COMPARISON OF DIRECT TORQUE CONTROL AND VECTOR CONTROL OF INDUCTION MOTOR

Thesis submitted in the partial fulfilment of the requirements
for the award of degree of

MASTER OF ENGINEERING
In
POWER SYSTEMS & ELECTRIC DRIVES

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June, 2011

CERTIFICATE

"I hereby declare that the work which is presented in the thesis report, entitled, **"COMPARISON OF DIRECT TORQUE CONTROL AND VECTOR CONTROL OF INDUCTION MOTOR"** in partial fulfilment of the requirements for the award of the Master's degree in Power Systems & Electric Drives, submitted in Electrical and Instrumentation Engineering Department, Thapar University, Patiala, is an authentic record of initial work carried out under the supervision of **Mr. SSSR Sarathbabu Duvvuri, EIED, THAPAR UNIVERSITY,PATIALA"**

Dated : 22/06/2011

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This is to certify that the above statement made by the candidate is correct to true to the best of my knowledge.

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ACKNOWLEDGEMENT

I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this project work. First of all, I thank the Almighty, who gave me the opportunity and strength to carry out this work. My greatest thanks are to my parents who bestowed ability and strength in me to complete this work.

I would like to express my gratitude to Mr.SSSR Sarathbabu Duvvuri, Lecturer EIED, Thapar University, Patiala, for guidance and support throughout this project work. They have been a constant source of inspiration to me throughout the period of this work. I consider myself extremely fortunate for having the opportunity to learn and work under there supervision over the entire period.

I would also take this opportunity to express my gratitude and sincere thanks to Dr. Smarajit Ghosh, Prof. & Head, EIED, Thapar University, Patiala for his valuable support. I am also thankful to the entire faculty and staff of EIED, Thapar University, Patiala for their help, inspiration and moral support.

My thanks to all my classmates for their encouragement and help.

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ABSTRACT

The basic theory of operation for the control techniques is presented. A mathematical model for the proposed DTC of the IM topology is developed. A simulation model is developed in MATLAB/SIMULINK and is used to verify the basic operation (performance) of the DTC technique.

In conventional Direct Torque Control (DTC), the selection of flux linkage and electromagnetic torque errors are made within the respective flux and torque hysteresis bands, in order to obtain fast torque response, low inverter switching frequency and low harmonic losses. However, DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. Space Vector Modulation (SVM) is the strategy to minimize the torque ripple of induction motor in which, the stator flux level is selected in accordance with the efficiency optimized motor performance. SVM method is incorporated with direct torque control (DTCSVM) for induction motor drives. However, the basis of the DTC SVM strategy is the calculation of the required voltage space vector to compensate the flux and torque errors exactly by using a predictive technique and then its generation using the SVM at each sample period.

In this thesis work, the simulation of DTC scheme has been carried out using MATLAB/SIMULINK and the results are compared with AC Vector Control drive using hardware setup.

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LIST OF SYMBOLS

Symbol	Description
V_{ds}	d-axis stator voltage
V_{qs}	q-axis stator voltage
V_{dr}	d- axis rotor voltage
V_{qr}	q- axis rotor voltage
i_{ds}	d-axis stator current
i_{qs}	q-axis stator current
i_{dr}	d- axis rotor current
i_{qr}	q- axis rotor current
ψ_{ds}	d-axis stator flux linkages
ψ_{qs}	q-axis stator flux linkages
ψ_{dr}	d- axis rotor flux linkages
ψ_{qr}	q- axis rotor flux linkages
ψ_{qm}	mutual flux linkages
Rs	stator winding resistance
Xls	stator winding leakage reactance
Rr	rotor winding resistance
Xlr	rotor winding leakage reactance
Xm	stator to rotor mutual reactance.
ω_b	base speed in rad/sec
ω_r	rotor speed in rad/sec
θ_a	arbitrary reference angle in radiance.
K	short circuit ratio.
ψ_s	stator resultant flux linkages
ψ_r	rotor resultant flux linkages

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LIST OF ABBREVATIONS

AC	Alternating Current
IM	Induction Motor
FOC	Field Oriented Control
DTC	Direct Torque Control
VC	Vector Control
PWM	Pulse Width Modulation
MATLAB	MATrix LABoratary
SVPWM	Space Vector Pulse Width Modulation
PWM VSI	Pulse Width Modulated Voltage Source Inverter
IGBT	Insulated Gate Bipolar Transistor
T	Torque
m.m.f.	magneto motive force
e.m.f.	electro motive force
d.c.	direct current
r.p.m.	revolution per minute
KW	Killowatt
MW	Megawatt
PID	Proportional Integral and Differential
PI	Proportional Integral
DSP	Digital Signal Processing
DFOC	Direct Field Oriented Control
IFOC	Indirect Field Oriented Control
PMSM	Permanent Magnet Synchronous Motor
A/D	Analog to Digital converter

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Chapter 1

Introduction

Chapter 1

1.1 INTRODUCTION:

In Industrial automation electric motors play crucial role as heart of the system. Therefore, the best performance motor control systems contribute to a great extent, to the desirable performance of automated sectors by enhancing the production rate and the quality of products. In fact the performance of today's automated systems is defined in terms of efficiency, smoothness and accuracy.

The recent developments of the power electronics industry leads to the considerable increase of the power that can be manipulated by semiconductor devices. Even though the maximum voltage supported by these devices remains the major obstacle in medium and high voltage applications. As in multilevel inverters, due to lower order harmonics there is distortion of the output voltages when compared to standard two-level inverters operating at the same switching frequency. The AC motor control including control of induction motors is a challenging task due to very fast motor dynamics and highly nonlinear models of the machines. Therefore, a major part of motor control development consists of deriving motor mathematical models in suitable forms.

In modern automated systems, there are two competing control strategies for AC motors i.e. field oriented control (vector control) and direct torque control (DTC). Nearly 30-32 years ago, in 1971 F. Blaschke presented the paper on field-oriented control (FOC) for induction motor control. At that time, the technique was completely developed and now it is mature from the industrial point of view. Today vector control drives are an industrial reality and are available in the market from several producers and with different performances.

Thirteen years later, a new control technique of induction motors was developed and presented by I. Takahashi as direct torque control (DTC) and by M. Depenbrock as direct self control (DSC). Since in the beginning, the new technique was characterized by simplicity and robustness. Using DTC it is possible to obtain a good dynamic control of torque without any mechanical transducers on the machine shaft. Thus, DTC can be considered as "sensor less type" control technique. The basic scheme of DTC is preferable in the high power range applications, where a lower inverter switching frequency can justify higher current distortion.

The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band (Hysteresis band) limits.

Unlike FOC, DTC does not require any coordinate transformation, current regulator and PWM signals. In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC.

In addition, DTC controller is very little sensible to the parameters detuning in comparison with FOC.

1.2 LITERATURE SURVEY:

State of the Art of Induction Motor Control[9], this paper proposes the historical and recent developments and major milestones in control of induction motors are pointed out first and second how research results were translated into today's field industrial standards, and third at last, what are the current trends in research and industry are summarized.

