DIRECT TORQUE CONTROL OF INDUCTION MOTOR DRIVE USING INTELLIGENT CONTROL

A Project Report

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ABSTRACT

This thesis describes an improved speed control scheme for direct torque and flux control of induction motor based on stator flux field orientation method. The Direct Torque Control (DTC) of an induction motor fed by a voltage source inverter is a simple scheme that does not need long computation time, can be implemented without mechanical speed sensors and is insensitive to parameter variation. In this principle, the motor terminal voltage and current are sampled and used to estimate the motor flux and torque. Based on the estimates of flux position and instantaneous error in torque and stator flux magnitude, a voltage vector is selected using Space Vector Pulse Width Modulation (SVPWM) to restrict the torque and the flux errors within their respective torque and flux hysteresis band. The implementation of this scheme requires flux linkage and torque computations, pulse generation of switching states for inverter through a feed back control of the torque and flux directly without inner current loops. This results in reduced complexity of the system.

The major problem generally encountered is the high flux and current pulsations. To overcome this, a torque hysteresis band with variable amplitude based on fuzzy logic is used. The proposed fuzzy controller reduces the current and flux ripples and improves the performance of DTC. The speed estimator employed has the structure of Model Reference Adaptive Controller (MRAC). The simulation results using MATLAB/SIMULINK shows that the proposed scheme is not only effective in controlling the current and flux ripples but also gives a better dynamic response and high efficiency than the conventional DTC method.

ஆய்வு சுருக்கம்

இந்த ஆய்வானது நேரடி முறுக்கு விசை மற்றும் அதை சார்ந்த இயக்கு விசையை கொண்டு இண்டக்ஷன் மோட்டாரின் வேகத்தைக் கட்டுபடுத்துவதற்காக பயன்படுத்தப்படும் ஒரு மேன்படுத்தப்பட்ட முறை பற்றியதாகும். இந்த முறையானது ஸ்டேடரின் இயக்கு விசையை அடிப்படையாக கொண்டு செயல்படுகின்றது.

வேகத்தினை கண்காணிக்கும் கருவிகள் இல்லாமை, குறைந்த கணக்கீட்டு நேரம் போன்றவை இதன் நிறைகளாகும். இதில் இயந்திரத்தின் மின்னழுத்தம் மற்றும் மின்னோட்டம் ஆகியவற்றைக் கொண்டு இயந்திரத்தின் முறுக்கு விசை மற்றும் அதை சார்ந்த இயக்கு விசை ஆகியவை கணக்கிடப்படுகின்றன. இந்த கணக்கீடுகளின் அடிப்படையில் மின்னழுத்த கோள்கள் ஸ்பேஸ் வெக்டர் பல்ஸ் வித் மாடுலேஷன் (SVPWM) மூலமாக தேர்வு செய்யப்படுகின்றது.

பசி லாஜிக்(FL)யினை அடிப்படையாகக் கொண்டு இயங்கும் இயக்கு விசை ஹிஸ்டரிசிஸ் குழுவின் மூலம் அதிகமாக காணப்படுகின்ற முறுக்கு விசை மற்றும் மின்னழுத்த துடித்தல் கட்டுப்படுத்தப்பட்டுள்ளது. வேகத்தை மதிப்பீடு செய்வதற்கு மாடல் ரெபரென்ஸ் அடாப்டிவ் கண்ட்ரோலர் (MRAC) பயன்படுத்தப்படுகிறது. இந்த முறையின் மூலம் முறுக்கு விசை மற்றும் மின்னழுத்த துடித்தல் பெரிதும் குறைவடைகிறது என்பதை சிமுலேஷன் வெளியீடுகளின் மூலம் உறுதி செய்யப்படுகின்றது.

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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 the rotor current dq-axes components in the stationary reference frame (A).
i_{qdr}.	Instantaneous values of the rotor current space vector in the stationary reference frame (A).
i_{qds}	Instantaneous values of the stator current space vector in the stationary reference frame (A).
J	Polar moment of inertia ($Kg \cdot m^2$).
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 (Ohm).
R_s.	Stator resistance (Ohm).
T_e	Electromagnetic torque (NM).
T_e^*	Reference torque (NM).
V_{qr}, V_{dr}.	Instantaneous values of the rotor voltage dq-axes components in the stationary reference frame (V).
V_{qs}, V_{ds}.	Instantaneous values of the stator voltage dq-axes components in the stationary reference frame (V).

V_{qdr}. Instantaneous values of the rotor voltage space vector in the stationary reference frame (V).

V_{qds}. Instantaneous values of the stator voltage space vector in the stationary reference frame (V).

λ_{qm} ,λ_{dm}. Instantaneous values of the air gap flux linkage dq-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 dq-axes components in the stationary reference frame (Wb).

λ_{qs},λ_{ds}. Instantaneous values of the stator flux linkage dq-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 (rads/sec).

λ^* Flux reference (Wb).

δT_e Torque error (NM).

T_{load} Load torque (NM).

ω_{ref} Speed reference (Rads/sec).

b_t Torque hysteresis band amplitude (NM).

CHAPTER I
INTRODUCTION

1.1. BACK GROUND

Before the introduction of microcontrollers and high switching frequency semiconductor devices, variable speed actuators were dominated by DC motors. Today, using modern high switching frequency power converters controlled by microcontrollers, the frequency, phase and magnitude of the input to an AC motor can be changed and hence the motor 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, and 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 are easy to build.

1.2. BASIC AC MOTOR DRIVE SYSTEM

Fig.1.1 shows the 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 microcontroller decides the switching states for the inverter to control the motor's torque or speed. A sensing unit feeds back the terminal values such as motor speed, voltage and current to the microcontroller 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 are sensitive to inaccuracy in the motor parameters values.

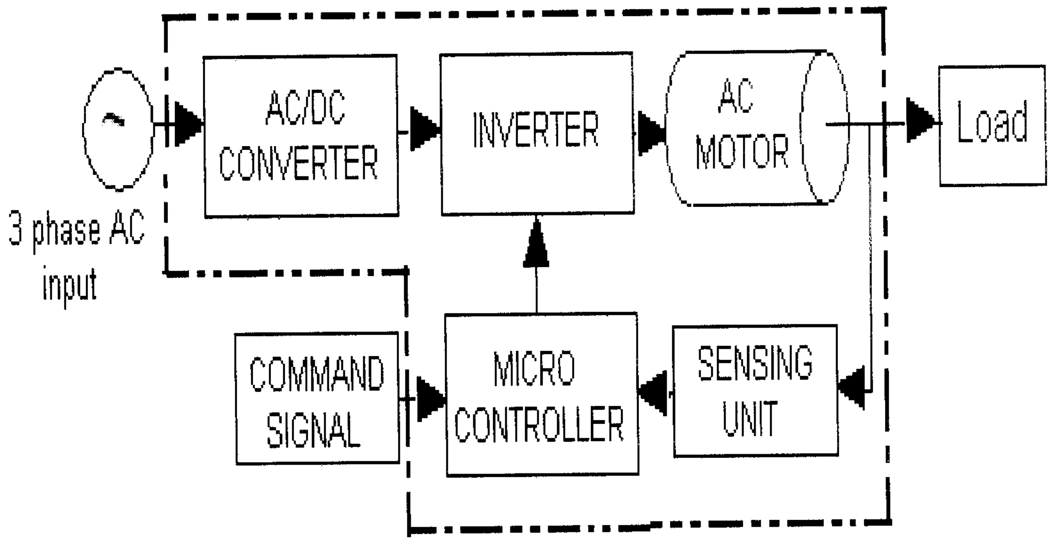


Fig.1.1 Block diagram of an AC motor drive system.

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 the 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 the 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 is less dependent on the motor model since the stator resistance value is the only parameter used to estimate the stator flux.

1.4 OBJECTIVE

The aim of my project is to reduce the flux and current ripple and to improve the dynamic performance and robustness of induction motor. Already existing DTC control has many disadvantages such as inherent flux and current 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 constructional 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 Direct Torque Control Method involving Model Reference Adaptive Control with PI and Fuzzy controller.

CHAPTER-5:

This chapter deals about with the simulation results.

CHAPTER-6:

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. 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. Furthermore, 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 stator with the winding displaced by 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 space 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 an 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, currents start 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 the 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 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 by,

$$\omega_s = 2\pi f_s \text{ rad/sec.} \qquad (2.1)$$

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

$$n_s = 120 * f_s / P. \qquad (2.2)$$

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 the 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 insinuated 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 the Fig. 2.1.

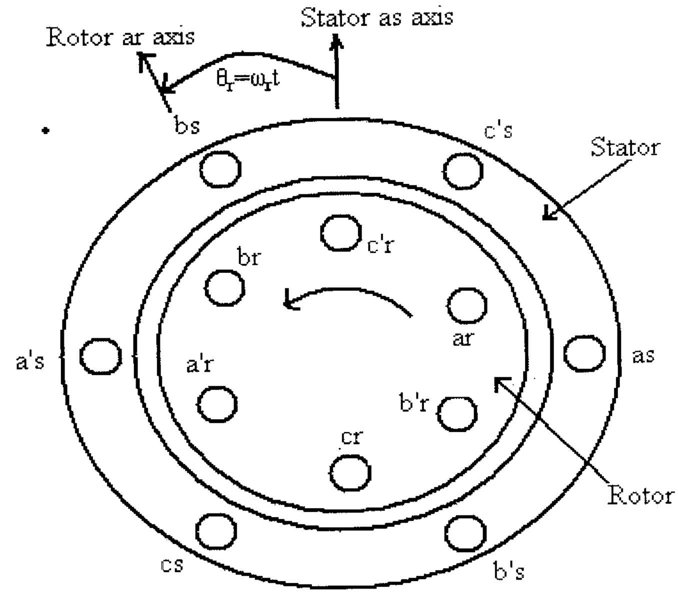


Fig. 2.1 Symbolic representation of induction motor

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 $V_r' = nSV_m$ in rotor phase, where n = rotor to stator turns ratio 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 consists of two components: a core loss components $I_c = V_m/R_m$ 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

$$I_r = nI_r' = (n^2 SV_m) / (R_r' + j\omega_{sl} L_{lr}'). \quad (2.3)$$

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

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 any 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.

