Direct Torque control of Induction Motor With Torque Ripple Minimization using Fuzzy Logic

A Project Report

Submitted by

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BONAFIDE CERTIFICATE

Certified that this project report entitled **"Direct Torque Control of Induction Motor with Torque Ripple Minimization using Fuzzy Logic"** is the bonafide work of

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Who carried out the project work under my supervision.

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Signature of the Supervisor
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ABSTRACT

In this project, an improved speed control scheme for Direct Torque Control (DTC) of induction motor using Fuzzy Logic has been developed. In Direct Torque Control, the motor terminal voltage and current are observed to estimate the motor flux and torque. By estimating the stator flux position and the errors between the reference and the estimated values of flux and torque it is possible to directly control the Voltage Source Inverter (VSI) switching states by the selection of a voltage vector using Space Vector Modulation (SVM) in order to reduce the torque and flux errors within the prefixed band limits. As DTC minimizes the use of machine parameters and mechanical speed sensors, the system complexity is reduced. The speed estimator employed has the structure has the structure of a Model Reference Adaptive Controller (MRAC). The major problem usually associated with DTC drive is the high torque and flux ripples. To overcome this, a torque hysteresis band adapted with variable amplitude is proposed based on Fuzzy Logic. The proposed Fuzzy controller minimizes the torque ripples and improves DTC performance. The simulation was done using MATLAB/SIMULINK and the hardware was implemented using PIC 16F877 in this project.

ஆய்வு சுருக்கம்

இந்த ஆய்வில் நேரடி இயக்கு விசை முறையை பசி லாஜிக் (FL)யினை அடிப்படையாக கொண்டு இண்டக்சன் மோட்டரின் வேகத்தை கட்டுப்படுத்துவதற்காக பயன்படுத்தப்படும் ஒரு மேன்படுத்தப்பட்ட முறை உருவாக்கப்பட்டுள்ளது. இந்த நேரடி இயக்கு விசை முறையில் இயந்திரத்தின் மின்னழுத்தம் மற்றும் மின்னோட்டம் ஆகியவற்றை கொண்டு இயந்திரத்தின் முறுக்கு விசை மற்றும் அதை சார்ந்த இயக்கு விசை ஆகியவை கணக்கிடப்படுகின்றன. இந்த கணக்கீடுகளின் மூலம் மின்னழுத்த கோள்கள் ஸ்பேஸ் வெக்டர் மாடுலேஷன் (SVM) மூலமாக தேர்வு செய்யப்பட்டு வோல்டேஜ் சோர்ஸ் இன்வெர்டரின் (VSI) ஸ்விட்ச்சிங் நிலைகள் நேரடியாக கட்டுப்படுத்தப்படுகின்றன. இயந்திரத்தின் வரையரைகள் மற்றும் வேகத்தினை கண்கானிக்கும் கருவிகள் இல்லாமை போன்றவை இந்த முறையை எளிதாக்குகின்றன. வேகத்தை மதிப்பீடு செய்வதற்கு மாடல் ரெபரன்ஸ் அடாப்டிவ் கண்ட்ரோலர் (MRAC) பயன்படுத்தப்படுகிறது.

இந்த நேரடி இயக்கு விசை முறை அமைப்பில், இயக்கு விசை மற்றும் மின்னழுத்தம் ஆகியவற்றில் அதிகமான தடுமாற்றங்கள் காணப்படுகின்றன. இதனை கட்டுபடுத்துவதற்காக பசி லாஜிக்-யினை அடிப்படையாகக் கொண்டு இயங்கும் இயக்கு விசை ஹிஸ்டரிஸிஸ் குலு பயன்படுத்தப்படுகிறது. இந்த மேம்படுத்தப்பட்ட முறை, இயக்கு விசையில் ஏற்படும் தடுமாற்றங்களை குறைப்பதன் மூலம் இயந்திரத்தின் செயற்பாட்டை மேம்படுத்துகிறது. இந்த ஆய்வில் மேட்லேப்\சிமுலிங்க் (MATLAB\SIMULINK) என் மூலம் சிமுலேசனும் பிக் மைக்ரோ கண்ட்ரோலர் (PIC 16F877)-ன் மூலம் ஹார்டு வேர் அமைப்பும் உருவாக்கப்பட்டுள்ளது.

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I would like to extend a special thanks to my friends, teaching and non-teaching staffs and my parents who have directly and indirectly contributed to the success of this project.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Complex operator $e^{3/2\Pi j}$
DTC	Direct Torque Control
i_a, i_b, i_c	Instantaneous values of stator phase a, b, and c currents (A)
i_{qr} , i_{dr}	Instantaneous values of rotor current d-q axes components in the stationary reference frame (A)
i_{qdr}	Instantaneous values of rotor current space vector in the stationary reference frame (A)
i_{qds}	Instantaneous values of stator current space vector in the stationary reference frame (A)
J	Polar moment of inertia ($Kg.m^2$)
L_M , M	Mutual inductance per phase (H)
L_r	Rotor self inductance per phase (H)
L_s	Stator self inductance per phase (H)
L_{lr}	Rotor leakage inductance per phase (H)
L_{ls}	stator leakage inductance per phase (H)
P	Number of poles
R_r	Rotor resistance (Ω)
R_s	Stator resistance (Ω)
T_e	Electromagnetic torque (NM)
T_e^*	Reference torque (NM)
V_{qr} , V_{dr}	Instantaneous values of rotor voltage d-q axes components in the stationary reference frame (V)
V_{qs} , V_{ds}	Instantaneous values of stator voltage d-q axes components in the stationary reference frame (V)
V_{qdr}	Instantaneous values of rotor voltage space vector in the stationary reference frame (V)
V_{qds}	Instantaneous values of stator voltage space vector in the stationary reference frame (V)

λ_{qm} , λ_{dm}	Instantaneous values of the air gap flux linkage d-q axes components in the stationary reference frame (Wb)
λ_{qdm}	Instantaneous values of the air gap flux linkage space vector in the stationary reference frame (Wb)
λ_{qr} , λ_{dr}	Instantaneous values of the rotor flux linkage d-q axes components in the stationary reference frame (Wb)
λ_{qs} , λ_{ds}	Instantaneous values of the stator flux linkage d-q axes components in the stationary reference frame (Wb)
λ_{qdr}	Instantaneous values of the rotor flux linkage space vector in the stationary reference frame (Wb)
λ_{qds}	Instantaneous values of the stator flux linkage space vector in the stationary reference frame (Wb)
ω	Rotor speed (rad/sec)
λ^*	Flux reference (Wb)
δT_e	Torque error (NM)
T_{load}	Load torque (NM)
ω_{ref}	Speed reference (rad/sec)
b_T	Torque hysteresis band amplitude(NM)

CHAPTER I
INTRODUCTION

1.1. INTRODUCTION

Variable speed actuators were dominated by DC motors before the introduction of micro-controllers and high switching frequency semiconductor devices. The modern high switching frequency power converters are controlled by micro-controllers. The frequency, phase and magnitude of the input to an AC motor can be changed and hence the motor's speed and torque can be controlled. AC motors combined with their drives have replaced DC motors in industrial applications due to their lower cost, better reliability, lower weight, and reduced maintenance requirement. Squirrel cage induction motors are more widely used than all the rest of the electric motors put together as they have all the advantages of AC motors and they are easy to build.

1.2. BASIC AC MOTOR DRIVE SYSTEM

Fig. 1.1 shows a block diagram of an AC motor drive system. A single-phase or three-phase AC power supply and an AC/DC converter provide a DC input to an inverter. A micro-controller decides the switching states for the inverter to control the motor's torque or speed. A sensing unit feeds back terminal values such as motor speed, voltage and current to the micro-controller as needed for the closed-loop control of the motor. Controllers used in AC motor drives are generally referred to as vector or field-oriented controllers. The field-oriented control methods are complex and sensitive to inaccuracy in the motor's parameter values.

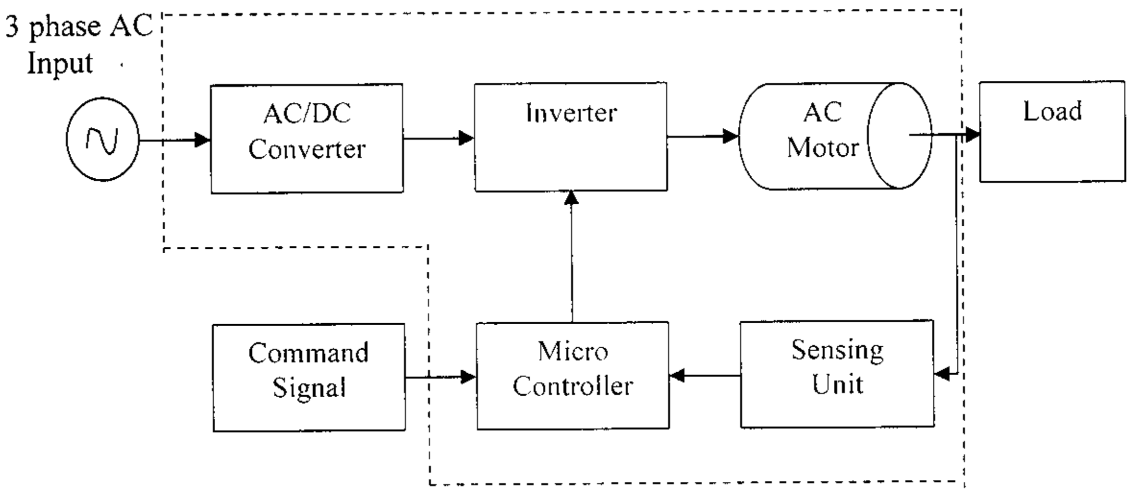


Fig.1.1.Block Diagram of an AC Motor Drive System

1.3. NEED FOR THE PROJECT

The high speed induction motors like those that are implemented in electric drives possess high power to weight ratio. Such induction motors typically have low inductance and therefore needs a controller with a fast current response.

A suitable torque controller is required for these drives. Torque control is preferred for these applications instead of precise closed loop speed control because it mimics the operation of non-linearities. It is important to make an electric drive like a standard drive.

To achieve this, a simplified variation of field orientation known as direct torque control (DTC) was developed by Takahashi and Depenbrock. In direct torque controlled induction motor drives, it is possible to control directly the stator flux linkage and the electromagnetic torque by the 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. DTC 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.

1.4. OBJECTIVE

The aim of the project is to reduce the torque ripples and to improve the dynamic performance and robustness of induction motor. The existing DTC control has many disadvantages such as inherent torque and flux ripple which results in acoustical noise. In order to overcome these disadvantages, the MRAC with Fuzzy Controller is proposed in this project.

1.5. ORGANIZATION OF THESIS

CHAPTER-1:

This chapter contains the information about the main objectives and need for the project.

CHAPTER-2:

This chapter contains information about the construction details, applications, advantages, disadvantages and control methods of the Squirrel Cage Induction Motor.

CHAPTER-3:

This chapter contains information about the Basic Principle of the Direct Torque Control Method and the various techniques involved.

CHAPTER-4:

This chapter contains information about the Simulation of Direct Torque Control Method with Fuzzy Logic Controller using MATLAB.

CHAPTER-5:

This chapter deals with the simulation results.

CHAPTER-6:

This chapter contains information about the Hardware model of Direct Torque Control Method and results obtained.

CHAPTER-7:

This chapter deals with conclusion and future scope.

CHAPTER II

CONTROL METHODS OF INDUCTION MOTOR

A number of modern manufacturing processes such as machine tools require variable speed motors. An effective way of producing a variable speed drive is to supply the motor with three-phase voltage of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages. The introduction of variable speed drives increases the automation in productivity and efficiency. The system efficiency can be increased by the introduction of variable speed drive operation in place of constant speed operation.

2.1. INDUCTION MOTOR

The AC Asynchronous Motor also named, Induction Motor (IM) is the most widely used electrical motor as it has its own advantages. The main advantage is that the induction motors do not require an electrical connection between the stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutators (brushes), leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and high overload capability. Therefore, they are cheaper and more robust, and less prone to failures at high speeds. Further more; the motor can work in explosive environments because no sparks are produced.

Because of the highly non-linear and coupled dynamic structure, an induction motor requires more complex schemes than dc motors. When high performance dynamic operation is required, more sophisticated control methods are needed to make the performance of induction motors comparable with dc motors. Recent developments in areas of drive control techniques, fast semiconductor power switches, etc., made induction motors alternatives to dc motors in industry. One of the most widely used induction motor drive control is Direct Torque Control (DTC).

2.2. BASIC PRINCIPLES OF IM

The AC induction motor is a rotating electric machine designed to operate from a three-phase source of alternating voltage. The stator is a classic three phase source with the winding displaced 120°. The most common type of induction motor has a squirrel cage rotor in which aluminium conductors or bars are shorted together at both ends of the rotor by cast aluminium end rings. When a set of three phase currents displaced in time from each other by angular intervals of 120° is injected into a stator having a set of three-phase windings displaced in phase by 120° electrical, a rotating magnetic field is produced. The interaction of the sinusoidally distributed air gap flux and induced rotor currents produces a torque on the rotor. The rotating magnetic field has a uniform strength and travels at an angular speed equal to its stator frequency. It is assumed that the rotor is at standstill. The rotating magnetic field in the stator induces electromagnetic forces in the rotor windings. As the rotor windings are short-circuited, current starts circulating in them, producing a reaction. As known from Lenz's law, the reaction is to counter the source of the rotor currents, i.e. induced emf in the rotor and in turn, the rotating magnetic field itself. The induced emf will be countered if the difference in the speed of the rotating magnetic field and rotor becomes zero. The only way to achieve it is for the rotor to run in the same direction as that of stator magnetic field in the stator magnetic field and catch up with it eventually. When the differential speed between the rotor and magnetic field in the stator becomes zero, there is zero emf, and hence zero rotor currents resulting in zero torque production in the motor. Depending on the shaft load, the rotor will settle down to a speed, ω_r always less than the speed of the rotating magnetic field, called synchronous speed of the machine, ω_s. The speed differential is known as the slip speed, ω_{sl}. The relationship between synchronous speed and stator frequency is given in eqn (2.1)

$$\omega_s = 2\Pi f_s \text{ rad/sec} \tag{2.1}$$

The speed of the stator magnetic field in rpm is given by,

$$n_s = 120 * f_s/p \tag{2.2}$$

where,

ω_s = synchronous speed of the machine (rad/sec),

f_s = stator frequency (Hz),

n_s = speed of the stator magnetic field (rpm),

p = number of poles.

2.3. CONSTRUCTION

2.3.1. Stator-Design

The stator is the outer body of the motor which houses the driven windings on an iron core. In a single speed three phase motor design, the standard stator has three windings, while a single phase motor typically has two windings. The stator core is made up of a stack of round pre-punched laminations pressed into a frame which may be made of aluminium or cast iron. The laminations are basically round with a round hole inside, through which the rotor is positioned. The inner surface of the stator is made up of a number of deep slots or grooves right around the stator. It is into these slots that the windings are positioned. The arrangement of the windings or coils within the stator determines the number of poles of the squirrel cage induction motor.

A standard bar magnet has two poles, generally known as North and South. Likewise, an electromagnet also has a North and a South Pole. As the induction motor stator is essentially like one or more electromagnets depending on the stator windings, it also has poles in multiples of two i.e., 2 pole,4 pole,6 pole,8 pole etc.

The voltage rating of the motor is determined by the number of turns on the stator and the power rating of the motor is determined by the losses which comprise copper loss and iron loss and the ability of the motor to dissipate heat generated by these losses. The stator design determines the rated speed of the motor and most of the full load, full speed characteristics.

2.3.2. Rotor Design

The rotor core is cylindrical and slotted on its periphery. The rotor consists of insulated copper or aluminium bars called rotor conductors. The bars are placed in the slots. These bars are permanently shorted at each end with the help of conducting copper ring called end ring. The bars are usually brazed at each end to provide good mechanical strength. The entire structure looks like a cage, forming a closed electrical circuit. So the rotor is called squirrel cage rotor. The construction is shown in Fig.2.1.

