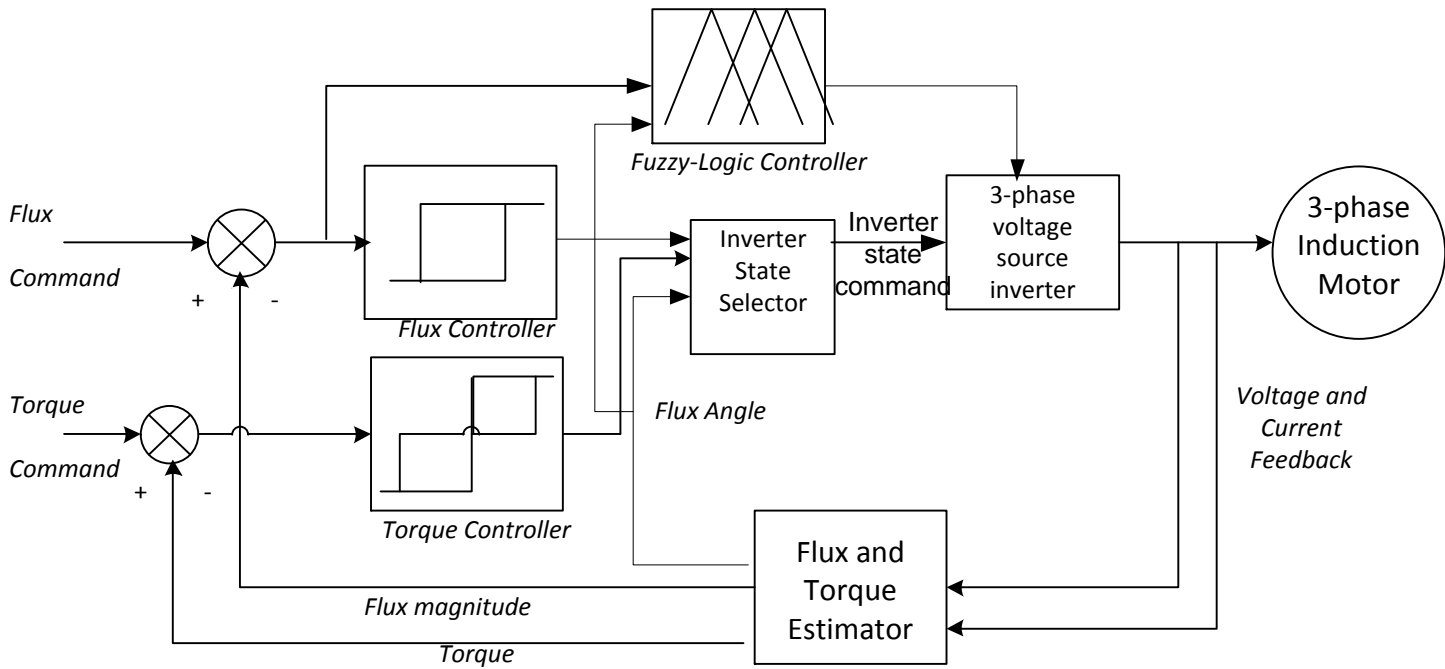


Figure 1-2 Block diagram of Fuzzy Logic Based DTC

Under constant load in steady state, an active switching state causes the torque to continue to increase past its reference value until the end of the switching period. Then a zero voltage vector is applied for the next switching period causing the torque to continue to decrease below its reference value until the end of the switching period. That results in high torque ripple. A possible solution to reduce the torque, stator flux linkage and current ripples, is to use a high switching frequency or changing the voltage source inverter topology. However, a Fuzzy logic duty ratio based DTC can reduce the torque and current ripples to some extents. The theme of this thesis is to verify by simulation that Fuzzy logic duty ratio based DTC controller reduces the torque and current ripples compared to conventional DTC.

1.5 Objectives of the Thesis

1.5.1 General Objective

The general objective of this thesis work is to study, analyze, design and simulation of Space Vector based Fuzzy controlled DTC of three phase induction motor drive.

1.5.2 Specific Objectives

In line with achieving the general objective, the thesis deals with the following specific objectives:

- To study the dynamic mathematical model of 3-phase induction motor
- To study the basic concept of DTC and its simulation by using MATLAB/Simulink
- To design a Fuzzy logic duty ratio controller
- To study and analyze an estimator design
- To simulate Fuzzy logic duty ratio based DTC of three phase induction motor using MATLAB/Simulink

1.6 Overview of the Thesis

The thesis consists of six chapters. Chapter 1 is an Introduction, literature reviews of the thesis, some theoretical background of DTC and the technique how to improve the disadvantages of the conventional DTC.

In Chapter 2 a theoretical and dynamic mathematical description of three phase induction motor in stationary reference frame are presented.

Chapter 3 introduces and explains in detail the DTC of induction motor drive control scheme from the basic ideas. It also introduces brief description of space vector voltage source inverter and the optimum switching state selection of an inverter by using switching table. The electromagnetic torque and stator flux linkage estimators are also introduced in this chapter.

Chapter 4 presents Fuzzy logic duty ratio based DTC. In this chapter the general Fuzzy logic controller structures are introduced and the design of Fuzzy logic duty ratio is introduced in this chapter.

Chapter 5 presents the developments of conventional DTC and Fuzzy logic duty ratio based DTC in MATLAB/Simulink and the simulation results are discussed.

Chapter 6 includes conclusion and some recommendations for future work.

CHAPTER 2

Three-Phase Induction Machine

2.1 Introduction

The Induction Machines are asynchronous speed Machines operating below synchronous speed when motoring and above synchronous speed when generating. It is rotating based on the rotating MMF by the stator winding current like the synchronous machine, but unlike the synchronous machine, the induction machine has no reluctance difference and no excitation flux on the rotor by the permanent magnet or by a separate field winding [6]. They are the workhorses of today's industry. As motors; they are rugged and require very little maintenance. However, their speeds are not as easily controlled as with dc motors, they draw large starting currents, typically about six to eight times their full load values, and Operate with a poor lagging power factor when lightly loaded.

2.2 Induction Motor Construction, Principles and Operation

2.2.1 Construction

Most induction motors are of the rotary type with basically a stationary stator and a rotating rotor unlike dc machines, induction machines have a uniform air gap. The stator is composed of laminations of high –grade sheet steel [14] .The rotor also consists of laminated ferromagnetic material, with slots cut on the outer surface [14] .The motor winding may be either of two types, the squirrel –cage type or the wound-rotor type. The squirrel-cage winding consists of aluminum or capper bars embedded in the rotor slots and shorted at both ends by aluminum or copper end rings.

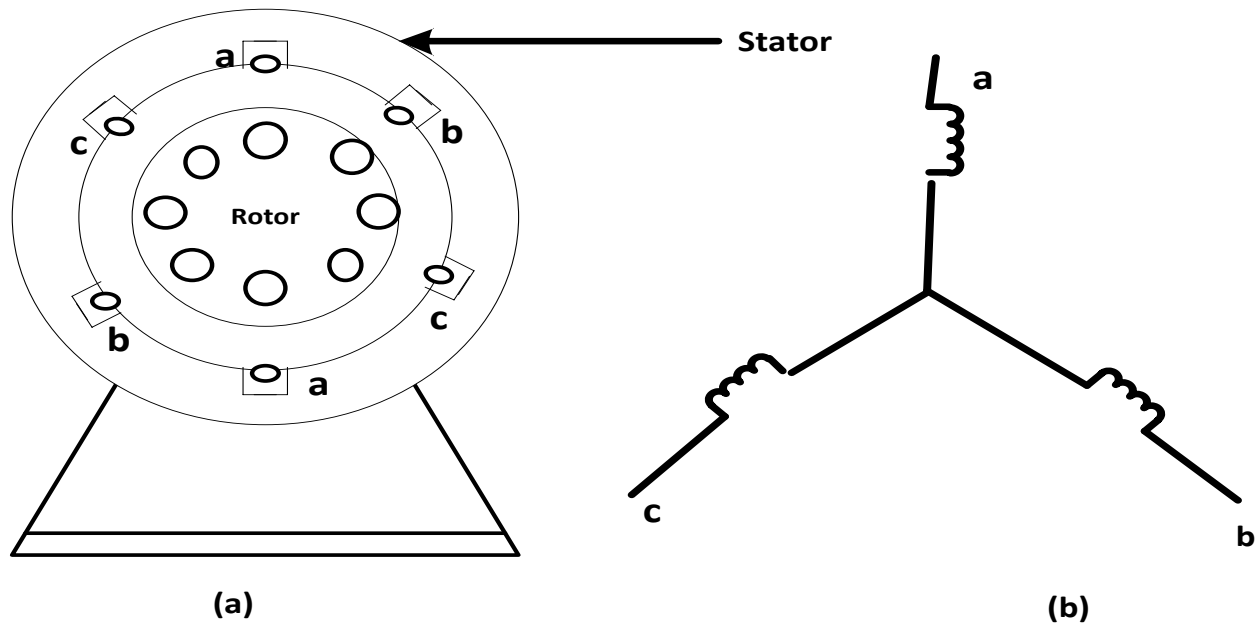


Figure 2.1 Three-phase squirrel-cage induction machines

a) Cross-sectional view

b) Star-connected stator winding

The three-phase stator winding, which in practice would be a distributed winding, is represented by three concentrated coils for simplicity. The axes of these coils are 120 electrical degrees apart. Coil aa' represents all the distributed coils assigned to the phase-a winding for one pair of poles. Similarly, coil bb' represents the phase-c distributed winding, and coil cc' represents the phase c distributed winding. The ends of these phase windings can be connected in a star (Figure 2.1.b) to form the three-phase connection. If balanced three-phase currents flow through these three-phase distributed windings, a rotating magnetic field of constant amplitude and speed will be produced in the air gap and will induce current in the rotor circuit to produce torque.

2.2.2 Operation Principle of Squirrel Cage Induction Motor

The induction machine is rotating based on the rotating MMF by the stator winding current. When the rotating MMF is applied to the squirrel cage rotor, EMF is induced at the conductors of the rotor, and EMF let the current flow in the conductor because the rotor is short circuited by the end rings.

The current in the rotor conductors, by the induced EMF, again generates a rotating MMF. With the interaction between the rotor current and the rotating MMF by stator current, the torque of the induction machine is generated. When the load torque applies, the flux by the load current of the rotor is canceled out by the additional stator current except for the leakage flux of the rotor flux. Hence, the air gap flux of the induction machine is constant regardless of the load condition if the excitation current of the stator winding is constant. So there is no armature reaction in the induction motor inherently. If the leakage flux at rotor and stator winding is neglected, then the air gap flux, the stator flux, and rotor flux are same and also in time.

The frequency of the current and Voltage of the rotor conductor of the induction machine is the difference between the angular frequency of the rotating MMF and that of the rotating speed of the rotor.

2.2.3 Steady-State Equivalent Circuit

The Operation principle of the induction machine is the same as that of the transformer, which is that the rotor current flows through the induced voltage from the variation of the stator flux with regard to the rotor conductors.

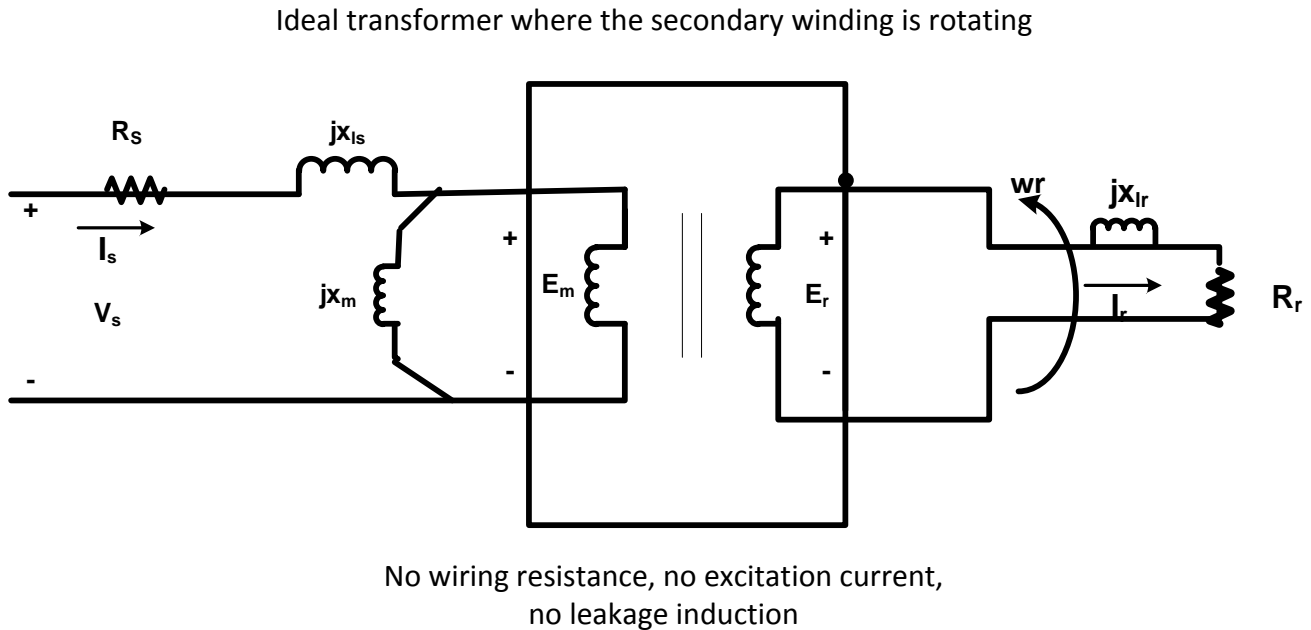


Figure 2.2 Steady-state per phase equivalent circuit of a squirrel cage rotor induction machine[4]

When the rotor is rotating at a steady speed of ωr mechanical radians per second. The relative or slip speed between the rotor and synchronous rotating stator field. Thus the slip of the induction machine can be defined as:-

$$S = \frac{\omega e - \omega r}{\omega e} \text{-----(2.1)}$$

From the circuit, the excitation voltage, E_m can be represented as:-

$$E_m = V_s - (R_s + jx_{ls})I_s \text{-----(2.2)}$$

If the induced voltage to the rotor circuit is E_r and the turn ratio between the stator circuit & rotor circuit is 1:1, then,

$$/E_r/ = s/E_m/ \text{-----(2.3)}$$

If there is no slip, $s = 0$, which means that the speed of rotating MMF and the rotor speed is the same, then the induced voltage to the rotor circuit is $/E_r/ = 0$. In this case, no current flows in the rotor conductors & no torque can be generated.

And, when $s = 1$, which means that the rotor is stationary, then the induction machine is exactly same to the transformer.

In general, the equivalent circuit of induction machine can be simplified by omitting the ideal transformer, where all rotor parameters are evaluated at the stator side and moreover, the control of the squirrel cage induction machine is always done in the stator side.

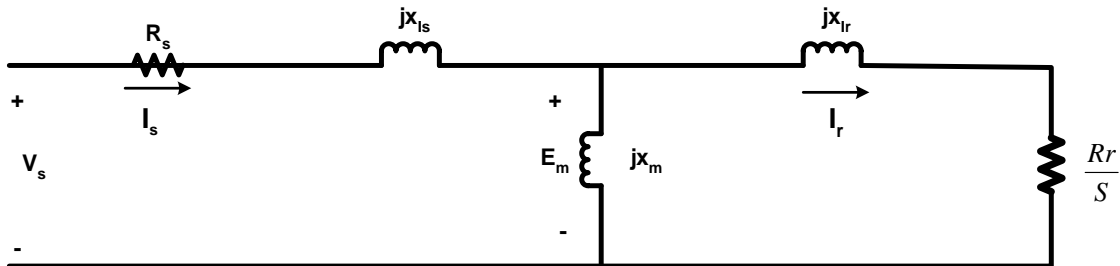


Figure 2-3 Simplified per-phase equivalent circuit of an induction machine [4]

2.3 Dynamic Mathematical Model of 3-phase Induction Motor

2.3.1 Introduction

The steady state model of induction motor which is represented by a steady equivalent circuit which describes only a steady state behavior of the induction motor. It is used when steady state analyses, such as efficiency, losses, steady state torque, currents are needed to be evaluated. Designing the machine drives based on this model will only produce a drive that normally has a poor transient performance when machine drives used for high performance application need to be designed, a model that can describe the transient as well as the steady state behavior of the dynamic mathematical model, which cannot be analyzed using steady state equivalent model, can be predicted and studied [4]. Due to the fact that the dynamic model of the machine could be just a good approximation of the real plant. Such a model can be obtained by means of two-axis theory of electrical machines.

For simplicity, the induction motor considered will have the following assumptions.

- (i) the induction motor is considered as symmetrical two poles ,three phase windings
- (ii) The winding on the stator is symmetrically distributed such that the spatial magnetomotive force (MMF) produced is sinusoidal.
- (iii) The surface windings have negligible depth .The core is assumed to have infinite permeability hysteresis, eddy current and slotting effects can be neglected.

2.3.2 Voltage Equations in Machine Variables

The stator and rotor voltage equations can be represented as (2.4) and (2.5) in vector form, respectively [6]

$$V_{abcs} = R_s I_{abcs} + p\lambda_{abcs} \quad (2.4)$$

$$V_{abcr} = R_r I_{abcr} + p\lambda_{abcr} \quad (2.5)$$

Where is a differential operator as d/dt in the above equations, each vector has following elements [6]

$$V_{abcs} = [V_{as} \quad V_{bs} \quad V_{cs}] \quad (2.6)$$

$$I_{abcs} = [I_{as} \quad I_{bs} \quad I_{cs}] \quad (2.7)$$

$$\lambda_{abcs} = [\lambda_{as} \quad \lambda_{bs} \quad \lambda_{cs}] \quad (2.8)$$

$$V_{abcr} = [V_{ar} \quad V_{br} \quad V_{cr}] \quad (2.9)$$

$$I_{abcr} = [I_{ar} \quad I_{br} \quad I_{cr}] \quad (2.10)$$

$$\lambda_{abcr} = [\lambda_{ar} \quad \lambda_{br} \quad \lambda_{cr}] \quad (2.11)$$

Where [-----]^T stands for the transpose of a matrix [-----] and s subscript denotes Variables and parameters associated with the stator circuits, and r subscript denotes variables and parameters associated with the rotor circuit.

The flux linkages for the stator and rotor winding can be expressed as (2: 12) in matrix form[6]

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_{ss} & L_{sr} \\ (L_{sr})^T & L_{rr} \end{bmatrix} \begin{bmatrix} I_{abcs} \\ I_{abcr} \end{bmatrix} \quad (2.12)$$

Where

$$L_{SS} = \begin{bmatrix} L_{ls} + L_{ms} & \frac{1}{2}L_{ms} & \frac{1}{2}L_{ms} \\ \frac{1}{2}L_{ms} & L_{ls} + L_{rs} & \frac{1}{2}L_{ms} \\ \frac{1}{2}L_{ms} & \frac{1}{2}L_{ms} & L_{ls} + L_{rs} \end{bmatrix} \text{Henry} \text{-----} (2.13)$$

$$L_{rr} = \begin{bmatrix} L_{lr} + L_{mr} & \frac{1}{2}L_{mr} & \frac{1}{2}L_{mr} \\ \frac{1}{2}L_{mr} & L_{lr} + L_{rr} & \frac{1}{2}L_{mr} \\ \frac{1}{2}L_{mr} & \frac{1}{2}L_{mr} & L_{lr} + L_{rr} \end{bmatrix} \text{Henry} \text{-----} (2.14)$$

An assumption is made that the mutual inductances between the stator and rotor windings are sinusoidal functions of the rotor angular displacement, θ_r Hence

$$L_{sr} = \begin{bmatrix} \cos \theta_r & \cos\left(\theta_r + \frac{2}{3}\pi\right) & \cos\left(\theta_r - \frac{2}{3}\pi\right) \\ \cos\left(\theta_r - \frac{2}{3}\pi\right) & \cos \theta_r & \cos\left(\theta_r + \frac{2}{3}\pi\right) \\ \cos\left(\theta_r + \frac{2}{3}\pi\right) & \cos\left(\theta_r - \frac{2}{3}\pi\right) & \cos \theta_r \end{bmatrix} \text{Henry} \text{-----} (2.15)$$

The flux linkage that enters in to the air gap region, has two parts and the mutual inductance between the rotor and stator is depending on the rotor position (θ_r). That means the rotor and stator equations are depending on each other.