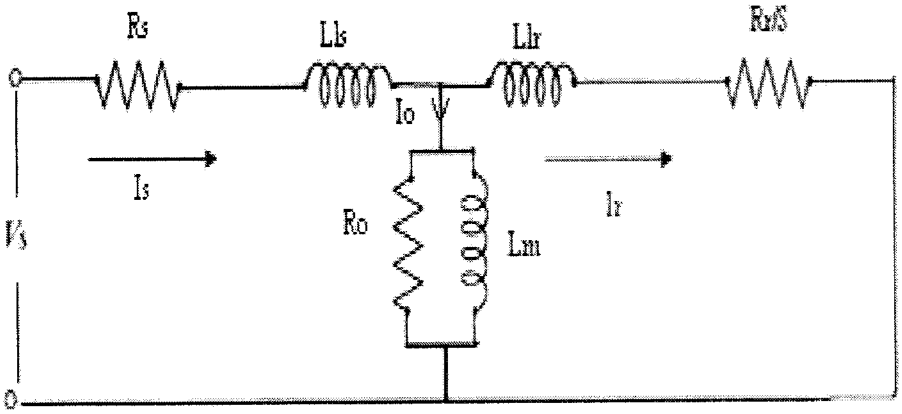


Fig.2.2 Per phase Equivalent circuit of induction motor

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

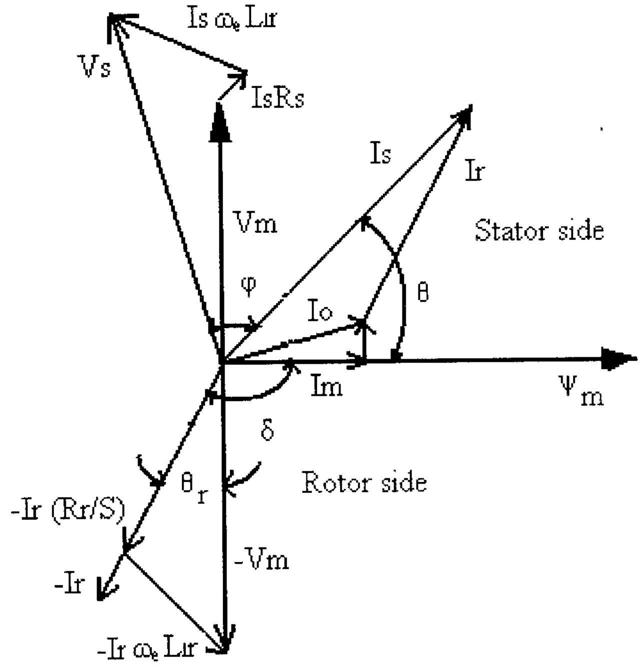


Fig. 2.3 Phasor diagram for equivalent circuit of Fig. 2.2

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 magnetising inductance as shunt elements. The rotor circuit likewise has rotor leakage reactance, rotor copper (aluminium) loss and shaft power as series elements. The transformer in the centre 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 magnetising 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 not load dependant. The magnetising current varies depending on the design of the motor. For small motors, the magnetising current may be as high as 60%, but for large two pole motors, the magnetising current is more typically 20 - 25%. At the design voltage, the iron is typically near saturation, so the iron loss and magnetising current do not vary linearly with voltage with small increases in voltage resulting in a high increase in magnetising 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
- Medium efficiency at low speed, high efficiency at high speed
- Driven by multi-phase Inverter controllers
- Sensor less speed control possible
- Low cost per horsepower
- 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 are possible.
- The network is no longer at constant high switching surge current as with that of direct switch ON of cage induction motor, and as 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,

i. It gives a sluggish response.

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 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.

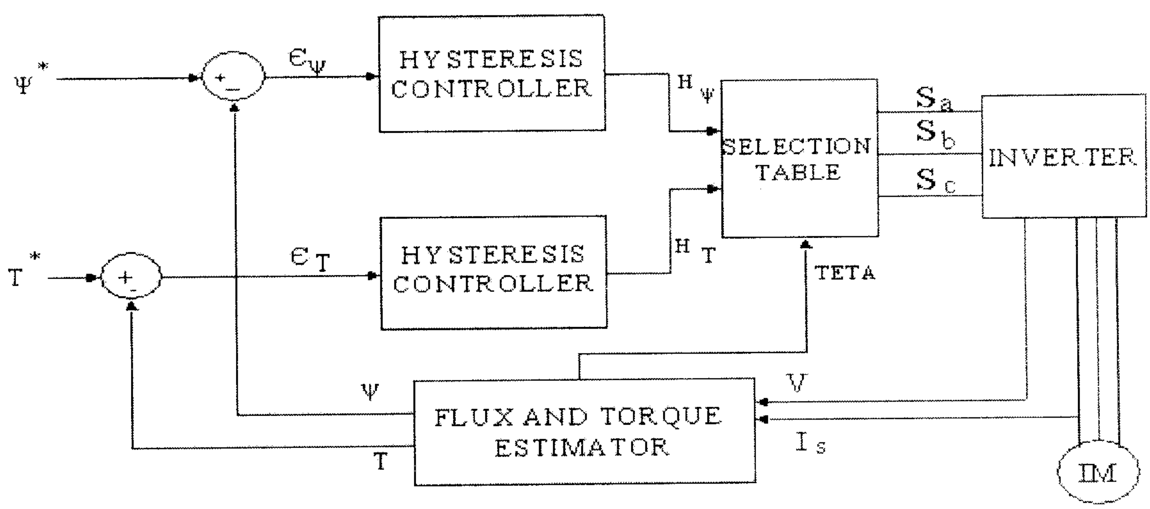


Fig. 3.1 General Block Diagram of DTC

DTC uses an induction motor model to predict 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 with in 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 & 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 & torque error with in 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 (DTC) 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 is defined from the dc-bus voltage and inverter switch positions. 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 controllers.

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 phasor is in sextant <2>, the right influencing voltage phasor has to be either VI or I. Voltage phasor I is $(90^\circ - \theta_{fs})$ and VI is $(150^\circ - \theta_{fs})$ 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 are calculated by using the formulae given below:

$$\lambda_s = \sqrt{[(\lambda_{qs})^2 + (\lambda_{ds})^2]}. \qquad (3.1)$$

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

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

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

The error value of the flux (λ_{er}) is compared with hyteresis value. The hyteresis value of flux is the maximum allowable tolerance value of the error. 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.

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

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

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

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

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

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

3.1.2 Torque Control

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

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

By using 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:

$$T_{er} = T_e^* - T_e. \tag{3.5}$$

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 δT_e is the acceptable tolerance window over the commanded torque. When the error exceeds δT_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_θ, a switching table can be realized to obtain the switching states of the inverter.

3.2. TORQUE EXPRESSION WITH STATOR AND ROTOR FLUXES

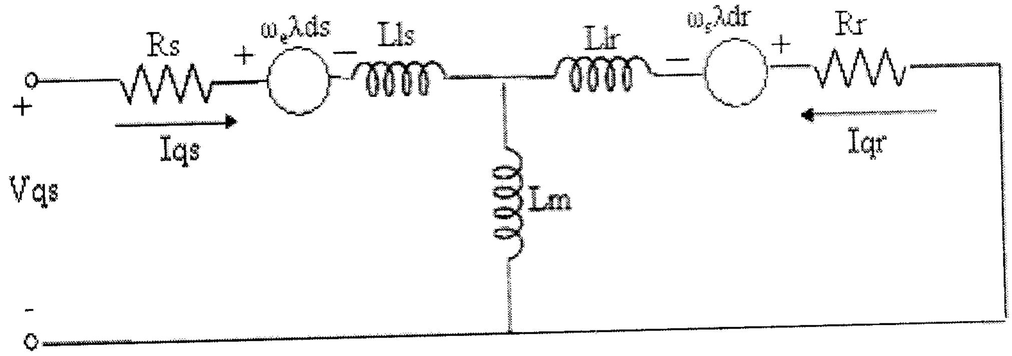
The torque expression given in equation $T_e = (3/2)\ (P/2)\ (\psi_{ds}^S\ i_{qs}^S - \psi_{qs}^S\ i_{ds}^S)$ can be expressed in the vector form as

$$T_e = (3/2)\ (P/2)\ \psi_s\ I_s. \tag{3.6}$$

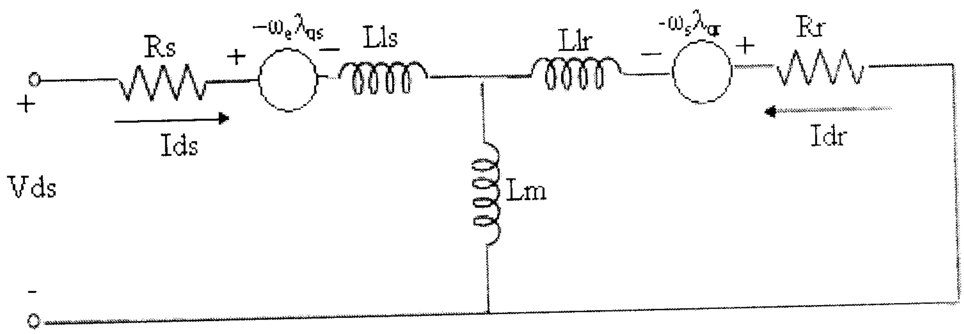
Where $\psi_s = \psi_{qs}^s - \psi_{ds}^s$ and $I_s = i_{qs}^s - j\, i_{ds}^s$. In this equation, I_s is to be replaced by rotor flux ψ_r. In the complex form, ψ_s and ψ_r can be expressed as function of current (from equivalent circuit) as

$$\psi_s = L_s I_s + L_m I_r. \tag{3.7}$$

$$\psi_r = L_r I_r + L_m I_s. \tag{3.8}$$



A. q – axis equivalent circuit



B. d – 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

$$\psi_s = (L_m / L_r)\, \psi_r + L_s' I_s. \tag{3.9}$$

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

$$I_s = (1/ L_s')\, \psi_s - (L_m / L_r L_s')\, \psi_r. \tag{3.10}$$

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

$$T_e = (3/2)\,(P/2)\,(L_m / L_r L_s')\, \psi_r\, \psi_s. \tag{3.11}$$

That is, the magnitude of torque is

$$T_e = (3/2)\,(P/2)\,(L_m / L_r L_s')\, |\psi_r|\, |\psi_s| \sin \gamma. \tag{3.12}$$

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, ψ_s, 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

$$\Delta T_e = (3/2)\ (P/2)\ (L_m / L_r L_s')\ |\psi_r|\ |\psi_s + \Delta\psi_s|\ \sin \Delta\gamma. \qquad (3.13)$$