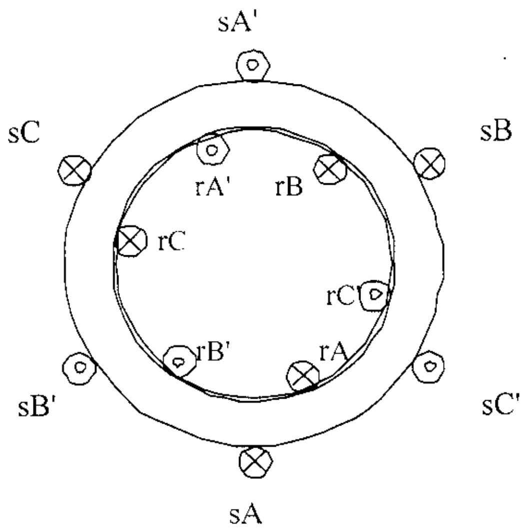


Fig.2.1. Symbolic representation of Induction Motor

As the bars are permanently shorted to each other through end ring, the entire rotor resistance is very small. Hence this rotor is also called short circuited rotor. As rotor itself is short circuited, no external resistance can have any effect on the rotor resistance. Hence no external resistance can be introduced in the rotor circuit. So slip ring and brush assembly is not required. Hence the construction of this type of rotor is simple.

Fan blades are generally provided at the ends of the rotor core. This circulates the air through the machine while operation, providing the necessary cooling. The air gap between stator and rotor is kept uniform as small as possible.

2.4. EQUIVALENT CIRCUIT

A simple per phase equivalent circuit model of an induction motor is a very important tool for analysis and performance prediction at steady state condition. The synchronously rotating air gap flux wave generates a counter emf V_m, which is then converted to slip voltage $V_r' = nSV_m$ rotor phase, where n = rotor to stator turns ratio slip and S = per unit slip. The stator terminal voltage V_s differs from voltage V_m by the drops in stator resistance R_s and stator leakage inductance L_{ls}. The excitation current $I_o = V_m/ R_m$ and a magnetizing component $I_m = V_m/\omega_e L_m$, where R_m = equivalent resistance for core loss and L_m = magnetizing inductance. The rotor-induced voltage V_r' causes rotor current I_r' at slip frequency ω_{sl} which is limited by the rotor resistance R_r' and the leakage reactance $\omega_{sl}L_{lr}'$.The stator current I_s consists of excitation components I_0 and the rotor-reflected current I_r. Fig.2.2. shows the equivalent circuit with respect to the stator, where I_r is given as

$$I_r = n\, I_r' = (n^2 S\, V_m) / (R_r' + j\omega_{sl} L_{lr}') \qquad (2.3)$$

$$I_r = V_m / ((R_r/S) + j\omega_e L_{lr}) \qquad (2.4)$$

and parameters R_r ($=R_r'/n^2$) and L_{lr} ($=L_{lr}'/n^2$) are referred to the stator. At standstill, S =1, and therefore, Fig.2.2. Corresponds to the short circuited transformer equivalent circuit. At synchronous speed, S = 0, current $I_r = 0$ and the machine takes excitation current I_0 only. At sub synchronous speed, 0<S<1.0, and with small value of S, the rotor current I_r is principally influenced by the R_r/S ($R_r/S >> j\omega_e L_{lr}$) parameter.

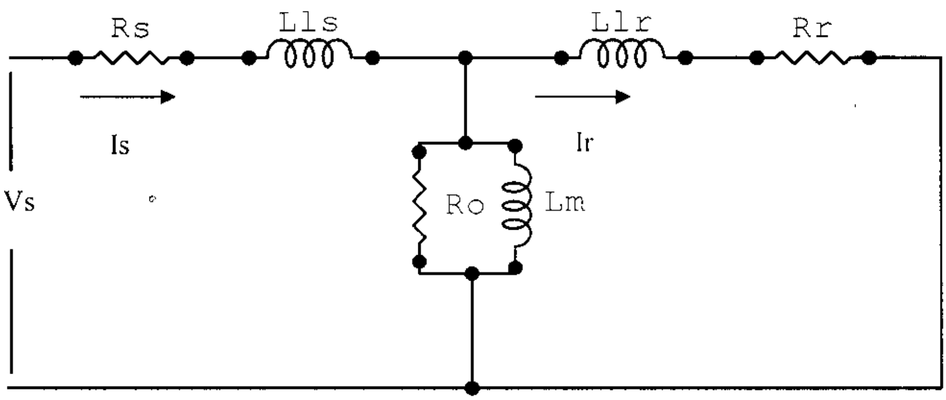


Fig.2.2. Per phase Equivalent circuit of induction motor

The phasor diagram for the equivalent circuit in Fig.2.2 is shown in Fig.2.3 where all the variables are in rms.

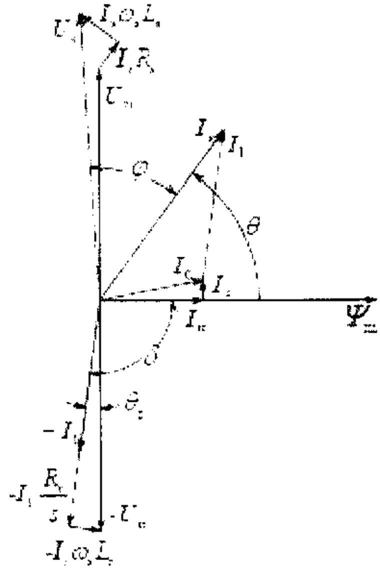


Fig.2.3. Phasor diagram for equivalent circuit

The induction motor can be treated essentially as a transformer for analysis. The induction motor has stator leakage reactance, stator copper loss elements as series components, and iron loss and magnetizing inductance as shunt elements. The rotor circuit likewise has rotor leakage reactance, rotor copper loss and shaft power as series elements. The transformer in the center of the equivalent circuit can be eliminated by adjusting the values of the rotor components in accordance with the effective turns ratio of the transformer. From the equivalent circuit and a basic knowledge of the operation of the induction motor, it can be seen that the magnetizing current component and the iron loss of the motor are voltage dependent and not load dependent.

Additionally, the full voltage starting current of a particular motor is voltage and speed dependant, but no load dependant. The magnetizing current varies depending on the design of the motor. For small motors, the magnetizing current may be as high as 60%, but for large two pole motors, the magnetizing current is more typically 20-25%. At the design voltage, the iron is typically near situation, so the iron loss and magnetizing current do not vary linearly with voltage with small increases in voltage resulting in a high increase in magnetizing current and iron loss.

2.5. SALIENT FEATURES

- Medium construction complexity, multiple fields on stator, cage on rotor
- High reliability (no brush wear), even at very high achievable speeds

- Driven by multi-phase inverter controllers
- Sensor less speed control possible
- Low cost per horse power
- Higher start torque than for single-phase, easy to reverse motor

2.6. APPLICATION

- Compressors
- Air conditioning units
- Pumps
- Simple industrial drives
- Electric cars
- Industrial machines

2.7. CONTROL METHODS

The speed of an induction motor depends upon the supply frequency and number of poles. The problem of speed control of ac motors has been very efficiently solved with the development of thyristor-controlled power converters, which can provide variable frequency, variable voltage supply. Using these converters it has been possible to achieve an ac motor having dc motor characteristics.

A converter fed induction motor has the following advantages:

- Smooth start-up is guaranteed by variable frequency starting from low value
- Soft starting and acceleration at constant current and torque is possible
- The network is no longer at constant high switching surge current as with that of direct switch ON of cage induction motor, and such special starting equipments can be omitted even at high ratings.

The main function of Variable Speed Drive (VSD) is to control the flow of energy from the mains to the process. Energy is supplied to the process through the motor shaft. Two physical quantities describe the state of the shaft, namely, torque and speed. To control the flow of energy, these quantities should be controlled. In practice, either one of them is controlled and is termed as "torque control" or "speed control". When the VSD operates in torque control mode, the load determines the speed. Likewise, when operated in speed control, the load determines the torque. Initially, DC motors were used as VSDs because they could easily achieve the required speed and torque without the need for sophisticated electronics.

However, the evolution of ac variable speed drive technology has been driven partly by the desire to emulate the excellent performance of the dc motor, such as fast torque response and speed accuracy, while using rugged, inexpensive and maintenance free ac motors.

Historically, there are several classical controllers developed for induction motor. They are

1. Scalar Control
   a. Voltage fed inverter control
      - Open Loop Volts/HZ control
      - Energy conservation effect by variable frequency drive
      - Traction drive with parallel machines
      - Speed control with slip regulation
      - Speed control with torque and flux control
      - Current control voltage fed inverter drive

   b. Current fed inverter control
      - Independent current & frequency control
      - Speed & Flux control in current fed inverter drive
      - Volts/Hz control of current fed inverter drive
2. Vector Control

   Field oriented control
      - Direct field oriented control
      - Indirect field oriented control
3. Direct Torque Control

2.7.1. Scalar Control

The scalar control is based only on the magnitude variation of the control variables and it disregards the coupling effect in the machine. For example, the voltage of a machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. However, flux and torque are also functions of frequency and voltage respectively. Thus, it does not act on space vector position during transients.

The advantage includes,

i. It is simple and easy to implement
ii. It finds application in all practical implementations

The disadvantages includes,

ii. The system is prone to instability because of a high order system effect

iii. The temporary dip in flux reduces the torque sensitivity with slip and lengthens the response time

2.7.2. Vector Control

The vector control method is also known as decoupling, orthogonal or Trans vector control because it decouples the stator and rotor fluxes thereby giving DC machine like performance. This method is based on the relations valid in the dynamic states, not only in magnitude and frequency, but also on the instantaneous positions of voltage, current and flux space vectors. It acts on the positions of the space vectors and provides a better orientation in both steady state and during transients.

In vector control, the motor equations are transformed into field Co-ordinates that rotate in synchronism with the rotor flux vector. In the field Co-ordinates, under constant flux amplitude there is a linear relationship between the control variables and torque. Moreover, like in a separately excited DC motor, the reference for the flux amplitude is reduced in the field weakening region in order to limit the stator voltage at high speed.

The disadvantages includes,

i. It requires park and ku transformations

ii. It requires compulsory identification of all machine parameters

iii. It involves huge computational capability

2.7.3. Direct Torque Control

The DTC is one possible alternative to the well-known Vector control of Induction machines. Its main characteristics are the good performance, obtaining results as good as the classical vector control but with several advantages based on its simpler structure and controller. The DTC scheme is characterized (in comparison with vector control) by the absence of,

- Co-ordinate transformations
- Current regulators
- Less dependent on motor model

which makes the Direct Torque Control scheme much simpler than Vector-Controlled drives.

CHAPTER III

DIRECT TORQUE CONTROL OF INDUCTION MOTOR

3.1. CONCEPT OF DIRECT TORQUE CONTROL (DTC)

In three phase induction motor drives a complete decoupling of flux and torque control variables is usually required. The torque command is generated from speed loop controller or directly by the user. The flux command is selected according to operation requirements, i.e., field weakening operation to achieve a wide speed range or flux regulation in accordance with load conditions to minimize motor losses.

In most control strategies the input commands are torque and flux, whereas the output commands are three phase reference currents. Then, the power converter has the ability to force only designed current waveform in to stator windings. For this purpose the current controlled VSI can be used. In order to obtain good performance the desired current waveform has to be well approximated leading to high switching frequency.

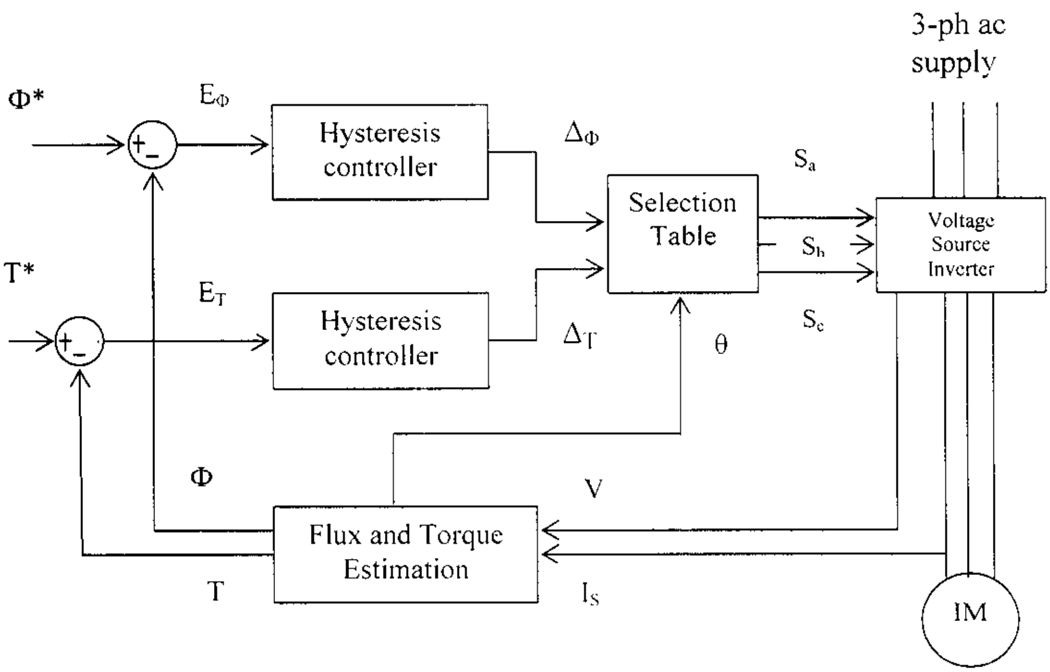


Fig.3.1 General Block Diagram of DTC

where,

Φ = actual flux, Φ^* = reference flux, E_Φ = flux error, Δ_Φ = flux hysteresis band output, T = actual torque, T* = reference torque, E_T = torque error, Δ_T = torque hysteresis band output, θ = stator flux position, S_a, S_b, S_c = switching pulses for voltage source inverter.

DTC uses an induction motor model to predict the voltage the voltage required to achieve a desired output torque. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period.

Fig.3.1 shows the block diagram of DTC, the voltage vector required to drive the error in the torque and flux to zero is calculated directly. If the inverter is not capable of generating the required voltage, then the voltage vector which will drive the torque and flux towards the demand values is chosen and held for the complete cycle.

In DTC induction motor drive supplied by a VSI, it is possible to control directly the stator flux linkage λ_s and the electromagnetic torque by the selection of an optimum inverter voltage vector. The selection of the voltage vector of the VSI is made to restrict the flux and torque error within their respective flux and torque hysteresis band and to obtain fastest torque response and highest efficiency at every instant. It enables both quick torque response in the transient operation and reduction of the harmonic losses and acoustic noise.

Direct Torque Control is an optimized ac drive control strategy where inverter switching directly controls the motor variables, namely, flux and torque. The input values to the DTC system are motor current and voltage. The voltage and current signals are inputs to a flux and torque estimator, which produces the actual measured value of stator flux and torque. These actual values are compared with the reference values to produce the torque and flux errors, which feed the hysteresis comparator.

Depending on the outputs from the hysteresis controllers, the switching logic directly determines the optimum inverter switch positions. The inverter switch positions again determine the motor voltage and current, which in turn influence the motor torque and flux and the control loop is closed.

Direct Torque Control scheme provides both

1. Flux Control
2. Torque Control

3.1.1. Flux Control

A uniformly rotating stator flux is desirable, and it occupies one of the sextants at any time. The stator flux phasor has a magnitude of λ_s, with an instantaneous position of θ_{fs} (theta). The corresponding d and q axis components are λ_{ds} and λ_{qs} respectively.

Assuming that a feedback of stator flux is available, its place in the sextant is determined from its position. Then the influencing voltage phasor is identified by giving a 90° phase shift. For example, if the stator-flux is in sextant <2>, the right influencing voltage phasor has to be either VI or I. Voltage phasor I is $(90° - \theta_{fs})$ and VI is $(150° - \theta_{fs})$ from flux phasor. One of these two sets increases λ_s, other decreases λ_s.

The stator flux linkage λ_s is calculated from the d and q axis stator flux linkages λ_{ds}, λ_{qs} respectively. The magnitude and angle of the stator flux linkage is calculated by using the formulae given below:

$$\lambda s = \sqrt{[(\lambda_{qs})^2 + (\lambda_{ds})^2]} \quad (3.1)$$

$$\theta_{fs} = \tan^{-1}(\lambda_{qs} / \lambda_{ds}) \quad (3.2)$$

The magnitude of the flux is compared with the command value of the flux i.e. reference value. The flux error is given by,

$$\lambda_{er} = \lambda_s{}^* - \lambda_s \quad (3.3)$$

The error value of the flux (λ_{er}) is compared with hysteresis value. The hysteresis value of flux is the maximum allowable tolerance value with hysteresis value. The flux error is processed in the hysteresis controller to produce the digital output S_λ. The switching logic to realize S_λ from λ_{er} is given by.