2.3.3 Machine Model in Arbitrary Reference Frames

There are three main reference frames of motion, which could be used to model the three phase induction machine in its three main regions of operation .These are the stationary reference frame for startup, the synchronous reference frame for equilibrium motion, and the rotor reference frame for changing speeds by acceleration or deceleration .The two commonly employed co-ordinate transformations with induction machine are the stationary and the synchronous reference frame. In order to obtain constant coefficients in the machine differential equations, the parks transform will be applied .He formulated a change of variables which, in effect, replaced the variables (voltages, currents and flux linkages)

associated with the stator windings of a synchronous machine with variables with findings rotating with the rotor [7]referring to figure (2.4) and deriving the equations for three phase induction machine in arbitrary reference frame with speed w in the same direction of rotor rotation. When $\omega = 0$, this means the reference frame does not move (stationary) and this transformation is commonly used in adjustable speed drives. Similarly, when the reference frame is revolving in the synchronous speed, the reference frame can be represented in synchronous reference frame.

By applying rotating coordinate transformations to the stator rotor voltages, current and flux linkage equations, which are represented in equations (2.4-2.15) those equations can be represented in simpler form by proper choice of reference frames.

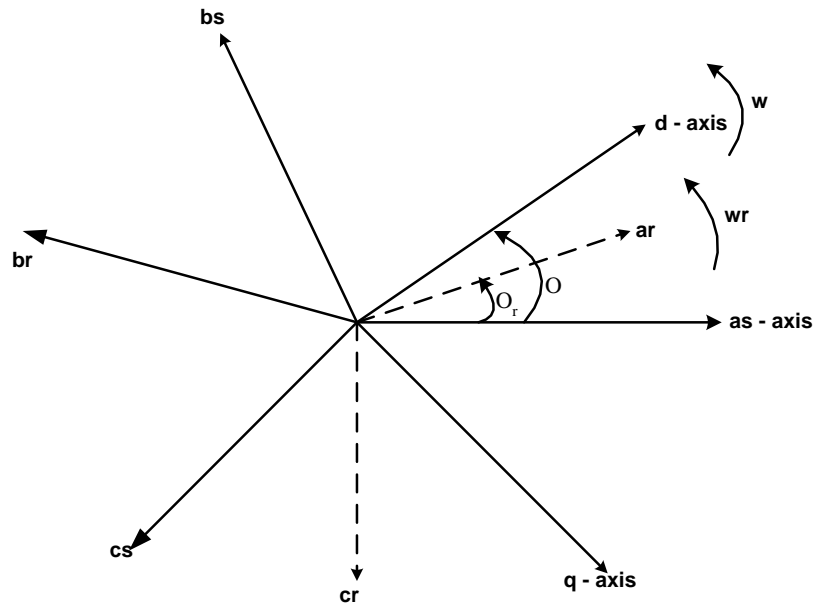


Figure 2-4 Relationship between abc and arbitrary QDO. [14]

$$\begin{bmatrix} fq \\ fd \\ fo \end{bmatrix} = [T_q do(\theta)] \begin{bmatrix} fa \\ fb \\ fc \end{bmatrix} \text{----- (2.16)}$$

Where can be stator or rotor voltage, current as well as a flux linkage of the stator or rotator of the induction machine ,located in the air gap region between stator and rotor tq do (θ) is the associated torque transformation matrix.

$$T_{qdo}(\theta) = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \text{----- (2.17)}$$

The inverse of the transformation matrix obtained by matrix method and this is :-

$$[T_{qdo}(\theta)]^{-1} = \begin{bmatrix} \cos \theta & \sin \theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \text{----- (2.18)}$$

2.3.3.1 Stationary Reference Frame Equations

The stationary coordinate system (fixed to the stator) $D - Q$,in this case, the angular speed of the reference frame is zero .In this coordinate system, the dynamic mathematical model equation of the motor can be written as of figure 2.5 and figure 2.6 are as follows. Thus, stator and rotor voltages can be expressed as:-

$$V_{sD} = R_s i_{sD} + \frac{d\lambda_{sD}}{dt} \text{----- (2.19)}$$

$$V_{sQ} = R_s i_{sQ} + \frac{d\lambda_{sQ}}{dt} \text{----- (2.20)}$$

$$0 = R_r i_{rD} + \frac{d\lambda_{rD}}{dt} + p w_m \lambda_{rQ} \text{----- (2.21)}$$

$$0 = R_r i_{rQ} + \frac{d\lambda_{rQ}}{dt} - p w_m \lambda_{rD} \text{----- (2.22)}$$

where $V_{rD} = V_{rQ} = 0$, since the rotor cage bars are short circuited.

Stator and rotor currents can be expressed as since the rotor cage bars are short circuited follows:-

$$i_{sD} = \lambda_{sD} \frac{L_r}{L_x} - \lambda_{rD} \frac{L_m}{L_x} \text{----- (2.23)}$$

$$i_{sQ} = \lambda_{sQ} \frac{L_r}{L_x} - \lambda_{rQ} \frac{L_m}{L_x} \text{----- (2.24)}$$

$$i_{rD} = \lambda_{rD} \frac{L_s}{L_x} - \lambda_{sD} \frac{L_m}{L_x} \text{----- (2.25)}$$

$$i_{rQ} = \lambda_{rQ} \frac{L_s}{L_x} - \lambda_{sQ} \frac{L_m}{L_x} \text{----- (2.26)}$$

where $L_x = L_s L_r - L_m^2$

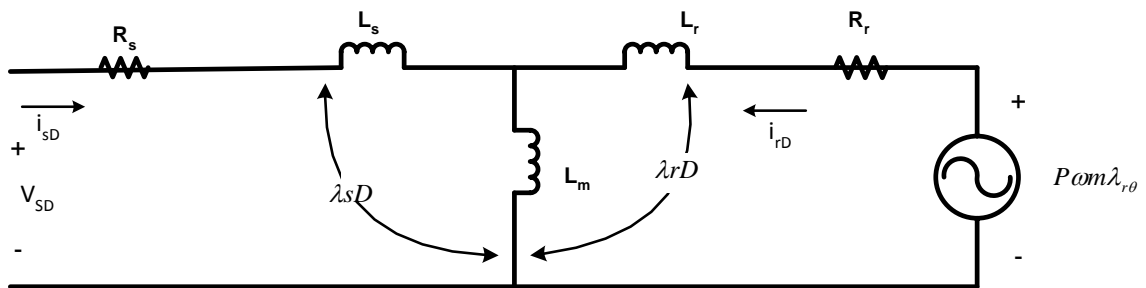


Figure 2-5 D-equivalent circuit of squirrel-cage induction motor in stationary reference frame

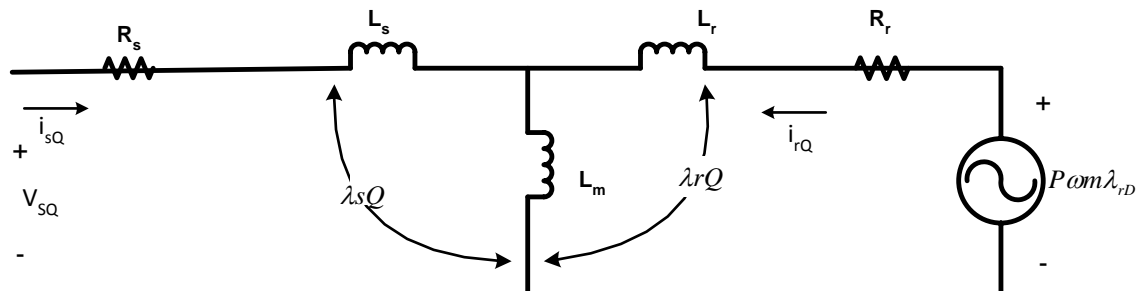


Figure 2-6 Q-equivalent circuit of squirrel-cage induction motor in stationary reference frame

The electromagnetic torque is developed by the interaction of air gap flux and rotor MMF which can be expressed in general form as:-

$$T_e = \frac{3}{2} P (\bar{\lambda}_s) (\bar{i}_r) \text{-----} (2.27)$$

Where $\bar{\lambda}_s$ - space phasor of the stator flux

\bar{i}_r - space phasor of the rotor current

The torque equations can be written in stationary reference frame with corresponding variables

$$T_e = \frac{2p}{3} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \text{-----} (2.28)$$

$$= \frac{2p}{3} (\lambda_{Dr} i_{Qr} - \lambda_{Qr} i_{Dr}) \text{-----} (2.29)$$

$$= \frac{2}{3} p L m (i_{\theta s} i_{Dr} i_{\theta r}) \text{-----} (2.30)$$

2.3.3.2 Motion Equation

The equation of the dynamic rotor rotation can be expressed as :-

$$\frac{d_{\omega m}}{dt} = \frac{1}{J} [T_e - T_L - B_{\omega m}] \text{-----} (2.31)$$

were T_e – electromagnetic torque

T_L – Load torque

B – Viscous constant

J – moment of inertia of the above rotor

Using the torque expression (2.28) the above motion equation

(2.31) can be expressed as follows:

$$\frac{d_{\omega m}}{dt} = \frac{1}{J} p [(\lambda_{Ds} i_{Qs} - \lambda_{Qs} i_{Ds}) - T_L - B_{\omega m}] \text{-----} (2.32)$$

The D-axis and Q-axis of the stator voltages are the input voltages of the induction motor that are modeled in the stationary reference frame.

Generally, the stator and rotor voltages and currents of the motor in stationary reference frame can be expressed as:-

$$v_{sD} = R_s i_{sD} + \frac{d\lambda_{sD}}{dt} \quad (2.37)$$

$$v_{sQ} = R_s i_{sQ} + \frac{d\lambda_{sQ}}{dt} \quad (2.38)$$

$$0 = R_r i_{rD} + \frac{d\lambda_{rD}}{dt} - p\omega_m \lambda_{rQ} \quad (2.39)$$

$$0 = R_r i_{rQ} + \frac{d\lambda_{rQ}}{dt} - p\omega_m \lambda_{rD} \quad (2.40)$$

$$i_{sD} = \lambda_{sD} \frac{l_r}{L_x} - \lambda_{rD} \frac{L_m}{L_x} \quad (2.41)$$

$$i_{sQ} = \lambda_{sQ} \frac{L_r}{L_x} - \lambda_{rQ} \frac{L_m}{L_x} \quad (2.42)$$

$$i_{rD} = \lambda_{rD} \frac{L_s}{L_x} - \lambda_{rD} \frac{L_m}{L_x} \quad (2.43)$$

$$i_{rQ} = \lambda_{rQ} \frac{L_s}{L_x} - \lambda_{sD} \frac{L_m}{L_x} \quad (2.44)$$

Where $L_x = L_s L_r - L_m^2$

The motion of the dynamic rotor rotation can be expressed as:

$$\frac{d\omega_m}{dt} = \frac{1}{J} [T_e - T_L - B\omega_m] \quad (2.45)$$

Where

$$T_e = \frac{2}{3} P (\lambda_{Ds} i_{Qs} - \lambda_{Qs} i_{Ds})$$

T_L – Load torque

B – Viscous constant

J – Moment of inertia

P – Number of poles

CHAPTER 3

Direct Torque Control of Three-phase Induction Motor

3.1 Introduction

A DC machine drives are simpler in control because they independently control flux, which, when maintained constant, contributes to an independent control of torque. This is made possible with separate control of field and armature currents which, in turn, control the field flux and torque independently. Moreover, the DC motor control requires only the control of the field or armature current magnitudes, providing a simplicity not possible with AC machine control. Induction motor drives require a coordinated control of stator current magnitudes, frequencies and their phases, making it a complex control. As with the DC drives, independent control of the flux and torque is possible in AC drives.

Direct torque control of three phase induction motor drive is one of the most excellent strategies of torque control in induction motor. It controls the torque and flux effectively. In this drive, the decoupling of the torque and flux components is accomplished by using hysteresis comparators which compares the actual and estimated values of the electromagnetic torque and stator flux. The DTC drive consists of torque and flux estimator, optimum switching vector selector, hysteresis controllers and a voltage source inverter.

3.2 Basic Principle of Direct Torque Control of Induction Motor

The DTC of induction motor drive is more used in controlling the induction motor because it is considered as a simple and robust method. On the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states to reduce the torque and flux errors within prefixed band limits. In spite of its simplicity, DTC allows for good torque control in steady – state and transient operating conditions.

The stator EMF depends on the stator flux, so the magnitude of the EMF depends on the stator voltage hence, $\lambda_s = \int (V_s - R_s i_s) dt$ and the torque, by definition is the cross product of the stator flux and the rotor flux. As a result, the magnitude of the stator flux and the developed electromagnetic torque can be adjusted by selecting the state of the inverter of space vectors of the stator voltage [3], [13]

Figure 3.1 shows the schematic diagram of simple form of the DTC induction motor drive, employing a VSI. In this scheme the stator flux is the controlled flux, thus it will be referred to as a stator – flux – based DTC induction motor drive.

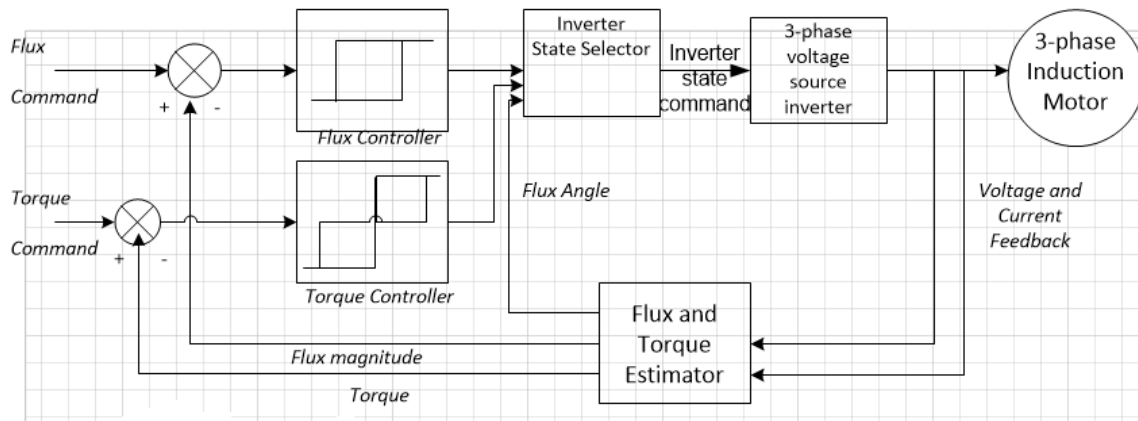


Figure 3.1 Simplified Block Diagram of DTC Scheme [3]

In figure 3.1 a voltage source inverter is a six – pulse inverter – fed stator flux – based DTC induction motor drive shown direct torque control involves the separate control of the stator flux and torque through the selection of optimum inverter switching modes. In figure 3.2, the reference value of the stator flux – linkage space vector modulus, $|\bar{\lambda}_{sref}|$, is compared with the actual modulus of the stator flux – linkage space vector, $|\bar{\lambda}_s|$, and the resulting error is fed into the two level stator flux hysteresis comparator.

Similarly, the reference value of the electromagnetic torque ($T_{e ref}$) is compared with its actual value (T_e) and the electromagnetic torque error signal is fed into the three – level torque hysteresis comparator.

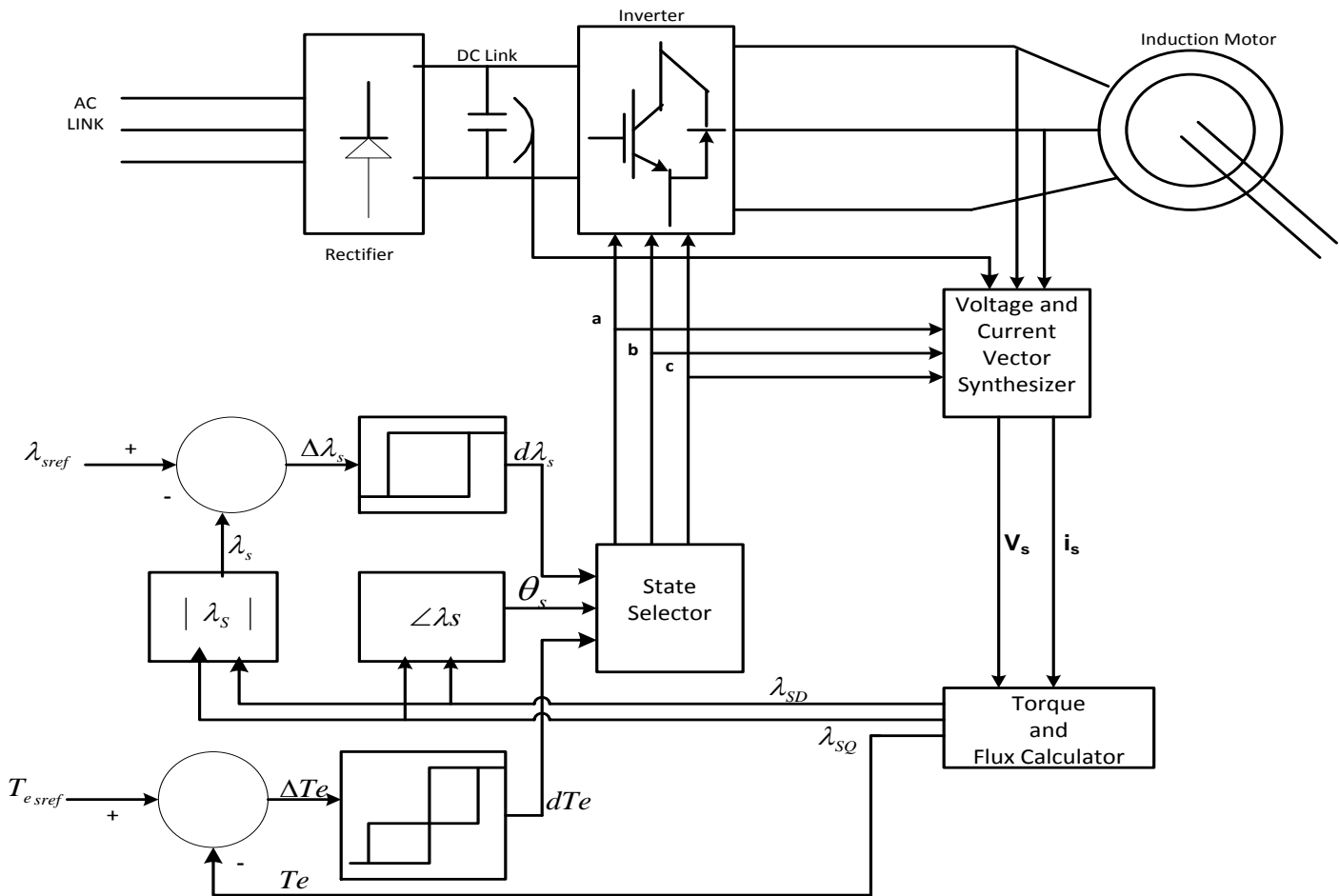


Figure 3.2 Block diagram of the DTC drive system [3]

The output of the flux and torque comparators ($\Delta\lambda_s, \Delta T_e$) are used in the inverter optimal switching table, which also uses the information of the position of the stator flux – linkage space vector.

The flux – linkage and electromagnetic errors are restricted within their respective hysteresis bands, which are $2\Delta\lambda_s$ and $2\Delta T_e$ wide respectively. The flux hysteresis band mainly affects the stator – current distortion in terms of low-order harmonics, and torque hysteresis band affects the switching frequency and thus the switching losses. The DTC scheme requires flux – linkage and electromagnetic torque calculators. Thus each part of the DTC will be discussed in detail in the following sections.

3.3 Direct Torque Control of a Voltage Source Inverter Fed Induction Motor

The basic premises and principles of the direct torque control (DTC) method proposed by Takahashi and Noguchi in 1985[3]. In DTC induction motor drive, supplied by a voltage source inverter, it is possible to control directly the stator flux linkage and the electromagnetic torque by the selection of optimum inverter switching modes. The selection is made to restrict the flux and torque errors with respective flux and torque hysteresis bands, to obtain fast torque response, low inverter switching frequency, and low harmonic losses. DTC allows very fast torque responses and flexible control of and induction motor.

In a symmetrical three-phase induction motor the instantaneous electromagnetic torque is proportional to the cross - vectorial product of the stator flux – linkage space vector and the stator – current space vector.

$$T_{e=\frac{3}{2}P\bar{\lambda}_s \times \bar{i}_s} \text{-----} (3.1)$$

Where $\bar{\lambda}_s$ is the stator flux – linkage Space vector and \bar{i}_s is the stator – current space vector.