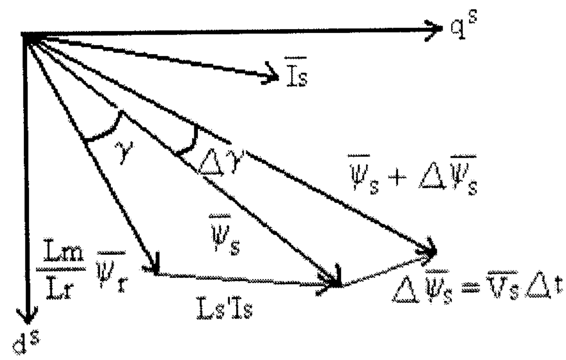


Fig 3.3 Stator flux, rotor flux, and stator current vector on $d^s - q^s$ plane

3.3 STATOR FLUX BASED DTC

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

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

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

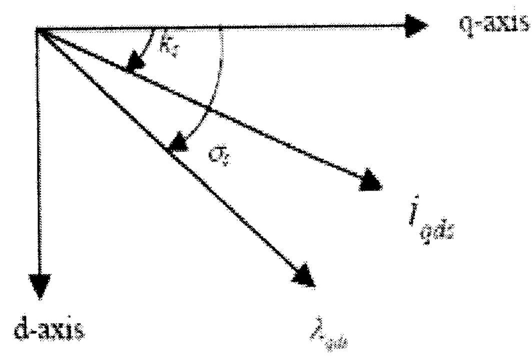


Fig 3.4 stator flux linkage and stator current space vectors

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

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

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

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

$$(r_r/L_m - j\omega_r\,(L_r/L_m))\,\lambda_{qds} + (L_r/L_m)\,P\lambda_{qds.} \qquad (3.15)$$

$$= (r_r L_s/L_m - j\omega_r\, L_r\, L_s\sigma/L_m)\; i_{qds} + L_r L_s\sigma/\,L_m\, P i_{qds.} \qquad (3.16)$$

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

$$i_{qds} = F\,(\lambda_{qds}). \qquad (3.17)$$

Substituting in equation (3.14), we can conclude that

$$T_e = g\,(\lambda_{qds}). \qquad (3.18)$$

This together with the fact that 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

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

Equation (3.19) shows that the rate of change of the electromagnetic torque (dTe/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

$$V_{qds} = r_s\, i_{qds} + P\lambda_{qds.} \qquad (3.20)$$

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

$$V_{qds} = P\lambda_{qds.} \qquad (3.21)$$

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 as 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 or 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:

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

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

And for clockwise rotation:

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

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

Similarly, for an increase in flux, the flux error is 1 and for a decrease in flux, the flux error is 0.

That is:

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

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

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
Te	↓	↑	↑	↑	↓	↓	↓

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
-1	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, current 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.

$$\lambda_{qds} = ((r_r\,(L_m/L_r))/\,(P + \omega b_r))\; i_{qds} + \sigma L_s\, i_{qds.} \qquad (3.25)$$

Where,

$$\omega b_r = r_r/L_r - j\omega_{r.} \qquad (3.26)$$

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

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

$$V_b = V_m \cos(\omega t - (2\pi/3)) \qquad (3.30)$$

$$V_c = V_m \cos(\omega t + (2\pi/3)) \qquad (3.31)$$

are applied to a three phase induction motor, using equation $V=2/3[v_{as} + av_{bs} + a^2v_{cs}]$, 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.

3.6.1d Converter Switching States

A three phase bridge inverter, as shown in figure. Have $2^3 = 8$ permissible switching states.

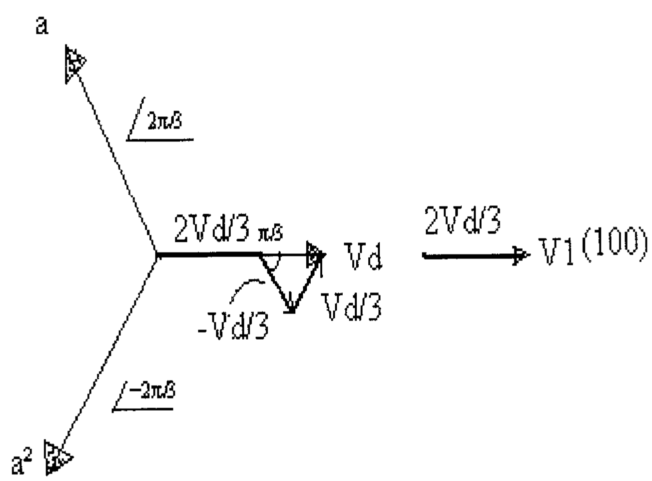


Fig 3.7 Construction of inverter space vector V_1 (100)

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	Van	Vbn	Vcn	Space voltage vector
0	$Q_4Q_6Q_2$	0	0	0	$V_0(000)$
1	$Q_1Q_6Q_2$	$2V_d/3$	$-V_d/3$	$-V_d/3$	$V_1(100)$
2	$Q_1Q_3Q_2$	$V_d/3$	$V_d/3$	$-2V_d/3$	$V_2(110)$
3	$Q_4Q_3Q_2$		.		$V_3(010)$
4	$Q_4Q_3Q_5$		:		$V_4(011)$
5	$Q_4Q_6Q_5$		.		$V_5(001)$
6	$Q_1Q_6Q_5$		.		$V_6(101)$
7	$Q_1Q_3Q_5$	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 $v_{an} = 2/3v_d$, $v_{bn} = -1/3v_d$, and $v_{cn} = -1/3v_d$. The inverter has six active states (1-6) when the voltage is impressed across the load, and two aero 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 $V = 2/3[v_{as} + av_{bs} + a^2v_{cs}]$ 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 $2/3V_d$ and is aligned in the horizontal direction as shown.

$$\sigma = 1 - (L_m^2 / L_s L_r). \quad (3.27)$$

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 introduces error at high rotor speed due to the variation in rotor parameters. However it manages to eliminate the sensitivity due to variation in stator resistance.

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.

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

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

This gives 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 VSI used in DTC control of induction motor that gives high number of possible number of possible output voltage vectors but the most common one is the six step inverter. A six step voltage source inverter provides the variable frequency AC voltage input to the induction motor in the direct torque control 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 AC source. Fig.3.5. shows the block diagram of a six step voltage source inverter. The inductor L is used to limit short through fault current. A large electrolytic capacitor C is inserted to stiffen the DC link voltage. The switching devices employed in the voltage source inverter bridge must be capable of instantaneous turn on and off. To achieve this, the IGBT's are used because 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.

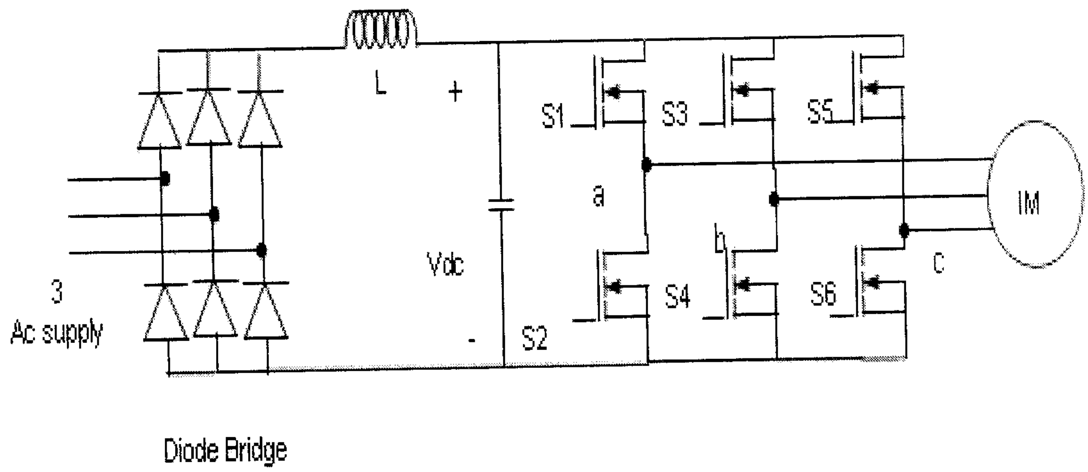


Fig.3.5 Block diagram of a six step voltage source inverter

Each leg of the inverter has two switches, one connected to the positive terminal of the DC link and the other to the negative terminal. Only one of the switches in the leg is turned on at any instant.

Considering the combinations of the status of phases a, b, c, the inverter has eight switching states (VaVbVc=000-111), in which the two are zero vectors V_0 (000) and V_7 (111) where the motor terminals are short circuited and the other six voltage vectors are non-zero voltage vectors, from V1 to V6. Each vector lies in the center of a sector of 60-degree width named as S1 to S6 according to the voltage vector.

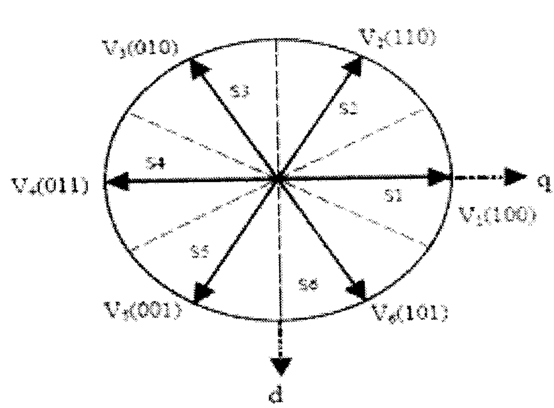


Fig. 3.6 Voltage vectors for the VSI switching states

3.6.1a Pulse Width Modulation

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.

3.6.1b 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 (SPWM)
- 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.

3.6.1c Space Vector PWM (SVPWM)

The PWM method is discussed so for have only considered implementation on a half bridge of a three phase bridge inverter. If the load neutral is connected to the centre 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

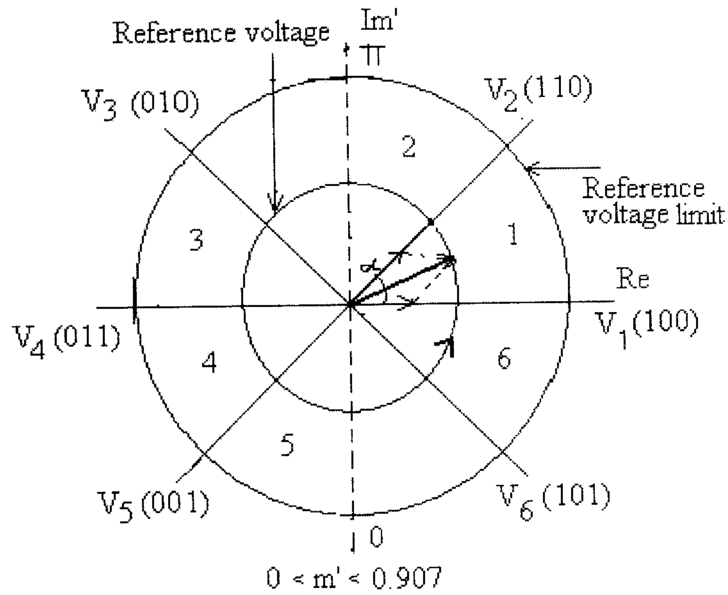


Fig 3.8 Space vectors of three-phase bridge inverter showing reference voltage trajectory and segment of adjacent voltage vectors

In the same way, all six active vectors and two zero vectors are derived and 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.