$\lambda_{er} > \lambda_s \longrightarrow 1$

$\lambda_{er} < \lambda_s \longrightarrow 0$

The flux angle is converted into digital output as S_θ. The value is between 1 and 6 depending upon the position of the flux angle. The stator flux angle is directly fed to the sextant calculator. The sextant calculator is an instrument with a graduated arc of 60° used for surveying the angle. The logic output created depends on the input angle.

The logic is given below.

$0 < \theta_{fs} < 60 \longrightarrow 2$

$-60 < \theta_{fs} < 0 \longrightarrow 3$

$-120 < \theta_{fs} < -60 \longrightarrow 4$

$-180 < \theta_{fs} < -120 \longrightarrow 5$

$120 < \theta_{fs} < 180 \longrightarrow 6$

$60 < \theta_{fs} < 120 \longrightarrow 1$

3.2.1. Torque Control

Torque control is exercised by comparing the command torque with the torque measured from the stator flux linkages and stator currents,

$$T_e = (3/2) * (P/2) * (\lambda_{ds}\, i_{qs} - \lambda_{qs}\, i_{ds}) \qquad (3.4)$$

By usimg the above formulae, the actual torque is calculated and is compared with the command torque i.e., the reference torque. The torque error is given by:

$$T_{er} = T_e * - T_e \qquad (3.5)$$

The torque error is processed in the hysteresis controller to produce digital output S_T as:

$$(T_e * - T_e) > \delta\, T_e \longrightarrow 1$$

$$-\delta\, T_e < (T_e * - T_e) < \delta\, T_e \longrightarrow 0$$

$$(T_e * - T_e) < -\delta\, T_e \longrightarrow -1$$

Where $\delta\, T_e$ is the acceptable tolerance window over the command torque. When the error exceeds $\delta\, T_e$, it is time to increase the torque, denoting it with a +1 signal. If the torque error is between positive and negative torque window, then the voltage phasor could be at zero state. If the torque error is below $-\delta\, T_e$, it amounts to calling for regeneration, signified by -1 logic signal. Combining S_λ, S_T and S_0 a switching table can be realized to obtain the switching states of the inverter.

3.2. TORQUE EXPRESSION WITH STATOR AND ROTOR FLUXES

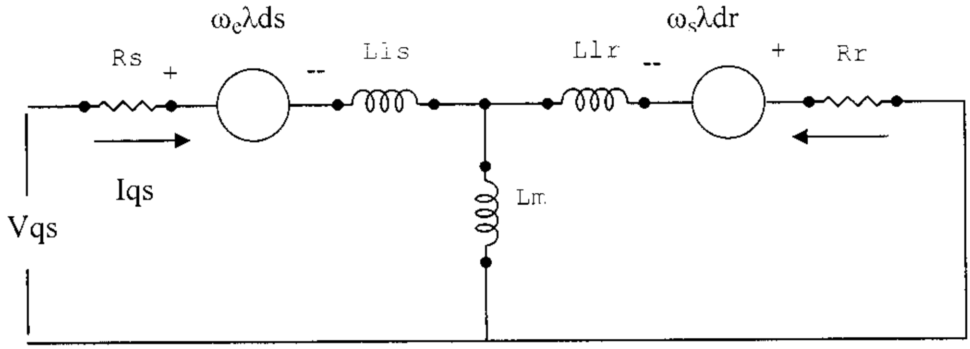
The torque expression as given in equation (3.4) can be expressed in the vector form as

$$T_e = (3/2) * (P/2) * \lambda_s I_s \qquad (3.6)$$

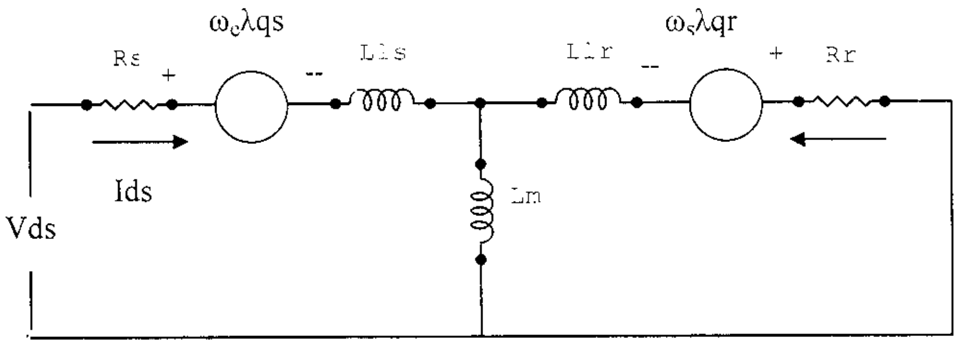
Where $\Psi_s = \Psi_{qs}{}^s - \Psi_{qs}{}^s$ and $I_s = i_{qs}{}^s - i_{ds}{}^s$. In this equation, I_s is to be replaced by rotor flux Ψ_r. In the complex form, Ψ_s and Ψ_r can be expressed as function of current (from equivalent circuit) as

$$\Psi_s = L_s I_s + L_m I_r \qquad (3.7)$$

$$\Psi_s = L_r I_r + L_m I_s \qquad (3.8)$$



A. d-axis equivalent circuit



B. q-axis equivalent circuit

Fig.3.2 Equivalent circuit of an IM in a dq reference frame

Eliminating I_r, from equation 3.7, we get

$$\Psi_s = (L_m/L_r)\,\Psi_r + L_s'\,I_s \qquad (3.9)$$

Where $L_s' = L_s L_r - L_m^2$. The corresponding expression of I_s is

$$I_s = (1/L_s')\,\Psi_s - (L_m/L_r L_s')\,\Psi_r \qquad (3.10)$$

Substituting equation (3.10) in equation (3.7) and simplifying yields

$$T_e = (3/2) * (P/2)*(L_m/L_r L_s')\,\Psi_r\,\Psi_s \qquad (3.11)$$

That is, the magnitude of torque is

$$T_e = (3/2) * (P/2)*(L_m/L_r L_s')\,|\Psi_r|\,\Psi_s|\sin\gamma \qquad (3.12)$$

Where γ is the angle between the fluxes. fig.3.3 shows the phasor (or vector) diagram for equation (3.11), indicating the vector Ψ_r, Ψs and I_s for positive developed torque. If the rotor flux remains constant and the stator flux is changed incrementally by stator voltage V_s as shown, and the corresponding change of γ angle is Δr, the incremental torque ΔT_e expression is given as

$$\Delta T_e = (3/2) * (P/2)*(L_m/L_r L_s')\,|\Psi_r|\,\Psi_s+\Delta\Psi_s|\sin\Delta\gamma \qquad (3.13)$$

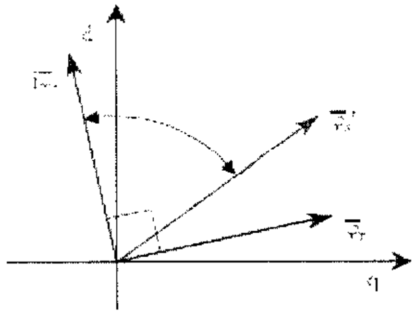


Fig.3.3 stator flux, rotor flux, and stator current vector on d^s - q^s plane

3.3 STATOR FLUX BASED DTC

In direct torque control fast response can be obtained by selecting the optimal VSI switching state if the flux magnitude is kept constant can be expressed as

$$T_e = (3/2) * (P/2)* |\lambda_{qds}| |i_{qds}| \sin(\sigma_s - k_s) \quad (3.14)$$

Where, σ_s - k_s is the angle between the stator flux linkage and stator current space vector as shown in fig.3.4

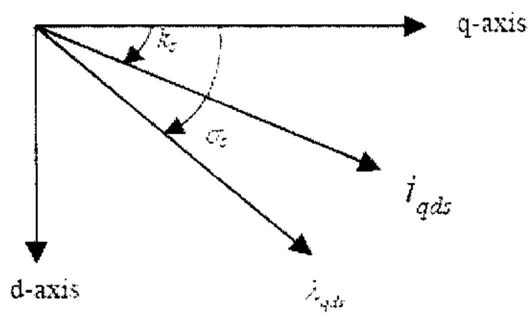


Fig 3.4 stator flux linkage and stator current space vectors

$$\lambda_{qds} = L_s\, i_{qds} + L_m\, i_{qdr}$$

$$\lambda_{qdr} = L_r/L_m(\lambda_{qds} - \sigma L_s\, i_{qds})$$

$$V_{qdr} = 0 = i_{qdr}\, r_r + p\,\lambda_{qdr} - j\omega_r\,\lambda_{qdr}$$

$$(r_r/L_m - j\omega_r(L_r/L_m)\,\lambda_{qds} + (L_r/L_m)\,p\,\lambda_{qds} \quad (3.15)$$

The rotor variables in equation (3.15) can be eliminated to get equation (3.16)

$$(r_r\, L_s\, /L_m - j\omega_r L_r\, L_s\sigma/ L_m)\, i_{qds} + L_r\, L_s\sigma/ L_m\, i_{qds} \quad (3.16)$$

From equation (3.16), it is clear that the stator current can be expressed as a function of the stator flux linkage i.e.,

$$i_{qds} = F(\lambda_{qds}) \quad (3.17)$$

Substituting in equation (3.14), we can conclude that

$$T_e = g(\lambda_{qds}) \quad (3.18)$$

This together with the stator flux magnitude is constant makes the resulting equation of electromagnetic torque as a function of motor parameters, the constant stator flux modulus $|\lambda_{qds}|$ and the stator flux position (σ_s).

The proposed torque equation is

$$T_e = g(c.\exp(j\,\sigma_s)) \quad (3.19)$$

Equation (3.19) shows that the rate of change of the electromagnetic torque ($d\,T_e/dt$) is proportional to the rate of change of the stator flux position ($d\,\sigma_s/dt$). Thus, a fast torque response can be obtained by controlling the stator flux position which in turn can be adjusted by selecting the appropriate stator flux vector. This can be achieved considering the stator voltage

$$V_{qds} = r_s\, i_{qds} + p\,\lambda_{qds} \quad (3.20)$$

If we assume that the stator resistance voltage drop can be neglected then the stator voltage becomes,

$$V_{qds} = p\,\lambda_{qds} \quad (3.21)$$

3.4. SWITCHING STRATEGY

From equation 3.21 it can be seen that the inverter voltage directly force the stator flux, the required stator flux locus will be obtained by choosing the appropriate inverter switching state. Thus the stator flux linkage move in space in the direction of the stator voltage space vector at a speed that is proportional to the magnitude of the stator voltage space vector. The appropriate stator voltage vector is selected by means of step by step procedure, so as to change the stator flux required.

If an increase of the torque is required then the torque is controlled by applying voltage vectors that advance the flux linkage space vector in the direction of rotation. If a decrease in torque is required then zero switching vector is applied, the zero vector that minimize inverter switching is selected.

For example if the stator flux vector lies in the K_{th} sector and the motor is running anticlockwise torque can be increased by applying stator voltage vectors V_{k+1} or V_{k+2}, and decreased by applying a zero voltage vector V_0 and V_7. Decoupled control of the torque and stator flux is achieved by acting on the radial and tangential components of the stator voltage space vector in the same directions, and thus can be controlled by the appropriate inverter switching.

In general, if the stator flux linkage vector lies in the K_{th} sector its magnitude can be increased by using switching vectors V_{k-1} (for clockwise rotation) or V_{k+1} (for anticlockwise rotation) and can be decreased by applying voltage vectors V_{k-2} (for clockwise rotation) or V_{k+2} (for anticlockwise rotation).

3.4.1 Lookup Table

The above can be tabulated in the look-up Table 3.2. The inputs to the look-up table are the torque error and the flux error generated by a three level hysteresis comparator and a two level hysteresis comparator respectively. The torque error is 1 if an increase in torque is required, 0 if a decrease is required.

For anticlockwise rotation:

$$dT = 1 \qquad \text{if} \quad T \le T_{ref} - |\Delta T| \qquad (3.22\ a)$$

$$dT = 0 \qquad \text{if} \quad T \ge T_{ref} \qquad (3.22\ b)$$

And for clockwise rotation:

$$dT = -1 \qquad \text{if} \quad |T| \le |T_{ref}| - |\Delta T| \qquad (3.23\ a)$$

$$dT = 0 \qquad \text{if} \quad T \le T_{ref} \qquad (3.23\ b)$$

The flux error is 1 if an increase in the flux is required, 0 if a decrease is required.

That is:

$$d\lambda = 1 \qquad \text{if} \quad |\lambda| \le |\lambda_{ref}| - |\Delta\lambda| \qquad (3.24\ a)$$

$$d\lambda = 0 \qquad \text{if} \quad |\lambda| \ge |\lambda_{ref}| + |\Delta\lambda| \qquad (3.24\ b)$$

Table 3.1 Flux and Torque due to applied voltage

(Arrow indicate magnitude and direction)

Voltage vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0 or V_7
Ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

Table 3.2 Takahashi look-up table

Flux Error $d\lambda$	Torque Error dT	S1	S2	S3	S4	S5	S6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

3.5 ESTIMATION OF STATOR FLUX IN DTC

Accurate flux estimation in vector controlled induction motor drives is important to ensure proper drive operation and stability. The flux estimation techniques proposed is based on voltage model, or the combination of both.

3.5.1 Current Model

The estimation based on current model described with the equations (3.25-3.27) is normally applied at low frequency, and it requires the knowledge of the stator current and rotor mechanical speed or position.

$$\lambda_{qds} = ((r_r(L_m/L_r))/(p + \omega b_r))\ i_{qds} + \sigma L_s\, i_{qds} \tag{3.25}$$

Where,

$$\omega b_r = r_r/L_r - j\,\omega_r \tag{3.26}$$

$$\sigma = 1 - (L_m^2/L_s L_r) \tag{3.27}$$

To get the accurate values of speed or position of the rotor, the encoders are used. The incremental use of encoder is undesirable because it reduces the robustness and reliability of the drive. The use of rotor parameters in the estimation introduces error at high rotor speed due to the rotor parameter variations. However the current model manages to eliminate the sensitivity due to the stator resistance variation.

3.5.2 Voltage Model

The voltage model, on the other hand, does not need a position sensor and the only motor parameter used is the stator resistance.

$$\lambda_{qs} = \int (V_{qs} - r_s\, i_{qs})\, dt \qquad (3.28\ a)$$

$$\lambda_{ds} = \int (V_{ds} - r_s\, i_{ds})\, dt \qquad (3.28\ b)$$

This gives the accurate estimation at high speeds however, at low speed, some problems arise. In practical implementation, even a small DC off-set present in the back emf due to noise or measurement error inherently present in the current sensor, can cause the integrator to saturate. Hence it is not suitable for low speed.

3.6 OVERALL DIRECT TORQUE CONTROL MODEL

The DTC block consists of the voltage source inverter fed from a dc voltage source. The pulses from the inverter is used to run the induction motor. The motor parameters are measured using the demux block whose output goes to the torque and flux estimator block where the flux, torque and theta of the motor are calculated. This value is compared with the reference and the error value is given to the switching control to determine the switching states for the inverter.

3.6.1 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 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 supplied from a three phase (or single phase) AC source. Fig.3.5 shows a six step voltage source inverter. The inductor L is inserted to limit shot through fault current. A large electrolytic 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 offer high switching speed with enough power rating. Each IGBT has an inverse parallel-connected diode. This diode provide alternate path for the motor current after the IGBT. is turned off.