Mathematical Model of Asynchronous Machine in MATLAB/Simulink[10],this paper proposes models with typical results and provides guidelines for their use The dynamic simulation of small power induction motor based on mathematical modeling is proposed in this paper. The dynamic simulation is one of the key steps in the validation of the design process of the motor drive systems and it is needed for eliminating inadvertent design mistakes and the resulting error in the prototype construction and testing. This paper demonstrates the simulation of steady-state performance of induction motor by MATLAB program. Three phase induction motor is modeled and simulated with Simulink model.

D,Q Reference Frames for the Simulation of Induction Motors[5],this paper presents the equations of three preferable reference frames for use in the simulation of induction machines when using the d, q 2-axis theory. It uses case studies to demonstrate that the choice of the reference frame depends on the problem to be solved and the type of computer available.

Dynamic model of induction motor for Vector Control [11], this paper proposes that in order to understand and analyze vector control of induction motors, the dynamic model is necessary. Unfortunately, the dynamic model equations are complex and there are many different forms of the model depending on the choice of reference frame. It is the objective to explain various forms in a concise way to understand clearly. In addition, the fundamental dynamic mechanism of the motor in the synchronous frame is developed and the basic principles of vector control are discussed in general terms.

Control Method Suitable for Direct Torque Control Based Motor Drive System Satisfying Voltage and Current Limitations[12],This paper proposes a control method suitable for limited armature voltage and current in a permanent magnet synchronous motor drive system based on direct torque control. First, this paper proposes torque-limiting and flux-weakening control that is suitable for a direct torque control based motor drive system. The proposed method utilizes a mathematical model in a rotating reference frame synchronized to the stator flux linkage. Second, this paper proposes an anti-windup scheme for the torque controller of the direct torque control system. Windup of the controller degrades the performances of torque limiting (current-limiting) control and of torque control. Applying the anti-windup results, improves the performance of the proposed torque limiting method in the transient state. This paper presents a direct torque control based drive system combined with a speed controller. The proposed system can achieve stable control, and its effectiveness is confirmed experimentally.

Simulation and Analysis of SVPWM Based 2-Level and 3-Level Inverters for Direct Torque of Induction Motor[15],In this paper, new scheme of direct torque control of induction motor for electric vehicles is proposed and the results of an investigation into suitable torque control schemes are also presented. The electric vehicle drive consists of rewound induction motors and a three-level IGBT inverter. The schemes investigated are Field Oriented Control, Direct Torque Control (DTC), and DTC using Space Vector Modulation. The results of MATLAB/Simulink simulation and a comparison between the control schemes are presented. It is found that the DTC using Space Vector Modulation scheme is best for this application.

Simulink Model of Direct Torque Control of Induction Machine[14], this paper proposes It is considered as an alternative to the field oriented control (FOC) or vector control technique.

These two control strategies are different on the operation principle but their objectives are the same. They aim to control effectively the torque and flux. Torque control of an induction machine based on DTC strategy has been developed and a comprehensive study is present in this research. The performance of this control method has been demonstrated by simulations performed using a versatile simulation package, MATLAB/Simulink. Several numerical simulations have been carried out in a steady state and transient operation on a speed control mode.

A Sector Advanced Technique to Improve Dynamic Response of a Direct Torque Controlled Induction Motor[7]*,*this paper proposes that dynamics of DTC drive can be improved by using estimators, observers, and machine intelligence systems. This paper proposes a new technique namely Sector Advancing Technique (SAT) for reducing the response time of the drive for a known torque command. Simulation studies are carried out using MATLAB/Simulink and results of DTC with SAT over conventional DTC are presented.

Three-phase Induction Motor Dynamic Mathematical Model[19]*,* this paper represents the induction motor dynamic model, frequently used in motor dynamic studies, is constituted by four voltage differential equations and one mechanical differential equation being very known among the electrical machine researchers. The main goal of this paper is to present a more comprehensive three-phase induction motor dynamic mathematical model including the skin effect, the temperature influence on the parameters and allowing for the stator and rotor winding and stator and rotor core average temperature evaluation. This model is useful for any type of motor dynamic studies mainly those including fast motor speed changing, intermittent loading and in case of motors fed from non-sinusoidal voltages contributing to the energy conservation and power quality subjects.

A Complete Dynamic Model for a PWM VSI-fed rotor flux oriented vector controlled Induction Motor Drive using Simulink [21].this paper describes the validation of a complete dynamic model of the induction motor, with an indirect rotor flux oriented vector controller using Simulink. This model is developed, with a view to studying the effects of parameter variations in a vector controlled drive, and to develop parameter estimators using Artificial Neural Networks and Fuzzy/Fuzzy Neural principles. The Simulink model developed simulates the dynamic model of three phase induction motor together with the inverter and the total control system.

Simulation of Vector Control Frequency Converter of Induction Motor Based on MATLAB */Simulink*[20],this paper is based on the theory of the mathematical model of induction motor, the model of induction motor vector control is proposed with the simulation toolkit of MATLAB /Simulink, and the related sub-system modules are described in detail and the specific illustrations of the sub-system are also given. Take a simulation of the system, the results such as the waveforms of the current, speed and so on could be got. The simulation results verify the model is correct, and the control system is effective, and the system has good dynamic and static performance.

Comparison of Field-Oriented Control and Direct Torque Control for Induction Motor Drives[16].This paper presents a comparative study on two most popular control strategies for induction motor drives: field-oriented control (FOC) and direct torque control (DTC). The comparison is based on various criteria including basic control characteristics, dynamic performance, parameter sensitivity, and implementation complexity. The study is done by simulation using the Simulink Power System Block set that allows a complete representation of the power section (inverter and induction motor) and the control system. The simulation and evaluation of both control strategies are performed using actual parameters of an 50-HP induction motor fed by an IGBT PWM inverter.

A Direct Field Oriented Induction Machine Drive with Robust Flux Estimator for Position Sensor less Control[17].The rotor flux is estimated for a direct field oriented induction machine drive using a voltage-current mode algorithm, or physical based algorithm. The estimated rotor flux is used to synthesize the components of the rotation matrix, $sin(\theta)$ and $cos(\theta)$. These angles are critical in transforming the command currents to the stationary frame such that field orientation is maintained. The principles of rotor flux estimation are presented, followed by examination of low speed effects, parameter sensitivity, and criteria for selection of the filter time constant *T,*. Computer simulation and extensive experimental results are included.

1.3 OVERVIEW OF THE THESIS:

Chapter 2 gives a detailed theoretical analysis of induction motor like popularity and advantages of stationary reference frame theory in induction motor. And also gives the details of modeling of the Induction Motor.

Chapter 3 gives the overview of Direct Torque control technique and a methodology is suggested to employ Direct Torque Control technique for a two level inverter driving the induction motor.

Chapter 4 gives the overview of Field oriented control technique and a methodology is suggested to employ Field oriented control technique for a two level inverter driving the induction motor.

Chapter 5 gives the simulation results of Direct Torque Control technique for a two level inverter and Field oriented control technique for a two level inverter and the results are compared.

Chapter 6 presents the conclusion and recommendations.