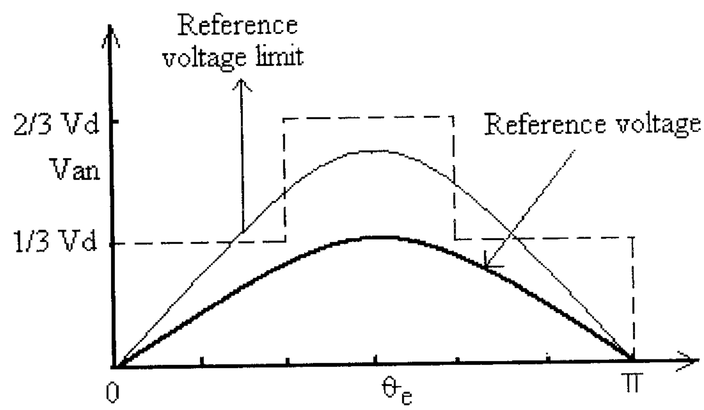


Fig.3.9 Corresponding reference phase voltage wave

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}, λ_{qs}) 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,

$$\lambda_{qs}= \int (V_{qs}-R_s i_{qs})\, dt. \quad (3.32)$$

$$\lambda_{ds}= \int (V_{ds}-R_s i_{ds})\, dt. \quad (3.33)$$

$$\lambda_s = \sqrt{(\lambda^2_{qs} + \lambda^2_{ds})}. \quad (3.34)$$

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

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

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

Fig.3.10 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 in to their respective dq reference frames. Then, the torque, flux and angle values are obtained by means of transfer function method from the dq reference signals.

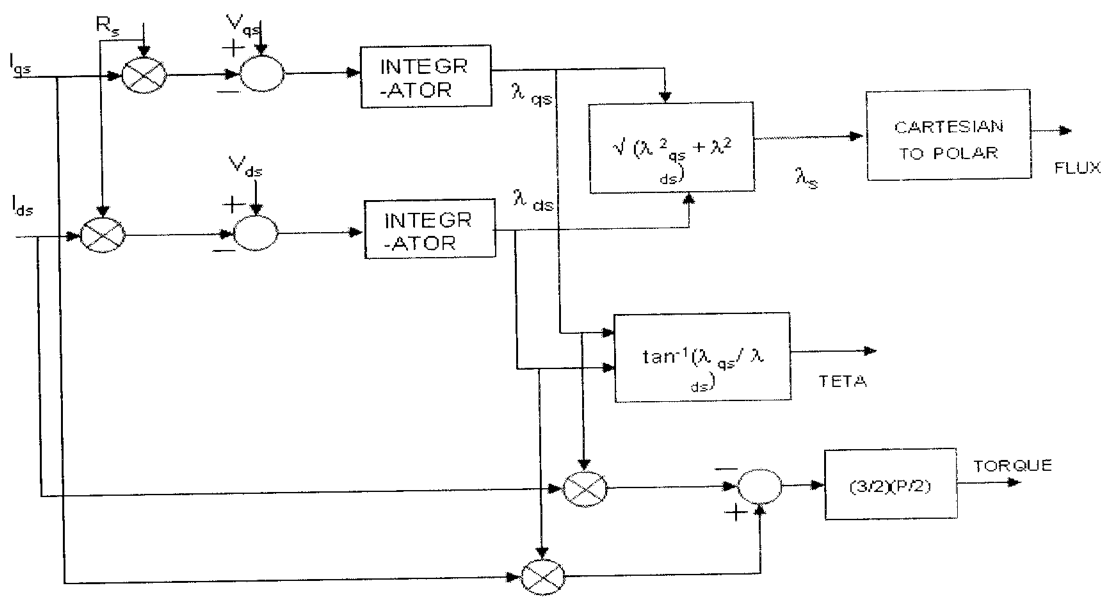


Fig.3.10 Block diagram of Torque and Flux Calculator

The torque and the 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 microseconds, 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.3.11. 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.

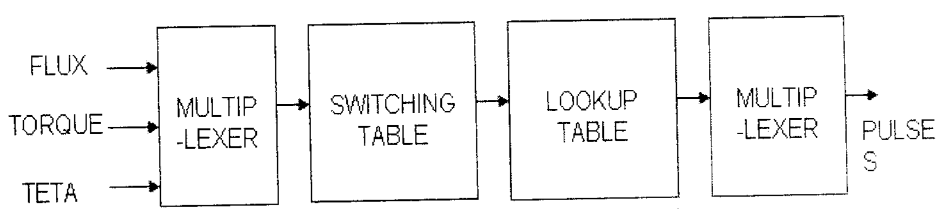


Fig.3.11 Block diagram for switching control

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 a 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 ripples cause 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 semiconductor devices are utilized because their switching losses are usually negligible with respect to on state losses by which the output current harmonic can be strongly reduced.

The hysteresis band needs to be set large to limit the inverter switching frequency below a certain level that is usually determined by thermal restriction of the 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 the low speed regions. In the torque hysteresis controller, an elapsing time to move from lower to upper limit and vice versa can be changed according to the operating conditions.

Most of the existing methods are computationally intensive. Hence the fuzzy approach is used to reduce the torque ripple. The fuzzy controller determinates the desired amplitude 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,

$$T_e=3/2\ PI_s\Phi_s. \tag{4.1}$$

$$Jd\ \omega/dt=T_e-T_{load}. \tag{4.2}$$

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),

$$e=\omega-\omega_{ref.} \tag{4.3}$$

which gives,

$$Jd\ (\omega_{ref}+e)/dt=J\ (d\omega_{ref}/dt)\ +Jde/dt=T_e-T_{load.} \tag{4.4}$$

For a constant speed reference signal and constant load, dωref/dt=0 and the change in speed error is related to the electrical motor torque by,

$$de/dt=(T_e-T_{load})\ /J. \tag{4.5}$$

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 WITH PI CONTROLLER

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,

$$\dot{\Phi}r=L_r/M\ (V_s-R_sI_s-\sigma L_sI_s). \tag{4.6}$$

The adjustable model is given by,

$$\dot{\Phi}_r=(-1/T_r+j\omega)\ \Phi_r+(M/Lr)\ Is. \tag{4.7}$$

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.

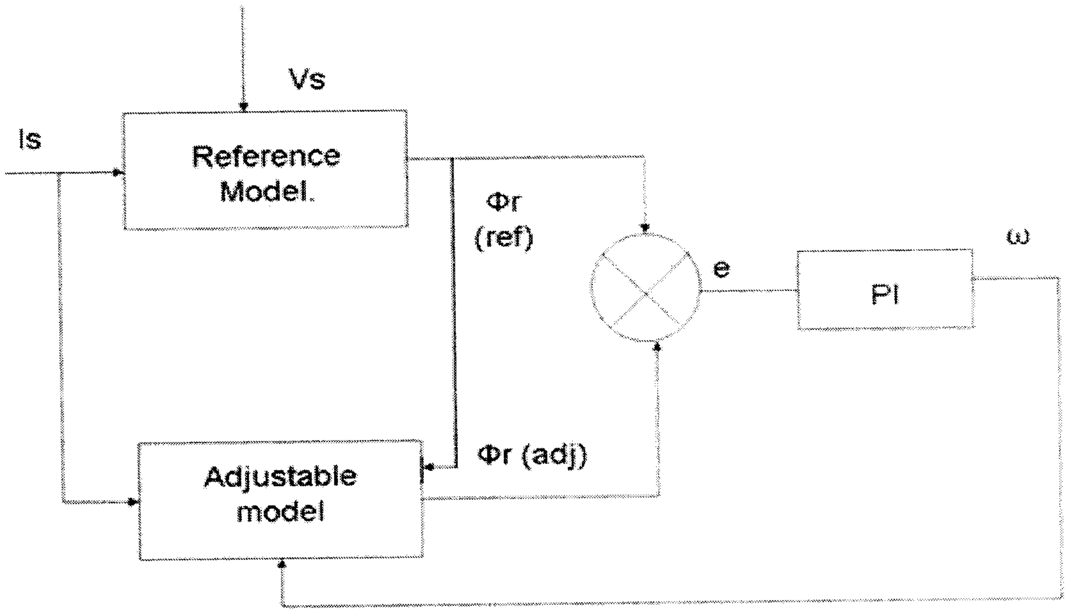


Fig.4.1 Block diagram of MRAC

The amplitude of the torque hysteresis band is prefixed using the PI 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 OVERALL BLOCK DIAGRAM OF DTC WITH MRAC-PI

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 PI 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 PI 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 of DTC with MRAC-PI controller is shown in Fig.4.2