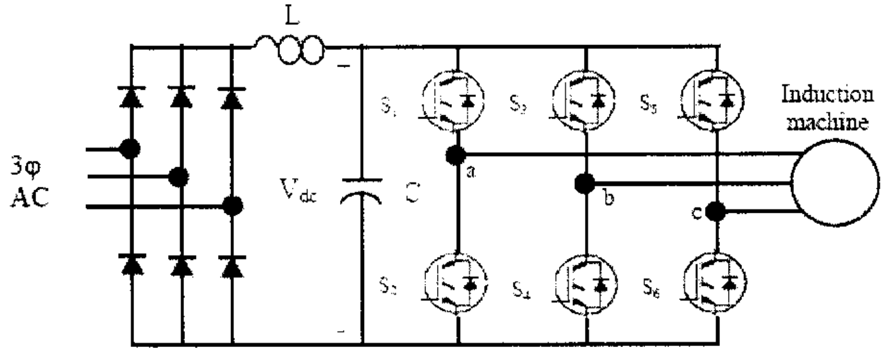


Fig.3.5 Block diagram of a six step voltage source inverter

Each leg of the inverter has two switches, one connected to the high side (+) of the DC link and the other to the low side (-); only one of the two can be on at any instant.

When the high side gate signal is on the phase is assigned the binary number 1, and assigned the binary number 0 when the low side gate signal is on. Considering the combinations of status of phases a, b and c the inverter has eight switching modes ($V_aV_bV_c$=000-111) two are zero voltage vectors V_0 (000) and V_1 to V_6. Each vector lies in the center of a sector of 60^o width named S1 to S6 according to the voltage vector.

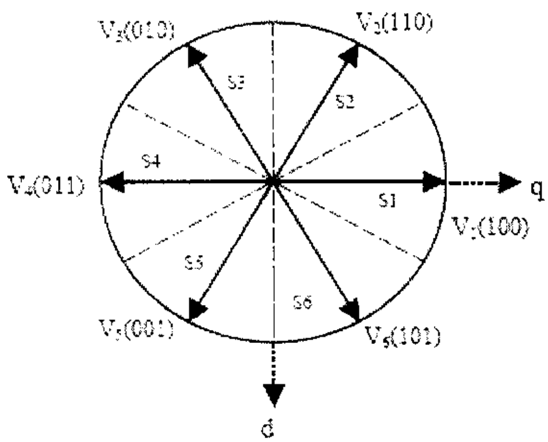


Fig.3.6 Voltage vectors for the VSI switching states

3.6.1.1 Pulse Width Modulation (PWM)

The inverter is simple and the switching loss is low because there are only six switching per cycle of fundamental frequency. Unfortunately, the lower harmonics of the six-step voltage wave will cause large distortions of the current wave unless filtered by bulky and uneconomical low-pass filters. Besides, the voltage control by the line-side rectifier has the usual disadvantages.

3.6.1.2 PWM Principle

An inverter contains electronic switches, it is possible to control the output voltage as well as optimize the harmonics by performing multiple switching within the inverter with the constant dc input voltage V_d.

The classifications of PWM techniques can be given as follows:

- Sinusoidal PWM (SVPWM)
- Selected harmonic elimination (SHE) PWM
- Minimum ripple current PWM
- Space-vector PWM(SVM)*
- Random PWM
- Hysteresis band current control PWM
- Sinusoidal PWM with instantaneous current control
- Delta modulation
- Sigma-delta modulation

The space-vector PWM (SVM) method is an advanced computation PWM method and is possibly the best among all the PWM techniques for variable frequency drive applications. Because of its superior performance characteristics, it has been finding widespread application in recent years.

3.6.1.3 Space Vector PWM (SVPWM)

The PWM method is discussed so far have only considered implementation on a half bridge of a three phase bridge inverter. If the load neutral is connected to the center tap of the dc supply, all three-bridges operate independently, giving satisfactory PWM performance. With a machine load, the load neutral is normally isolated, which causes interaction among the phases. This interaction was not considered before in the PWM discussion. The SVM method considers this interaction of the phases and optimizes the harmonic content of the three phase isolated neutral load. For example, if the three-phase sinusoidal and balanced voltages given by the equation

$$V_a = V_m \cos\omega t \quad (3.29)$$

$$V_b = V_m \cos(\omega t-(2\Pi/3)) \quad (3.30)$$

$$V_c = V_m \cos(\omega t+(2\Pi/3)) \quad (3.31)$$

are applied to a three phase induction motor, using equation $V = 2/3\ [v_{as} + a\ v_{bs} + a^2 v_{cs}]$, it can be shown that the space factor with magnitude V_m rotates in a circular orbit at angular velocity ω where the direction rotation depends on the phase sequence of the voltages. With the sinusoidal three phase command voltages, the composite PWM fabrication at the inverter output should be such that the average voltage follows these command voltages with a minimum amount of harmonic distortion.

3.6.1.4 Converter Switching States

A three phase bridge inverter, as shown in fig.3.5 have $2^3 = 8$ permissible switching states.

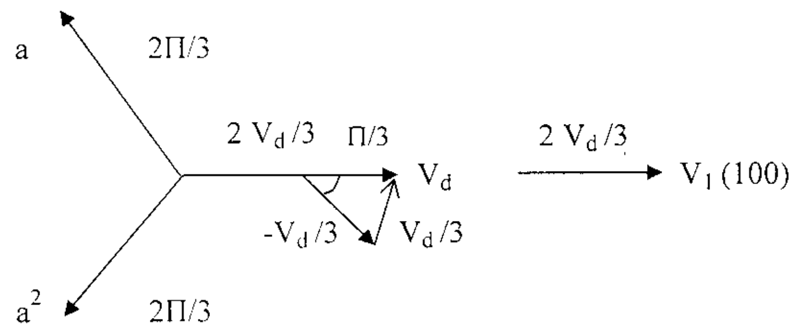


Fig 3.7 Construction of inverter space vector V_1 (100)

Table 3.3 gives a summary of the switching states and corresponding phase to neutral voltage of an isolated neutral machine.

Table 3.3 Summary of inverter switching states

State	ON devices	V_{an}	V_{bn}	V_{cn}	Space Voltage Vector
0	$Q_4\ Q_6\ Q_2$	0	0	0	$V_0(000)$
1	$Q_1\ Q_6\ Q_2$	$2V_d/3$	$-V_d/3$	$-V_d/3$	$V_1(100)$
2	$Q_1\ Q_3\ Q_2$	$V_d/3$	$V_d/3$	$-2V_d/3$	$V_2(110)$
3	$Q_4\ Q_3\ Q_2$	$-V_d/3$	$2V_d/3$	$-V_d/3$	$V_3(010)$
4	$Q_4\ Q_3\ Q_5$	$-2V_d/3$	$V_d/3$	$V_d/3$	$V_4(011)$
5	$Q_4\ Q_6\ Q_5$	$-V_d/3$	$-V_d/3$	$2V_d/3$	$V_5(001)$
6	$Q_1\ Q_6\ Q_5$	$V_d/3$	$-2V_d/3$	$V_d/3$	$V_6(101)$
7	$Q_1\ Q_3\ Q_5$	0	0	0	$V_7(111)$

Consider, for example, state 1, when switches Q_1, Q_6, and Q_2 are closed. In this state, phase A is connected to the positive bus and phases B and C are connected to the negative bus. The simple circuit solution indicates that $V_{an} = 2V_d/3$, $V_{bn} = -V_d/3$, and $V_{cn} = -V_d/3$. The inverter has six active states (1 to 6) when the voltage is impressed across the load, and two zero states (0 and 7) when the machine terminals are shorted the lower devices or upper devices, respectively. The sets of phase voltages for each switching state can be combined with the help of equation $V = 2/3\ [v_{as} + a\ v_{bs} + a^2 v_{cs}]$ to derive the corresponding space vectors. The graphical derivation of V_1 (100) in fig 3.8 indicates that the vector has a magnitude of $2V_d/3$ and is aligned in the horizontal direction as shown.

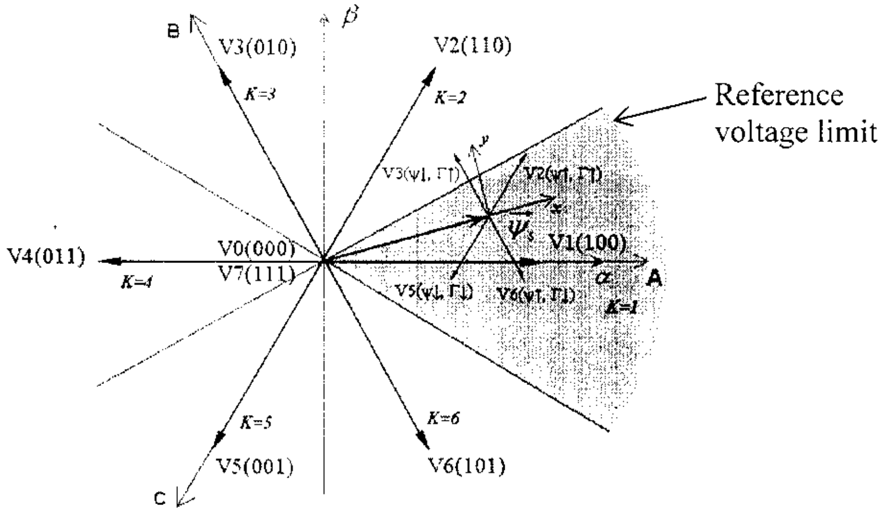


Fig 3.8 Space vectors of three-phase bridge inverter

In the same way, all six active vectors and two zero vectors are plotted. The active vectors are Π/3 angle apart and describe a hexagon boundary (shown as dotted). The two zero vectors V_0 (000) and V_7 (111) are at the origin. For three-phase, square wave operation of the inverter as shown in Fig 3.8, it can be easily verified that the vector sequence is $V_1 \rightarrow V_2 \rightarrow V_3 \rightarrow V_4 \rightarrow V_5 \rightarrow V_6$. with each dwelling for an angle of Π/3, and there are no zero vectors.

3.6.2 Torque and Flux calculator

The d and q axis voltage and currents are taken from the measurement block. Using these values, the torque (T_e), d-axis and q-axis flux linkages (λ_{ds}, λqs) are calculated. The magnitude (λ_s) and angle (θ_{fs}) of stator flux linkage are calculated from the measured d and q axis flux linkages using magnitude and phase resolver (MAR). The flux angle is termed theta. λ_s and T_e is calculated using the following formulae,

$$\lambda_{qs} = \int (V_{qs} - r_s\, i_{qs})\, dt \qquad (3.32)$$

$$\lambda_{ds} = \int (V_{ds} - r_s\, i_{ds})\, dt \qquad (3.33)$$

$$\lambda s = \sqrt{[(\lambda_{qs})^2 + (\lambda_{ds})^2]} \qquad (3.34)$$

$$\theta_{fs} = \tan^{-1} (\lambda_{qs} / \lambda_{ds}) \qquad (3.35)$$

$$T_e = (3/2) * (P/2) * (\lambda_{ds}\, i_{qs} - \lambda_{qs}\, i_{ds}) \qquad (3.36)$$

Thus the values of torque (T_e), flux (λ_s) and theta (θ_{fs}) are calculated.

Fig 3.9 shows the block diagram of the torque and flux calculator. The voltage and current values obtained from the DTC measure block acts as the input to the torque and flux calculator block. The voltage and current values are transformed into their respective dq frames. Then, the torque, flux and angles values are obtained by means of transfer function method from the dq reference signals.

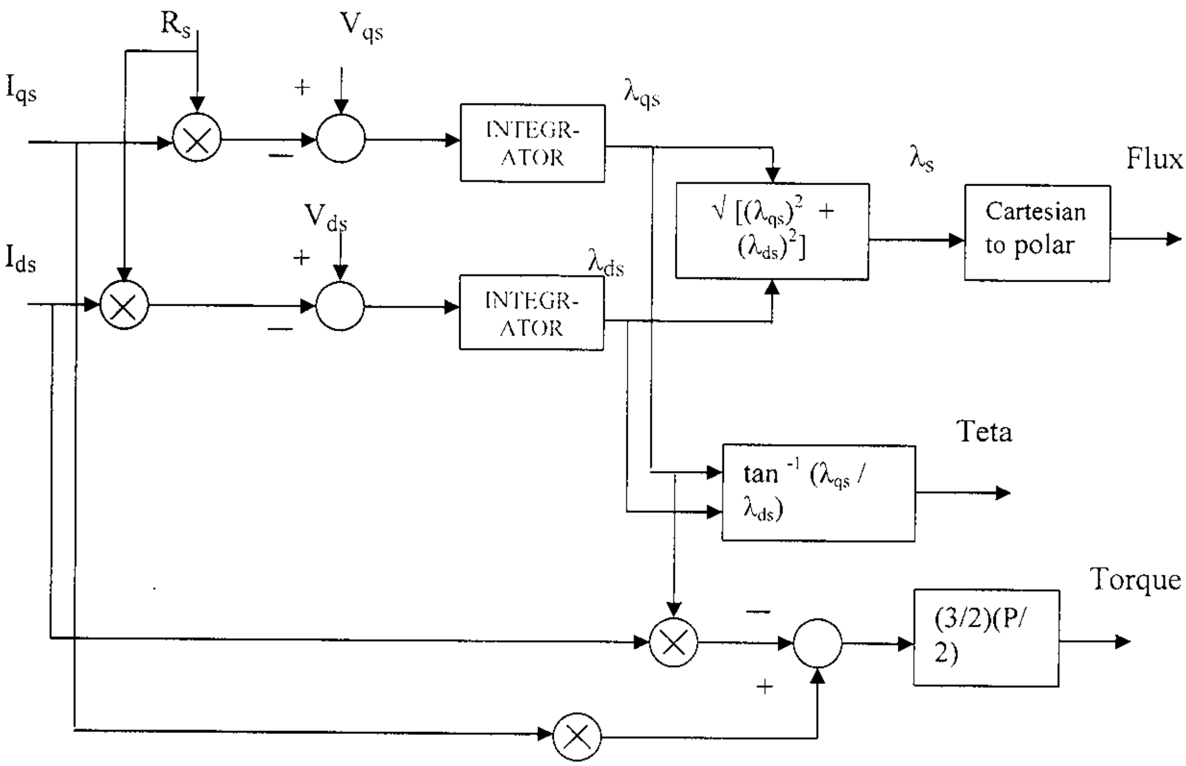


Fig 3.9 Block diagram of Torque and Flux Calculator

The torque and flux hysteresis controller block takes the reference torque and flux values along with the calculated torque and flux values from the torque and flux calculator. The information to control power switches is produced in the torque and flux controller block. Both the actual torque and actual flux are fed to the comparators where they are compared, every 25 milliseconds, to the torque and flux reference values. Torque and flux status signals are then calculated using a two level hysteresis control methods. These signals are then fed to the optimum pulse selector or switching table.

3.6.3 Switching States for Inverter

S_A, S_B, S_C are used to decide the turn-on and turn-off conditions of the switching devices present in the inverter. The voltage to the various phases is applied by using Gate Logic Drive. The realization of switching table and the Gate Logic Drive are shown. In the overall model it is shown as a subsystem.

Table 3.4 Inverter Switching States

STATES	S_A	S_B	S_C
I	1	0	0
II	1	0	1
III	0	0	1
IV	0	1	1
V	0	1	0
VI	1	1	0
VII	0	0	0
VIII	1	1	1

The outputs from the torque and flux hysteresis controller and the flux sector selection acts as the input to the switching table as in fig 3.10. The switching table is the block where the optimal vector for the inverter is decided and given as the gate to the inverter unit. The vectors are selected based on whether an increase or decrease in torque or flux is required.

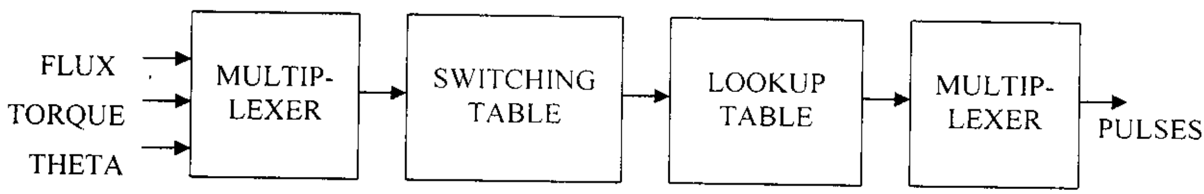


Fig 3.10 Block diagram for switching control

3.7 FEATURES OF DIRECT TORQUE CONTROL

The main features of DTC are:

- Direct torque control and direct stator flux control
- Indirect control of stator currents and voltages
- Approximately sinusoidal stator flux and stator currents
- High dynamic performance

- Absence of co-ordinate transform
- Absence of voltage modulator as well as PI-controllers for flux and torque estimation
- Minimal torque response time. even better than vector controllers
- Reduced parameter sensitivity –sensitive only to stator resistance
- Drive system is realized without a tachogenerator or encoder. Hence the motor is robust and cabling to the motor is reduced.