Chapter 2

MATHEMATICAL MODELLING OF INDUCTION MOTOR

Chapter 2

MATHEMATICAL MODELLING OF INDUCTION MOTOR

2.1 INTRODUCTION:

The induction motor, which is the most widely used motor type in the industry, has been favoured because of its good self-starting capability, simple and rugged structure, low cost and reliability, etc.A three phase induction motor is a singly excited a.c. machine in the sense that it is supplied power from a single a.c. source. Its stator winding is directly connected to a.c. source, whereas its rotor winding receives its energy from stator by means of induction. The two m.m.f. waves generated that are stator m.m.f. and rotor m.m.f. both rotate in air gap in same direction at synchronous speed. These two m.m.f. waves combine to give the resultant air gap flux density wave of constant amplitude and rotating at synchronous speed. The stator of induction motor is essentially similar to that of synchronous motor. The development of steady electromagnetic torque is possible at all speeds but not at synchronous speed. So, induction motors could not run at synchronous speed, that's why they are also known as asynchronous machines.

In this section, an equivalent two-phase circuit model of a three-phase Induction machine is derived and the concept of the Park's transformation and the relation between three-phase quantities and their equivalent two-phase quantities are also discussed.

2.2 INDUCTION MOTOR:

Induction motors have been widely used in constant speed drives, for loads requiring low starting torques and for loads requiring severe starting conditions. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. They are popular because of their ruggedness, simplicity, low cost and reduced maintenance charges. The most common applications are fans, centrifugal pumps, most machinery tools, wood working tools, compressors, crushers, reciprocating pumps, punching presses, shears, hoists, cranes, elevators etc[18]. So, induction motors have wide area of applications.

Depending on type of rotor construction induction motors are of two types:-

1. Squirrel cage induction motor.
2. Wound-rotor motor, also called slip ring induction motor.

These two types of induction motors differ by the construction of rotor, having certain advantages and disadvantages over each other.

The popularity of Induction motors comes from their desirable features:

- They have inherent self starting torque.
- They require no d.c. excitation.
- They can operate at lagging power factor.
- Speed control is possible.
- Induction motors with speeds above 500 r.p.m. and ratings below 120 KW are cheaper than synchronous machines.
- Lower maintenance cost.
- Simplicity and ruggedness.
- Compact structure.
- Constant speed.

However, induction motors can be used to supply only mechanical loads and they can operate at lagging power factors. Which makes them restrictive for some applications.

Induction motors are being used more than ever before in industry and individual machines of up to 10 MW in size are no longer a rarity. During start-up and other severe motor Operations the induction motor draws large currents, produces voltage dips, oscillatory torque and can even generate harmonics in the power system. It is therefore important to be able to model the induction motor in order to predict these phenomena. Various models have been developed, and the d,q or two-axis model for the study of transient behaviour has been well tested and proven to be reliable and accurate. It has been shown that the speed of rotation of the d,q axes can be arbitrary although there are three preferred speeds or reference frames as follows:

(a) The stationary reference frame when the d,q axes do not rotate;

(b) The synchronously rotating reference frame when the d,q axes rotate at synchronous speed;

(c) The rotor reference frame when the d,q axes rotate at rotor speed.

Most authors use one or other of these reference frames without giving specific reasons for their choice. Whilst either the stationary or the synchronously rotating reference frames are most frequently used, the particular reference frame should be chosen in relation to the problem being investigated and the type of computer (analog or digital) that is used[5].

2.3 THEORY:

Fig. 2.1 shows a schematic diagram of a 3-phase induction motor with the d, q axes superimposed. The q-axis lags the d-axis by 90°. A voltage V_{as} is applied to stator phase A while the current flowing through it is i_{as}. Phases B and C are not shown on the diagram in an attempt to maintain clarity. In the d, q model coils DS and QS replace the stator phase coils AS, BS and CS, while coils DR and QR replace the rotor phase coils AR, BR and CR[5].

Although the d q axes can rotate at an arbitrary speed, there is no relative speed between the four coils DS, QS, DR and QR. The physical significance of showing the D,Q coils in Fig.2.1 is to illustrate that in effect the 3- phase induction motor with its six coils is replaced by a new machine with four coils. In order to predict the mechanical and electrical behavior of the its own original machine correctly, the original ABC variables must be transformed into d, q variables, but this transformation depends on the speed of rotation of the D,Q coils, hence each reference frame has transformation. In general, for any arbitrary value of θ, the transformation of stator ABC phase variables $[F_{ABC}]$ to d,q stator variables $[F_{Odq}]$is carried out through Park transform are as:

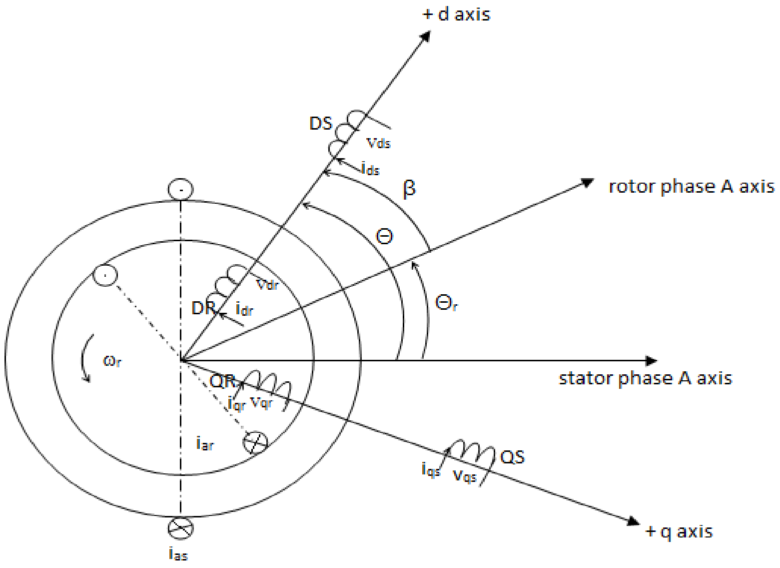

Fig. 2.1: D, Q axes superimposed onto a three-phase induction motor

$$[F_{0dq}] = [P_\theta][F_{ABC}] \tag{2.1}$$

$$[P_\theta] = 2/3\begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos\theta & \cos(\theta-\lambda) & \cos(\theta+\lambda) \\ \sin\theta & \sin(\theta-\lambda) & \sin(\theta+\lambda) \end{bmatrix} \tag{2.2}$$

A new variable called the zero sequence component is included with the d,q variables in order to handle unbalanced voltages and to invert Park's transform. The transformation of rotor ABC variables to rotor d,q variables is again carried out using Park's transform, but this time the angle β in Fig.2.1 is used instead of θ. The voltage balance equations for the d,q coils are as follow

$$V_{ds} = R_s I_{ds} + p\psi_{ds} + \psi_{qs} p\theta \tag{2.3a}$$

$$V_{qs} = R_s I_{qs} + p\psi_{qs} - \psi_{qs} p\theta \tag{2.3b}$$

$$V_{dr} = R_r I_{dr} + p\psi_{dr} + \psi_{qr} p\beta \tag{2.3c}$$

$$V_{qr} = R_r I_{qr} + p\psi_{qr} - \psi_{dr} p\beta \tag{2.3d}$$

Where

$$\begin{bmatrix} \Psi_{ds} \\ \Psi_{dr} \\ \Psi_{qs} \\ \Psi_{qr} \end{bmatrix} = \begin{bmatrix} L_{ss} & L_m & 0 & 0 \\ L_m & L_{rr} & 0 & 0 \\ 0 & 0 & L_{ss} & L_m \\ 0 & 0 & L_m & L_{rr} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{dr} \\ i_{qs} \\ i_{qr} \end{bmatrix} \tag{2.4}$$