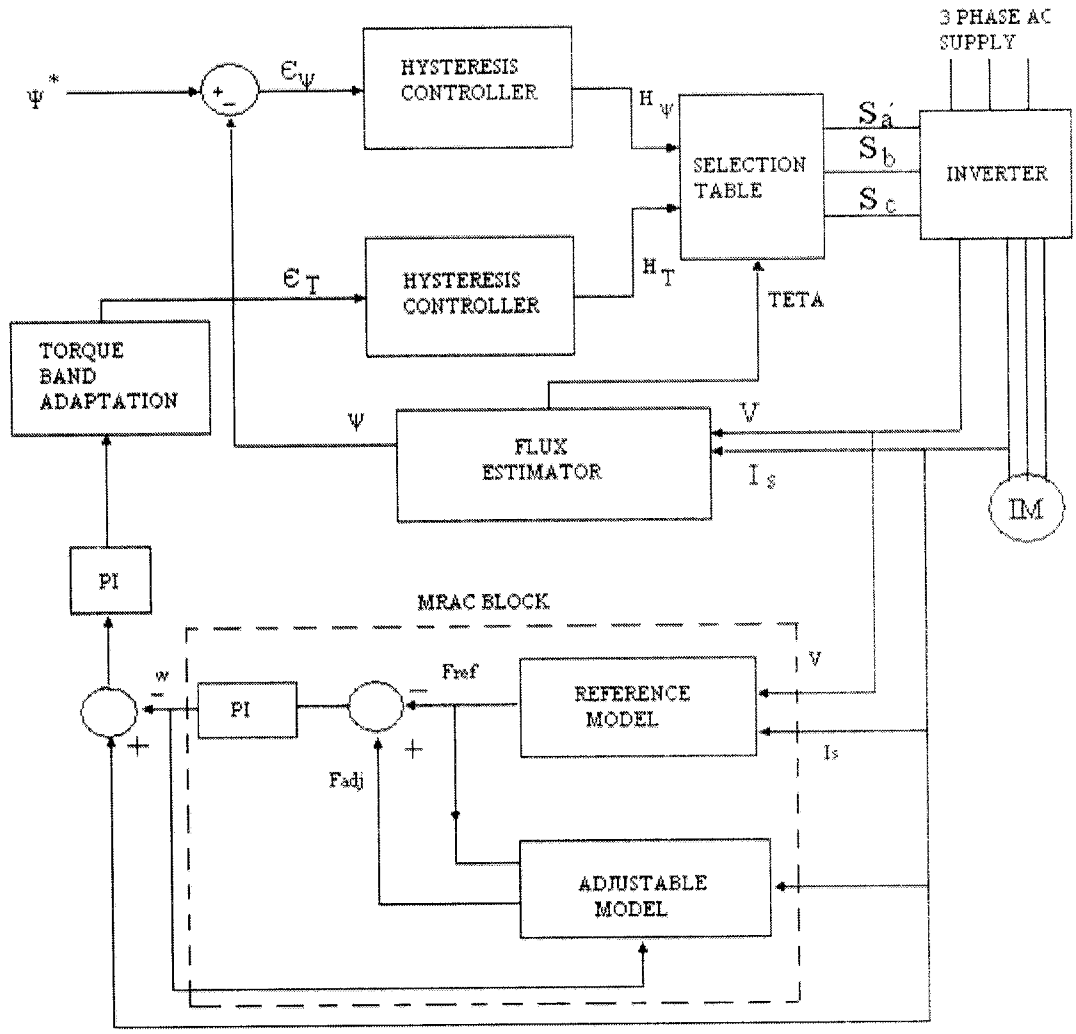


Fig.4.2 Overall block diagram of DTC with MRAC-PI

4.6 ADVANTAGES AND DISADVANTAGES OF DTC WITH MRAC-PI CONTROLLER

The advantages of DTC with MRAC-PI compared to conventional DTC are,

- Reduced transients in current waveform.
- Settling time of flux to the reference value is reduced.
- Torque and speed response is good

The disadvantages of this method includes,

- The overshoot in current which would result in more losses.

- The flux ripples are more.

To eliminate these disadvantages the conventional PI controller is replaced with the Fuzzy controller.

4.7 MRAC WITH FUZZY CONTROLLER

The fuzzy logic is a powerful tool that is capable of resolving many problems. The fuzzy controller is the reasonable choice to evaluate the amplitude of torque hysteresis band according to the torque ripple level. The amplitude of the torque hysteresis band is not prefixed but it is determined 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

$$I_s = \sqrt{(I^2_{\alpha s} + I^2_{\beta s})}. \tag{4.11}$$

The crisp output Δb_T (incremental amplitude of torque hysteresis band) is integrated to obtain the amplitude of torque hysteresis band. Fig.4.3 shows the proposed torque hysteresis controller with adapted band b_T.

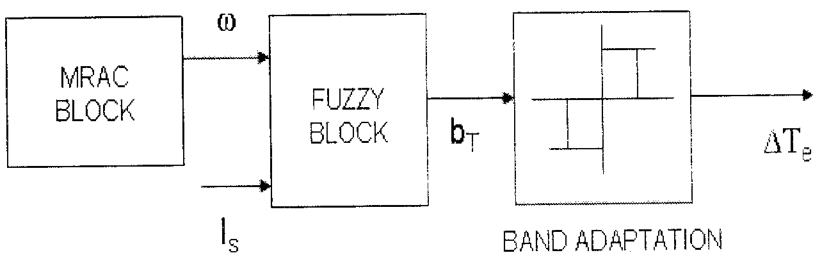


Fig.4.3 Torque hysteresis controller adapted band

The fuzzy controller design is based on intuition and simulation. For different values of motor speed and current, the values reducing the torque and flux ripple is found. These values composed a training set which is used to extract the table rule Δb_T (e_1:e_2). The shape of the membership function is refined through simulation and testing. The rule sets is shown in Table.5. The rules are formulated using the analysis data obtained from simulation of the system using various values of torque hysteresis band.

Table.4.1 Fuzzy rules for torque hysteresis controller

ΔC \ ΔS	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB

Where NB: Negative Big. PB: Positive Big. Z: Zero.

NM: Negative Medium. PM:Positive Medium.

NS: Negative Small. PS: Positive Small.

If the amplitude of b_T is set too small, then the overshoot may touch the upper band which causes a reverse voltage vector to be selected. This voltage will reduce rapidly the torque causing undershoot in torque response, thereby increasing the torque ripple.

The linguistic rules can be expressed by the following examples:

- If (e_1 is NB or NM and e_2 is NB or NM) then (Δb_T is NB or NM).

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

- If (e_1 is PB and e_2 is PB or PM) then (Δb_T is PB or PM).

In this case, the overshoot in torque error touches the upper bands which will cause a reverse voltage vector to be selected. This 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, so is set positive to avoid the overshoots. The Fig.4.4 shows the block diagram of DTC with MRAC-FUZZY controller.

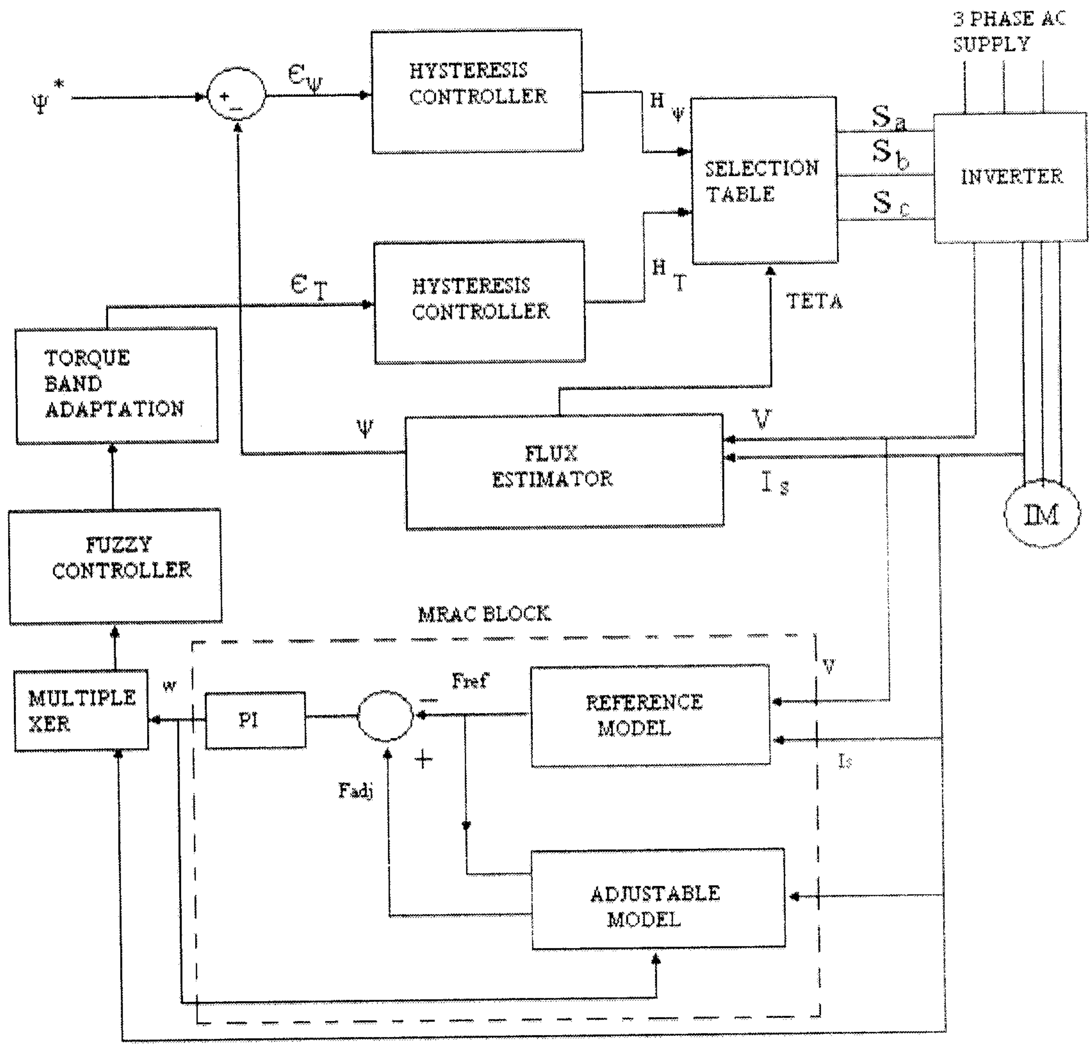


Fig.4.4 Block diagram of DTC with MRAC-FUZZY controller

The advantages of this method are

- Reduced overshoot in current.
- Reduced flux ripples.
- Improved speed response.
- Transient period of current is reduced.
- Improves 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 an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation Algorithm development Data acquisition Modelling, 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, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others.

The Direct Torque Control of the induction motor is developed using Simulink. The Induction Motor parameters are summarised in Table.5.1

Table.5.1 Machine Parameters

P	Nominal power	3HP
R_s	Stator resistance	0.087Ω
R_r	Rotor resistance	0.228Ω
L_s	Stator inductance	0.8mH
L_r	Rotor inductance	0.8mH
L_M	Mutual inductance	34.7mH
J	Rotor inertia	1.662 kg.m2
2p	Number pole pairs	2

5.2 SIMULINK MODEL FOR DTC

The 3-phase supply is given to the Induction Motor through 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, dq-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.