However, DTC suffers from the following drawbacks:

- High current
- Torque ripple
- Current ripple

A substantial reduction of current and torque ripple in DTC scheme can be obtained by using Space Vector Modulation Technique, which permits the system to generate any voltage vector. But this method results in the change of switching frequency. The second method for reducing torque and flux ripple is the multilevel inverter which is costlier and is more complex, thereby eliminates the simplicity of DTC. The improved voltage-current model speed observers based on MRAC structure is used to estimate the rotor speed.

CHAPTER IV

DIRECT TORQUE CONTROL WITH MRAC

4.1 MODEL REFERENCE ADAPTIVE CONTROL (MRAC)

In MRAC, as the name indicates, the plant's response is forced to track the response of the reference model, irrespective of the plant's parameter variation and the load disturbance effect. The reference model may be fixed or adaptive and is stored in any memory.

4.2 TORQUE RIPPLE ANALYSIS

Some of the inverter vectors are unable to generate the exact stator voltage required to produce the changes in the torque and flux. The torque and flux ripple causes a real problem in DTC induction motor drive.

According to the principle of operation of DTC, the torque presents a pulsation that is directly related to the amplitude of its hysteresis band. The torque pulsation is required to be as small as possible because it causes vibration and acoustic noise.

A small flux hysteresis bands should be preferred when high-switching speed semi- conductor devices are utilized because their switching losses are usually negligible with respect on state losses. In this way the output current harmonic can be strongly reduced.

The hysteresis band has to be set large enough to limit the inverter switching frequency below a certain level that is usually determined by thermal restriction of power devices. Since the hysteresis bands are set to cope with the worst case, the system performance is inevitably degraded in a certain operating range, especially in a low speed region. In torque hysteresis controller, an elapsing time to move from lower to upper limit, and vice versa can be changed according to operating condition.

Most of the existing methods are computationally intensive. Hence the fuzzy approach is proposed to reduce torque ripple. This goal is achieved by the Fuzzy controller which determinates the desired amplitude b_T of torque hysteresis band.

4.3 TORQUE RIPPLE MINIMIZATION STRATEGY

The torque and the mechanical dynamics of the induction machine are modeled by the following equations as.

$$T_e = (3/2)\, P\, I_s\, \Phi_s \quad (4.1)$$

$$J d\omega/dt = T_e - T_{load} \quad (4.2)$$

Where T_e is the motor torque, J is the moment of inertia of the system and T_{load} is the load torque. The variance value of the change of speed error is used to measure or to estimate the torque smoothness. Replacing the speed error signal, in equation (4.2) with equation (4.3),

$$e = \omega_e - \omega_{ref} \quad (4.3)$$

which gives,

$$J d(\omega_{ref} + e)/dt = J(d\omega_{ref}/dt) + J d_e/dt = T_e - T_{load} \quad (4.4)$$

For a constant speed reference signal $d\omega_{ref}/dt = 0$ and constant load, the change of speed error is related to the electrical motor torque by:

$$d_e/dt = (T_e - T_{load})/J \quad (4.5)$$

From equation (4.5), it shows that the change of speed error signal is indeed a good measurement and good indicator for controlling motor torque ripple.

4.4 MRAC SPEED ESTIMATOR

The speed estimator is designed with the structure of a Model Reference Adaptive Controller (MRAC), which is mainly based on the error between the two models namely, the reference model and the adjustable model.

The reference model which is the rotor flux estimator given by,

$$\Phi_r = L_r/M\, (V_s - R_s I_s - \sigma L_s I_s) \quad (4.6)$$

The adjustable model is given by,

$$\Phi_r = (-1/T_r + j\omega)\, \Phi_r \,/\, (M/\, L_r)\, I_s \quad (4.7)$$

Using the error between the rotor fluxes of the two models, rotor speed ω is calculated and corrected by a proportional integral (PI) adaptation mechanism, as in Fig 4.1.

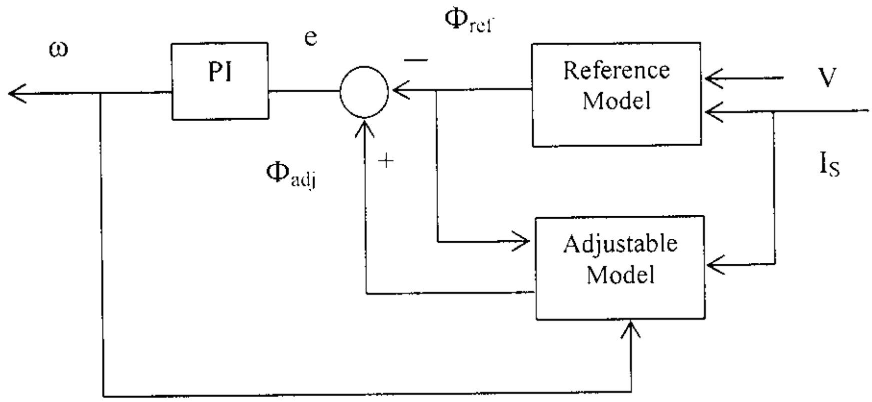


Fig 4.1 Block diagram of MRAC

The amplitude of the torque hysteresis band is prefixed using thePI controller whose input includes the speed error variation and the stator current variation.

$$e1\ (k) = \omega\ (k) - \omega\ (k-1) \quad (4.8)$$

$$e2\ (k) = I_s\ (k) - I_s\ (k-1) \quad (4.9)$$

The amplitude of the torque hysteresis band is limited as,

$$b_t\ (k) = b_t\ (k - 1) + \Delta b_t\ (k) \quad (4.10)$$

4.5 MRAC WITH FUZZY CONTROLLER

The fuzzy logic is a powerful tool that is capable of resolving many problems. A fuzzy controller seems to be a reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. The amplitude of torque hysteresis band is not prefixed but it is determinate by a fuzzy controller. The inputs to the fuzzy controller are the speed error variation and the stator current variation. The magnitude of the stator current is defined as

$$I_S = \sqrt{I_{\alpha s}^2 + I_{\beta s}^2} \quad (4.11)$$

The crisp output Δb_t (incremental amplitude of torque hysteresis band) is integrated in such way that the amplitude of torque hysteresis band. Fig 4.2 shows the proposed torque hysteresis controller with adapted band b_T.

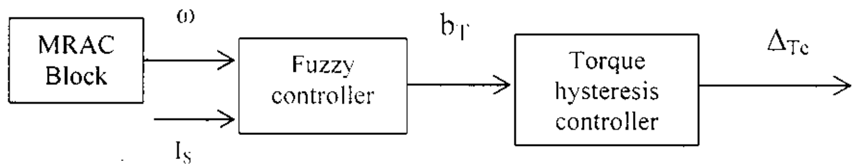


Fig 4.2 Torque hysteresis controller adapted band

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing torque and flux ripple were found. These values composed a training set which is used to extract the table rule $\Delta b_T(e1;e2)$.The shapes of membership functions are refined trough simulation and testing. The rules sets are shown in Table 4.1. Figure 4.3 shows the membership functions of input and output variables assinned through MATLAB/ Fuzzy Inference System. The rules were formulated using analysis data obtained from the simulation of the system using different values of torque hysteresis band.

Table 4.1 Fuzzy rules of torque hysteresis controller

e1 / e2	NH	NM	NS	ZE	PS	PM	PH
N	N	N	NS	ZE	PS	PS	P
ZE	N	N	NS	ZE	PS	P	P
P	N	NS	NS	ZE	PS	P	P

Where PH: positive high; NH: negative high;

PM: positive medium; NM: negative medium;

PS: positive small; NS: negative small;

ZE: zero; N: negative

If the amplitude b_T is set too small, the overshoot may touch the upper band which will cause a reverse voltage vector to be selected. This voltage will reduce rapidly the torque causing undershoot in torque response, consequently the torque ripple will remain high.

The linguistic rules can be expressed by the following example:

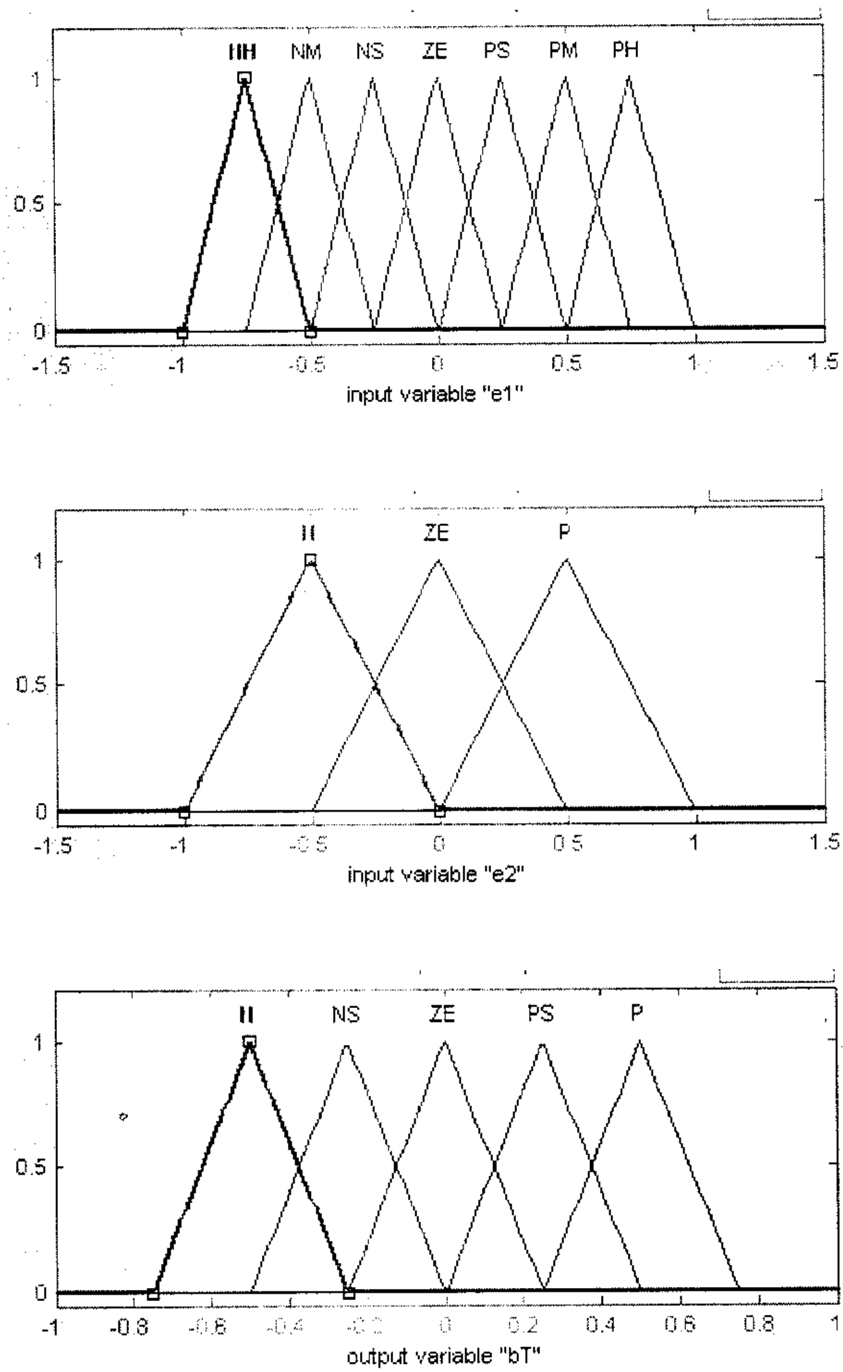
- If (e1 is NH or NM and e2 is N) then (Δb_T is N):

This case corresponds to a big overshoot in torque error, consequently high torque ripple. To reduce the torque ripple, the value Δb_T should be reduced.

- If (e1 is PH and e2 is P) then (Δb_T is P):

In this case, the overshoot in torque error can touch the upper band which will cause a reverse voltage vector to be selected. This one will result in a torque to be reduced rapidly and causes undershoot in the torque response below the hysteresis band. Thus, Δb_T should not be too small, Δb_T is set Positive in order to avoid this situation.

Fig 4.3 Membership functions of Fuzzy Input/Output variables



4.6 DISADVANTAGES OF CONVENTIONAL DTC METHOD

The disadvantages of this method includes,

- The overshoot in current which would result in more losses
- The torque ripples are more

To eliminate these disadvantages the conventional DTC method is replaced by DTC with MRAC-Fuzzy.

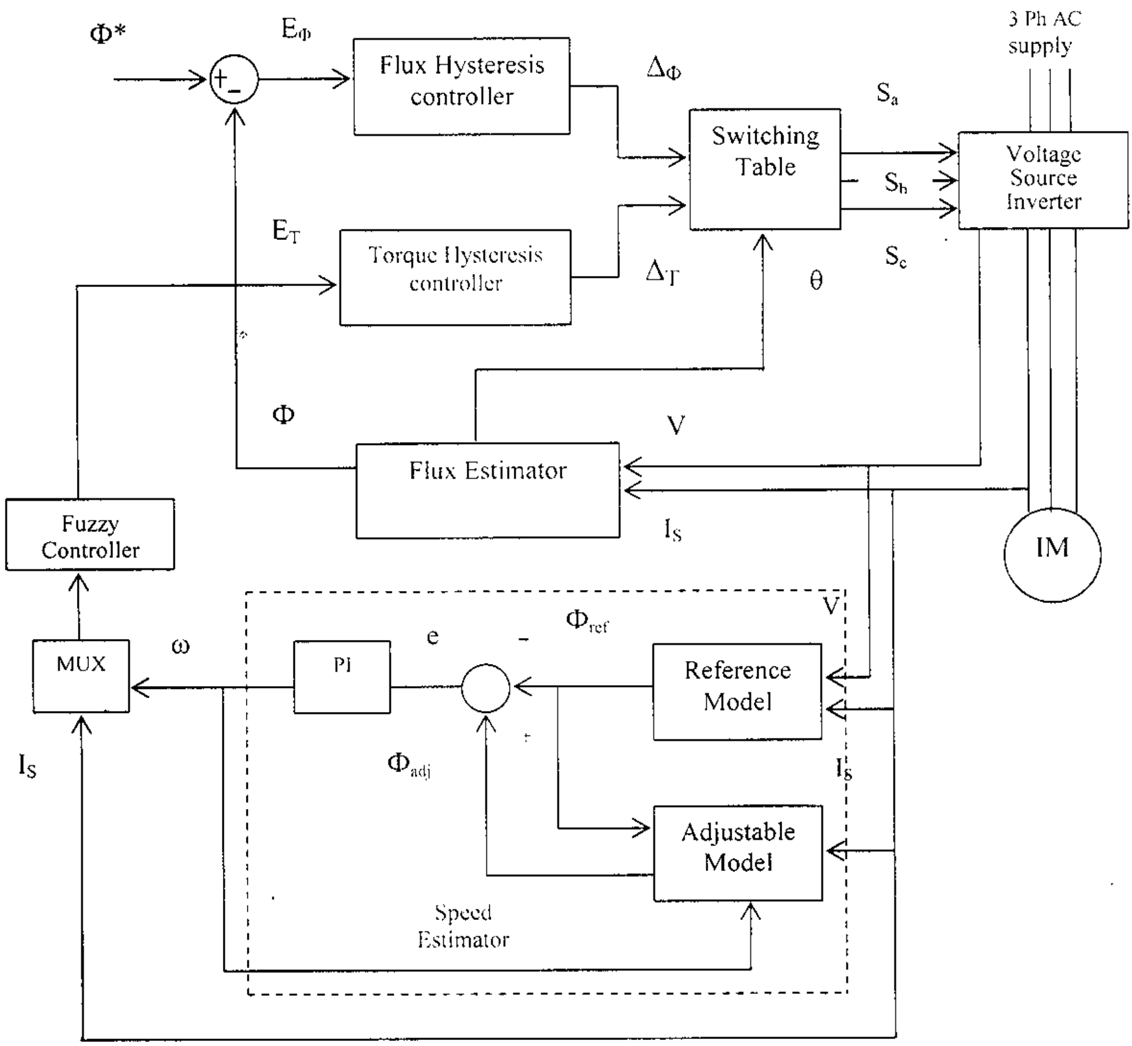


Fig 4.4 Overall block diagram of DTC with MRAC-FUZZY

4.7 OVERALL BLOCK DIAGRAM OF DTC WITH MRAC-FUZZY

The voltage and the currents are taken from the induction machine and given to the MRAC block. In the DTC with MRAC, the flux and teta are calculated using the flux estimator block. By using the current and voltage values, the reference flux is calculated by the reference model. With the current, reference flux and the speed values the adjustable flux is calculated from the adjustable model. These two fluxes are compared and the error value is found and given to the Fuzzy controller which produces the speed error output. With the help of the current and speed, the previous state values are calculated by introducing the unit delay elements. These two values are multiplexed and given as the inputs to the Fuzzy controller, which produces the torque error. This torque error is then band limited and given to the switching control for selecting the switching states for the inverter. The overall block diagram with MRAC- Fuzzy controller is shown in Fig 4.4.