In equations (3.1), both space vectors are expressed in the stationary reference frames. By considering that

$\bar{\lambda}_s = |\bar{\lambda}_s| \exp(j < \lambda_s)$, where $< \lambda_s$ is the angle of the stator flux linkage space vector with respect to the direct axis of the stator reference frame and

$\bar{i}_s = |\bar{i}_s| \exp(j \times s)$, where x_s is the angle of stator current space vector with respect to the direct axis of the stator reference frame. We can put equations (3.1) into the following form:

$$T_{e=\frac{3}{2}P|\bar{\lambda}_s||\bar{i}_s| \sin(x_s - \lambda_s)} \text{-----} (3.2)$$

where $\alpha_s = \angle \lambda_s - \angle i_s$ is the angle between the stator flux linkage and stator current space vector. The relationship between the stator flux linkage and stator current space vectors is shown in figure (3.1)

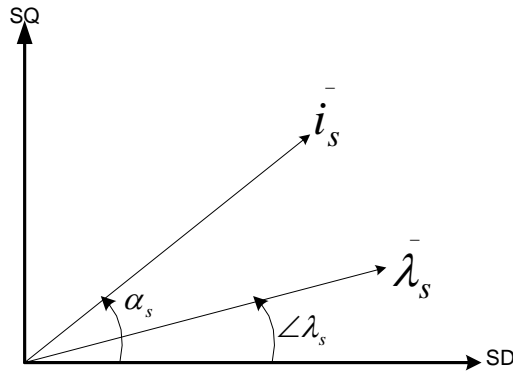


Figure 3-3 Stator flux linkage and stator current space vectors [8]

From the motor voltage equation (2.19), for the omitted voltage drop on the stator resistance, the stator flux can be expressed as:

$$\frac{d\bar{\lambda}_s}{dt} = \bar{v}_s \text{-----(3.3)}$$

Taking into consideration the output voltage of the inverter in the above equation it can be written as:

$$\bar{v}_s = \int_0^t V_k dt \text{-----(3.4)}$$

where

$$\bar{v}_k = \begin{cases} \frac{3}{2} v_{dc} e^{j(k-1)\pi/3} , & k = 1 \text{-----} 6 \\ 0 & \end{cases} \text{-----(3.5)}$$

$k = 7, 8$

Equation (3.4) describes eight voltage vectors which correspond to possible inverter states.

3.3.1 Voltage Source Inverter

There are many topologies for the voltage source inverter used in DTC control of induction motors that give high number of possible output voltage

vectors [9]_[12] but the most common one is the six step inverter. A six step voltage inverter provides the variable frequency Ac voltage input to the induction motor in DTC method. The DC supply to the inverter is provided either by a dc source like a battery, or a rectifier and the so-called dc link, composed of a capacitor, c, and inductor, L supplied form a three phase (or a single phase) AC source Figure (3.4)shows a six step voltage source inverter. The inductor L is inserted to limit shot through fault current. A large electromagnetic capacitor C is inserted to stiffen the dc link voltage.

The switching devices in the voltage source inverter bridge must be capable of being turned off and on Insulated gate bipolar transistors (IGBT) are used because they have this ability in addition; they offer high switching speed with enough power rating. Each IGBT has an inverse parallel-connected diode. This diode provides alternate path for the motor current after the IGBT is turned off [2].

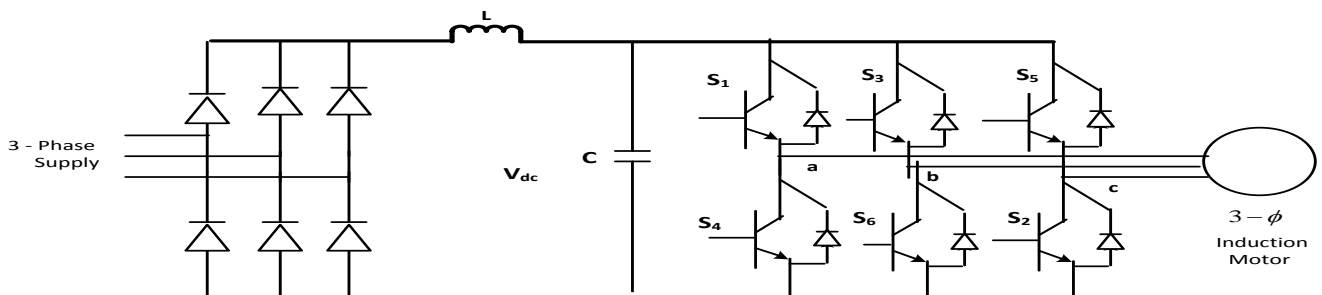


Figure 3.4 Voltage Source Inverter

The inverter produces six non-zero active-switching space vectors ($\bar{v}_1, \bar{v}_2, \dots, \bar{v}_6$) and two zero space vectors (\bar{v}_7, \bar{v}_8). These eight switching states are shown in figure (3.5).

The six active inverter- switching vectors can be expressed as

$$\bar{v}_s = \bar{v}_k = \frac{2}{3} v_{dc} \exp \left[j (k - 1) \frac{\pi}{3} \right] \text{-----} (3.6)$$

Where V_{dc} is the DC link voltage and $k=1, 2, \dots, 6$. For $k=7$ and $8, \bar{V}_k=0$ holds for the two zero – switching states where the stator winding are short circuited, and $\bar{V}_s = \bar{V}_k=0$

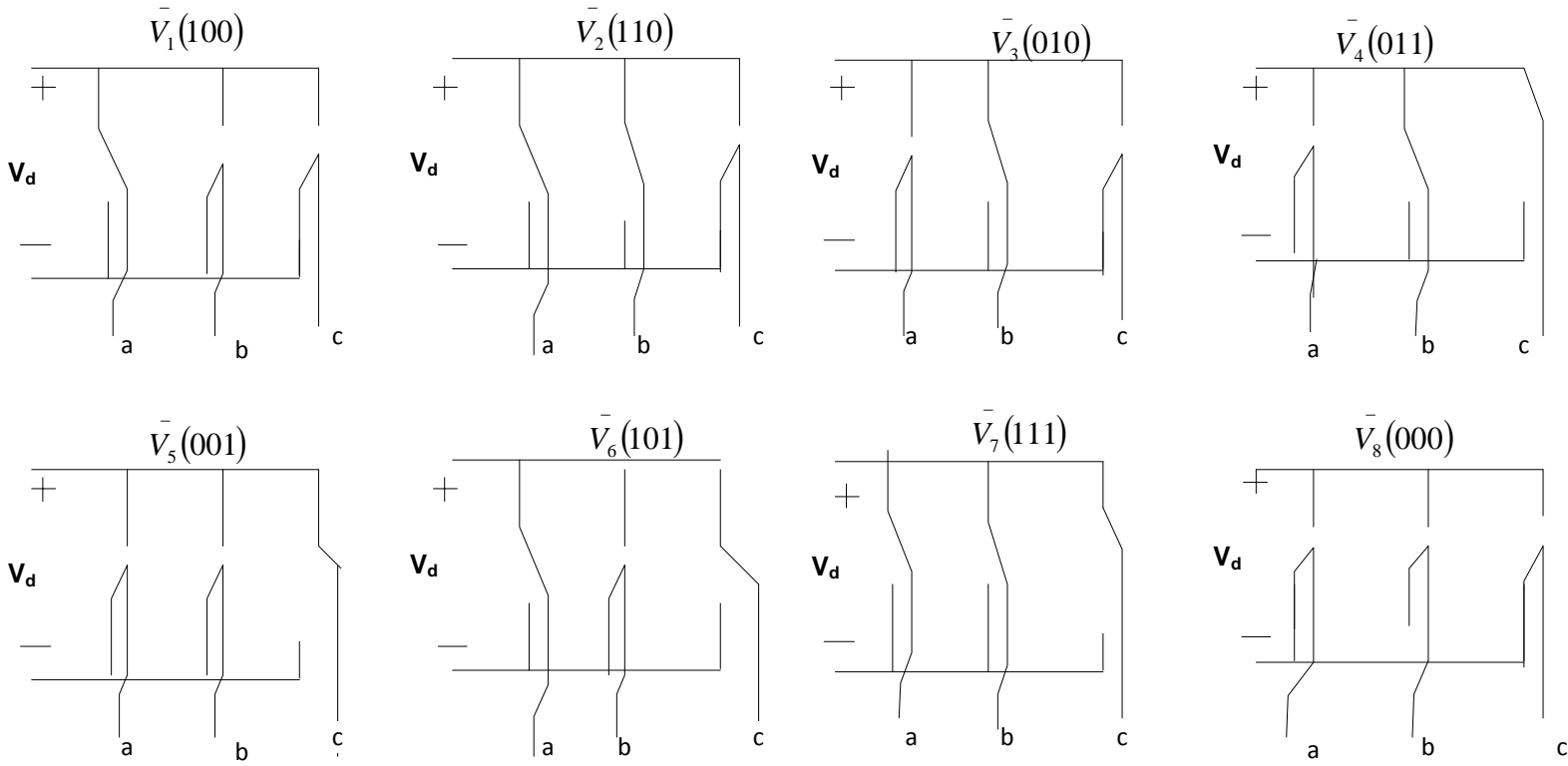


Figure 3.5 Eight Switching States of the PWM VSI inverter [8]

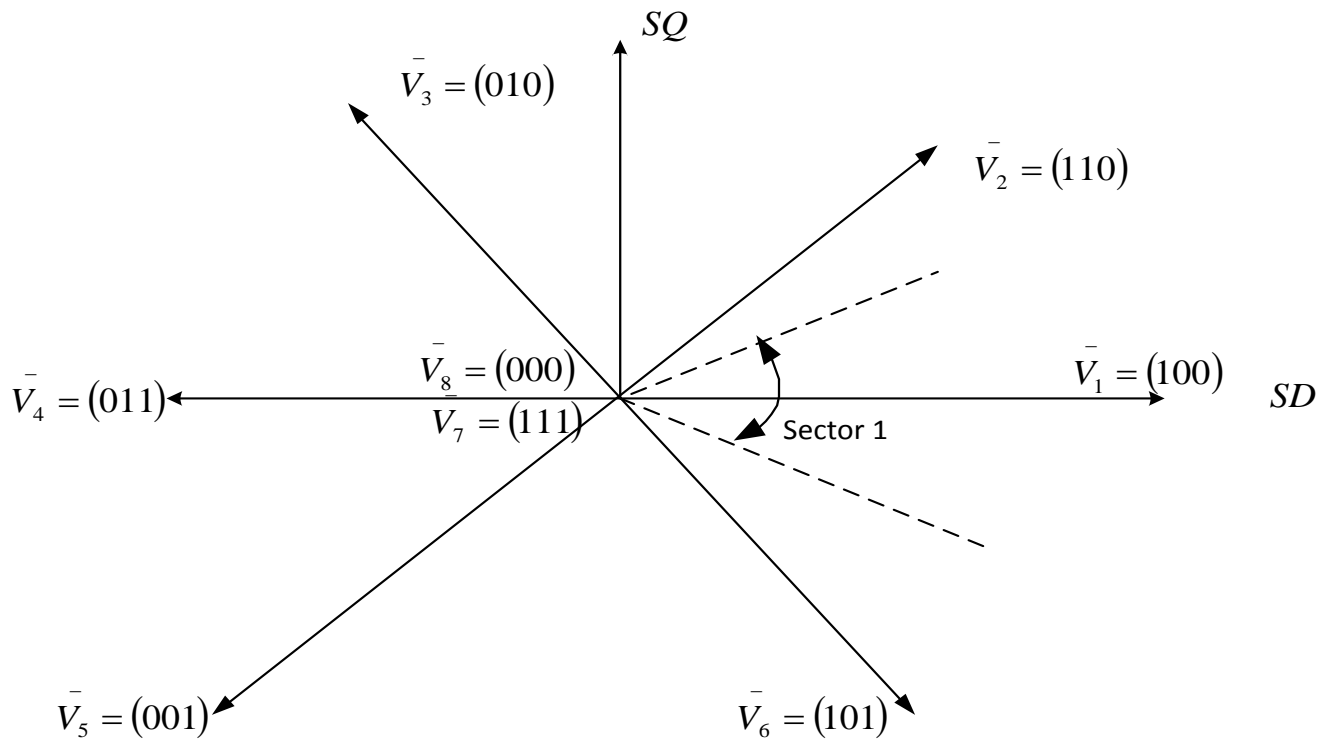


Figure 3.6 Eight corresponding switching space vectors [8]

Voltage source inverter are so controlled that one switch in each leg is on and the other leg is off. In this way, the turned-on switch connects one of the input terminals to the output terminal, and potentials of all three output terminals are always known. To avoid the so-called shot-through, that is, potentially damaging simultaneous condition of both switches in the same leg, turn-on of a switch is delayed a little with respect to turn-off of the other switch. This delay, on the order of few microseconds, is called a dead time or blanking time.

3.3.1.1 PWM Voltage Source Inverter Switching States and Space Vectors

A six- pulse PWM VSI-fed inverter is shown in figure (3.7).

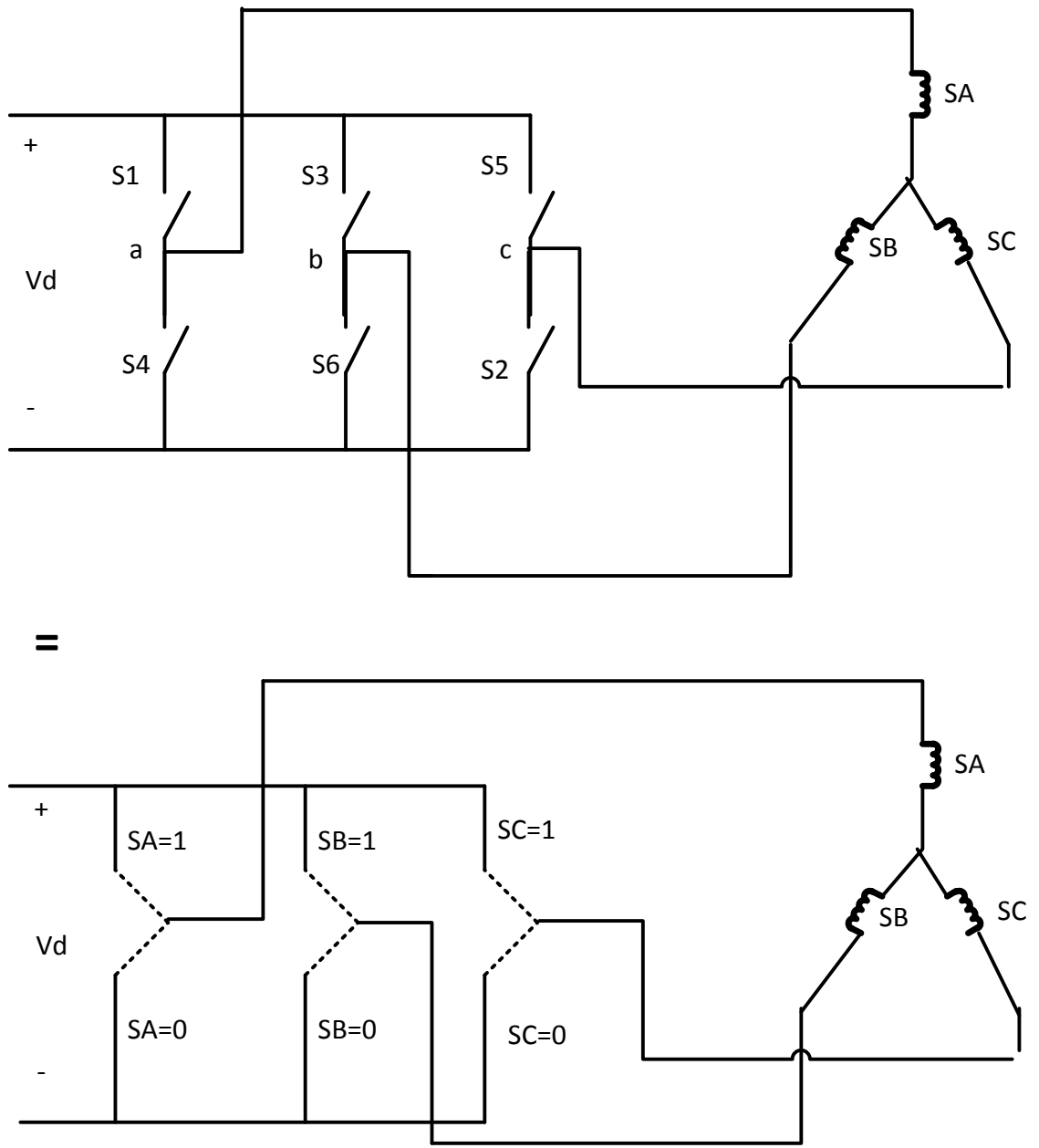


Figure 3.7 Schematic of PWM VSI inverter [8]

3.3.2 Stator Flux Vector Estimation

In the DTC induction motor drive the stator – flux – linkage components have to be estimated due to two reasons. First, these components are required in the optimum switching vector selection and secondly, they are also required for the estimation of the electromagnetic torque. It follows directly from the stator voltage equation in the stator reference frame that:

$$\lambda_{sD} = \int (V_{sD} - R_s i) dt \text{----- (3.7)}$$

$$\lambda_{sQ} = \int (V_{sQ} - R_s i) dt \text{----- (3.8)}$$

Since $\bar{\lambda}_s = \lambda_{sD} + j\lambda_{sQ}$, the stator flux angle ($\angle \lambda_s$) can be determined by using the estimated values of the direct and quadrature – axis stator flux linkages in the stationary reference frame ($\lambda_{sD}, \lambda_{sQ}$); thus

$$\angle \lambda_s = \tan^{-1}(\lambda_{sQ} / \lambda_{sD}) \text{----- (3.9)}$$

Alternatively

$$\angle \lambda_s = \cos^{-1}(\lambda_{sD} / \bar{\lambda}_s) \text{----- (3.10)}$$

Can also be used, where $|\bar{\lambda}_s| = (\lambda_{sD}^2 + \lambda_{sQ}^2)^{1/2}$

Or the expression

$$\angle \lambda_s = \sin^{-1}(\lambda_{sQ} / |\lambda_s|) \text{----- (3.11)}$$

3.3.3 Electromagnetic Torque Estimation

For instantaneous torque control it is necessary to have a very accurate electromagnetic torque estimator. There are many possibilities for estimating the electromagnetic torque, for example, it can be obtained by using the estimated flux linkages and monitored stator currents.

$$T_e = \frac{3}{2} P (\lambda_{sD} i_{sQ} - \lambda_{sQ} i_{sD}) \text{----- (3.12)}$$

3.3.4 Hysteresis Controllers

DTC of induction motor drives requires two hysteresis controllers. The drive performance is influenced by the width of the hysteresis bands in terms of flux and torque ripples, current harmonics and switching frequency of power electronics devices.

3.3.4.1 Flux Hysteresis Controller

The flux hysteresis controller is a two level controller. Thus the flux control loop has two digital outputs. The stator flux error $\Delta\lambda_s$ is given to the flux hysteresis controller and the output is flux error status ($d\lambda_s$) which can have two values and 1. The width of the hysteresis band is $2\Delta\lambda_s$. flux error status is given to the switching table for the optimum voltage vector selection for the voltage source inverter.