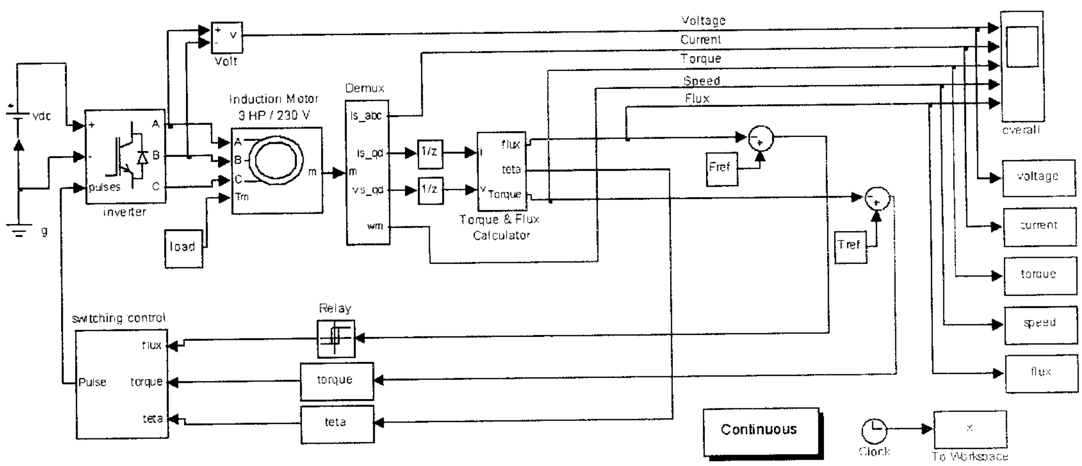
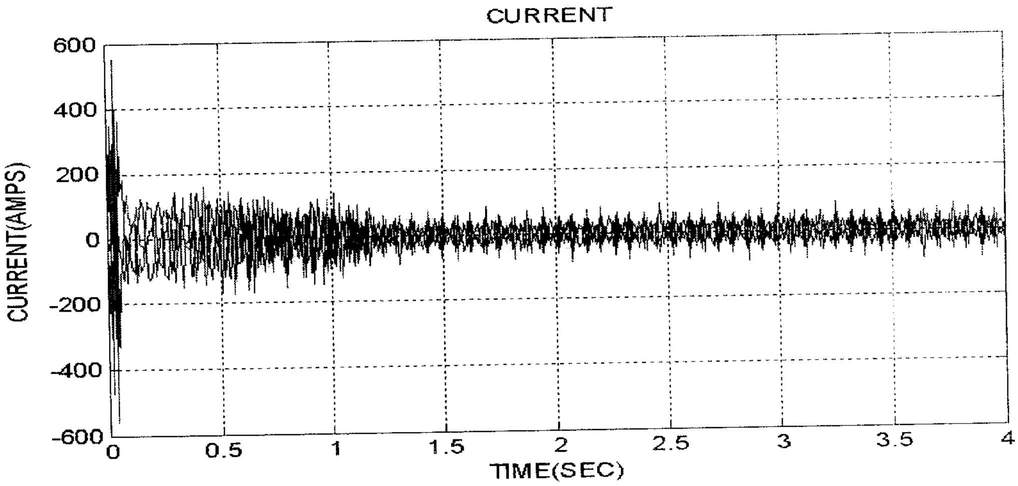
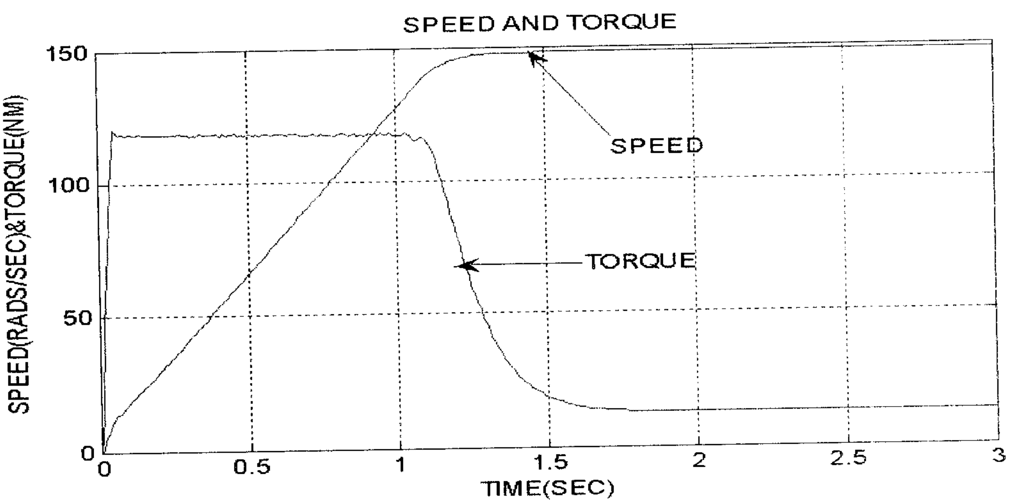


Fig.5.1 Overall direct torque control block

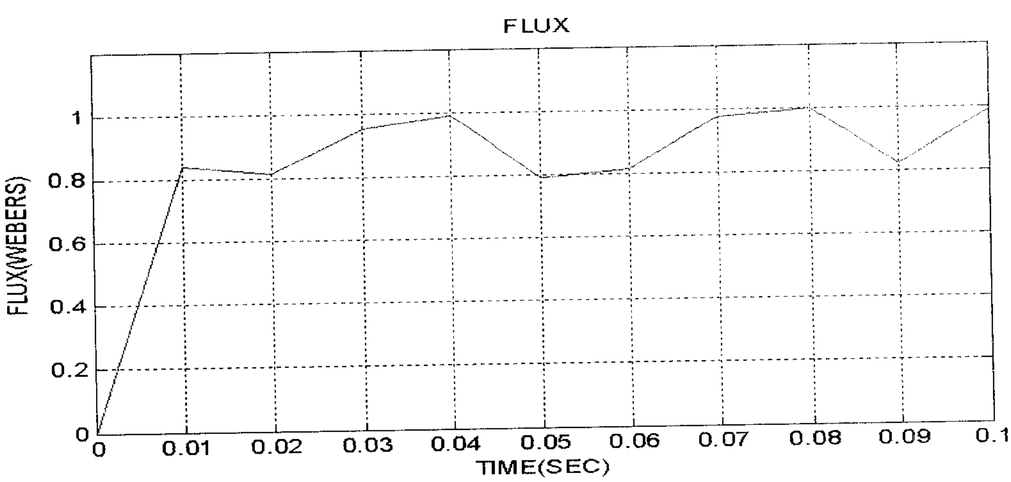
Fig.5.2 gives the response of the system for a flux reference of 0.9 webers and torque reference of 120 NM. The steady state speed of 150 Rads/Sec is achieved in 1.5 seconds. The current reaches the steady state value only at 1.5 seconds. The reference flux value is tracked only after 0.03 seconds. Thus, the response of the system is slow and has more ripples.



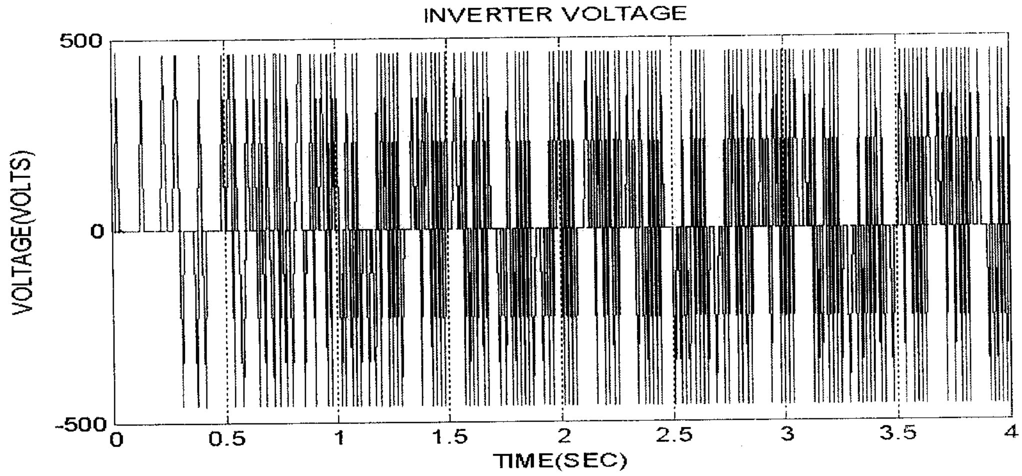
(A).Stator current.



(B).Motor torque and speed.



(C).Stator flux.



(D).Inverter voltage.

Fig.5.2 Output waveform for DTC

5.3 SIMULINK MODEL FOR DTC WITH MRAC-PI

To eliminate the ripples in torque and flux the Model Reference Adaptive controller is used. In this method the PI adaptation is used to estimate the torque error. The simulink model is shown in Fig.5.3