The advantages of this method are,

- Reduced overshoot in current
- Reduced torque ripples
- Improved speed response
- Improved steady state response

CHAPTER V

SIMULATION RESULTS

5.1 SOFTWARE INTRODUCTION

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in any easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development Data acquisition medelling, simulation, and prototyping Data analysis, exploration, and visualization scientific and engineering graphics application development, including graphical user interface building MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or FORTRAN. The name MATLAB stands for Matrix Laboratory.

MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. Today, MATLAB engines incorporate the LAPACK and BLAS libraries, embedding the state of the art in software for matrix computation. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis. MATLAB features a family of add-on application specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, image processing, control systems, neural networks, fuzzy logic, wavelets, simulink, and many others.

The Direct Torque Control of the induction motor is developed using simulink. The induction motor parameters are summarized in Table 5.1.

Table 5.1 Machine Parameters

Parameter	Description	Value	Unit
P	Nominal power	3	HP
R_s	Stator resistance	0.087	Ω
R_r	Rotor resistance	0.228	Ω
L_s	Stator inductance	0.8	mH
L_r	Rotor inductance	0.8	mH
M	Mutual inductance	34.7	mH
J	Rotor inertia	1.662	$Kg.m^2$
2p	Number of pole pairs	2	-

5.2 SIMULINK MODEL FOR DTC

The 3-phase supply is given to the induction motor trough an Inverter Bridge. It is a universal bridge, which accepts dc supply and produces 3-phase ac supply through the terminals ABC. The 3-phase supply from the output of the inverter is given to the Induction Motor model. The parameters of the motor are in SI units. The motor parameters are measured using the block called Measurement Demux Block. The motor parameters such as stator current, inverter voltage, speed, d-q axis currents and voltages of stator and rotor, etc., can be measured using the Measurement Block. From the measured values the torque and flux are calculated directly and then the inverter switching is done based on the voltage sector selection values and the respective voltage vectors as per the requirement from the preset switching table. The Fig 5.1 shows the overall direct torque control block.

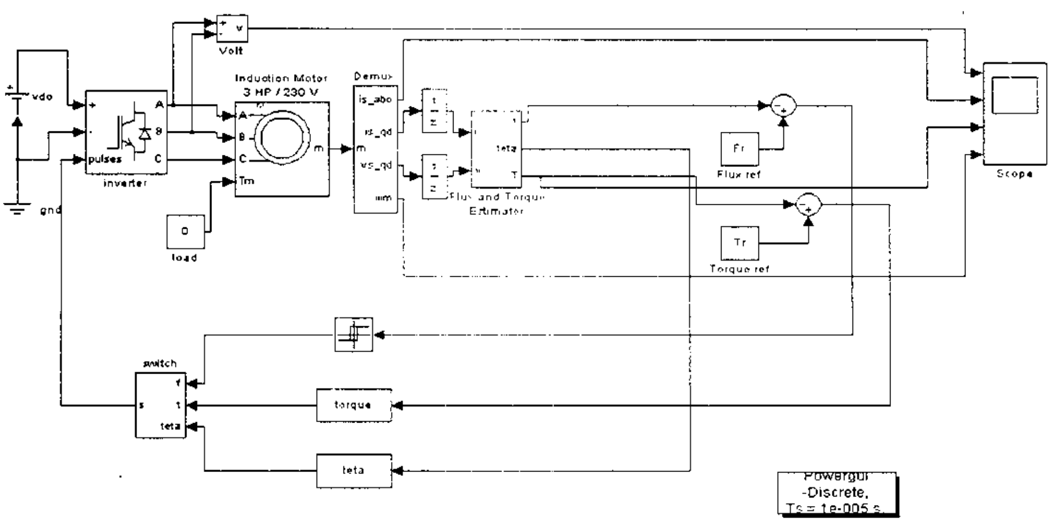


Fig 5.1 Overall Direct Torque Control block

Fig 5.2 gives the response for the system for a flux reference of 0.9 webers and torque reference of 300 NM. The steady sate speed of 125 rad/sec is achieved in 2.5 seconds. The torque takes 2.5 seconds to settle at the value of 10 NM due to more number of ripples in torque. Thus, the response of the system is slow.

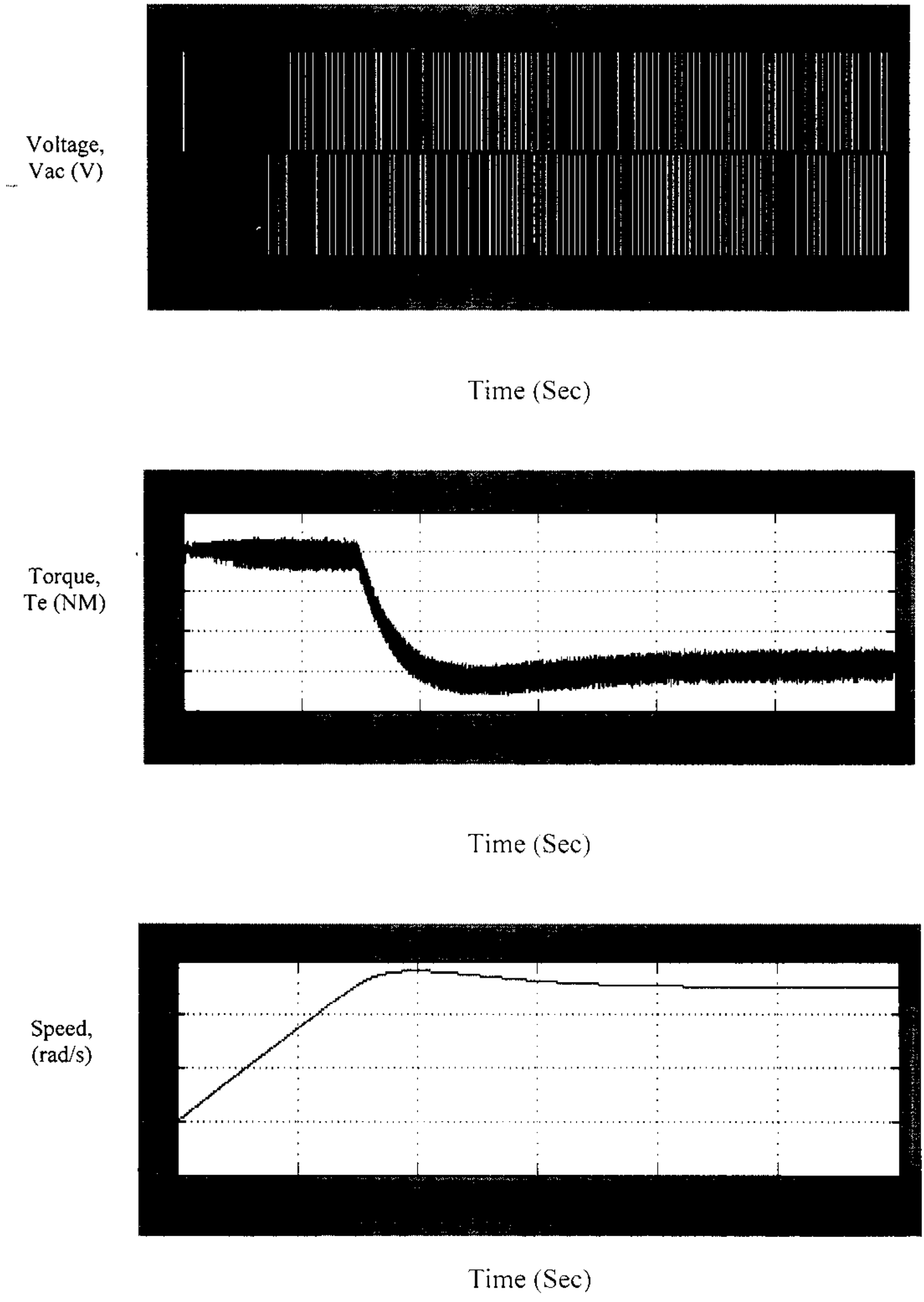


Fig 5.2 Output waveforms for DTC

5.3 SIMULINK MODEL FOR DTC WITH MRAC-FUZZY

The Fig 5.3 shows the Simulink model of DTC with MRAC-FUZZY. To reduce the steady state ripples in torque the Model Reference Adaptive Control (MRAC) with Fuzzy is implemented in the Simulink model of DTC.

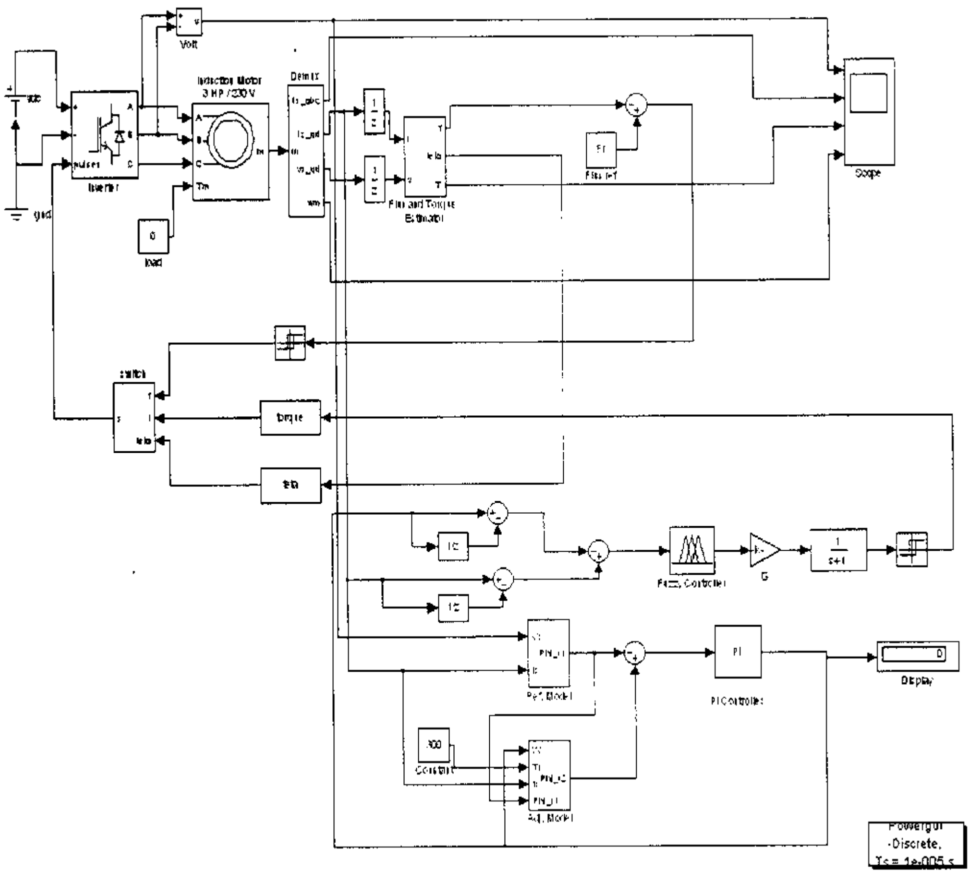
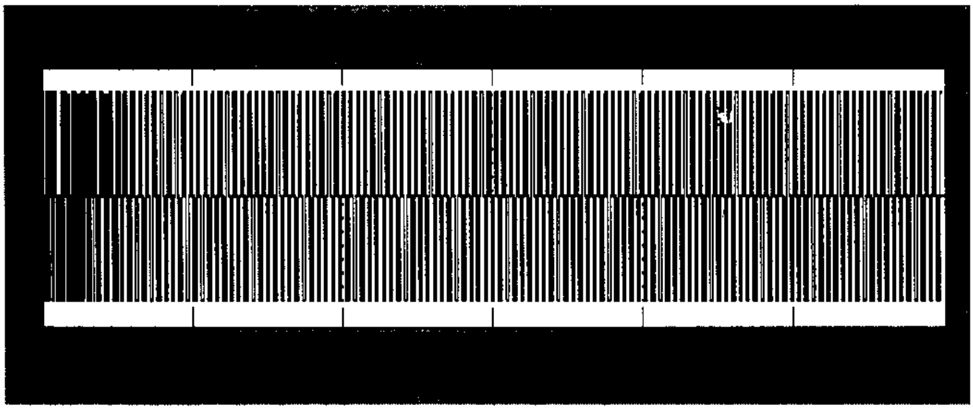


Fig 5.3 Simulink model of DTC with MRAC-FUZZY

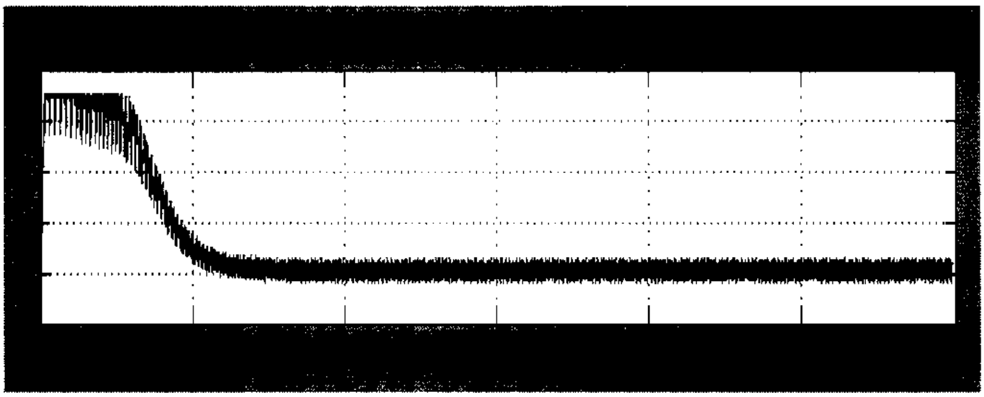
Fig 5.2 gives the response for the system for a flux reference of 0.9 webers and torque reference of 300 NM. The steady sate speed of 128 rad/sec is achieved in 1 second. The torque takes 1 second to settle at the value of 10 NM due to minimization of ripples in torque by the Fuzzy controller action. Thus, the response of the system is improved. The Inverter switching is uniform after the settling of torque at steady state value.

Voltage,
Vac (V)



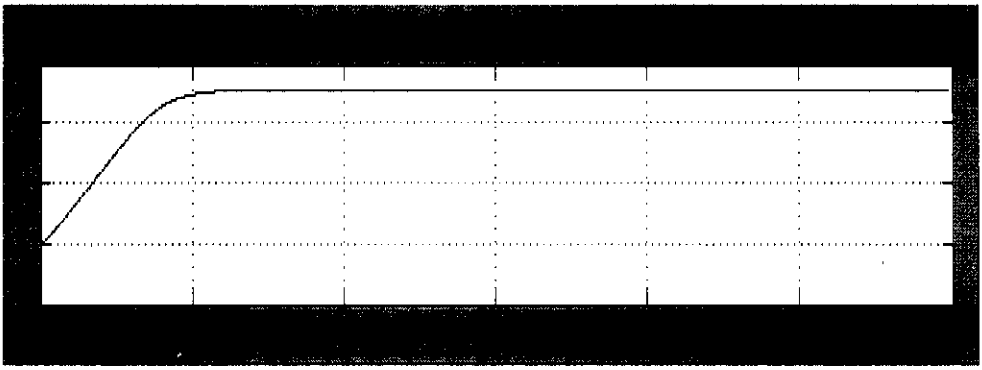
Time (Sec)

Torque,
Te (NM)



Time (Sec)

Speed,
(rad/s)



Time (Sec)

Fig 5.4 Output waveform for DTC with MRAC-FUZZY

CHAPTER VI
HARDWARE RESULTS

6.1 HARDWARE INTRODUCTION

6.1.1 Introduction to PIC

The microcontroller that has been used for this project is from PIC series. PIC microcontroller is the first RISC based microcontroller fabricated in CMOS (complimentary metal oxide semiconductor) that uses separate bus for instruction and data allowing simultaneous access of program and data memory.