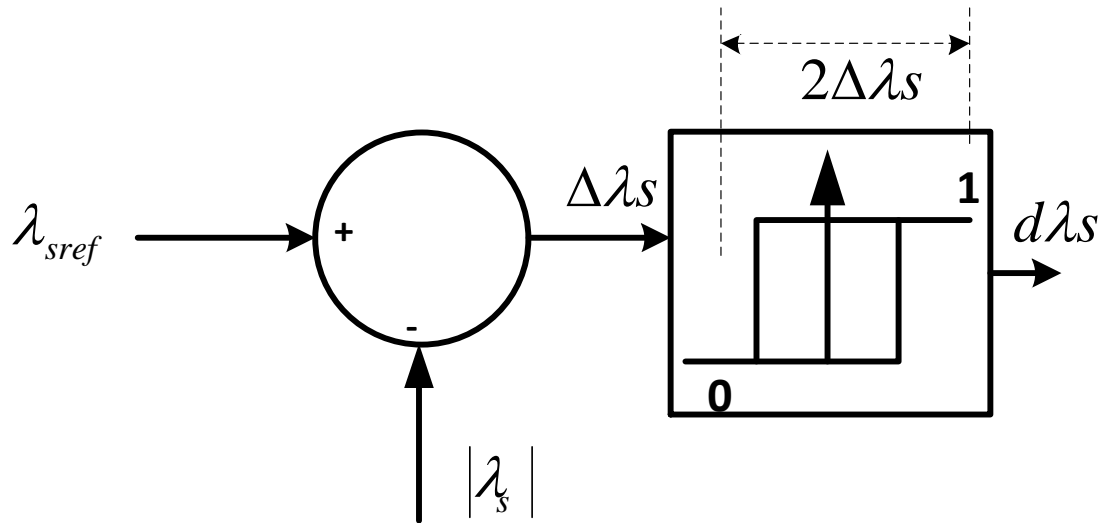


Figure 3.8 Flux hysteresis controller

$$\text{Stator flux error, } 2\Delta\lambda_s = \lambda_{sref} - |\lambda_s| \text{ ----- (3.13)}$$

$$|d\lambda_s|=1 \text{ if } |\lambda_s| < |\lambda_{sref}| - |\Delta\lambda_s|: \text{ flux to be increased -----(3.14)}$$

$$|d\lambda_s|=0 \text{ if } |\lambda_s| < |\lambda_{sref}| + |\Delta\lambda_s|: \text{ flux to be decreased ----- (3.15)}$$

3.3.4.2 Torque Hysteresis Controller

The torque hysteresis controller is a three level controller. It means the torque control loop has three levels of digital outputs. The torque error ΔT_e is given to the torque hysteresis controller and the output is torque error status (dT_e) which can have three values -1,0 or 1. The width of the hysteresis band is $2\Delta T_e$. Torque error status is given to the switching table for optimum voltage selection for the voltage source inverter.

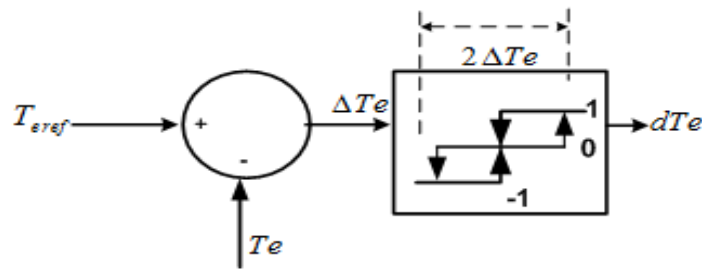


Figure 3-9 Torque hysteresis control

$$\text{Torque error, } \Delta T_e = T_{ref} - T_e \text{ ----- (3.16)}$$

$$dT_e = 1 \text{ if } |T_e| < |T_{ref}| - \Delta T_e : \text{Torque to be increased} \text{ --- (3.17)}$$

$$dT_e = -1 \text{ if } |T_e| > |T_{ref}| + \Delta T_e : \text{Torque to be decreased} \text{ --- (3.18)}$$

$$dT_e = 0 \text{ if } |T_e| = |T_{ref}| : \text{Torque remain unchang} \text{ --- (3.19)}$$

3.3.5 Controlling Torque and Flux through Hysteresis

During every sampling period, we select switching vectors to keep the stator flux linkage errors within the required tolerance band and the torque error. The upper limit is one Δ above the reference and the lower limit is one Δ below. In terms of low order harmonics, the flux hysteresis band mainly affects the stator current distortion. The torque Hysteresis band affects the switching frequency and, thus, the switching losses. This scheme requires the use of flux linkage and torque estimators.

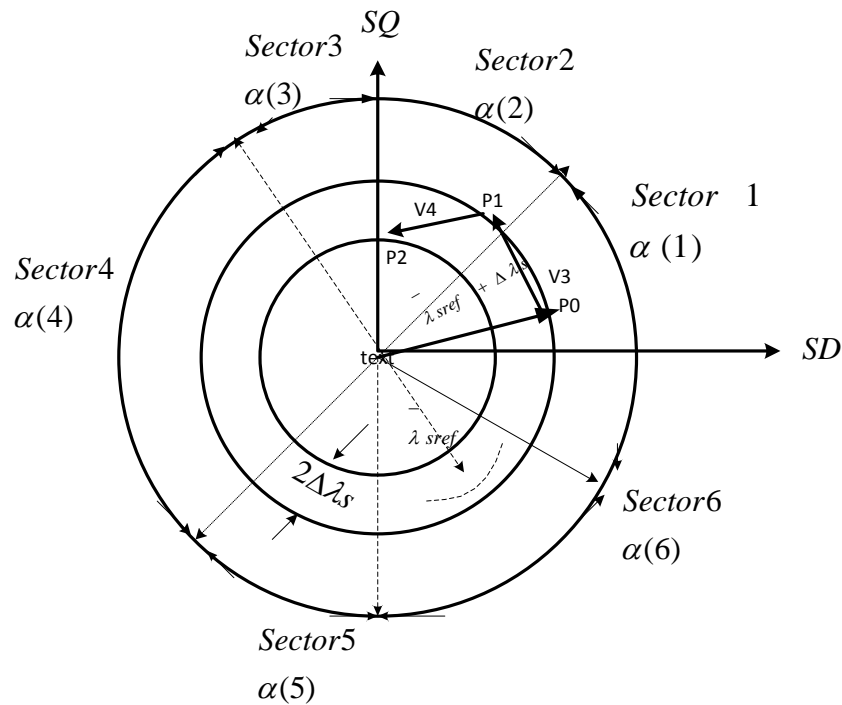


Figure 3.10 Control of the stator flux linkage space vector: Stator flux linkage space vector:stator flux linkage space vector locus and inverter switching errors. [8]

The objective is to keep the modulus of the stator flux linkage space vector $|\bar{\lambda}_s|$ within the hysteresis band, denoted by the two circles whose width is $2\Delta\lambda_s$, as shown in figure (3.10). Due to the six-step inverter, the locus of the flux linkage space vector is divided into the six sectors shown in figure (3.10). If the stator flux linkage space vector is initially at point p_0 (sector one) and rotating counterclockwise, then the stator flux linkage is at the upper limit and must be reduced. As shown in figure (3.10) applying \bar{v}_3 achieves reduction. The stator flux linkage space vector moves from p_0 to p_1 (sector 2) and, once again, reaches the upper limit. Once again (when rotating counterclockwise) applying the switching vector \bar{v}_4 reduces the stator flux linkage appropriately. Now, $\bar{\lambda}_s$ moves from p_1 to p_2 (still in sector 2). If at point p_1 , the rotation of the stator flux linkage space vector must be stopped, then a zero switching vector, either \bar{v}_7 (111) or \bar{v}_8 (000), has to be applied. Since the last switching vector applied was \bar{v}_3 (010), then \bar{v}_8 is used because only the switching of the second switch from 1 to 0 is required. The

switching vector that requires the minimum amount of switching should always be chosen [8]

As discussed above, stopping the rotation of the stator flux linkage space vector corresponds to the case when the electromagnetic torque does not have to be changed when it has to be changed. In either the clockwise or counterclockwise direction, then the stator flux linkage space vector has to be rotated in the appropriate direction. When the stator flux linkage rotates counterclockwise and if an increase in torque is required (ie, the stator flux linkage space is at point p1 where the flux linkage is at its upper limit) then the increase in torque is required but the flux linkage is at the lower limit and must be increased, then this is achieved by applying switching vector v1 because this moves the stator flux linkage space vector in the clockwise direction (or in the direction of negative torque) and also increases the flux linkage.

In order to make more comprehensive controlling of torque and flux through hysteresis, he can see the following analysis. For the stator flux vector laying in sector 1 (figure 3.11) in order to increase its magnitude the voltage vectors $\overline{v_1}, \overline{v_2}$ can be selected. Conversely, a decrease can be obtained by selecting, $\overline{v_3}, \overline{v_4}, \overline{v_5}$. By applying one of the zero vectors v_8 or v_7 the integration in equation (3,4) is stopped. The stator flux vector is not changed.

For the torque control between stator and rotor flux is used. Therefore, to increase motor torque the voltage vectors $\overline{v_2}, \overline{v_3}, \overline{v_4}$ can be selected and to decrease the torque $\overline{v_1}, \overline{v_5}, \overline{v_6}$ can be selected. The above considerations allow construction of the selection table as discussed in the next section

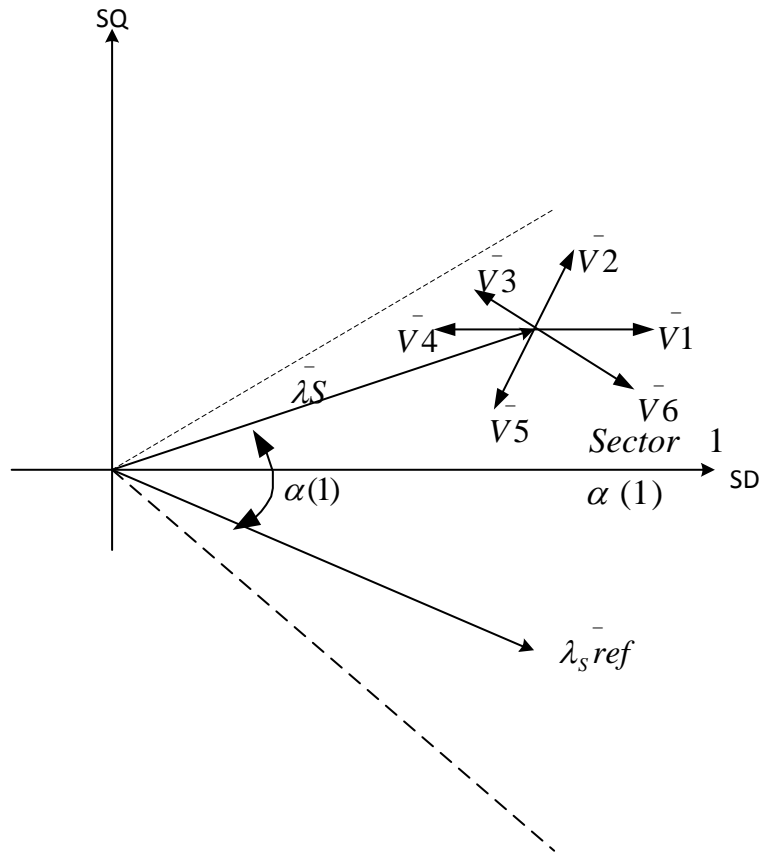


Figure 3-11 Selection of the optimum voltage vectors for the stator flux vector in sector 1

3.3.6 Optimum Switching Vector Selection

The locations of the various stator flux linkage vector, if the stator flux linkage space vector is in one of the six sectors are shown in figure (3.12)

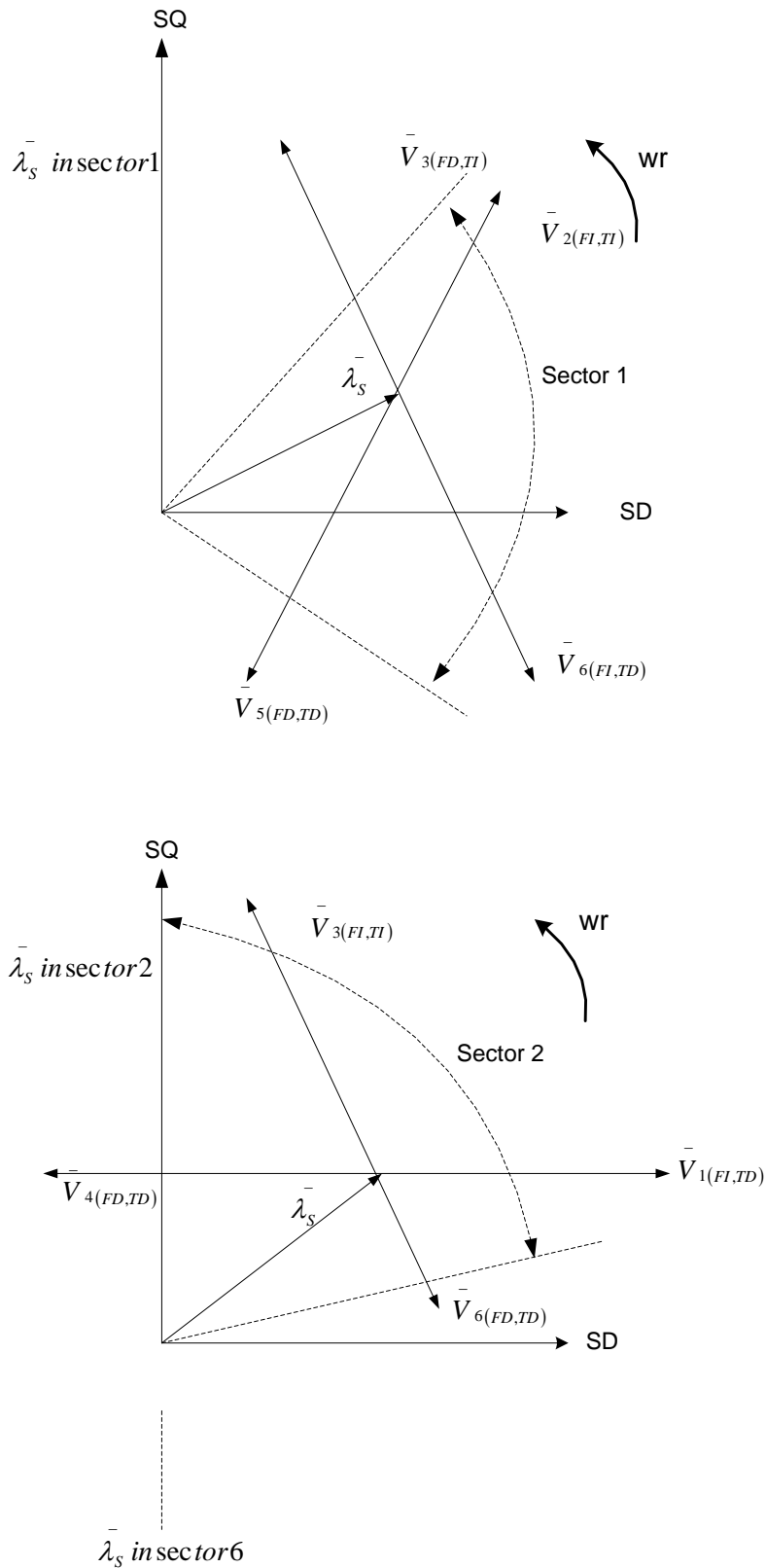


Fig. (3-19) Position of various stator flux linkage space vectors and section of the optimum switching vectors: FI: flux increase; FD: flux decrease; TI: torque increase; TD: torque decrease [8]

The table (3.1) given below gives the optimum selection of the switching vectors for all the possible stator flux-linkage space-vector positions (six positions, corresponding to the six sectors shown in figure (3.10)), where sector 1 is in the range of (1) , sector 2 is the range of $\alpha(2)$ ----- sector 6 is in the range of $\alpha(6)$ and the desired control inputs (which are the reference values of the stator flux-linkage modulus and the electromagnetic torque respectively)

If a stator flux increase is required then $d\lambda_s = 1$, if a stator flux-linkage decrease is required $d\lambda_s = 0$. The notation corresponds to the fact that the digital output signals of a two-level flux hysteresis comparator are $d\lambda_s$ where

$$/d\lambda_s/ = 1 \text{ if } / \bar{\lambda}_s / < / \bar{\lambda}_s^{ref} / - / \Delta \lambda_s / \text{ ----- (3.20)}$$

$$/d\lambda_s/ = 0 \text{ if } / \bar{\lambda}_s / > / \bar{\lambda}_s^{ref} / + / \Delta \lambda_s / \text{ ----- (3.21)}$$

If a torque increase is required then $dTe = 1$, if a torque decrease is required then $dTe = -1$ and if no change in the torque is required then $dTe = 0$

The notation corresponds to the fact that the digital output signals of a three-level hysteresis comparator are dTe , where for anticlockwise rotation (forward rotation)

$$/dTe/ = 1 \text{ if } /Te/ < /Teref/ - / \Delta Te / \text{ ----- (3.22)}$$

$$/dTe/ = 0 \text{ if } /Te/ = /Teref/ \text{ ----- (3.23)}$$

$$/dTe/ = -1 \text{ if } /Te/ > /Teref/ + / \Delta Te / \text{ ----- (3.24)}$$

Table 3.1 Optimum voltage switching vector look-up table [8]

	$\alpha(1)$	$\alpha(2)$	$\alpha(3)$	$\alpha(4)$	$\alpha(5)$	$\alpha(6)$	
	Sector 1	Sector 2	Sector 3	Sector 4	sector5	Sector 6	
dT_e							
$d\lambda_s$	1	\bar{v}_2	\bar{v}_3	\bar{v}_4	\bar{v}_5	\bar{v}_6	\bar{v}_1
1	0	\bar{v}_7	\bar{v}_8	\bar{v}_7	\bar{v}_8	\bar{v}_7	\bar{v}_8
	-1	\bar{v}_6	\bar{v}_1	\bar{v}_2	\bar{v}_3	\bar{v}_4	\bar{v}_5
	1	\bar{v}_3	\bar{v}_4	\bar{v}_5	\bar{v}_6	\bar{v}_1	\bar{v}_2
0	0	\bar{v}_8	\bar{v}_7	\bar{v}_8	\bar{v}_7	\bar{v}_8	\bar{v}_7
	-1	\bar{v}_5	\bar{v}_6	\bar{v}_1	\bar{v}_2	\bar{v}_3	\bar{v}_4

Active switching vectors $\bar{v}_1(100)$; $\bar{v}_2(110)$; $\bar{v}_3(010)$; $\bar{v}_4(011)$; $\bar{v}_5(001)$; $\bar{v}_6(101)$

Zero switching vectors: $\bar{v}_7(111)$; $\bar{v}_8(000)$

CHAPTER 4

Fuzzy Controlled Direct Torque Control of Induction Motor Drive

4.1 Introduction

Traditionally mathematical-model-based analysis techniques have always been for the steady-state and transient analysis of electrical machines. There are many techniques, but they mainly differ in their complexity and the many assumptions used. The main advantages of using AI (Artificial Intelligence) are the design does not require a mathematical model of the plant and to reduce the tuning efforts associated with the controllers and also to obtain improved responses [8].

However, it is possible to perform the simulations and also implementations of estimators, controllers etc in real time by using artificial intelligence based techniques (e.g Artificial Neural Networks (ANN), Fuzzy-logic Systems, Fuzzy-Neural Networks, etc), which does not require a mathematical model of the machine and drive system [8]. Such a system is not restricted by the many assumptions used in conventional electrical machine and linear control theories. It can also yield the results more quickly than by using the conventional approach.

Among the different artificial intelligence techniques either fuzzy logic or neural network can be selected as in the case of Direct Torque Control of induction motor drive. And both show the best control strategies in conventional Direct Torque Control drawbacks. Thus, in this thesis fuzzy logic controller is selected to design the switching vector selection of the conventional Direct Torque Control.

The main features of the selection of fuzzy logic controller are:

- Fuzzy logic controller incorporates ambiguous human logic into computer programs. It suits control problems that cannot be easily represented by mathematical models. For instance, weak mathematical model, parameter validation problem, unavailable or incomplete data, very complex plants,

with these difficulties. Fuzzy logic controller has good qualitative understanding of plant or process operation.

- Because of its unconventional approach, design of such controllers leads to faster development or implementation cycles.
- It is comfortable in implementation like FPGA

4.2 Fuzzy Logic Controller

Fuzzy logic is a technique to embody human like thinking into a control system. It can be designed to emulate human deductive thinking, that is, the process people used to infer conclusions from what they knew [17].

There are many types of fuzzy-logic controllers. The most used are Takagi-Sugeno(T-S) and mamdani type of fuzzy-logic controller. Mostly for controllers, the fuzzy mamdani type is used and so does for the conventional Direct Torque Control of Induction Motor Drive.

Figure 4.1 shows the basic configuration of Fuzzy-Logic Controller [8], which comprises four main parts: fuzzifier, knowledge base, inference engine and defuzzifier two of which perform transformations.