At this stage θ has not been defined and is quite arbitrary. However, certain simplifications in the equations occur if it is restricted to be one of the following three angles[1]:

2.4 Stationary reference frame

Now θ = 0; this is called the stationary reference frame because the d, q axes do not rotate. In addition, the +d-axis is chosen to coincide with the stator phase A axis. from Fig. 2.1,

$$i_{dr}\,\omega = p\theta = 0 \tag{2.5}$$

$$i_{qs}\,\beta = \theta - \theta_r = -\theta_r \tag{2.6}$$

$$p\beta = -p\theta_r = -\omega_r \tag{2.7}$$

Substituting eqns. (2.5) - (2.7) into eqn. (2.3),

$$V_{ds} = R_s i_{ds} + p\psi_{ds} \tag{2.8a}$$

$$V_{qs} = R_s i_{qs} + p\psi_{qs} \tag{2.8b}$$

$$V_{dr} = R_r i_{dr} + p\psi_{dr} + \psi_{qr} p\beta \tag{2.8c}$$

$$V_{qr} = R_r i_{qr} + p\psi_{qr} - \psi_{dr} p\beta \tag{2.8d}$$

Replacing the flux linkages in eqn. (2.8) by currents (using eqn. (2.4))

$$[v] = [R][i] + [L]p[i] + \omega_r [G][i] \tag{2.9}$$

where

$$[v] = [v_{ds} \quad v_{dr} \quad v_{qs} \quad v_{qr}]^T \tag{2.10}$$

$$[i] = [\, i_{ds} \quad i_{dr} \quad i_{qs} \quad i_{qr} \,]^T \tag{2.11}$$

and the other matrices appear in Appendix A. Equation (2.9) can be rearranged in state space form for solution on a digital computer as follows:

$$p[i] = [B]\,\{[v] - [R][i] - \omega_r [G][i]\} \tag{2.12}$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\frac{p}{2}(\psi_d i_q - \psi_q i_d) \tag{2.13}$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{2.14}$$

Despite the fact that the behavior of the physical variables as predicted by each reference frame is identical, the d,q variables in the respective frames of reference are different; this difference can be exploited by careful matching of the reference frame to the problem being solved, as illustrated in the following section.

In Stationary reference frame the d-axis is fixed to and thus coincident with the axis of the stator phase A winding. This means that the m.m.f. wave of the stator moves over this frame at the same speed as it does over the stator phase A windings. This reference frame's stator d-axis variables therefore behave in exactly the same way as do the physical stator phase A variables of the motor itself.. It is therefore not necessary to go through the inverse of Park's transform to compute the phase A current, thus saving in valuable computer time[5].

The model of induction motor has been developed on stator reference frame using the following assumptions:

1) Saturation is neglected.

2) The induced EMF is sinusoidal.

3) Eddy currents and hysteresis losses are negligible.

4) There are no field current dynamics.

2.5 SUMMARY:

This chapter presents a theoretical review of induction motors drives which includes classification of the induction motors, the construction and advantages. And also deals with the detailed modeling of induction motor and derives equivalent two phase mathematical model of the induction motor which can be easily implemented in MATLAB/Simulink.

Chapter 3

Direct Torque Control of IM Drive

Chapter 3

DIRECT TORQUE CONTROL (DTC) OF IM DRIVE

3.1 INTRODUCTION:

There are many different ways to drive an induction motor. The main differences between them are the motor's performance and the viability and cost in its real implementation.

Despite the fact that "Voltage/frequency" (V/f) is the simplest controller, it is the most widespread, being in the majority of the industrial applications. It is known as a scalar control and acts imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback[2]. However, this controller doesn't achieve a good accuracy in both speed and torque responses mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (except in a very low speed) and the dynamic response can be

approximately around 50ms.

The most popular method, vector control was introduced more than 25 years ago in Germany by Hasse, Blaske and Leonhard. The vector control method, also called Field Oriented Control (FOC) transforms the motor equations into a coordinate system that rotates in synchronism with the rotor flux vector.

Under a constant rotor flux amplitude there is a linear relationship between the control variables and the torque. Transforming the AC motor equations into field coordinates makes the FOC method resemble the decoupled torque production in a separately excited DC motor. Over the years, FOC drives have achieved a high degree of maturity in a wide range of applications. They have established a substantial world wide market which continues to increase.

When there was still a trend toward standardization of control systems based on the FOC method, direct torque control was introduced in Japan by Takahashi and Nagochi and also in Germany by Depenbrock. Their innovative studies depart from the idea of coordinate transformation and the analogy with DC motor control. These innovators proposed a method that relies on a bang-bang control instead of a decoupling control which is the characteristic of vector control. Their technique (bang-bang control) works very well with the on-off operation of inverter semiconductor power devices.

After the innovation of the DTC method it has gained much momentum[7]. The basic concept behind the DTC of AC drive, as its name implies, is to control the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors found in lookup tables. The possible eight voltage space vectors used in DTC are shown in fig.3.1

In Direct Torque Control it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. Its main features are as follows

- Direct torque control and direct stator flux control.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents.
- High dynamic performance even at locked rotor.

This method presents the following advantages:

- Absence of co-ordinate transforms.
- Absence of voltage modulator block, as well as other controllers such as PID for flux and torque.
- Minimal torque response time, even better than the vector controllers.

Although, some disadvantages are present:

- Possible problems during starting.
- Requirement of torque and flux estimators, implying the consequent parameters identification.
- Inherent torque and flux ripples.

The typical DTC includes two hysteresis controllers, one for torque error correction and one for flux linkage error correction[2]. The hysteresis flux controller makes the stator flux rotate in a circular fashion along the reference trajectory. The hysteresis torque controller tries to keep the motor torque within a pre-defined hysteresis band. The control algorithm determines a control signal whose amplitude depends on the difference between desired and actual value.

This control signal can assume any value in a given interval. The three signals used in the control action of a DTC system are torque error, flux linkage error and the angle of the resultant flux linkage vector.

One revolution is divided into six sectors. In each sector the DTC chose between 4 voltage vectors. Two of the vectors increase and the other two decrease torque. Another pair of vectors increase and decrease flux.

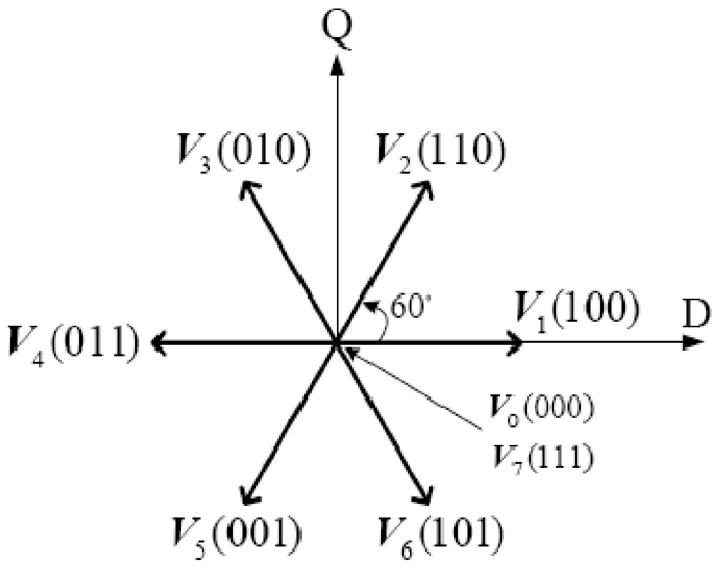

Fig. 3.1 Eight possible voltage space vectors obtained from VSI.