The main advantage of CMOS and RISC combination is low power consumption resulting in a very small chip size with a small pin count. The main advantage of CMOS is that it has immunity to noise than other fabrication techniques.

6.1.2 PIC (16F877):

Various microcontrollers offer different kinds of memories. EEPROM, EPROM, FLASH etc. are some of the memories of which FLASH is the most recently developed. Technology that is used in pic16F877 is flash technology, so that data is retained even when the power is switched off. Easy Programming and Erasing are other features of PIC 16F877.

6.1.3 PIC START PLUS Programmer:

The PIC start plus development system from microchip technology provides the product development engineer with a highly flexible low cost microcontroller design tool set for all microchip PIC micro devices. The PIC START PLUS development system includes PIC START PLUS development programmer and MPLAB IDE (Integrated Development Environment).

The PIC START PLUS programmer gives the product developer ability to program user software in to any of the supported microcontrollers. The PIC START PLUS software running under MPLAB provides for full interactive control over the programmer.

6.1.4 Special Features of PIC Microcontroller:

Core Features:

- High-performance RISC CPU
- Only 35 single word instructions to learn
- All single cycle instructions except for program branches which are two cycle
- Operating speed:
  - i.DC - 20 MHz clock input
  - ii.DC - 200 ns instruction cycle
- Up to 8K x 14 words of Flash Program Memory,
- Up to 368 x 8 bytes of Data Memory (RAM)
- Up to 256 x 8 bytes of EEPROM data memory
- Pin out compatible to the PIC16C73/74/76/77
- Interrupt capability (up to 14 internal/external
- Eight level deep hardware stack
- Direct, indirect, and relative addressing modes
- Power-on Reset (POR)
- Power-up Timer (PWRT) and Oscillator Start-up Timer (OST)
- Watchdog Timer (WDT) with its own on-chip RC Oscillator for reliable operation
- Programmable code-protection
- Power saving SLEEP mode
- Selectable oscillator options
- Low-power, high-speed CMOS EPROM/EEPROM technology
- Fully static design
- In-Circuit Serial Programming (ICSP) via two pins
- Only single 5V source needed for programming capability
- In-Circuit Debugging via two pins
- Processor read/write access to program memory
- Wide operating voltage range: 2.5V to 5.5V
- High Sink/Source Current: 25 mA
- Commercial and Industrial temperature ranges
- Low-power consumption:
  - i.< 2mA typical @ 5V, 4 MHz
  - ii.20mA typical @ 3V, 32 kHz

Peripheral Features:

- Timer0: 8-bit timer/counter with 8-bit prescaler
- Timer1: 16-bit timer/counter with prescaler, can be incremented during sleep Via external crystal/clock
- Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler
- Two Capture, Compare, PWM modules
  - i.Capture is 16-bit, max resolution is 12.5 ns,
  - ii.Compare is 16-bit, max resolution is 200 ns,
  - iii.PWM max. resolution is 10-bit
- 10-bit multi-channel Analog-to-Digital converter
- Synchronous Serial Port (SSP) with SPI. (Master Mode) and I2C. (Master/Slave)
- Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) with 9- bit address detection.
- Brown-out detection circuitry **for Brown-out Reset (BOR)**

Table 6.1 Specifications of PIC 16F877

DEVICE	PROGRAM FLASH	DATA MEMORY	DATA EEPROM
PIC 16F877	8K	368 Bytes	256 Bytes

6.2 HARDWARE MODEL OF DTC

The single phase 230V supply is given to the step down transformer. The step down transformer step down the voltage level to 15-0-15 V. The power supply circuit produces four output levels as +5V, -5V, +12V, -12V, and GND. The +5V supply is given to the PIC 16F877 Microcontroller Unit (MCU). The keypad is interfaced to the Port B of the PIC 16F877 MCU. The keypad is used to set the reference value of Torque (T_{ref}).

Two Ports P1 & P2 of Port C in PIC 16F877 MCU produces the PWM pulses for the MOSFET Inverter according to the given T_{ref}.

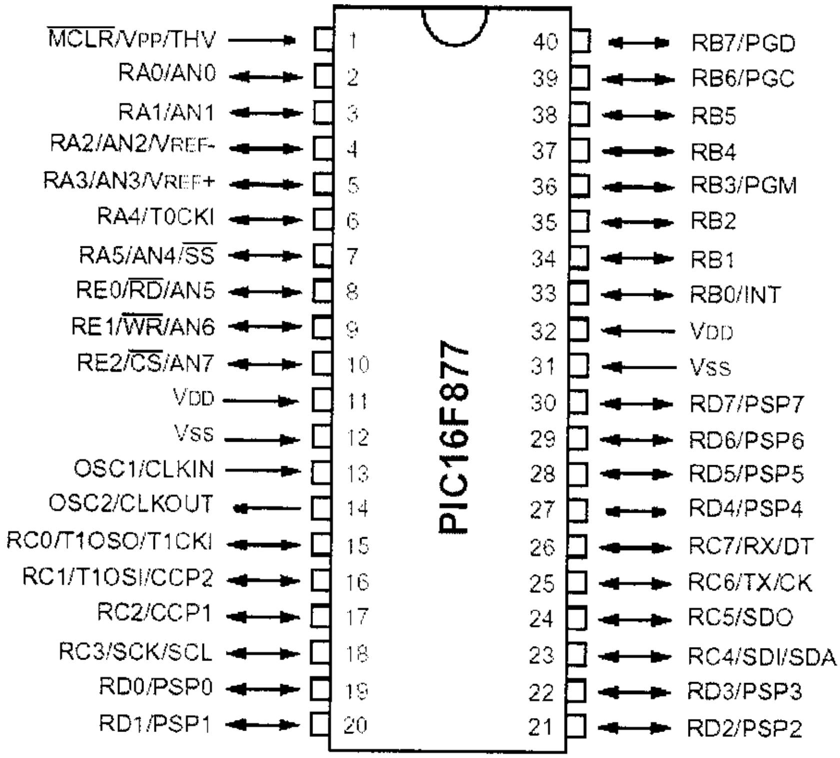


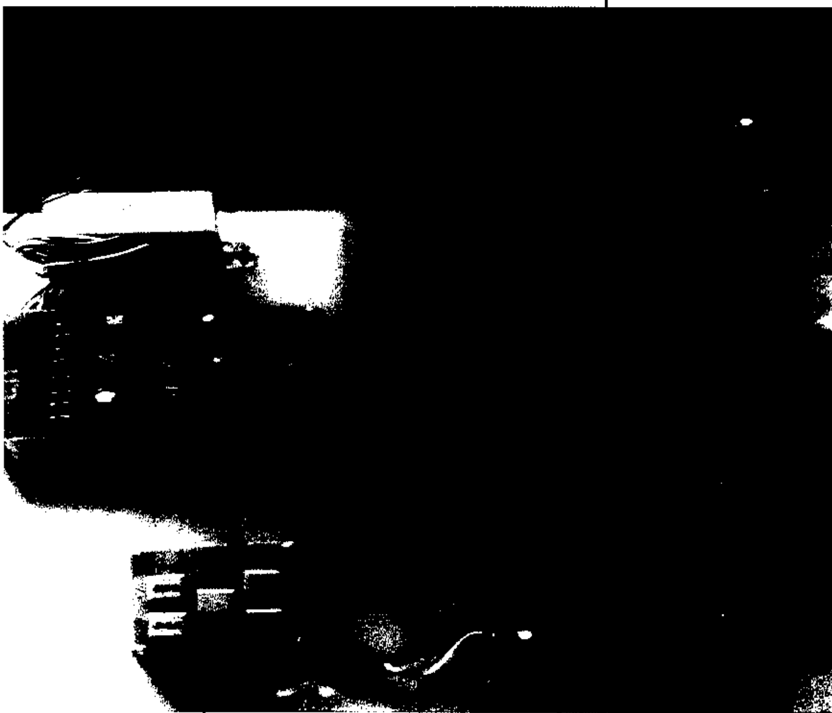
Fig 6.1 Pin Diagram of PIC 16F877

The IC7408 with four transistors forms the gate drive circuit for the MOSFET Inverter. The gate drive circuit operates according to the PWM pulses produced from the PIC MCU.

When the gate pulse is given to the MOSFET it will conduct and forms a closed circuit due to the flow of charges from higher potential to lower potential. A 12V battery provides the DC supply to the MOSFET Inverter circuit.

The AC output signal generated from the MOSFET Inverter is given to the single phase Induction Motor. The speed of the Induction Motor can be controlled by achieving different switching states provide for the MOSFET Inverter according to the reference torque value (T_{ref}).

a. PIC Microcontroller Unit



b. Inverter Circuit

c. Single Phase Induction Motor

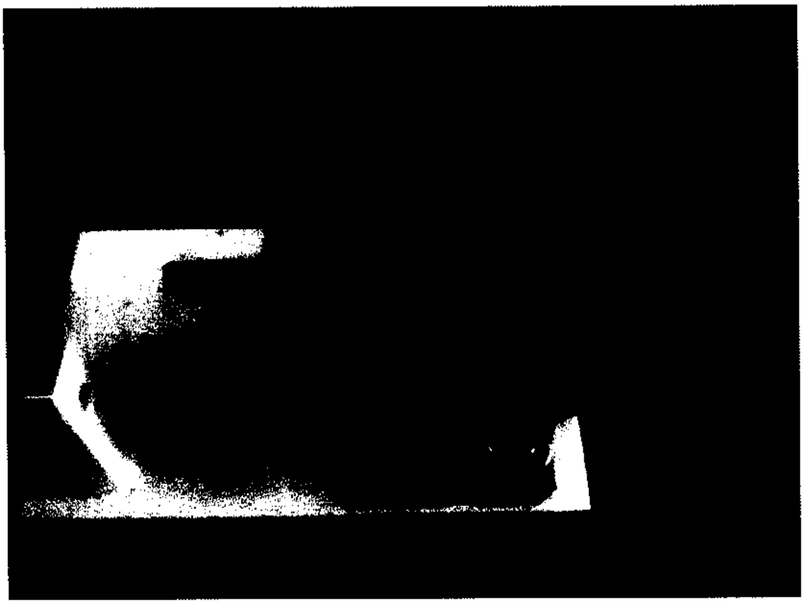


Fig 6.2 Hardware Model of DTC using Fuzzy Logic

Table 6.2 Induction Motor Parameters

Parameter	Description	Value	Unit
P	Nominal power	0.25	HP
V	Voltage	230	v
n_r	Rated Speed	1440	rpm
2p	Number of pole pairs	2	-