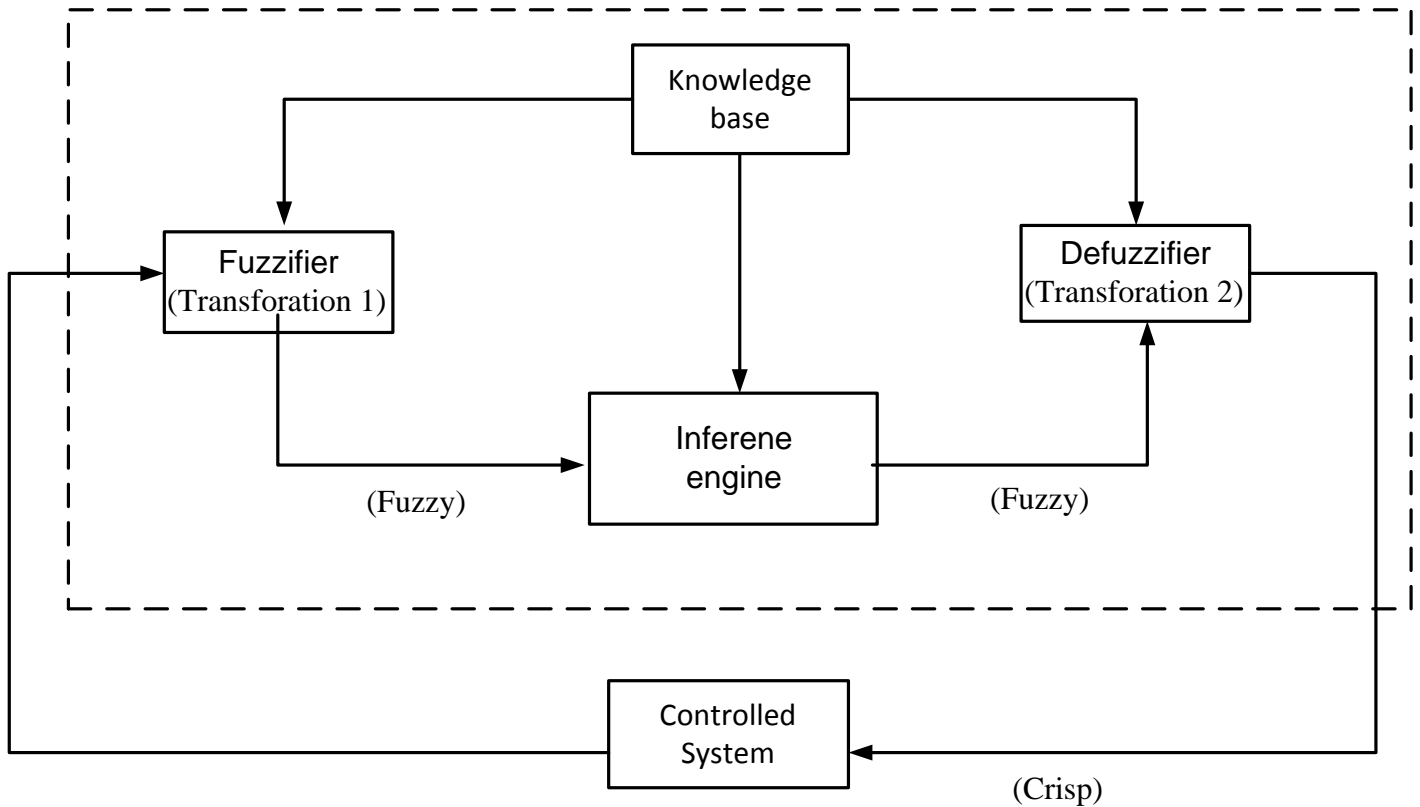


Figure 4.1 Schematic block diagram of a control system containing a mamdani type of fuzzy logic controller

The fuzzifier is the input part of Fuzzy-Logic Controller which performs measurement of the input signals (input variables, real variables), scale mapping and fuzzification (transformation1). Thus all the monitored input signals are scaled and fuzzification means that the measured signals (crisp input quantities which have numerical values) are transferred into fuzzy quantities (which are also referred to as linguistic variables). This transformation is performed by using membership functions. The number and shapes of membership functions are initially determined by the user. A membership function has a value between 0 and 1 and it indicates the degree of belongingness of a quantity to a fuzzy set. The membership function can take many forms including triangular, Gaussian, bell-shaped, trapezoidal etc. the

initial forms of the membership function can be obtained by using expert considerations or by clustering the input data.

The knowledge base consists of the database and the linguistic-control rule base. The database provides the information which is used to define the linguistic control rules and the fuzzy data manipulation in the Fuzzy-Logic Controller. The rule based specifies the control goal actions by means of a set of linguistic control rules. The Fuzzy-Logic Controller looks at the input signals and by using the expert rules determines the appropriate output signals. The rule base contains a set of IF-THEN rules. The main methods of developing the rule base are modeling the control action of the operator and modeling the process.

The inference engine is the kernel of a Fuzzy-Logic Controller and has the capability both of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions by using fuzzy implication and fuzzy-logic rules of inference. In other words, once all the monitored input variables are transformed into their respective linguistic variables, the inference engine evaluates the set of if-then rules and thus a result is obtained which is again a linguistic value for the linguistic variable. This linguistic result has then to be transformed into a real output value of the Fuzzy-Logic Controller and that is why there is a second transformation in the Fuzzy-Logic Controller.

Defuzzification decides the crisp output from fuzzy output of the inference section. It is the second transformation which performs scale mapping as well as defuzzification. The defuzzification yields a non-fuzzy, real control action from the inference fuzzy control action by using membership functions. There are many defuzzification techniques, but due to the simplicity of its implementation and simpler training algorithms, the center of gravity method is adopted here. Physically, this corresponds to taking a weighted average of the control action contributions from each of the various fuzzy rules.

4.3 Design of Fuzzy-Logic Based duty-ratio Controller

4.3.1 Introduction

In the DTC induction motor drive, there are torque and flux ripples, since none of the inverter switching vectors is able to produce the desired changes in the electromagnetic torque and stator flux linkage in most of the switching instances. However, the ripples in electromagnetic torque and stator flux linkages can be reduced by using various techniques, some of which do not involve high switching frequency and change of inverter topology like duty ratio control.

In a DTC induction motor drive, increased switching frequency is desirable since it reduces the harmonic content of the stator currents, and also leads to reduce torque harmonics. However, if high switching frequency is used, this will result insignificantly increased switching losses which leads to reduce efficiently and increased stress on the semiconductor devices of the inverter. Furthermore, in the case of high switching frequency, a fast processor is required since the control processing time becomes small. When an alternative inverter topology is used, it is possible to use an increased number of switches, but this also increases the cost. However, if instead of applying a voltage vector for the entire switching period, it is applied for a portion of the switching period, then the ripple can be reduced. This is defined as duty ration control in which the ration of the portion of the switching period for which a non-zero voltage vector is applied & the complete switching period is known as the duty ratio (δ).

4.3.2 Fuzzy Logic Based Duty Ratio Control

In the conventional DTC a voltage vector is applied for the entire switching period, and this causes the stator current and electromagnetic torque to increase over the whole switching period. Thus for small errors, the electromagnetic torque exceeds its reference value early during the cycle, and continues to increase, causing a high torque ripple. This is then followed by switching cycle in which the zero switching vectors are applied inorder to reduce the electromagnetic torque to its reference value.

The ripple in the torque and flux can be reduced by applying the selected inverter vector not for the entire switching period, as in the conventional DTC induction motor drive, but only for a part of the switching period. The time for which a non-zero voltage vector has to be applied is chosen so as to increase the electromagnetic torque to its reference value. When the electromagnetic torque reaches its reference value, a zero voltage is forced on the machine on the machine, and thus the electromagnetic torque is almost constant, it only decreases slightly.

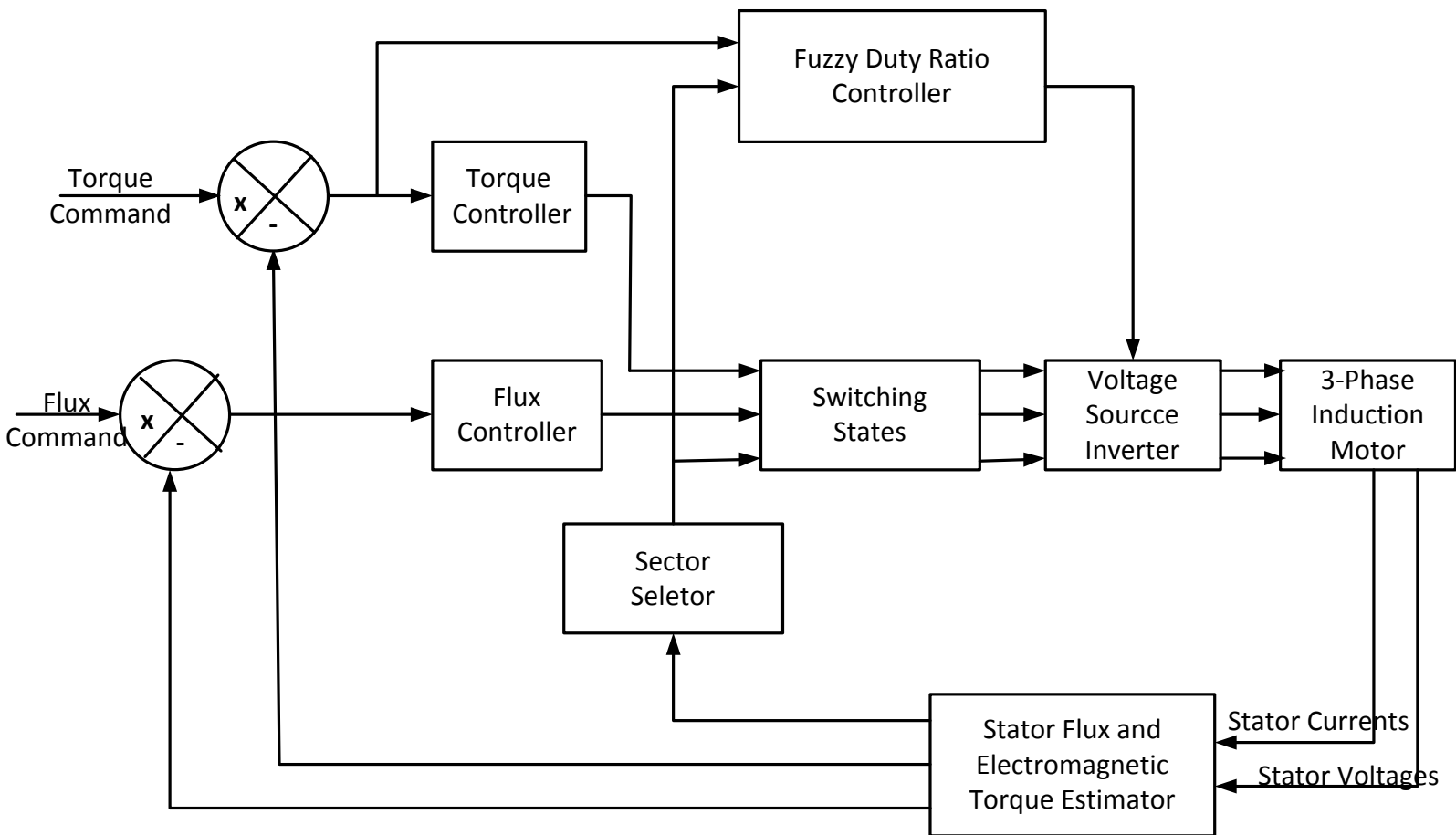


Figure 4.2 General Block Diagram of DTC of three phase induction motor using duty ratio fuzzy controller

Figure 4.2 shows a DTC induction motor drive with a fuzzy logic based duty-ratio controller. The average input DC voltage to the motor during the application of each switching vector is δV_{dc} . By varying the duty ratio between zero and one, it is possible to apply any voltage to the motor with an average value between 0 and V_{dc} during each switching period. This increases the choice of the voltage vector, which is limited by the number of switching vectors in the conventional DTC induction motor drive. The duty ratio is selected to give a voltage vector whose average over the switching cycle gives the desired torque change, thus resulting in reduced torque ripples.

The duty ratio of each switching state is a non-linear function of the electromagnetic torque error, stator flux linkage error and the position of the stator flux-linkage space vector. Thus, it is difficult to model this non-linear function. However, by using a fuzzy-logic based DTC system, it is possible to perform fuzzy-logic based duty ratio control, where the duty ratio is determined during every switching cycle. In this fuzzy-logic system, there are two inputs, the electromagnetic torque error $e_{Te} = T_{e \text{ ref.}} - T_e$ and the stator flux-linkage position $\angle \lambda^* s$. The output of the Fuzzy Logic Controller is the duty ratio (δ).

The Fuzzy-Logic Controller shown in figure 4.2 above is a mamdani type of controller and contains a rule base, but this comprises two groups of rules, each of which contains nine rules. The first group is used when the stator flux linkage is smaller than its reference values and the second group of rules is used when it is greater than its reference values.

4.3.3 Fuzzy Variables

The fuzzy logic controller is designed to have two groups of rules and each have two fuzzy state variables and one control variable for achieving direct torque control induction motor drive drawbacks. Thus, there are two input variables in fuzzy controller: electromagnetic torque error and angle of stator flux linkage and the output of each fuzzy controller is the duty ratio.

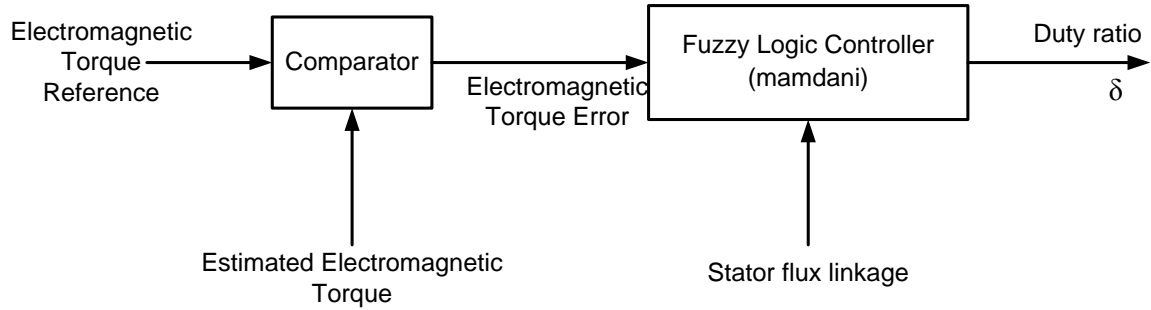


Figure 4.3 Fuzzy Logic Controller duty-ratio estimator

4.3.3.1 Electromagnetic Torque Errors

The error of the electromagnetic torque is the difference between the reference and estimated values of electromagnetic torque.

Electromagnetic Torque errors, $\Delta T_e = T_{e \text{ ref.}} - T_e$

The number of fuzzy sets of electromagnetic torque errors can be represented by three fuzzy sets: small, medium and large.

The three membership functions for the electromagnetic torque errors can be constructed according to the particular machine used here in this thesis. It can vary with the electromagnetic torque and the constant values shown for the torque depend on the specific machine used.

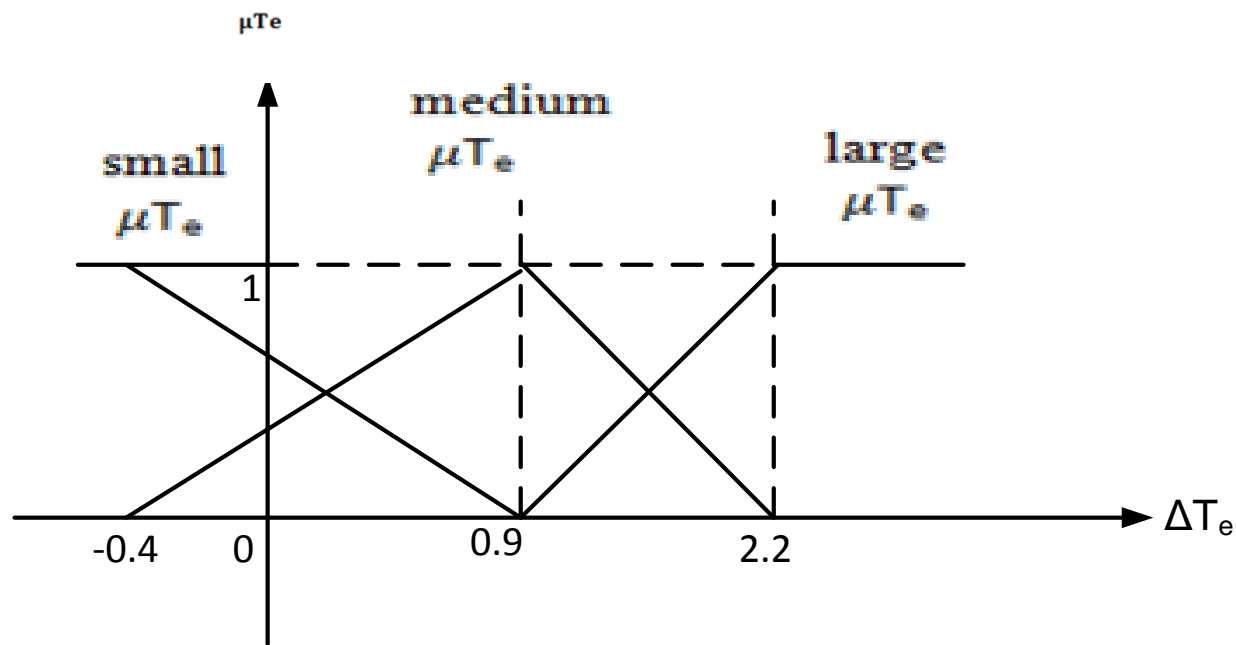


Figure 4.4 The fuzzy membership functions for Electromagnetic Torque

4.3.3.2 Angle of Stator Flux Linkage

The angle of flux linkage is the angle of the stator flux linkage space vector with respect to the direct axis of the stator reference frame.

The actual stator flux angle to the fuzzy logic controller is the difference between the original stator flux angle to the new stator flux angle which is formulate by $\pi/3$.

The number of fuzzy sets of stator flux linkage angles can be represented by three fuzzy sets: small, medium and large.

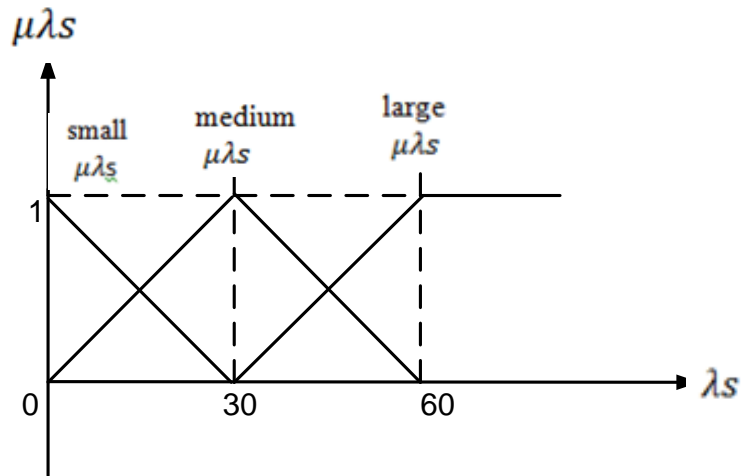


Figure 4.5 The fuzzy membership functions for angles of flux linkage

4.3.3.3 Duty Ratio

The control variable is the duty ratio that varies from zero to one. The number of fuzzy sets of the duty ratio can be represented by three fuzzy sets: small, medium and large.

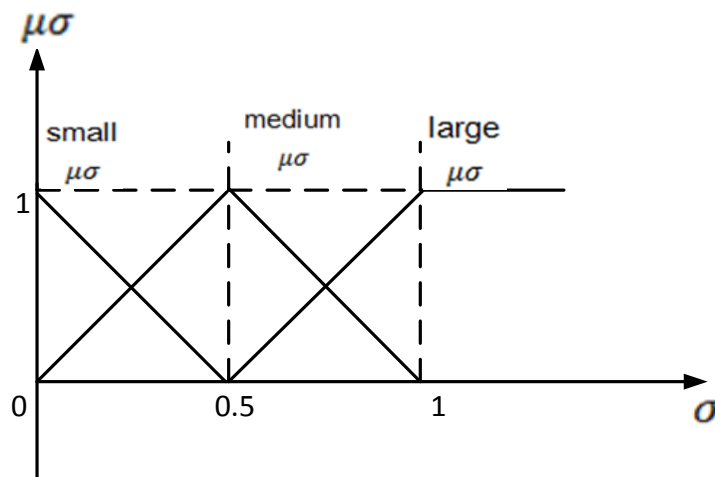


Figure 4.6 The fuzzy membership functions for duty ratio

4.3.4 Fuzzy Control Rules

A fuzzy control rule is the heart of the Fuzzy-Logic Controller. It has a rule base and contains individual rules (sub rules). In general, these linguistic rules are in the form of IF-THEN rules. For a given numerical values of the measured scaled inputs to the FLC, several rules can be activated simultaneously. This follows from the fact that a given numerical values can be a member of more than one fuzzy set (this is determined by the membership functions.)