For each combination of the torque and flux hysteresis comparator states there is only one of the four voltage vectors which at the same time compensate torque and flux as desired.

3.2 TORQUE CONTROL STRATEGY IN DTC OF IM DRIVE:

The instantaneous torque in terms of stator and rotor flux linkages is given by

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m \bar{\Psi}_s * \bar{\Psi}_r}{\sigma L_s' L_r} \tag{3.1}$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m \Psi_s \Psi_r}{\sigma L_s' L_r}\sin\delta \tag{3.2}$$

Where

$$\Psi_s = \Psi_{qs} - j\,\Psi_{ds} \tag{3.3}$$

$$\Psi_r = \Psi_{qr} - j\,\Psi_{dr} \tag{3.4}$$

Also

$$\Psi_s = L_s I_s + L_m I_r \tag{3.5}$$

$$\Psi_r = L_r I_r + L_m I_s \tag{3.6}$$

$$L_s' = L_r L_s - L_m^2 \tag{3.7}$$

Where δ is the torque angle between flux vectors Ψ_s and Ψ_r. If the rotor flux remains constant and the stator flux is changed incrementally by the stator voltage, V_s then the torque variation ΔT_e, expression can be written as:

$$\Delta T_e = \frac{3}{2}\frac{P}{2}\frac{Lm}{LrLs}\left|\Psi r\right|\left|\Psi s + \Delta\Psi\right|\sin\delta \tag{3.8}$$

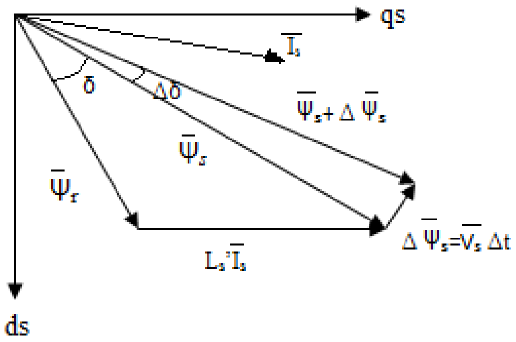

Fig. 3.2 Stator flux, rotor flux & stator current vectors on ds-qs.

As it can be seen from, if the load angle, δ, is increased then torque variation is increased. To increase the load angle, δ, the stator flux vector should turn faster than rotor flux vector. The rotor flux rotation depends on the mechanical speed of the rotor, so to decrease load angle, δ, the stator flux should turn slower than rotor flux[15]. Therefore, according to the torque, the electromagnetic torque can be controlled effectively by controlling the amplitude and rotational speed of stator flux vector, Ψ_s.

To achieve the above phenomenon, appropriate voltage vectors are applied to the motor terminals. For counter-clockwise operation, if the actual torque is smaller than the reference value, then the voltage vectors that keep the stator flux vector, Ψ_s, rotating in the same direction are selected. When the load angle, δ, between Ψ_s and Ψ_r increases the actual torque increases as well.

Once the actual torque is greater than the reference value, the voltage vectors that keep stator flux vector, Ψ_s, rotating in the reverse direction are selected instead of the zero voltage vectors. At the same time, the load angle, δ, decreases thus the torque decreases.

3.3 FLUX CONTROL STRATEGY OF IM DRIVE:

If the resistance term in the stator flux estimation algorithm is neglected, the variation of the stator flux linkage (incremental flux expression vector) will only depend on the applied voltage vector as shown in Fig. 3.3

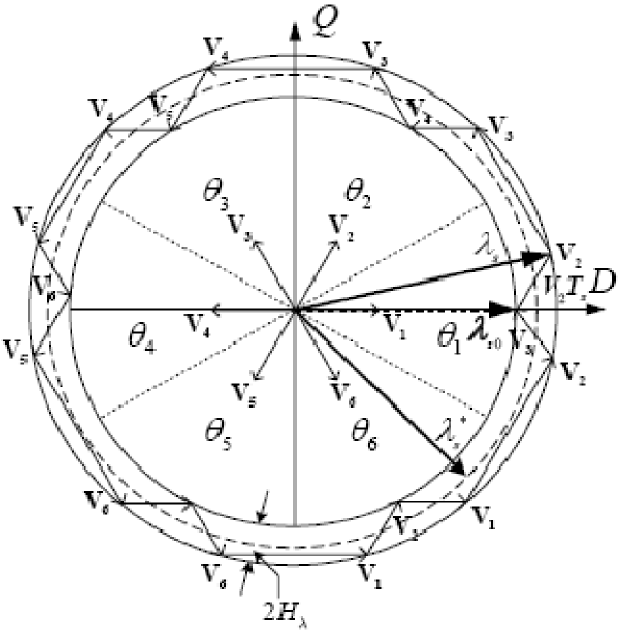

Fig. 3.3. Incremental stator flux linkage space vector representation in the DQ-plane.

For a short interval of time, namely the sampling time, $T_s = \Delta t$, the stator flux linkage, Ψ_s position and amplitude can be changed incrementally by applying the stator voltage vector, V_s. As discussed above, the position change of the stator flux linkage vector, Ψ_s, will affect the torque[2]. The stator flux linkage of a IM that is depicted in the stationary reference frame is written as:

$$\Psi_s = \int (V_s - R_s i_s)\mathrm{dt} \tag{3.9}$$

During the sampling interval time or switching interval, one out of the six voltage vectors is applied, and each voltage vector applied during the pre-defined sampling interval is constant, eqn (3.9) can be rewritten as

$$\Psi_s = \mathrm{V_s t} - \mathrm{R_s} \int i_s dt + \Psi_{s\mathrm{t=0}} \tag{3.10}$$

Where $\Psi_{st=0}$, is the initial stator flux linkage at the instant of switching, V_s, is the measured stator voltage, i_s, is the measured stator current, and R_s, is the estimated stator resistance. When the stator term in stator flux estimation is removed implying that the end of the stator flux vector, Ψ_s, will move in the direction of the applied voltage vector, as shown in Fig. 3.3, we obtain:

$$\Delta\Psi_s = \mathrm{V_s}\,\Delta\mathrm{t} \tag{3.11}$$

By applying a required voltage vector stator flux linkage amplitude can be controlled [7]. To select the voltage vectors for controlling the amplitude of the stator flux linkage the voltage plane is divided into six regions, as shown in Fig. 3.3.

In each region two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the amplitude of stator flux linkage, respectively. For example, according to the Table I, when the voltage vector V_2 is applied in Sector 1, then the amplitude of the stator flux increases when the flux vector rotates counter-clockwise. If V_3 is selected then stator flux linkage amplitude decreases[2].