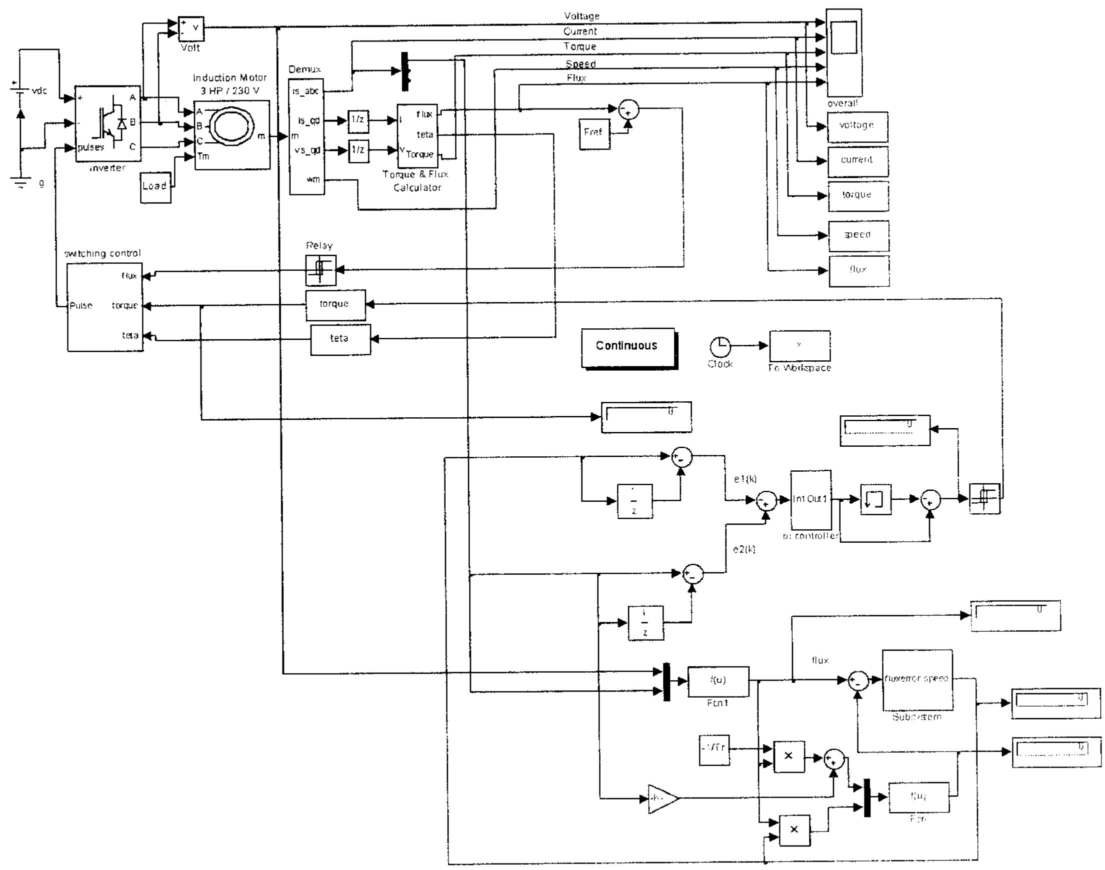
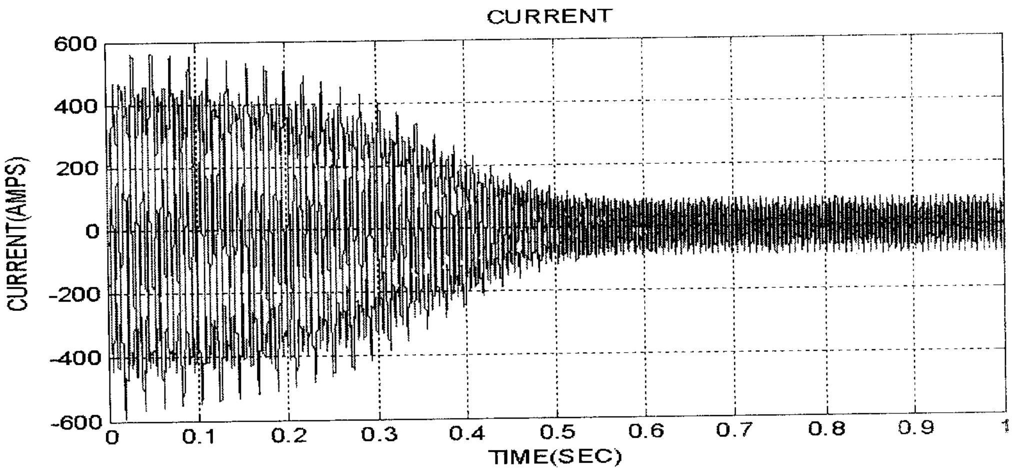
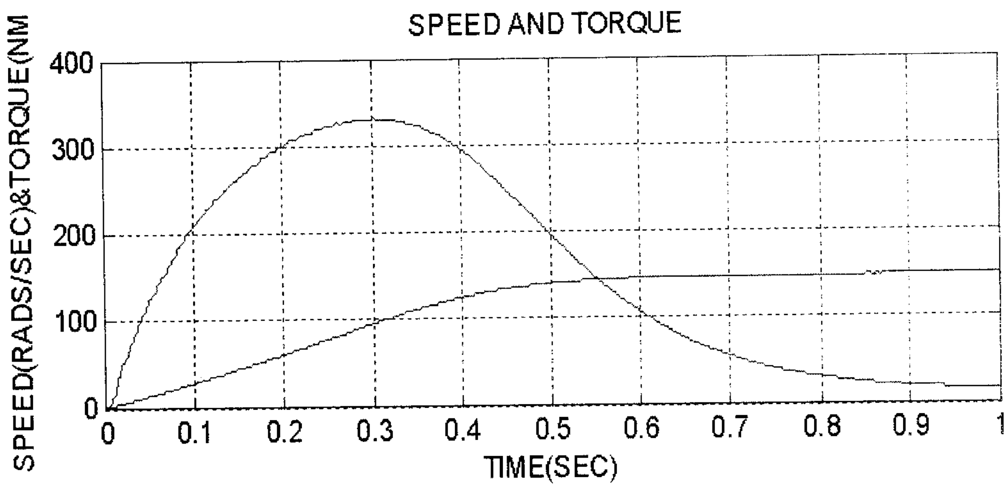


Fig.5.3 Simulink model for DTC with MRAC-PI

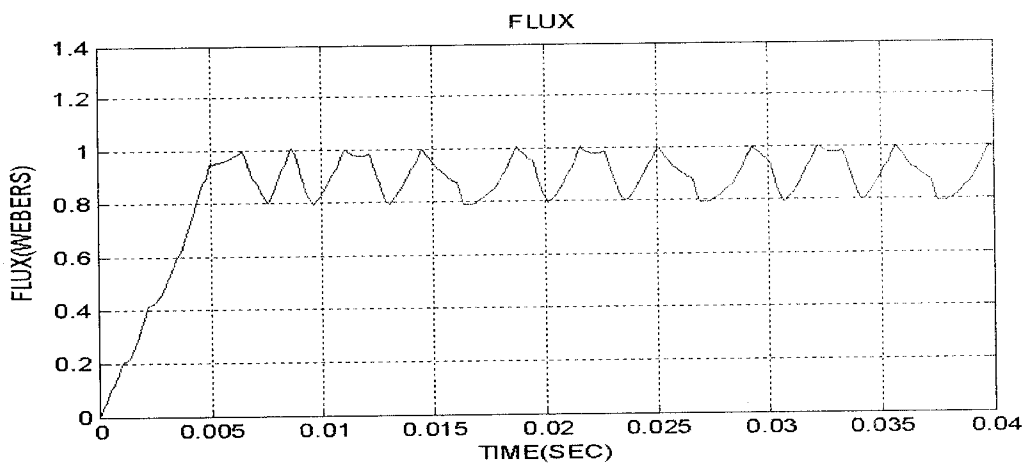
Fig.5.4 shows the response of the system for the flux reference of 0.9 webers. The stator current transient is reduced and the steady state current is achieved at 0.5 seconds. The reference flux is traced within 0.005 seconds. The steady state torque is achieved at 0.8 seconds and that of speed at 0.6 seconds.



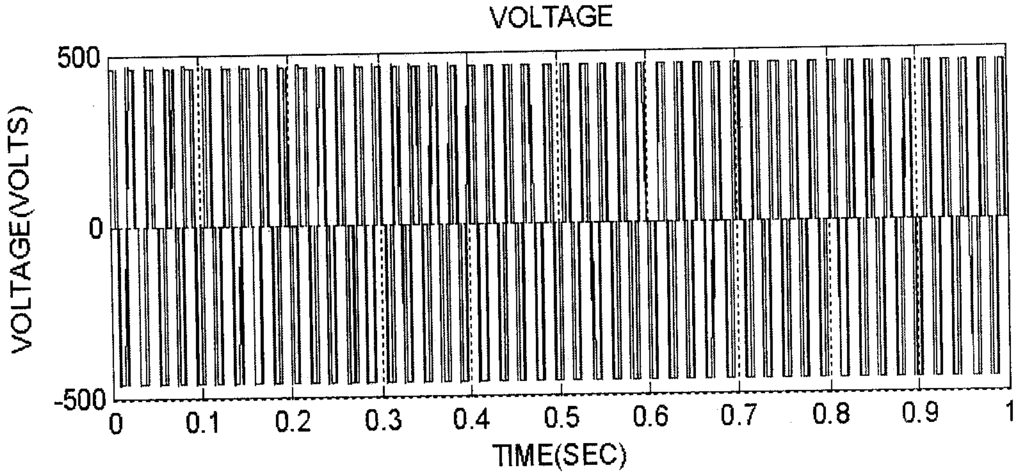
(A).Stator current.



(B).Motor torque and speed.



(C).Stator flux.



(D).Inverter voltage.

Fig.5.4 Output waveform for DTC with MRAC-PI

Thus, the response is improved but still the overshoot is more in current and the flux ripples are also more.

5.4 SIMULINK MODEL OF DTC WITH MRAC-FUZZY

Fig.5.5 shows the model of DTC with MRAC –FUZZY. To improve the robustness of the system, the PI adaptation is replaced with the fuzzy controller. The fuzzy controller gives a better performance than the conventional PI controllers.

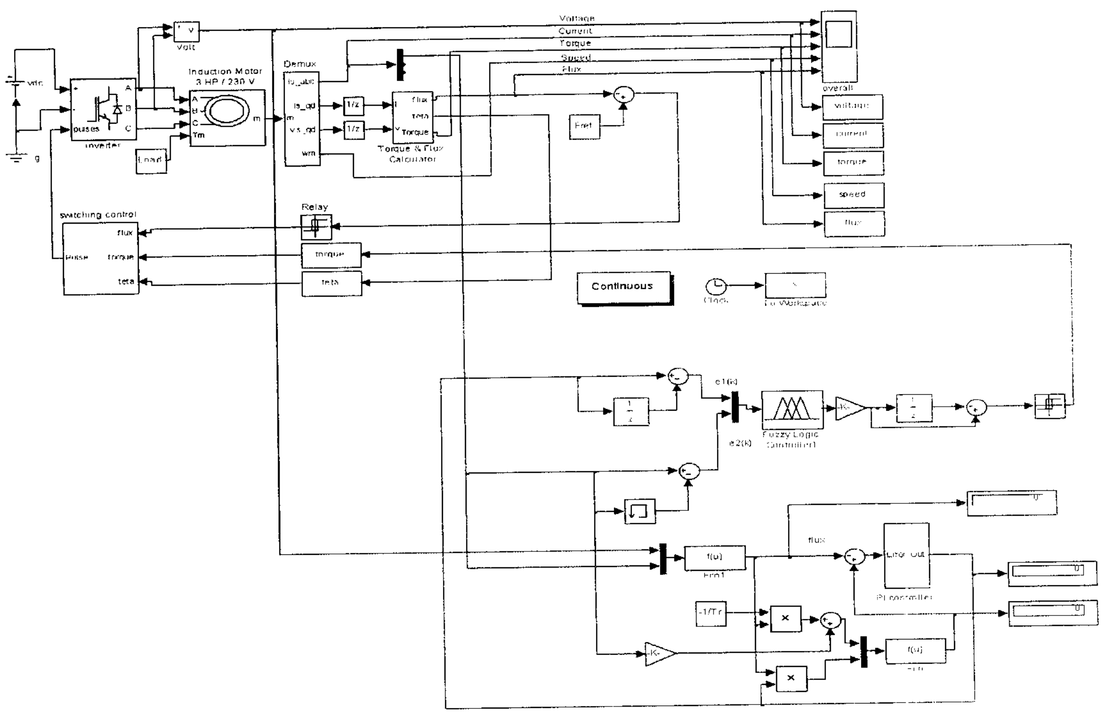
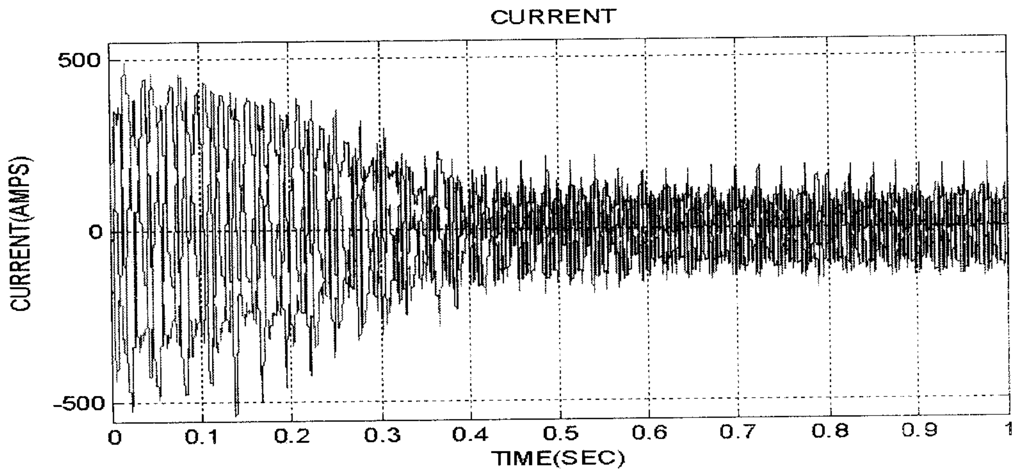
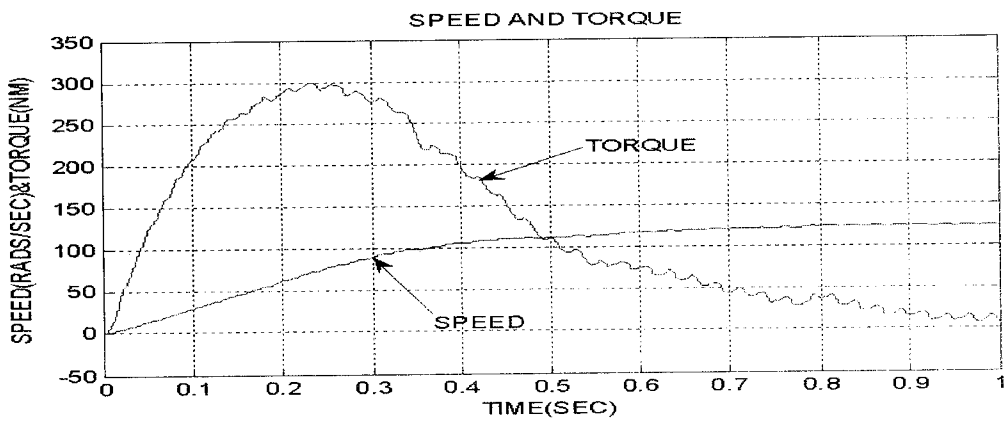