Although several rules are fired simultaneously, only a single control action must be performed. So the main task is to combine an appropriate manner the contribution of each rule is to obtain the duty ratio. The developments of the fuzzy rules are basically difficult. Among the different methods of developing the fuzzy rules, the experience and knowledge of an expert for the application and the control goals are used here. Each rule can be formulated using the state variables (ΔT_e and $\angle \lambda_s$).

The duty ratio is proportional to the torque error, since the torque rate of change is proportional to the angle between the stator flux and the applied voltage vector, the duty ratio depends also on the flux position within each sector.

The duty ratio is selected proportional to the magnitude of the torque error. The fuzzy rules are then adjusted and tuned to reflect the effects of the flux linkage vector position and torque error. The fuzzy rules are then adjusted and tuned to reflect the effects of electromagnetic torque and stator flux position. If the torque error is medium and stator flux angle lies in sector k with a magnitude greater than its reference value then the voltage vector V_{k+2} is selected. If the flux position is small that means there is a large angle between the flux and the selected voltage vector more effective in increasing the torque so the duty ratio is set as small. The fuzzy rule is stated as:-

If ΔT_e is small and $\angle \lambda_s$ is small then δ is medium

If ΔT_e is small and $\angle \lambda_s$ is medium then δ is medium

If ΔT_e is small and $\angle \lambda_s$ is large then δ is small

-
-
-

The rule base comprises two groups of rules each of which contains 9 rules. The first group (table 4.1 a) is used when the stator flux linkage is smaller than its reference value and the second group (table 4.1 b) of rules is used when it is greater than its reference value. Center of gravity method is used for defuzzification.

Table 4.1 Tables a and b are Fuzzy rules

duty ratio 1

λ_s ΔT_e	small	medium	large
small	medium δ	medium δ	small δ
medium	medium δ	medium δ	large δ
large	large δ	large δ	large δ

(a)

duty ratio 2

λ_s ΔT_e	Small	medium	large
small	Small Δ	small δ	medium δ
medium	Small Δ	medium δ	large δ
large	Medium Δ	large δ	large δ

(b)

CHAPTER 5

Simulation and Result Discussion

5.1 Introduction

In the design and implementation of AC drives, a dynamic model is required to design a controller to control the various parameters. In order to design the controller of a DTC of three phase induction motor drive, the machine should exhibit the proper working condition in steady state as well as in transient conditions.

The electromagnetic torque, stator flux trajectory, (D and Q axis of stator flux in stationary reference frame), three-phase stator currents and speed waveforms at different speed variations, obtained from simulation of conventional DTC of three phase induction motor drive, it is cleared that all waveforms has high ripples. These ripples are the main drawback of conventional DTC. In order to overcome the mentioned drawbacks, the use of fuzzy controlled DTC minimizes the ripples. Since the main task of the thesis is minimizing the ripples, simulation of fuzzy controlled DTC that shows the improved mentioned parameters that are simulated using MATLAB/Simulink at last.

5.2 Simulation of Conventional DTC of three phase Induction Motor Drive Using MATLAB/Simulink

The complete model of the conventional DTC using MATLAB/Simulink is developed based on the main sub-blocks of the basic DTC scheme as shown in Figure 3.1. The model is simulated and waveforms for the selected induction motor electromagnetic torque, stator flux trajectory, three phase stator currents and speed response at different speed variations, which is obtained from simulation of MATLAB program is presented and verified with simulink waveforms.

The reference torque and the magnitude of stator flux are compared with the estimated instantaneous torque and stator flux. The difference between the

estimated and the desired, the error, is controlling the parameters. Flux error and Torque errors are then input to a two-level and three-level hysteresis controllers respectively. These controllers can be represented using the relay function block. If the torque error is bigger than the upper limit, the output will become 1. The output will become -1 if the error is less than the lower limit. Otherwise the output is 0 if the error is in between the upper and lower limit. This is order of error torque to maintain in the hysteresis bandwidth. Then the level digital output will be the input to the switching table.

The optimum switching vector selector which is explained in section (3.3.6) is used to produce the switching states of the voltage source inverter to generate PWM three phase voltages to feed the induction motor. The inputs to the switching vector are electromagnetic torque comparator, stator flux magnitude comparator and stator flux angle. The switching vector is defined for a flux position in a bandwidth of $\frac{\pi}{3}$ radians. There are only six sectors considered.

The switching vector selector selects the optimum switching states of the inverter based on table 3.1. The outputs of three phases VSI, which is the stator voltages of the machine, should be changed to three -phase to two-phase voltages in stationary coordinate reference frame. Thus, the D and Q-axis of the stator voltages are inputs to the motor which is modeled in stationary coordinate reference frame that the angular speed of the frame is zero. The D and Q axis of the transformed voltages are:-

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & -1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \text{----- (5.1)}$$

where V_{as} , V_{bs} , and V_{cs} are the rms (root mean square) value of the grid voltage supply.

The stator and rotor voltages and currents of the motor used for developing the machine in MATLAB/Simulink in stationary reference frame can be expressed by the equations from (2.37 to 2.45)

The stator flux-linkage components can be estimated from the D and Q-axis of voltage and currents in stationary coordinate reference frame. It is required for the estimation of the electromagnetic torque and for the optimum switching vector selection table. These estimated electromagnetic torque and flux magnitude again compared with the reference values. The switching vector selects the switching states of the voltage source inverter by considering the changed in electromagnetic torque, flux magnitude and the stator flux sector. Figure 5.1 shows the overall MATLAB/Simulink model of the conventional DTC of three phase induction motor drive.

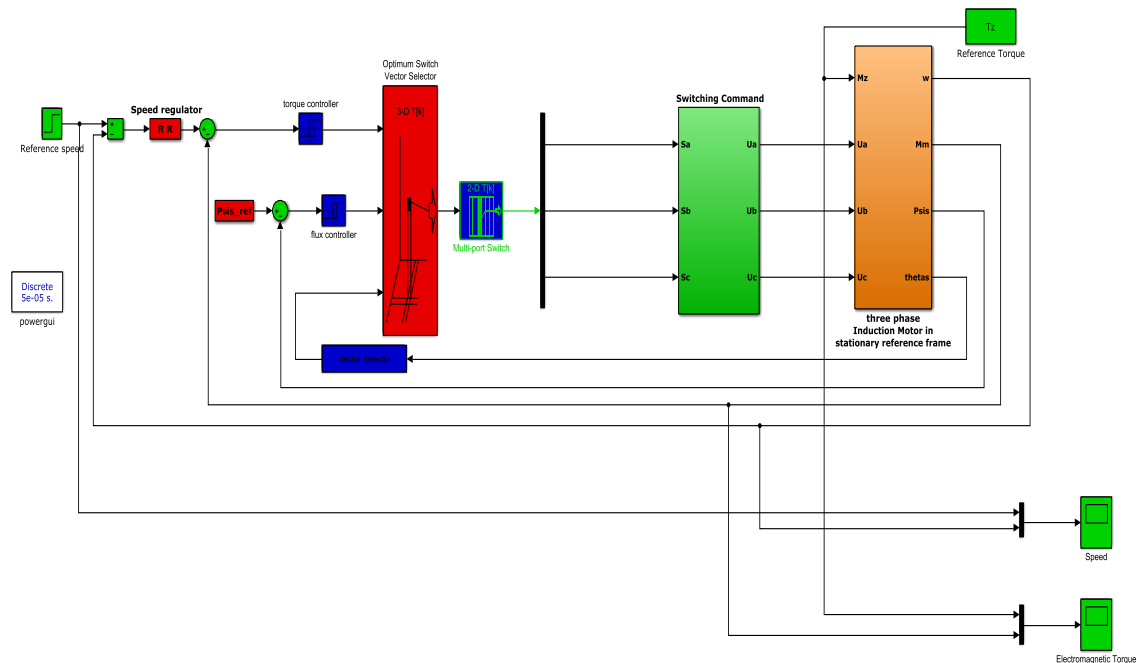


Figure 5.1 MATLAB/Simulink model of conventional DTC of three phase Induction Motor Drive

5.3 Simulation of Fuzzy Controlled DTC of three phase Induction Motor Drive Using MATLAB/Simulink

In the conventional implementation of the DTC drive, the electromagnetic torque, stator flux trajectory, three-phase stator currents have high ripples and it has speed fluctuations and sluggish speed response at low speed in different speed level and step speed input. However, these ripples and the speed problems can be reduced

by using Fuzzy controlled duty ratio, δ . The input voltage to the induction motor during the application of each voltage switch vector is δV_{dc} . V_{dc} is the DC link voltage of the inverter. By changing the duty ratio between 0 and 1, it is possible to apply any voltage between 0 and V_{dc} during each switching period. If the switching state selected in accordance with the position of flux within each bandwidth, improved controller responses can be obtained.

The overall MATLAB/Simulink model of Fuzzy controlled DTC drive is modeled by the addition of fuzzy duty ratio apart from the model of conventional DTC as shown in Figure 5.2

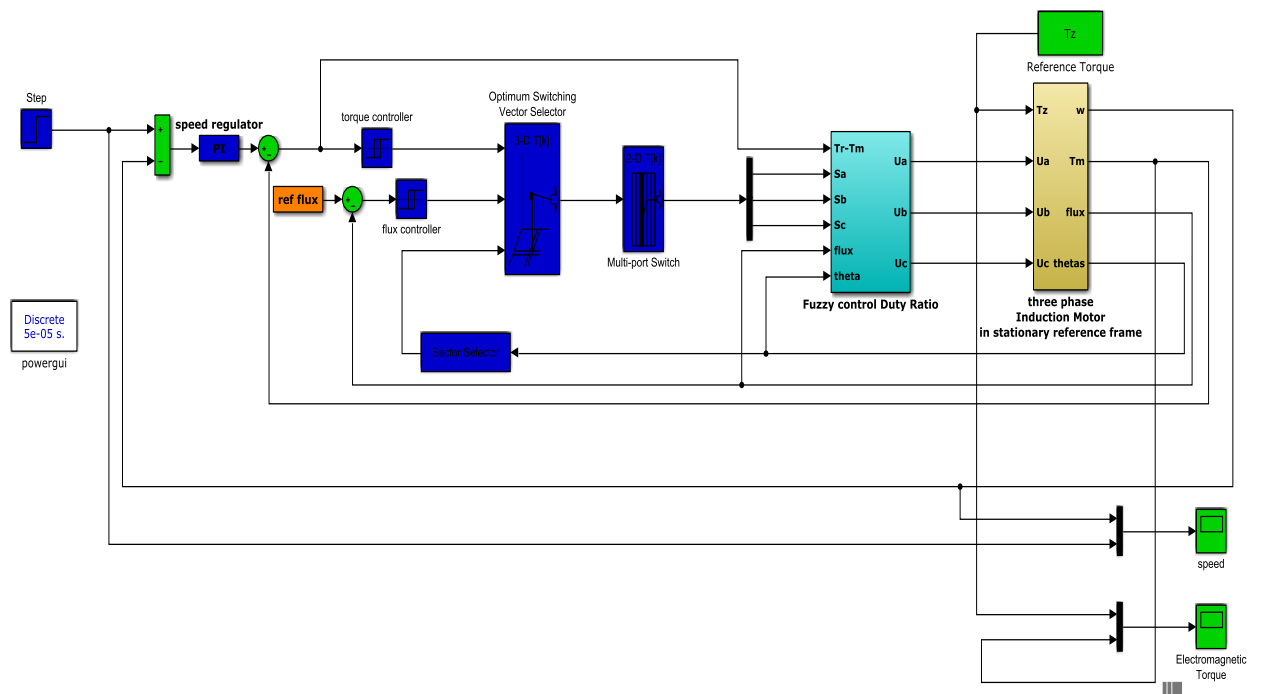
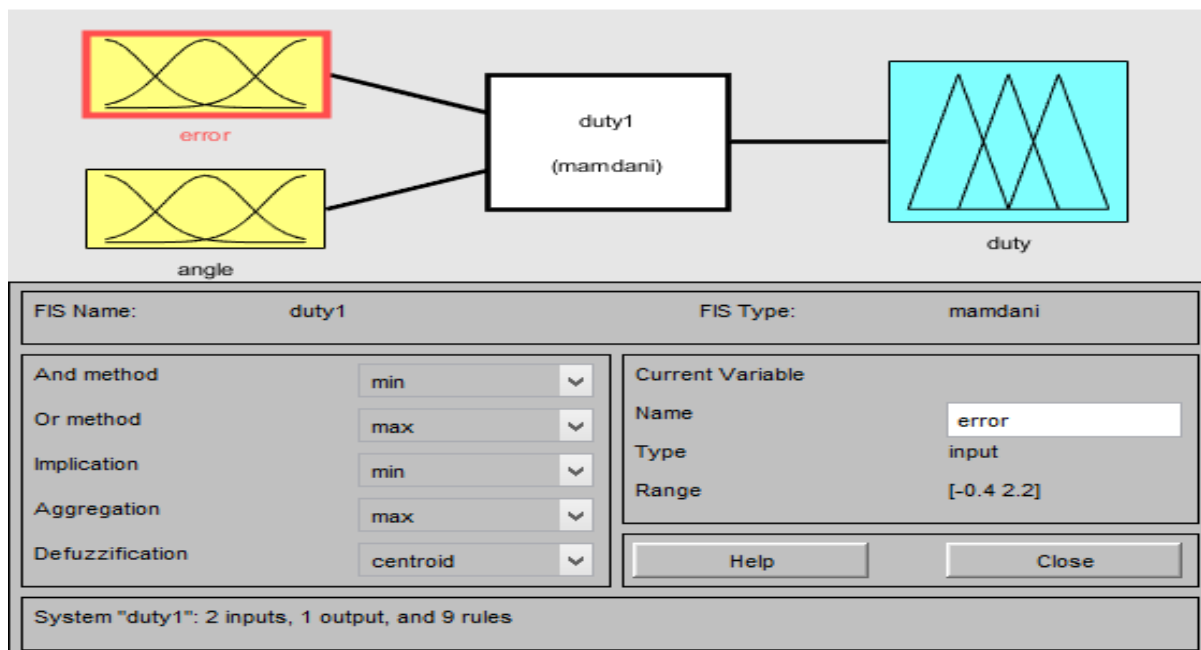


Figure 5.2 MATLAB/Simulink model of Fuzzy controlled DTC of three phase Induction Motor Drive

The two groups of rules, each of which contains nine rules. The first group, duty 1 is used when stator flux linkage vector is smaller than its reference value and the second group, duty 2, of rules is used when the stator flux linkage vector is greater than its reference value.

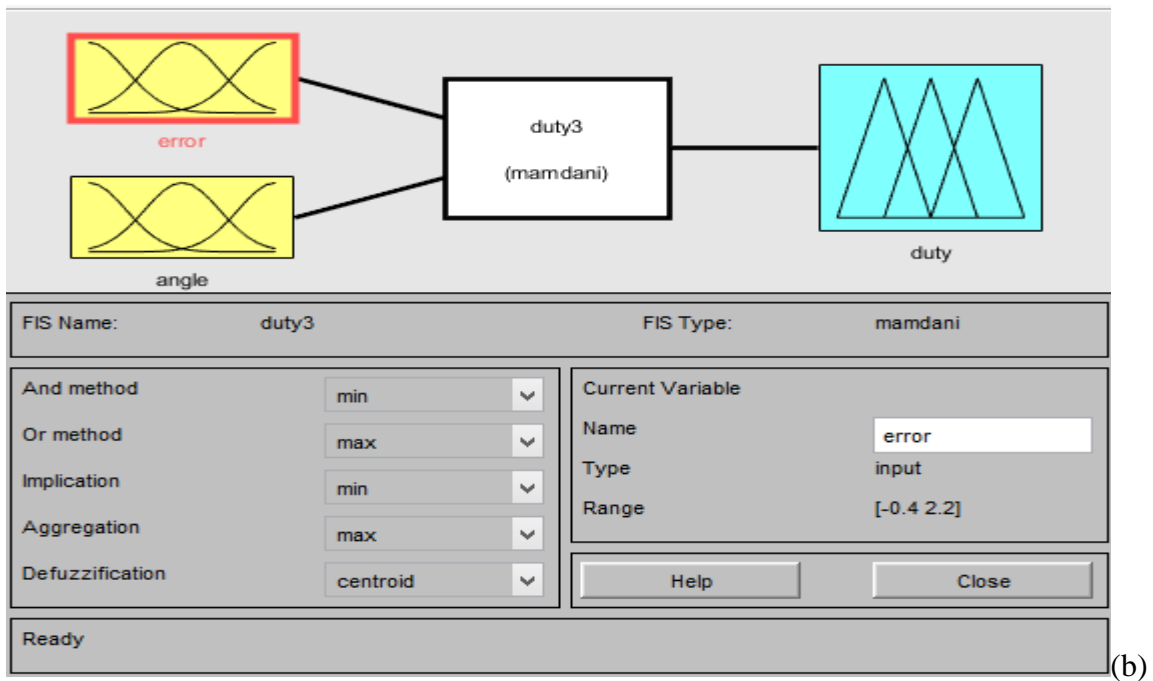
The mamdani type inference engine is used in the simulation. The membership functions and the fuzzy rules are adjusted until an optimal ripples reduction is achieved.

The MATLAB Fuzzy Logic designer is used to implement the two groups of membership functions for the inputs, the torque error and the flux position and the output, the duty ratio as shown in Figure 5.3 (a and b) and the two sets of fuzzy rules can also be shown in Figure 5.4 (a and b) .The surface viewer also shown in Figure 5.5 (a and b).