Fig. 3.4 is a basic graph that shows how flux and torque can be changed as a function of the applied voltage vector. According to the figure, the direct component of applied voltage vector changes the amplitude of the stator flux linkage and the indirect component changes the

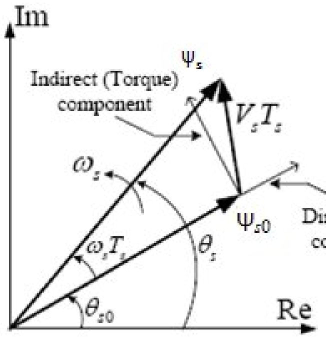

Fig. 3.4. Representation of direct and indirect components of the stator flux linkage vector.

flux rotation speed which changes the torque [8]. If the torque needs to be changed abruptly then the flux does as well, so the closest voltage vector to the indirect component vector is applied. If torque change is not required, but flux amplitude is increased or decreased then the voltage vector closest to the direct component vector is chosen. Consequently, if both torque and flux are required to change then the appropriate resultant mid-way voltage vector between the indirect and direct components is applied. It seems obvious from (3.9) that the stator flux linkage vector will stay at its original position when zero voltage vectors S_a (000) and S_b (111) are applied. This is true for an induction motor since the stator flux linkage is uniquely determined by the stator voltage.

3.4 VOLTAGE VECTOR SELECTION IN DTC OF IM DRIVE:

As discussed before, the stator flux is controlled by properly selected voltage vectors, and as a result the torque by stator flux rotation. The higher the stator vector rotation speed the faster torque response is achieved.

The estimation of the stator flux linkage components described previously requires the stator terminal voltages. In a DTC scheme it is possible to reconstruct those voltages from the DC-link voltage, V_{dc}, and the switching states (S_a, S_b, S_c) of a six-step voltage-source inverter (VSI) rather than monitoring them from the motor terminals [2]. The primary voltage vector, V_s, is defined by the following equation:

$$V_s = (2/3)(v_a + v_b\, e^{j(2/3)} + v_c\, e^{j(4/3)}) \qquad (3.12)$$

where, v_a, v_b and v_c and are the instantaneous values of the primary line-to-neutral voltages. When the primary windings are fed by an inverter, as shown in Fig. 3.5, the primary voltages v_a, v_b and v_c are determined by the status of the three switches, S_a, S_b and Sc. If the switch is at state 0 that means the phase is connected to the negative and if it is at 1 it means that the phase is connected to the positive leg.

For example, v_a is connected to V_{dc} if S_a is one, otherwise v_a is connected to zero. This is similar for v_b and v_c. The voltage vectors that are obtained this way are shown in Fig. 3.1. There are six nonzero voltage vectors: $V_1(100)$, $V_2(110)$, …, and $V_6(101)$ and two zero voltage vectors: $V_7(000)$ and $V_8(111)$. The six non-zero voltage vectors are 60^{o} apart from each other as in Fig. 3.1.

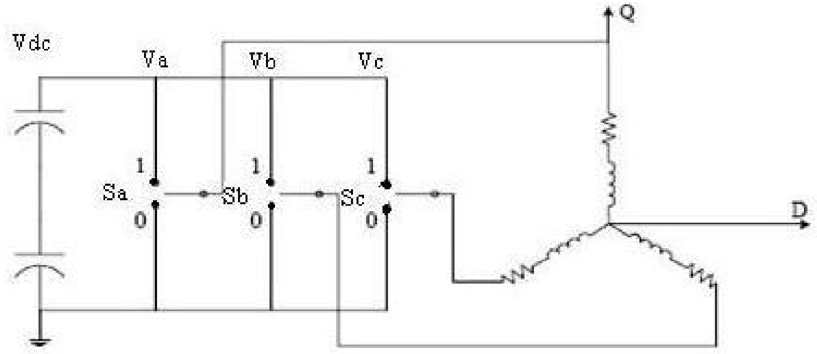

Fig. 3.5. Voltage source inverter (VSI) connected to the R-L load.

The stator voltage space vector (expressed in the stationary reference frame) representing the eight voltage vectors can be shown by using the switching states and the DC-link voltage, V_{dc}, as:

$$V_s(S_a,S_b,S_c) = (2/3)V_{dc}(S_a + S_b e^{j(2/3)} + S_c e^{j(4/3)}) \qquad (3.13)$$

Where V_{dc}, is the DC-link voltage and the coefficient of 2/3 is the coefficient comes from the Park's Transformation. Equation (3.13) can be derived by using the line-to-line voltages of the AC motor which can be expressed as:

$$V_{ab} = V_{dc}(S_a - S_b)\ ,\ V_{bc} = V_{dc}(S_b – S_c)\ ,\ v_{ca} = V_{dc}(S_c – S_a) \qquad (3.14)$$

The stator phase voltages (line-to-neutral voltages) are required for (3.12). They can be obtained from the line-to-line voltages as.

$$V_a = (V_{ab} - V_{ca})/3\ ,\ V_b = (V_{bc} - V_{ab})/3\ ,\ V_c = (V_{ca} – V_{bc})/3 \qquad (3.15)$$

If the line-to-line voltages in terms of the DC-link voltage, V_{dc}, and switching states are substituted into the stator phase voltages it gives:

$$V_a = (1/3)\, V_{dc}(2S_a - S_b - S_c) \tag{3.16}$$

$$V_b = (1/3)\, V_{dc}(-S_a + 2S_b - S_c) \tag{3.17}$$

$$V_c = (1/3)\, V_{dc}(-S_a - S_b + 2S_c) \tag{3.18}$$

Equation (3.14) can be summarized by combining with (3.12) as:

$$V_a = \mathrm{Re}(v_s) = (1/3)\, V_{dc}(2S_a - S_b - S_c) \tag{3.19}$$

$$V_b = \mathrm{Re}(v_s) = (1/3)\, V_{dc}(-S_a + 2S_b - S_c) \tag{3.20}$$

$$V_c = \mathrm{Re}(v_s) = (1/3)\, V_{dc}(-S_a - S_b + 2S_c) \tag{3.21}$$

To determine the proper applied voltage vectors, information from the torque and flux hysteresis outputs, as well as stator flux vector position, are used so that circular stator flux vector trajectory is divided into six symmetrical sections according to the non zero voltage vectors as shown in Fig. 3.3 [14].

According to Fig. 3.6, while the stator flux vector is situated in sector i, voltage vectors V_{i+1} and V_{i-1} have positive direct components, increasing the stator flux amplitude, and V_{i+2} and V_{i-2} have negative direct components, decreasing the stator flux amplitude. Moreover, V_{i+1} and V_{i+2} have positive indirect components, increasing the torque response, and V_{i-1} and V_{i-2} have negative indirect components, decreasing the torque response. In other words, applying V_{i+1} increases both torque and flux but applying V_{i+1} increases torque and decreases flux amplitude.

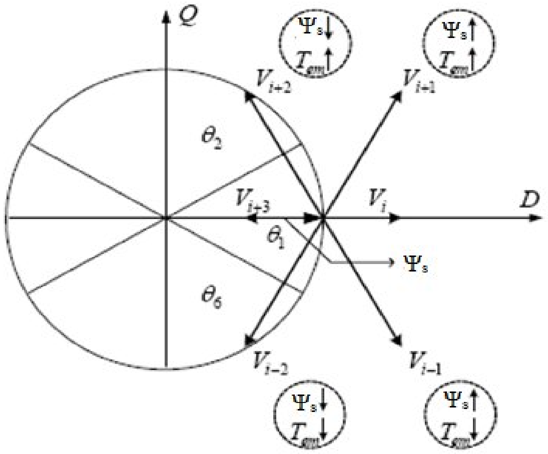

Fig. 3.6. Voltage vector selection when the stator flux vector is located in sector *i*.