Fig.5.5 Simulink model of DTC with MRAC-FUZZY

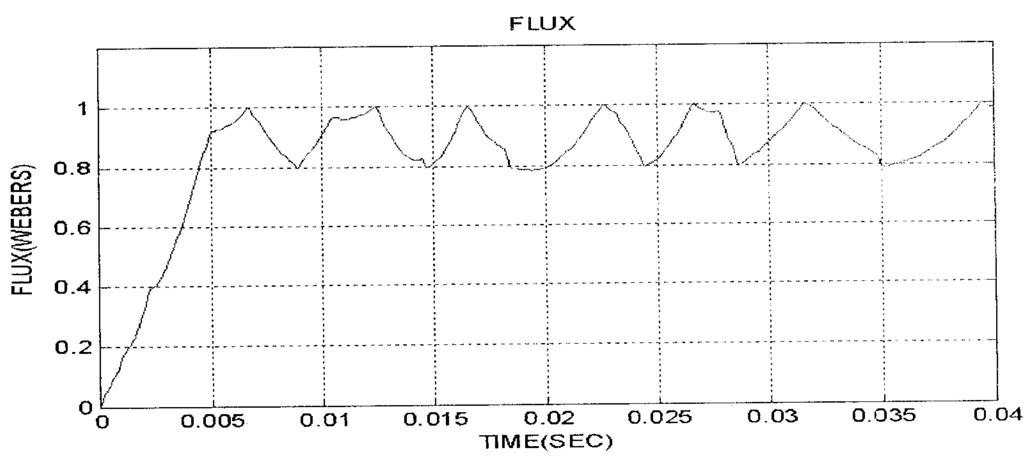
The performance of the fuzzy controller is shown in Fig.5.6. In this method the transient period of current is further reduced to 0.4 seconds. The peak overshoot of the current is reduced from ± 600 to ± 500. The flux ripples are reduced from 5 ripples / cycle to 3 ripples / cycle.



(A).Stator current.



(B).Motor torque and speed.



(C).Stator flux.

CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1. CONCLUSION

Direct torque control is supposed to one of the best controllers for driving any induction motor. Its main principle have been introduced and deeply explained. It is also demonstrated in this thesis that the method of DTC also allows the independent and decoupled control of motor torque and motor stator flux.

Two different speed estimators for Model Reference Adaptive Control have been fully developed and verified. It is also apparent from the 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 drive has better dynamic response was verified by simulation using MATLAB. The use MATLAB gave satisfactory results and reduces the computation burden by avoiding unnecessary complex mathematical modeling of the nonlinear systems. By using MATLAB/SIMULINK the specific motor performance can be achieved at a lower switching frequency compared to the vector control method, which in turn increases the efficiency of the drive by reducing losses due to currents and flux harmonics.

Table.6.1 Comparative results

SIMULATION	CURRENT Ts SEC	TORQUE Ts SEC	SPEED Ts SEC	FLUX Ts SEC	FLUX RIPPLES PER CYCLE	CURRENT OVERSHOOT VOLTS
CONVENTIONAL	1.5	2	1.5	0.03	UNEVEN	+/-600V
MRAC-PI	0.5	0.6	0.8	0.005	5	+/-600V
MRAC-FUZZY	0.4	0.6	0.7	0.005	3	+/-500V

The comparative results for the conventional DTC, DTC with MRAC-PI and DTC with MRAC-FUZZY controller are given in Table. 6.1. The conventional method produces an uneven flux response. The comparative results shows that MRAC-FUZZY has produced improved current and flux responses. Hence, the proposed scheme provides an improved response.

6.2 FUTURE WORK

All future work is summarized below:

- ➢ Development of new Fuzzy Logic Controllers to achieve better performance. The new fuzzy controller should, at least, take into account the following ideas:
  - Develop a completely auto adaptive controller.
  - The controller must be adaptive to any motor.
  - Try to overcome the electrical noises, which appears in any power drives.
  - To reduce the reactive power consumption through the stator flux estimator.

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APPENDICES

S function for Torque calculation:

```
function [sys,x0,str,ts]=torque(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(u<-2)
sys=-1;
elseif((-2<u)&(u<2))
```

```
sys=0;
else
sys=1;
end
```

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;
elseif((60<u)&(u<=120))
sys=1;
elseif((120<u)&(u<=180))
sys=6;
elseif((-180<u )&(u<=-120))
sys=5;
elseif((-120<u)&(u<=-60))
sys=4;
else
sys=3;
end
```

S function for Switching Table:

```
function [sys,x0,str,ts] = switching(t,x,u,flag)
switch flag,
case 0,
[sys,x0,str,ts] = mdlInitializeSizes;
case 2,
sys = [];
case 3,
sys = mdlOutputs(t,x,u);
case 9,
sys = [];
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      = 3;
sizes.DirFeedthrough = 1;
sizes.NumSampleTimes = 1;
sys = simsizes(sizes);
x0  = [];
str = [];
ts  = [1e-5 0];
function sys = mdlOutputs(t,x,u)
if(u(1)== 1 & u(2)==1&u(3)==1)
sys=6;
elseif(u(1)== 1 & u(2)== 0&u(3)==1)
sys=8;
elseif(u(1)== 1 & u(2)==-1&u(3)==1)
sys=2;
elseif(u(1)== 0 & u(2)== 1&u(3)==1)
sys=5;
elseif(u(1)== 0 & u(2)== 0&u(3)==1)
sys=7;
elseif(u(1)== 0 & u(2)==-1&u(3)==1)
sys=3;
elseif(u(1)== 1 & u(2)==1&u(3)==2)
sys=1;
elseif(u(1)== 1 & u(2)== 0&u(3)==2)
sys=7;
elseif(u(1)== 1 & u(2)==-1&u(3)==2)
sys=3;
elseif(u(1)== 0 & u(2)== 1&u(3)==2)
sys=6;
elseif(u(1)== 0 & u(2)== 0&u(3)==2)
sys=8;
elseif(u(1)== 0 & u(2)==-1&u(3)==2)
sys=4;
elseif(u(1)== 1 & u(2)==1&u(3)==3)
```

```
sys=2;
elseif(u(1)== 1 & u(2)== 0&u(3)==3)
sys=8;
elseif(u(1)== 1 & u(2)==-1&u(3)==3)
sys=4;
elseif(u(1)== 0 & u(2)== 1&u(3)==3)
sys=1;
elseif(u(1)== 0 & u(2)== 0&u(3)==3)
sys=7;
elseif(u(1)== 0 & u(2)==-1&u(3)==3)
sys=5;
elseif(u(1)== 1 & u(2)==1&u(3)==4)
sys=3;
elseif(u(1)== 1 & u(2)== 0&u(3)==4)
sys=7;
elseif(u(1)== 1 & u(2)==-1&u(3)==4)
sys=5;
elseif(u(1)== 0 & u(2)== 1&u(3)==4)
sys=2;
elseif(u(1)== 0 & u(2)== 0&u(3)==4)
sys=8;
elseif(u(1)== 0 & u(2)==-1&u(3)==4)
sys=6;
elseif(u(1)== 1 & u(2)==1&u(3)==5)
sys=4;
elseif(u(1)== 1 & u(2)== 0&u(3)==5)
sys=7;
elseif(u(1)== 1 & u(2)==-1&u(3)==5)
sys=6;
elseif(u(1)== 0 & u(2)== 1&u(3)==5)
sys=3;
elseif(u(1)== 0 & u(2)== 0&u(3)==5)
sys=8;
elseif(u(1)== 0 & u(2)==-1&u(3)==5)
```

```
sys=1;
elseif(u(1)== 1 & u(2)==1&u(3)==6)
sys=5;
elseif(u(1)== 1 & u(2)== 0&u(3)==6)
sys=7;
elseif(u(1)== 1 & u(2)==-1&u(3)==6)
sys=1;
elseif(u(1)== 0 & u(2)== 1&u(3)==6)
sys=4;
elseif(u(1)== 0 & u(2)== 0&u(3)==6)
sys=8;
else
sys=2;
end
```