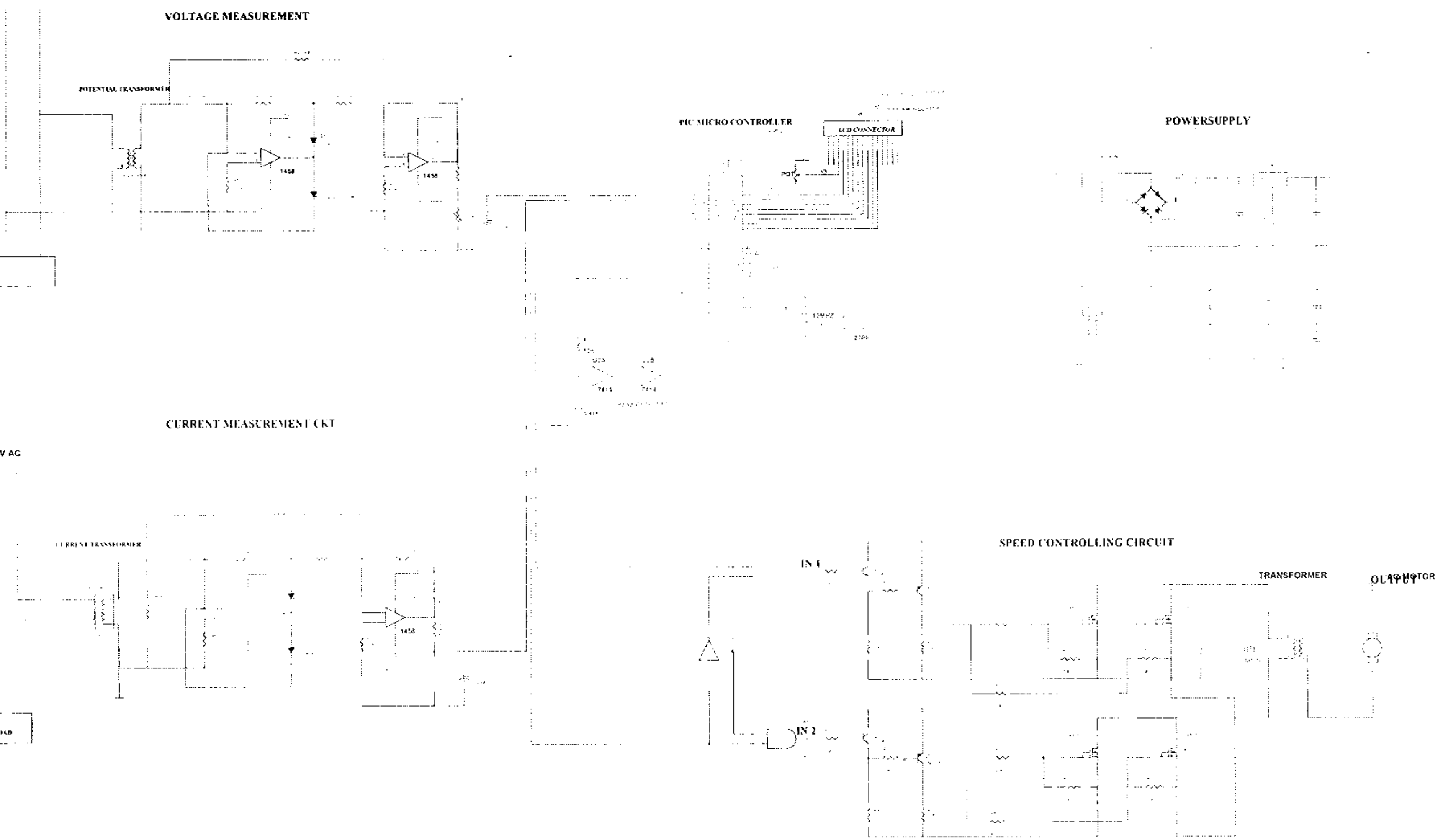


Fig 6.3 Circuit Diagram of DTC with PIC 16F877

6.3 PROGRAM

```
#include<pic.h>
#include<lcd.h>

void adc_init();
void adc0();
void adc1();
void hex_dec_a(unsigned int);
void set_mode();
void hex_dec_cur(unsigned char);

static bit p2 @((unsigned) &PORTC*8+2);
static bit p1 @((unsigned) &PORTC*8+1);
static bit k1 @((unsigned) &PORTB*8+0);
static bit k2 @((unsigned) &PORTB*8+1);
static bit k5 @((unsigned) &PORTB*8+2);
static bit k3 @((unsigned) &PORTB*8+3);

unsigned int on,count,off,temp0,temp1,temp2,torq;
unsigned int sv,prev,difr;
unsigned char volt,curr,j;
float vv;

void main()
{
TRISC=0x00;                      // PortC as o/p port
TRISB=0xff;
p1=p2=0;
lcd_init();                      // LCD Initialization
adc_init();                      // ADC Initialization
command(0x80);
lcd_condis("V:000 V I:00.0 A",16);
command(0xc0);
```

```
lcd_condis("T:00.00  ST:000 ",16);
set_mode();
on=count=0;
GIE=1;                          // enable global interrupt
PEIE=1;                         // enable peripheral interrupt
T0IE=1;                         // enable timer0 interrupt
OPTION = 0x01;                  // set prescale (00)
TMR0 = 0xfc;                    // timer reg set value for ten micro sec  F7

while(1)
{
adc0();
command(0x82);
hex_dec(volt);

adc1();
command(0x8a);
hex_dec_cur(curr);

torq=(float)((float)(volt*curr*7.64)/100);
command(0xc2);
hex_dec_a(torq);

if(torq<sv)
{
difr=sv-torq;
if(difr>20 && on<148) on+=10;
else if(difr>10 && on<153) on+=5;
else if(difr>5 && on<155) on+=3;
else if(on<158) on++;

off=on+160;
}
```

```
{
difr=torq-sv;
if(difr>20 && on>10) on-=10;
else if(difr>10 && on>5) on-=5;
else if(difr>5 && on>3) on-=3;
else if(on>0) on--;

off=on+160;
}

if(k5==0) set_mode();

}
}

void adc_init()
{
 ADCON1=0x09;                    // 8-channel,ADC control
 TRISA=0xff;                     // to select the port A as input port
}

void adc0()
{
temp0=0;
for(j=0; j<5; j++)
{
  ADCON0=0x00;                   // Channel select (Cha: 0)
  ADON=1;                        // ADC module ON
  delay(55);
  ADCON0 =0x05;          // selecting a particular channel and making the go/done bit high
  while(ADCON0!=0X01);           // Chk whether conversion finished or not
 temp0 = temp0 + ADRESH;
}
```

```
}

void adc1()
{
temp0=0;
for(j=0;j<5;j++)
 {
   ADCON0=0x08;
   ADON=1;
   delay(55);
   ADCON0 =0x0d;          // selecting a particular channel and making the go/done bit high
   while(ADCON0!=0x09);
//   temp1 = ADRESH;
 temp0 = temp0 + ADRESH;
 }
curr=temp0/5;
}

void interrupt function(void)
{
 if(T0IF==1)
 {
  T0IF=0;
  count++;
        if(count>160) {count=0; p2=!p2;}            //200
        if(count<on) p1=1;
        else p1=0;
//      if(count>160&&count<=off) p2=1;
//      else p2=0;
  TMR0 = 0Xfc;
 }
}
```

```
void hex_dec_a(unsigned int val)
{
 th=val/1000;
 thr=val%1000;
 h=thr/100;
 hr=thr%100;
 t=hr/10;
 o=hr%10;
 lcd_disp(th+0x30);
 lcd_disp(h+0x30);
 lcd_disp('.');
 lcd_disp(t+0x30);
 lcd_disp(o+0x30);
}

void hex_dec_cur(unsigned char val)

{
 h=val/100;
 hr=val%100;
 t=hr/10;
 o=hr%10;
 lcd_disp(h+0x30);
 lcd_disp(t+0x30);
 lcd_disp('.');
 lcd_disp(o+0x30);
}

void set_mode()
{
p1=0; p2=0;
GIE=T0IE=0;
command(0x01);
```

```
lcd_condis("  Set Mode...   ",16);
while(k5==0);
delay(60000);
command(0x01);
command(0x80);
lcd_condis("Set the Torque  ",16);
command(0xc0);
lcd_condis("Torque.:00.0 Nm ",16);
sv=0;

while(1)
{
if(k1==0)
{
if(sv<99) sv++;
command(0xc8);
hex_dec_cur(sv);
delay(15000);
}
if(k2==0)
{
if(sv>0) sv--;
command(0xc8);
hex_dec_cur(sv);
delay(15000);
}
if(k3==0) goto end;
//if(k4==0) {sv=prev; goto end;}

}
end:
command(0x80);
lcd_condis("V:000 V I:00.0 A",16);
```

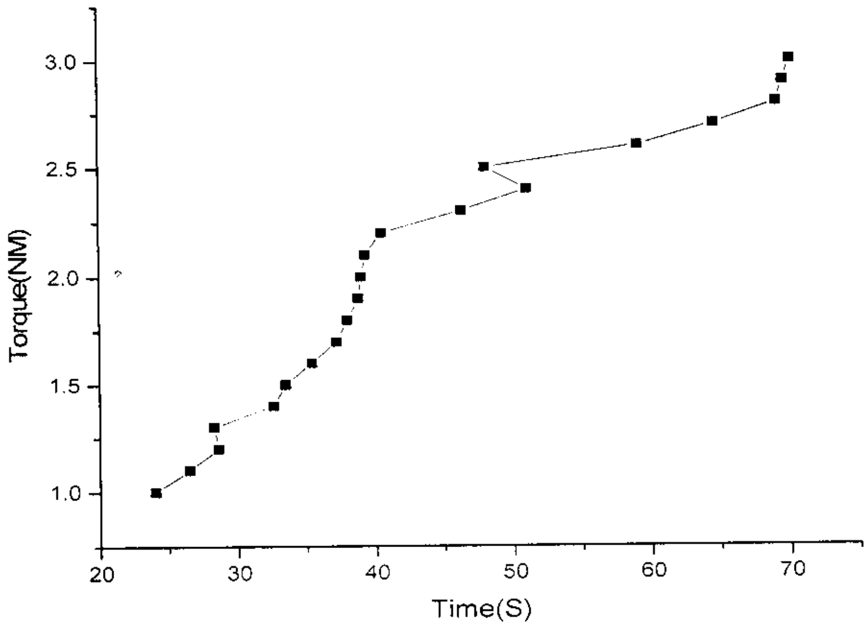
```
lcd_condis("T:00.00  ST:000 ",16);
command(0xcc);
hex_dec_cur(sv);
sv=sv*10;
 p1=0; p2=0; on=off=0;
GIE=T0IE=1;
}
```

6.4 RESULTS FOR HARDWARE MODEL OF DTC

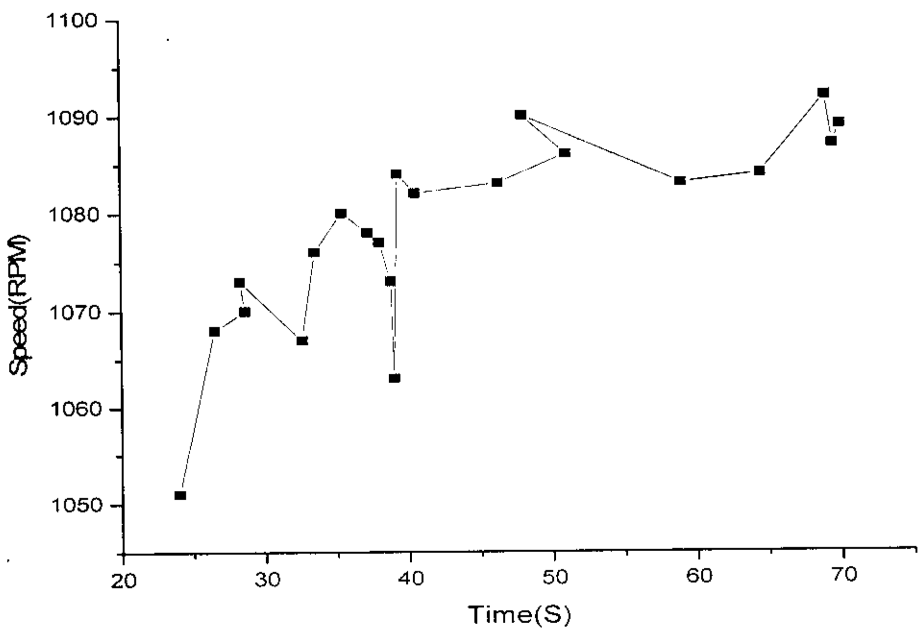
Table 6.3 Results for Hardware Model of DTC using Fuzzy Logic

S.No.	Voltage (V)	Current (A)	Time (S)	Torque (NM)	Speed (RPM)
1	133	1.0	24.0	1.0	1051
2	135	1.1	26.5	1.1	1068
3	141	1.1	28.6	1.2	1070
4	142	1.2	28.3	1.3	1073
5	147	1.2	32.6	1.4	1067
6	149	1.3	33.5	1.5	1076
7	150	1.4	35.4	1.6	1080
8	153	1.4	37.2	1.7	1078
9	158	1.5	38.0	1.8	1077
10	159	1.5	38.8	1.9	1073
11	160	1.6	39.0	2.0	1063
12	162	1.7	39.3	2.1	1084
13	165	1.8	40.5	2.2	1082
14	164	1.9	46.3	2.3	1083
15	161	2.0	51.0	2.4	1086
16	173	2.0	48.0	2.5	1090
17	177	2.0	59.0	2.6	1083
18	178	2.0	64.5	2.7	1084
19	179	2.2	69.0	2.8	1092
20	178	2.3	69.5	2.9	1087
21	179	2.4	70.0	3.0	1089

a. Torque vs Time



b. Speed vs Time



c. Speed vs Torque

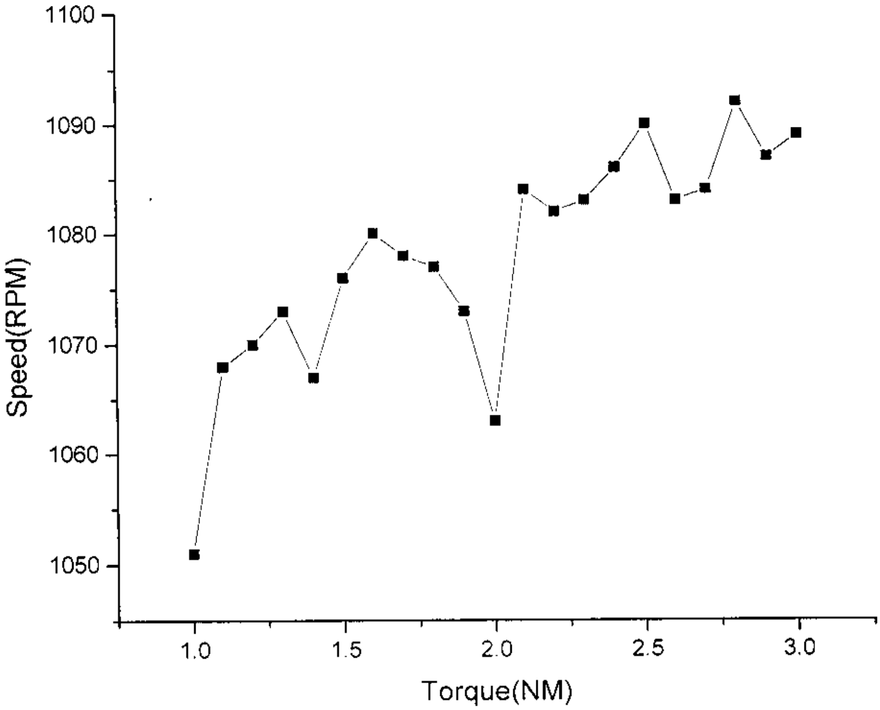


Fig 6.4 Results for Hardware Model of DTC using Fuzzy Logic

CHAPTER VII

CONCLUSION AND FUTURE WORK

7.1 CONCLUSION

Direct Torque Control method is supposed to be one of the best controllers for driving any induction motor

The Model Reference Adaptive Control speed estimator has been fully developed and verified. It is also apparent from earlier investigation reported that DTC strategy is simpler to implement than the vector control method because voltage modulators and co-ordinate transformations are not required.

The theoretical claim that the DTC induction motor has better dynamic response was verified by simulation using MATLAB. The MATLAB gives satisfactory results and reduces computational difficulties by avoiding unnecessary complex mathematical modeling of the non-linear systems. By using MATLAB/SIMULINK the specific motor performance can be achieved at a lower switching frequency, which in turn increases the performance of the drive by minimizing the torque ripples.

Table 7.1 Comparative Results

SIMULATION	VOLTAGE Vac (V)	TORQUE Ts (Sec)	SPEED Ts (Sec)	TORQUE RIPPLES
Conventional	+/- 500V	2.5	2.5	20
MRAC-FUZZY	+/- 500V	1	1	10

Where, Ts = Settling time.

The comparative results for the conventional DTC, DTC with MRAC-FUZZY controller are given in table 7.1. The conventional method produces more ripples in torque. The comparative results shows that MRAC-FUZZY has improved torque and speed responses due to torque ripple minimization. Hence the proposed scheme provides an improved response.

From table 6.3 it is evident that for the given torque reference (T) value, the induction motor attains the constant speed in minimum time in the range of seconds due to the minimization of torque ripples while using the Hardware Model for DTC using Fuzzy Logic.

7.2 FUTURE WORK

New Fuzzy controllers can be developed to achieve better performance. The new fuzzy controller may have the following features:

- Completely auto adaptive controller.
- Adaptive to any kind of motor.
- Overcome the electrical losses which appear in any electrical drives.

REFERENCES

[1] Fatiha Zidani and Rachid Nait Said. "Direct Torque Control of Induction Motor with Fuzzy Minimization Torque Ripple". Journal of Electrical Engineering, Vol. 56, No. 7-8, 2005, 183–188.

[2] L.Tang and M.F.Rahman,"A new Direct Torque Control Strategy for flux and torque ripple reduction for induction motors drive by using space vector modulation", in conf.Rec.IEEE 32nd Annu. PESC'01, vol.3, 2001, pp.1440-1445.

[3] J.K.Kang,"Torque Ripple minimization strategy for direct torque control of induction motor", Conf.Rec.IEEE-IAS annual meeting. pp.438-443.

[4] M.P.Kazmierkowsi,"Review of Direct Torque Control methods for voltage source inverter fed induction motors", in conf.Rec.IEEE-IAS, 2003, pp.981-981.

[5] C. Lascu, I. Boldea, and F. Blaabjerg, "A modified direct torque control (DTC) for induction motor sensorless drive," in Conf. Rec. IEEE-IAS Annu. Meeting, vol. 1, 1998, pp. 415–422.

[6] Rakesh Parekh," AC Induction Motor Fundamentals", Microchip Technology Inc., AN887, 12/18/03.

[7]T.G.Habetler, F.Profumo, M.Pastorelli, and M.Tolbert,"Direct Torque Control of induction machines using space vector modulation", IEEE Trans. on Industrial Applications,Vol.28,no.5,sep\oct.1992,pp.1045-1053.

[8] I.Takahasi and Y.Ohmori,"High Performance Direct Torque Control of an Induction Motor", IEEE Trans. on Industrial Applications, vol.25, no.2, 1989, pp.257-264.

[9] Kang, J.K.etal : Direct Torque Control of Induction Machine with Variable Amplitude Control of Flux and Torque Hysteresis Bands, Conf. Rec. IEEE-IAS, pp. 640–642, 1999.

[10] Takahashi, I. etal: A New Quick-Response and High-Efficiency Control Strategy for an Induction Motor, IEEE Trans.Ind. Applicat. IA-22 (1986).

[11] Bimal K.Bose,"Modern Power Electronics and AC drives", Second Indian Reprint, 2003.

[12] Vas, P. "Sensorless vector and direct torque control", Oxford University Press Inc, Clarendon, 1998.

[13] P.Z. Grabowski, "A Simple Direct Torque Neuro-Fuzzy control of PWM inverter fed induction motor drive", IEEE Trans. On Industrial Electronics, vol.47, 2000, pp.863-870.

[14] D.Casedi, "Improvement of direct torque control performance by using discrete SVM technique", Proc.of.conf.IEEE-IAS, 1998, pp.997-1003.

[15] H.Tadjima, "Speed sensorless field-oriented control of the induction machine", IEEE Trans.on Industrial applications, vlo.29, no.1, 1993, pp.175-180.

APPENDIX

Simulation Coding

S function for Flux calculation:

```
function [sys,x0,str,ts]=teta(t,x,u,flag)
switch flag
case 0
   [sys,x0,str,ts] = mdlInitializeSizes;
case 2
   sys = [];
case {1,9}
   sys = [];
case 3
   sys = mdlOutputs(t,x,u);
otherwise
   error(['unhandled flag = ',num2str(flag)]);
end
function [sys,x0,str,ts] = mdlInitializeSizes
sizes= simsizes;
sizes.NumContStates  = 0;
sizes.NumDiscStates  = 0;
sizes.NumOutputs     = 1;
sizes.NumInputs      = 1;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;
sys = simsizes(sizes);
str = [];
x0  = [];
ts  = [1e-5 0];
function sys = mdlOutputs(t,x,u)
if((0<u)&(u<=60))
   sys=2;
```