The switching table for controlling both the amplitude and rotating direction of the stator flux linkage is given in Table I [2]. The voltage vector plane is divided into six sectors so that each voltage vector divides each region into two equal parts. In each sector, four of the six non-zero voltage vectors may be used [2].The output of the torque hysteresis comparator is denoted as τ, the output of the flux hysteresis comparator as ψ and the flux linkage sector is denoted as θ. The torque hysteresis comparator is a two valued comparator; $\tau = 0$ means that the actual value of the torque is above the reference and out of the hysteresis limit and $\tau = 1$ means that the actual value is below the reference and out of the hysteresis limit.

The flux hysteresis comparator is a two valued comparator as well where $\psi = 1$ means that the actual value of the flux linkage is below the reference and out of the hysteresis limit and $\psi = 0$ means that the actual value of the flux linkage is above the reference and out of the hysteresis limit. Instead, a non zero vector which decreases the absolute value of the torque is used. Their argument was that the application of a zero vector would make the change in torque subject to the rotor mechanical time constant which may be rather long compared to the electrical time constants of the system. This results in a slow change of the torque [2].

Table 3.1. Switching table

Ψ	τ	θ					
		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
Ψ=1	τ=1	V_2(110)	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_3(010)
	τ=0	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
Ψ=0	τ=1	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
	τ=0	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

We define ψ and $\boldsymbol{\tau}$ to be the outputs of the hysteresis controllers for flux and torque, respectively, and $\theta(1)$ -$\theta(6)$ as the sector numbers to be used in defining the stator flux linkage positions. In Table I, if $\psi = 1$, then the actual flux linkage is smaller than the reference value. On the other hand, if $\psi = 0$, then the actual flux linkage is greater than the reference value. The same is true for the torque.

3.5 CONVENTIONAL DIRECT TORQUE CONTROL SYSTEM:

In this section the basic DTC control system is presented in detail and the functions of all system blocks are explained. Figure 3.7 shows the block diagram of the DTC. Each block is described in detail below.Let's start with the motor currents and follow the signals around the system to the Voltage Source Inverter output.

3.5.1 CURRENT TRANSFORM:

As seen in the figure only two of the input currents are sensed. The motor in a drive system is normally operated with its neutral point floating, in this case $i_a + i_b + i_c = 0$ so the current not sensed is given of them other two. The i_{abc} current is then transformed to its quadrature and direct axes components according to the Park Transformation.

In the DTC system, variables are transformed into the αβ stator reference frame, which does not make use of any angular information.

This transformation becomes a simple mapping

$$\begin{pmatrix} i_q^s \\ i_d^s \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{3.22}$$

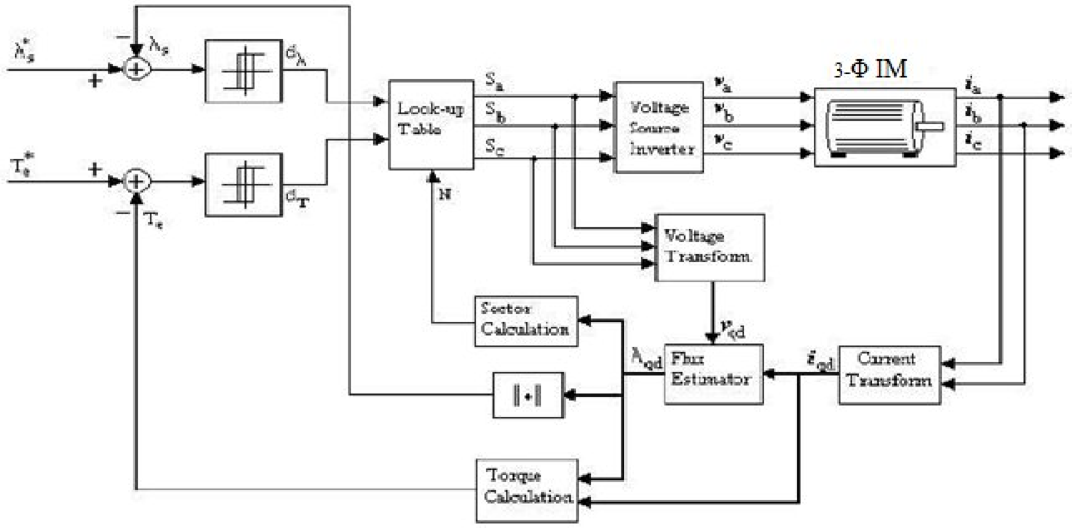

Fig. 3.7. DTC scheme.

3.5.2 FLUX ESTIMATOR:

Now that the current, $i_{\alpha\beta}$, is known, the signal continues into the flux estimator. Into this block also enters the VSI voltage vector transformed to the αβ-stationary reference frame. The voltage, $V_{\alpha\beta}$, is calculated as in eqn.3.16 so no further explanation is needed.

The dq-volatge eqn's with zero components left is

$$V_{dq} = R_s i_{dq} + \omega_r \begin{pmatrix} -\Psi_q \\ \Psi_d \end{pmatrix} + \frac{d}{dt}\Psi_{dq} \quad (3.23)$$

One can directly obtain a means for stator flux estimation by noting that w_r=0 and rearranging

$$\Psi_{\alpha\beta} = \int (V_{\alpha\beta} - R_s i_{\alpha\beta})dt \quad (3.24)$$

This formula is the foundation of implementing the flux estimator.

3.5.3 TORQUE ESTIMATOR:

The torque in the induction motor drive rotor reference frame is given by

$$T_e = (3/4)P(\Psi_d i_q - \Psi_q i_d) \quad (3.25)$$

which is true for all dq-reference frames. The torque in induction motor is estimated from the calculated currents and fluxes in the stationary αβ-reference frame. To calculate torque one only has to substitute the corresponding, already, calculated fluxes and currents. Torque calculation is thus a simple operation.

3.5.4 SECTOR CALCULATION:

The control action taken by the DTC control is based on the states of the flux and torque hysteresis comparators. Flux is increased by applying a vector pointing in the Ψ_{dq} direction and torque is increased by applying a vector pointing in the rotational direction.

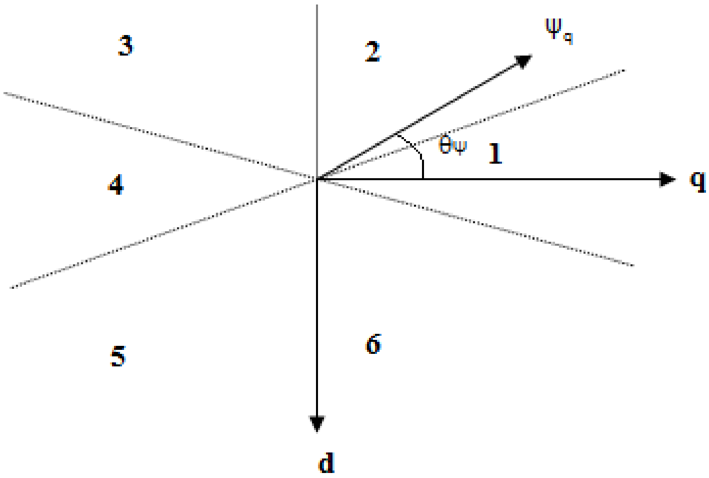

Fig. 3.8. DTC sectors and reference frames.