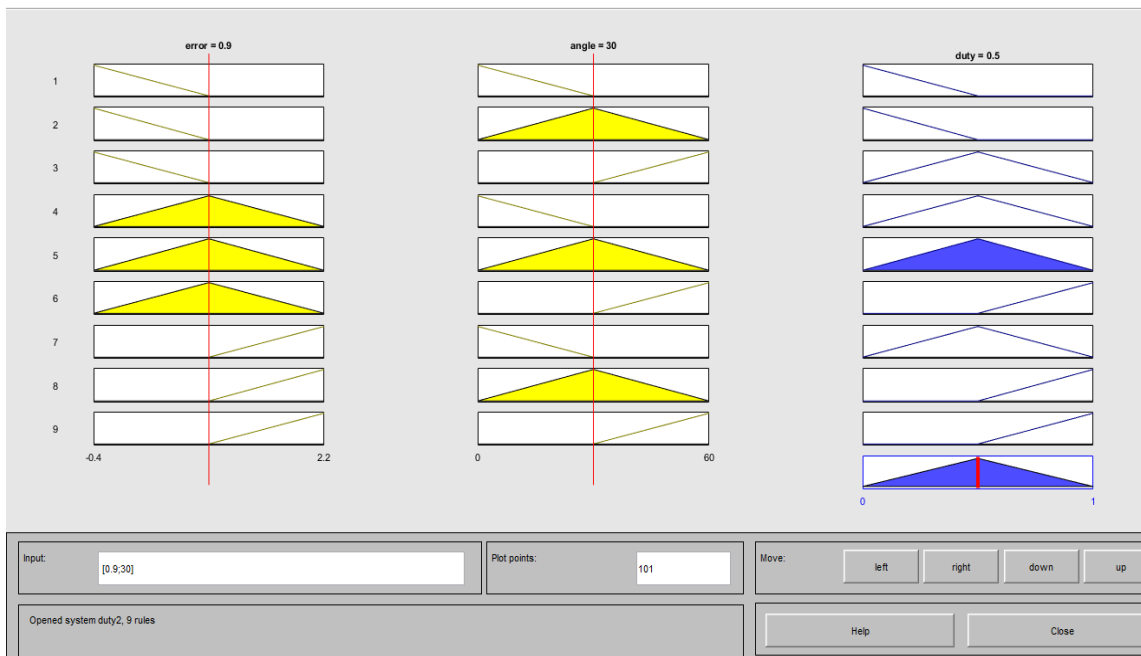
(a) duty ratio 1

Space Vector Based Fuzzy Controlled DTC of three phase induction Motor Drive

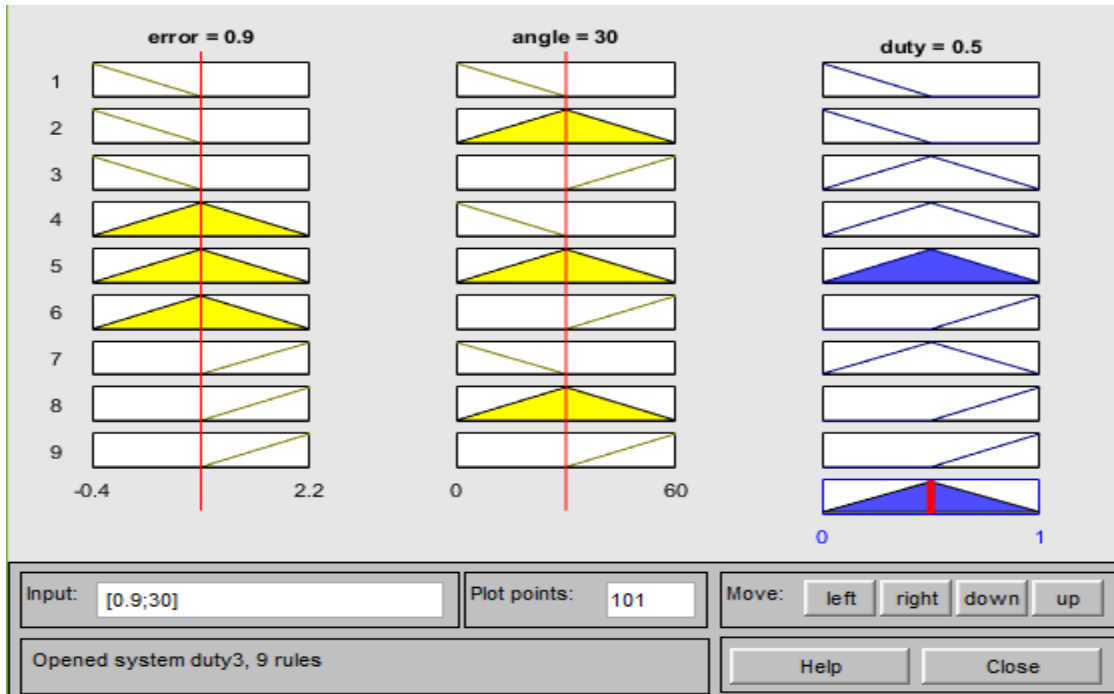


duty ratio 2

Figure 5.3 (a and b) Membership functions of Fuzzy Controlled DTC

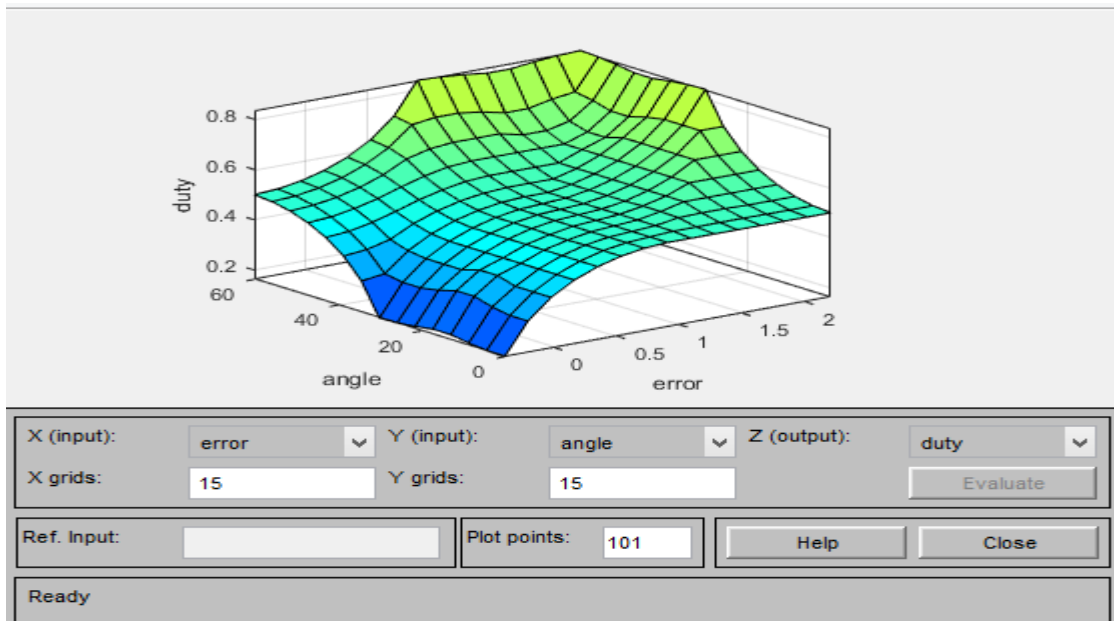


(a) duty ratio 1



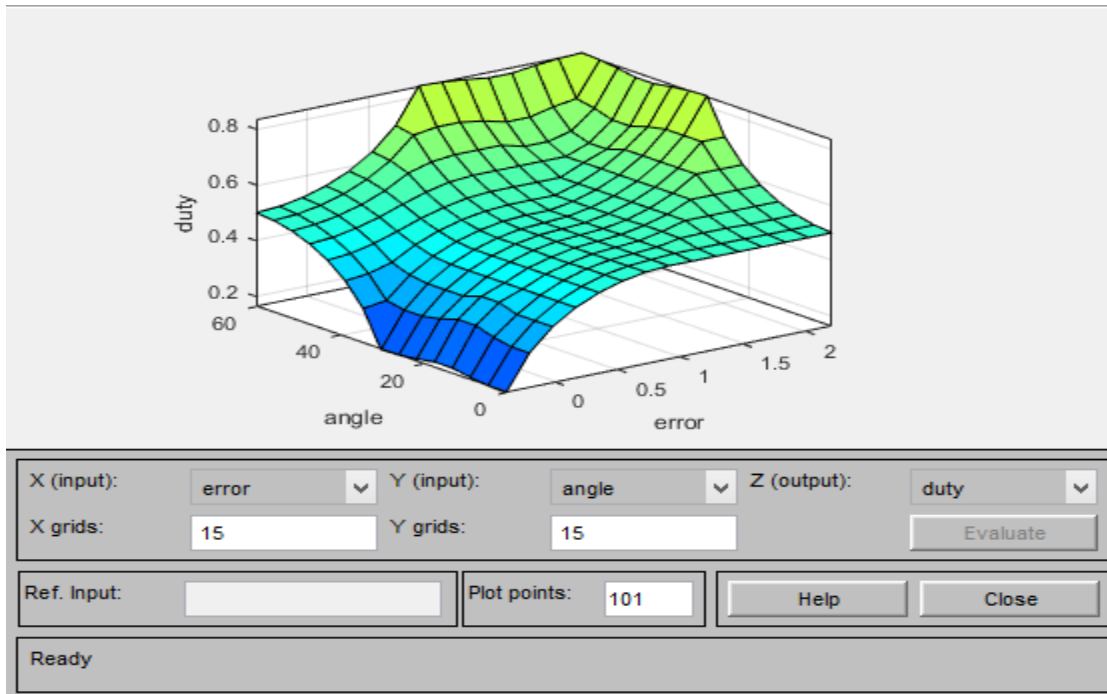
(b) duty ratio 2

Figure 5.4 (a and b) Rule viewer of Fuzzy Controlled DTC



duty ratio 1

(a)



(b) duty ratio 2

Figure 5.5 Surface Viewer of Fuzzy Controlled DTC

5.4 Simulation Results

The Simulation results are carried out for different reference torques and fluxes under different conditions. The load torque varied in steps. At $t=0$ second, motor is no loaded, at $t=0.3$ seconds the load torque is 4 Nm, at $t=0.5$ seconds the motor is no loaded and at $t=0.7$ seconds the load torque is 4 Nm. The corresponding variations in stator currents, the estimated electromagnetic torque and stator flux linkage are observed. It is also observed that the step speed response and the variation of the speed response at different speed level. PI controller is used to control the speed of the motor then in turn to control the electromagnetic torque. The simulation time is one second. The parameter of the motor which is found from MATLAB.

Table 5-1 Induction motor parameters

DC link voltage	V _{dc} = 400V
Rated power	1.1 KW
Frequency	50 Hertz
Stator resistance	R _s = 7.608 ohm
Rotor resistance	R _r = 3.7 ohm
Stator inductance	L _{ls} = 0.6015ohm
Rotor inductance	L _{lr} = 0.6015ohm
Mutual inductance	L _m = 0.5796 ohm
Moment of inertia	J= 0.0017Kg.m ²
Number of poles	P= 2

5.4.1 Simulation Results of Conventional DTC

The following simulation results are the conventional DTC of the selected three phase induction motor.

The simulation results of the D and Q axis of stator flux linkages in the stationary reference frame are based on equations (3.7) and (3.8). It can also possible to show the stator flux linkage space vector trajectory using the estimated values of the direct and quadrature axis of stator flux linkages in the stationary reference frame ($\lambda_{SD}, \lambda_{SQ}$) from the simulation of DTC of three phase induction motor drive. From the simulation results in figure (5.6) shown below, it can be seen that the stator flux linkages have high ripples.

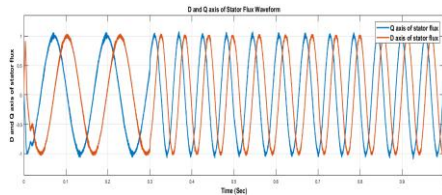


Figure 5.6 D and Q axis of Stator flux waveforms

The output of the motor, which is modeled in the stationary reference frame of D and Q axis of reference frame, is the stator currents. These currents are changed to two-phase to three-phase by using inverse park transformation. The simulation results of the three phase stator currents are shown in figure (5.7) below. At $t=0$ second, there is no load torque. The motor draws 3 Amperes until the load torque applied at $t=0.3$ seconds, the 4Nm load torque is applied to the motor. The motor draws 4 Amperes up to $t=0.5$ seconds. Thus, the motor draws 3 Amperes when there is no load torque and it draws 4 Amperes when the 4Nm load torque is applied to the motor. From the simulation results, it can be seen that, the three phase stator currents show high ripples.

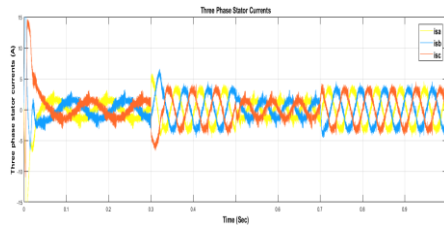


Figure 5.7 Three phase Stator Current waveforms

The simulation result of the electromagnetic torque is based on equation (2.45) shown in figure (5.8) below. The 4Nm load torque is applied at $t=0.3$ seconds and $t=0.7$ seconds. At $t=0$ second and $t=0.5$ seconds there is no load torque. The estimated electromagnetic torque shows high ripples since none of the inverter switching vectors is able to generate the exact stator voltages required to produce the desired changes from no load to 4Nm load torque in the electromagnetic torque in most of the switching instants. The simulation results show that, the estimated electromagnetic torque has high ripples.

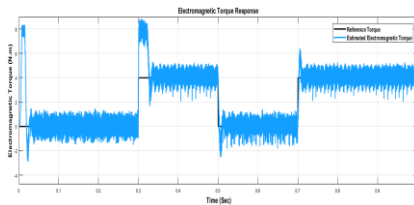


Figure 5.8 Electromagnetic Torque waveform

The control of speed during start up and speed variations are the other task of the thesis apart from minimization of the above mentioned ripples. The simulation results of the speed variations at different speed level is shown in figure (5.9) below. The reference speed is constant, 50 rad/sec at $t=0$ second and it starts to increase suddenly at $t=0.3$ seconds until the speed becomes 100 rad/sec. From the simulation results, it can be seen that there is a sluggish speed response at start up and has some speed fluctuations when the speed changes from 50 rad/sec to 100 rad/sec at $t=0.3$ seconds and when the 4Nm load torque is applied at $t=0.3$ seconds, $t=0.5$ seconds and $t=0.7$ seconds respectively.

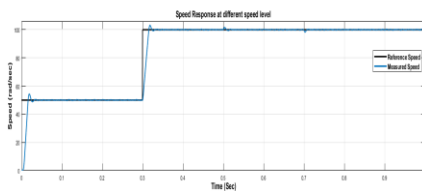


Figure 5.9 The Variation of the speed at different speed level

The speed fluctuations when the 4Nm load torque is applied at $t=0.3$ seconds, $t=0.5$ seconds and $t=0.7$ seconds, some peak overshoot and slight sluggish speed response are the drawback of the step speed response of the conventional DTC. The settling time of the step speed response is 6.835 milliseconds and its peak overshoot is 2.352%. The simulation results of step speed response is shown in figure (5.10) below.

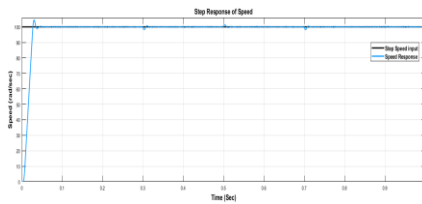


Figure 5.10 Step response of speed

5.4.2 Simulation Results of Fuzzy controlled DTC

The following simulation results are Fuzzy controlled DTC of the selected three phase induction motor.

Figure (5.11), (5.12) and (5.13) shows fuzzy logic duty ratio controller based DTC of stator flux linkage, three phase stator currents and electromagnetic torque waveforms respectively. It can be seen that, the ripples are minimized when the simulation results of fuzzy logic based DTC compared to the conventional DTC. FFT (Fourier Fast Transfer) is one method to compare the ripples of conventional DTC and fuzzy logic based DTC by calculating the THD (Total Harmonic Distortion) of the ripples.

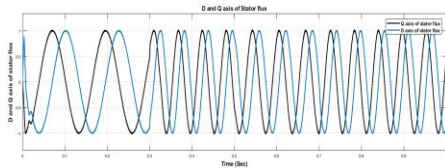


Figure 5.11 Stator flux linkage waveforms

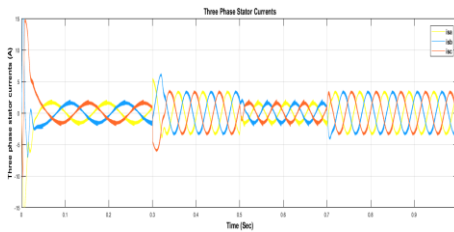


Figure 5.12 Three phase stator current waveforms

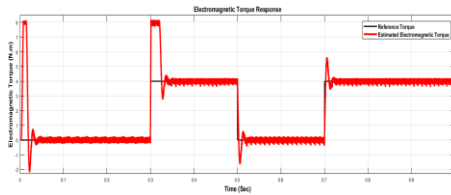


Figure 5.13 Electromagnetic Torque waveform

The use of fuzzy logic duty ratio controller decreases the speed fluctuations remarkably when the 4 Nm load torque is applied than the conventional DTC. And it has fast speed response when the speed changes from 50 rad/sec to 100 rad/sec suddenly and at the start up speed response. The simulation results of fuzzy logic based DTC speed variations at different speed level is shown in figure (5.14) below.

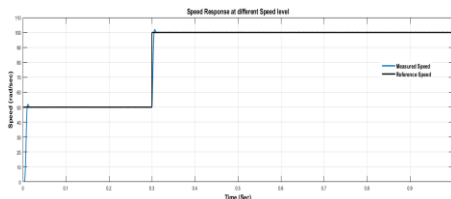


Figure 5.14 The variations of the speed at different speed level

The use of fuzzy logic duty ratio controller removes the step speed response of speed fluctuations when the 4 Nm load torque is applied, remarkably than the

conventional DTC. And it has fast step speed response when it is compared with the conventional DTC. The settling time is 4.122 milliseconds and its peak overshoot is 1.531 %. The simulation results of step speed response using fuzzy logic duty ratio controller is shown in figure (5.15) below.

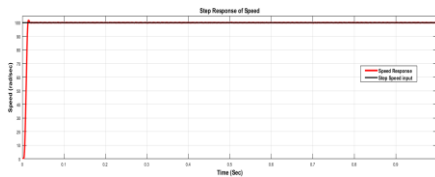


Figure 5.15 Step Response of Speed

In order to compare the ripples of the simulation results of the conventional DTC and fuzzy logic duty ratio controller based DTC of the selected three phase induction motor drive, an FFT (Fourier Fast Transfer) is made. This is done by using the estimation of THD using MATLAB/Simulink. Total Harmonic Distortion (THD) is the summation of all harmonic components of the torque or current waveform against the fundamental component of the torque or current waveform. THD should be kept as low as possible. Lower THD means less ripples and higher efficiency.

Space Vector Based Fuzzy Controlled DTC of three phase induction Motor Drive

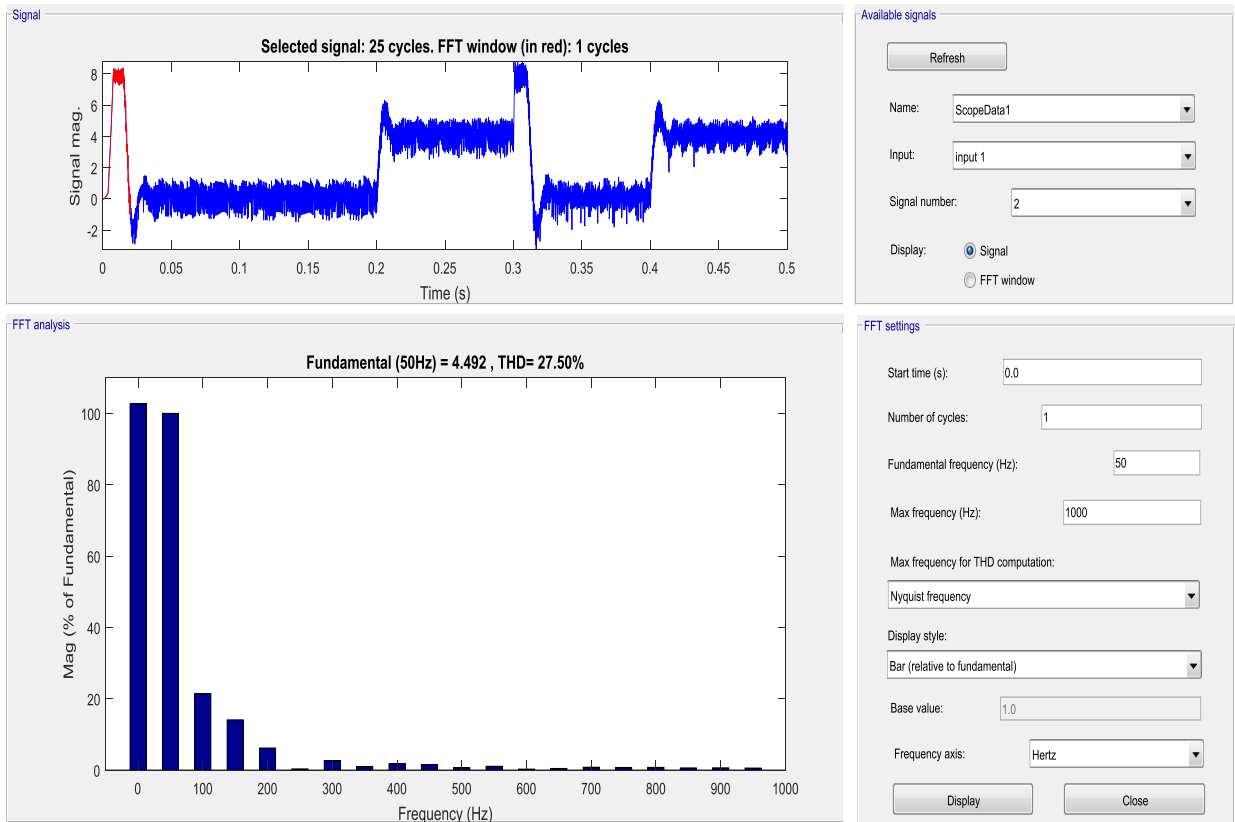


Figure 5.16 FFT analysis of conventional DTC

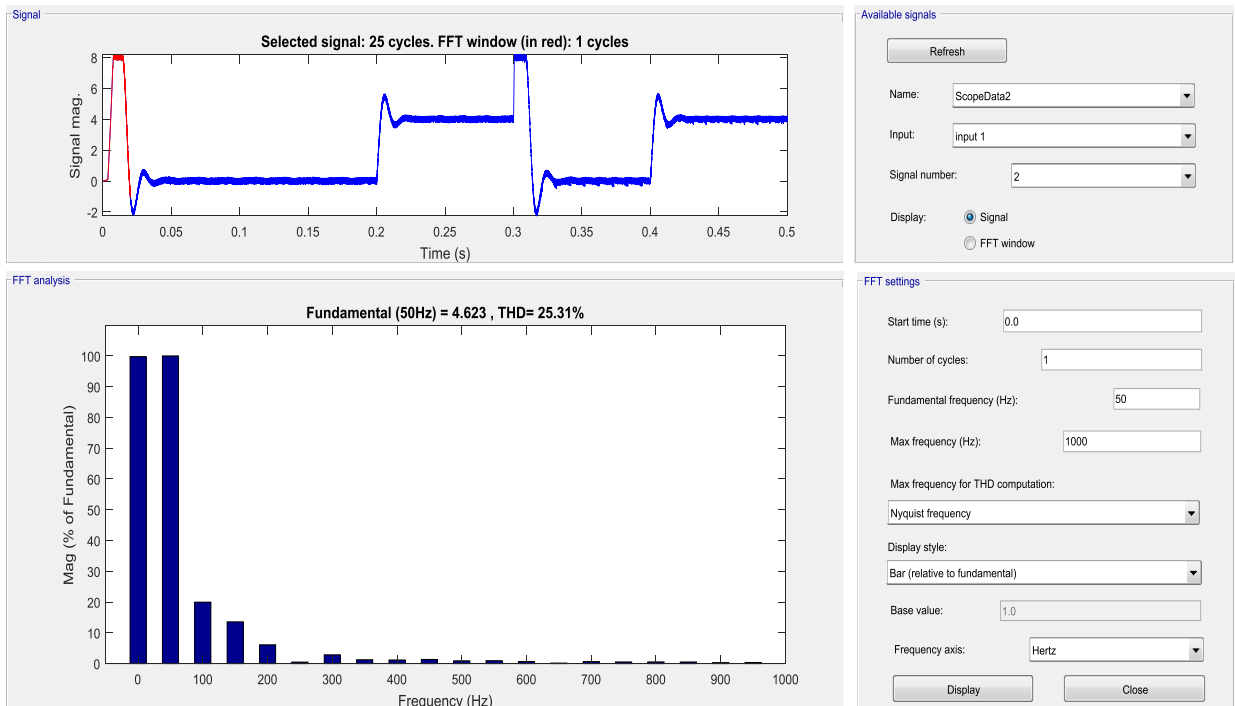


Figure 5.17 FFT analysis of Fuzzy based DTC

CHAPTER 6

Conclusion and Recommendations

6.1 Conclusion

Direct Torque Control has a better dynamic performance for driving a three phase induction motor. Its main principles have been discussed and deeply explained. It is also demonstrated in this thesis that the method of DTC allows the independent and decoupled control of motor torque and stator flux linkage. A simulink model has been fully developed. From the results, it is apparent that DTC strategy is simpler to implement than flux vector control method because voltage modulators and coordinate transformations are not required. Although, it introduces some disadvantages, being the mentioned ripples are the worst.

From the obtained simulations result of conventional DTC and Fuzzy logic based DTC, the ripples of stator flux linkage, the estimated electromagnetic torque and stator currents are reduced by 2.2% which is evaluated by using MATLAB FFT analysis. It also seen that, the speed response at different speed variations and the step speed response, is better when Fuzzy logic based DTC is used. The settling time of the step response of the speed is 6.835 milliseconds and 4.122 milliseconds of conventional DTC and Fuzzy logic based DTC respectively. This shows that the Fuzzy logic based DTC has fast speed response. The peak overshoot of the step speed response is 1.531% and 2.352 % of fuzzy logic based DTC and conventional DTC respectively. Thus it is cleared that fuzzy logic based DTC minimizes the ripples and gives a better speed response at different speed level and at step speed response.

6.2 Recommendations

It is recommended to the future that:-

- Minimization of the ripples of conventional DTC not only with fuzzy duty ratio controllers but also with multilevel inverters, which means changing the three phase voltage source inverter topology. This makes the witching states very fast.

- Apply different Fuzzy logic controller to minimize the ripples of conventional DTC.
- Different Fuzzy logic controllers that are implemented in FPGA ,reduces the ripples of conventional DTC as well as it enhances the overall performance of the system.

References

- [1] ISAO TAHASHI MEMBER ,IEEE, AND TOSHIHIKO NOGUCHI "A New Quick-Response and High-Efficiency Control Strategy for an Induction Motor " IEEE Transaction on Industry Applications, vol.22, no.5 pp.820-827, 1986
- [2] MUHAMMAD H.RASHID "Power Electronics Circuits, Devices And Applications" Third Edition, Pearson Education, Inc.2004
- [3] Andrzej M. Trzynadlowski Department of Electrical Engineering University of Nevada, Reno Nevada "Control of Induction Motors" 2011
- [4] NUR HAKIMAH AB AZIZ, Master's Thesis, University of South Australia "Three-phase Squirrel cage Induction Motor Drive Analysis Using LabVIEW " 2006
- [5] Domenico Casadei, Member, IEEE, Francesco Profumo, Senior Member, IEEE,Giovanni, serra, Member, IEEE and Angelo Tani" FOC and DTC: Two variable Schemes for Induction Motors Torque Control" September 2002
- [6] Seung-Ki Sul IEEE PRESS "Control of Electric Machine Drive Systems " 2011
- [7] Paul C.Krause, Oleg Wasynczuk and Scott D. sudhoff IEEE PRESS "Analysis of Electric Machinery And Drive Systems" Piscataway,NJ:John Wiley and Sons, Second Edition, 2002
- [8] V.Peter, "Sensoreless Vector and Direct Torque Control", Oxford, United Kingdom: Oxford University Press 1998
- [9] ISAO TAKAHASHI,Member IEEE, and YOUICHI OHMORI "High-Performance Direct Torque Control of an Induction Motor", March/April 1989
- [10] O Zkan AKIN, Irfan ALAN "The use of FPGA in Field Oriented Control of an Induction Machine" 2010
- [11] Muhammad Afiq Bin Mohd Noordin "Scalar Control of Three phase Induction Motor" July 2013

- [12] Perelmuter, V. "Three level inverters with Direct Torque Control " IEEE proc on Industry Applications, pp.1368-1373, 2000
- [13] P. Wach, "Dynamics and Control of Electric Drives" : Springer, 2011
- [14] CHEF-MUN ONG, "Dynamic Simulation of Electric Machinery: using MATLAB/SIMULINK" vol.5: prentice Hall PTR upper saddle River, NJ,1998
- [15] M.Gopal," Digital Control and state variable Methods" second Edition, 1998
- [16] www.Mathworks.com, R2017a (9.2.0.538062) February 23, 2017
- [17] www.wikipedia.com
- [18] Haitham Abu-Rub, Atif Iqbal, Jaroslaw Guzinski "High Performance Control of AC Drives with Matlab/Simulink Models" 2nd Edition, April 2012
- [19] Eric Monmasson,Senior Member,IEEE, and Macian N. Cirstea, Senior Member, IEEE "FPGA Design Methodology for Industrial Control Systems-A Review" August 2007
- [20] Daijin Kim, Member, IEEE "An Implementation of Fuzzy Logic Controller on the Reconfigurable FPGA System" June 2000
- [21] Anjana Manuel, Jebin Francis Assistant Proffesor, Dept. of EEE,Rajagiri school of Engineering and Technology, Kakkanada,Kerala, India " Simulation of Direct Torque Controlled Induction Motor Drive by using space vector pulse width Modulation for Torque Ripple Reduction" September 2013.
- [22] Cei Jiang "Dynamic Simulations of Electric Machinery Using MATLAB/SIMULINK" 1997
- [23] Ahmad I.I.N.Al-Shawi, "Space Vector Modulation Direct Torque Speed Control of Induction Motor", Thesis Nahrain University, Dec,(2007)
- [24] P.A. Arias Ph.D Thesis University of catalunya "Improvements in Direct Torque Control of motor induction" 2000

- [25] J.N.Nash, "Direct Torque Control, induction Motor vector control without an encoder," IEEE Transactions on Industry Applications, Vol.33.no.2, March/April 1997
- [26] Mustapha MESSAOUDI,Habib KRAIEM, Mouna BEN HANED, Lassaad SBITA and Mohamed Naceur ABDELKRIM, "A Robust Sensorless Direct Torque Control of Induction Motor Based on MARS and Extended Kalman Filter" January-June 2008.
- [27] A.Mishra, P.Choudhary," Speed Control of An Induction Motor By using Indirect Vector Control Method" IJETAE, Volume 2, ISSUE 12,December 2012
- [28] Antoni Arias Pujol, "Direct Torque Control of Induction Motors" December, 2011
- [29] M.Sundar Raj, T.Saravanan and V. Srinivasan, Department of BME, Bharath University, Chennai, India "A modified Direct Torque Control of Induction Motor using space vector Modulation Technique " 2014
- [30] Devender Kumar, Ishan Thakur,Kanika Gupta. Electrical Departement, Baddi University,India "Direct Torque Control For Induction Motor Using Intelligent Artificial Neural Technique" July-August 2014
- [31] S.Lisauskas, D.Udris, D.Uznys. Department of Automation, Vilnius Gediminas Technical University "Direct Torque Control of Induction Drive Using Fuzzy Controller" 2013

Appendix

1. Induction Motor Parameters and Switching state selector

```
clear all
%Induction motor parameters%
Pn=1100;
Un=400;
p=2;
nn=2840;
Ls=0.6015;
Lr=0.6015;
Lm=0.5796;
Rs=7.608;
Rr=3.7;
J=0.0017;
Tr=0.1626;
s=0.0715;
T=1/100000;
fsw=100000;
Lls=Ls-Lm;
Llr=Lr-Lm;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Lss=s*Ls;
Ra=Rs+Rr*Ls/Lm;
Ta=Lss/Ra;
Tr=Lr/Rr;
Psisz=1;

%%The Selection of Switching State%%

Twp=0.0002;

Tpi=Ta;
Kpi=Ta*Ra/Twp;
Kp=Kpi;
Ip=Kpi/Tpi;

Pp=Kpi;
Sp=Kpi*T/Tpi;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Twt=0.05;

cit=[Kp*Lss (Ra*Kp+Ip*Lss-Rs*Kp) (Ra*Ip-Rs*Ip)];
men=[Lss Ra+Kp (Ip+Rs/Tr+Kp/Tr) Ip/Tr];
cit1=roots(cit);
men1=roots(men);
zos=cit(1)/(men(1));
ncit=[1 -cit1(2)]*zos;
nmen=[1 -men1(1)-men1(3) men1(1)*men1(3)];
ncit1=ncit/(nmen(3));
```

Space Vector Based Fuzzy Controlled DTC of three phase induction Motor Drive

```
nmen1=nmen/(nmen(3));

Rt=ncit1(2);
Tt=nmen1(2);
Tpt=Tt;
Kpt=Tpt/(Rt*Twt);

Pt=Kpt;
St=Kpt*T/Tpt;

Twm=0.002;

Tpm=0.0008;
Kpm=Tpm/(1.7619*Twm);

Pm=Kpm;
Sm=Kpm*T/Tpm;

Twr=0.03;

Tpr=0.03;
Kpr=0.6;

Pr=Kpr;
Sr=Kpr*T/Twr;

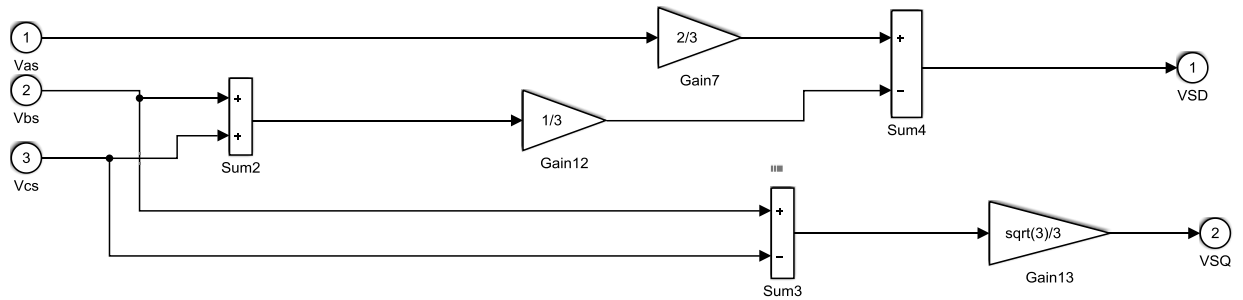
kr=Lm/Lr;
Mmax=11;
Imax=12;
Umax=280;

HF=0.01;
HT=0.4;

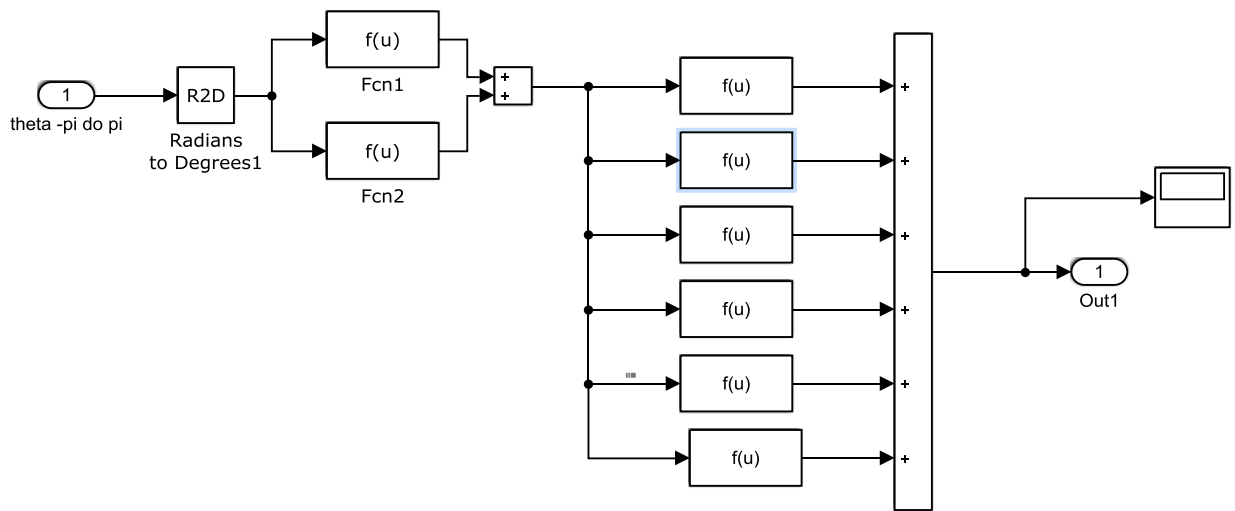
tabstav(:, :, 1)=[5 6;3 2];
tabstav(:, :, 2)=[6 1;4 3];
tabstav(:, :, 3)=[1 2;5 4];
tabstav(:, :, 4)=[2 3;6 5];
tabstav(:, :, 5)=[3 4;1 6];
tabstav(:, :, 6)=[4 5;2 1];

fuzzy duty1;
fuzzy duty2;
```

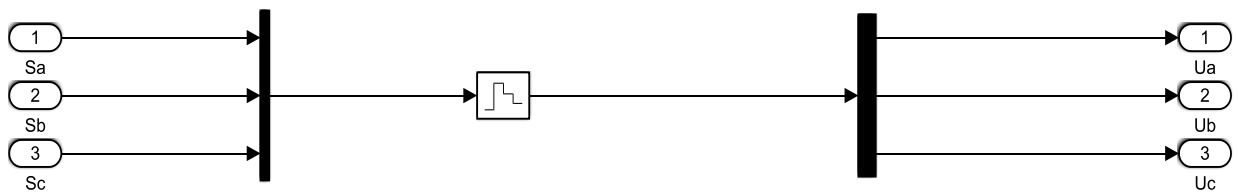
2. Stator Voltage Transformation



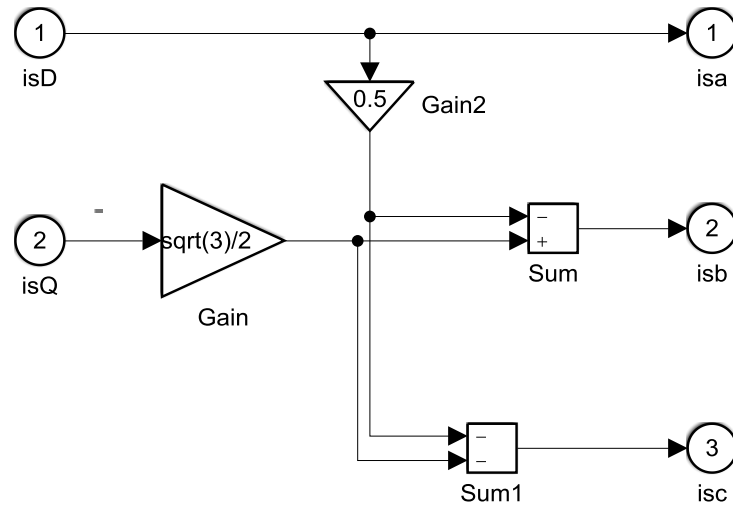
3. Stator Flux Sector Selector



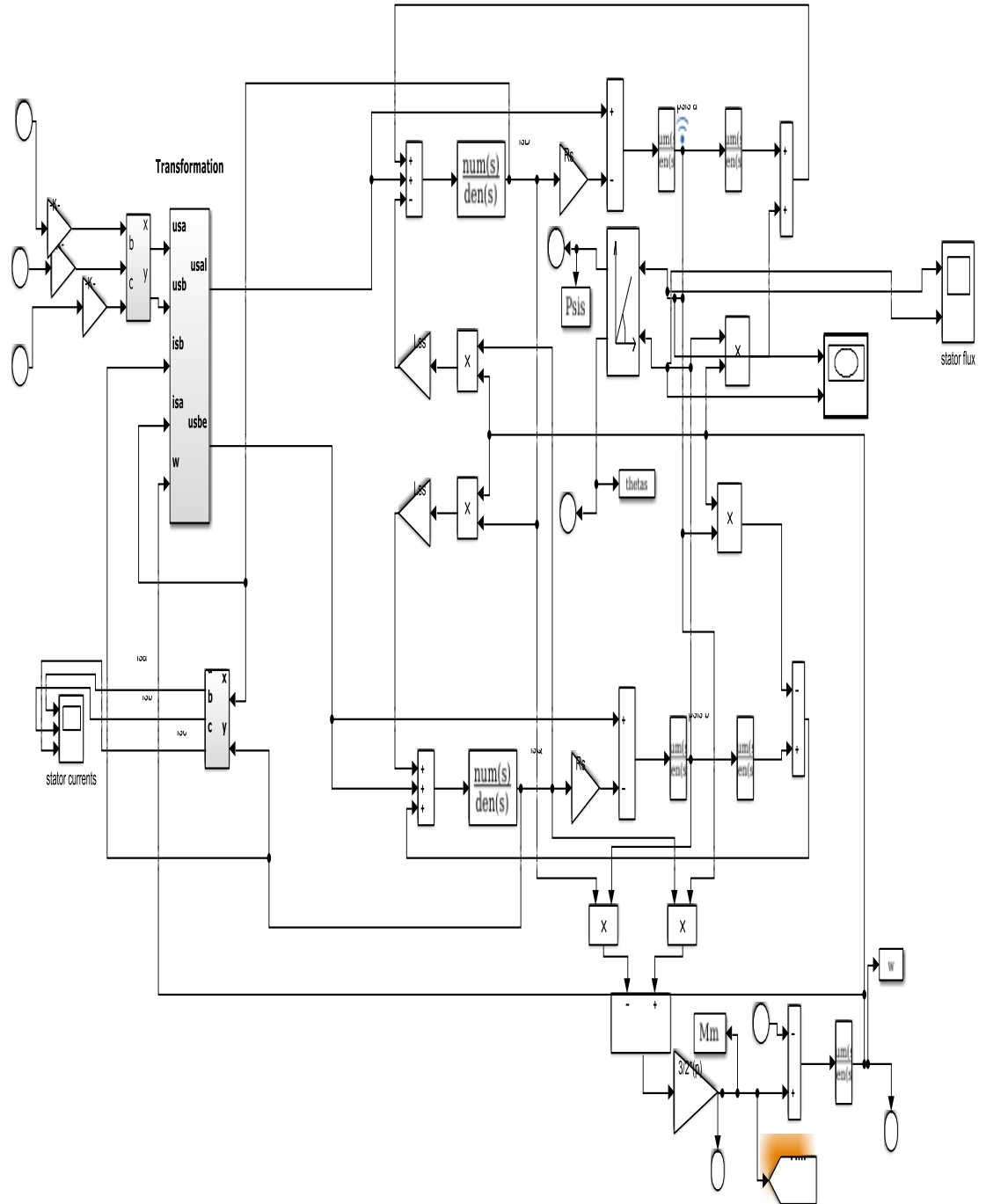
4. Switching States of conventional DTC



5. Stationary reference frame D and Q axis stator currents to three phase stator currents



6. Dynamic simulink model of the induction Motor in stationary Reference Frame and Electromagnetic Torque and Stator flux linkage estimator.



7. Fuzzy duty ratio controller simulink model