In order to do so, the angular position of the stator flux vector must be known so that the DTC can choose between an appropriate set of vectors depending on the flux position.
Each sector spans 60^o degrees, the sectors are numbered as in fig 3.8.

$$\theta = \tan^{-1}(\Psi_\beta / \Psi_\alpha) \tag{3.26}$$

If Ψ_{dq} belongs to sector 1, switch vectors $v_{2,}$ $v_{3,}$ v_5 and v_6 are used.

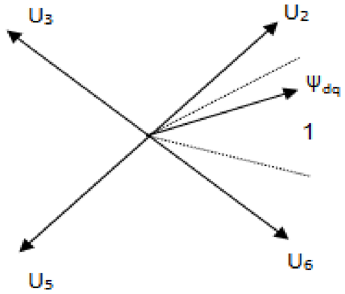

Fig. 3.9. VSI vectors used when Ψ_{dq} is in sector 1

3.5.5 TORQUE AND FLUX HYSTERESIS COMPARATORS:

Now we know in which sector is the flux and we also know how much torque the motor develops. Estimated torque and flux are compared to their command values. The difference between command and estimated value is compared in the hysteresis comparators.

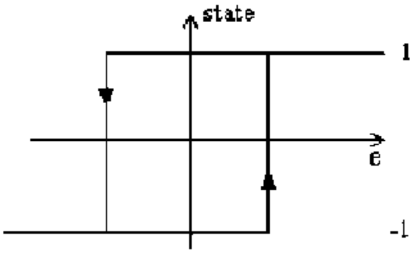

Fig. 3.10. 2-level hysteresis comparator.

3.5.6 LOOK –UP TABLE:

The hysteresis comparator states, dλ and dτ, together with the sector number N, are now used by the Look-up Table block to chose an appropriate voltage vector,

Table 3.2. Voltage Vector Switching Table

		N					
DΨ	Dτ	1	2	3	4	5	6
-1	-1	U_5	U_6	U_1	U_2	U_3	U_4
	1	U_3	U_4	U_5	U_6	U_1	U_2
1	-1	U_6	U_1	U_2	U_3	U_4	U_5
	1	U_2	U_3	U_4	U_5	U_6	U_1

The selected voltage vector is applied at the gate of the Voltage source inverter (VSI).

3.5.7 VOLTAGE SOURCE INVERTER:

The VSI synthesizes the voltage vectors commanded by the look up table block. In the case of DTC this task is quite simple since no pulse width modulation is used; the output devices stay in the same state during the entire sampling period.

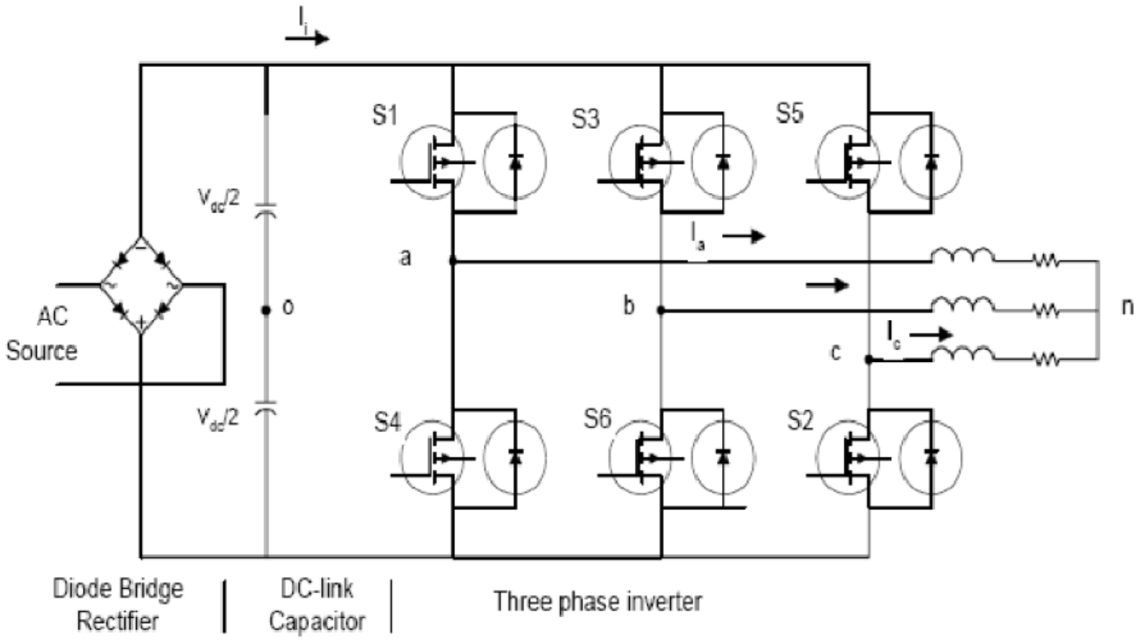

Fig. 3.11. VSI and how the motor windings are connected.

Figure 3.11 shows a simplified sketch of the VSI output stage, and how the motor windings are connected. The output-signals from the Look-up Table block in Fig. 3.7 are named

S_a, S_b and S_c. These are Boolean variables indicating the switch state in the inverter output-branches. Let $S_i = 1$ when the high or upper switch is on and the lower is off, and $S_i = 0$ when the lower is on and upper is off. The inverter states (S_a S_b S_c), generating each voltage vector then are:
u1 = (1 0 0), u2 = (1 1 0), u3 = (0 1 0), u4 = (0 1 1), u5 = (0 0 1), u6 = (1 0 1)
The VSI inverter terminals are connected to motor abc terminals.

3.6 ADVANTAGES AND DISADVANTAGES OF THE DIRECT TORQUE CONTROL TECHNIQUE:

There are many advantages of direct torque control over other high-performance torque control systems such as vector control. Some of these are summarized as follows [9]-[16]:

- The only parameter that is required is stator resistance
- The switching commands of the inverter are derived from a look-up table, simplifying the control system and also decreasing the processing time unlike a PWM modulator used in vector control.
- Instead of current control loops, stator flux linkage vector and torque estimation are required so that simple hysteresis controllers are used for torque and stator flux linkage control.
- Vector transformation is not applied because stator quantities are enough to calculate the torque and stator flux linkage as feedback quantities to be compared with the reference values.

Although there are several advantages of the DTC scheme over vector control, it still has a few drawbacks which are explained below:

- A major drawback of the DTC scheme is the high torque and stator flux linkage ripples. Since the switching state of the inverter is updated once every sampling time, the inverter keeps the same state until the outputs of each hysteresis controller changes states. As a result, large ripples in torque and stator flux linkage occur.
- The switching frequency varies with load torque, rotor speed and the bandwidth of the two hysteresis controllers.
- Stator flux estimation is achieved by integrating the difference between the input voltage and the voltage drop across the stator resistance. The applied voltage on the motor terminal can be obtained either by using a DC-link voltage sensor, or two voltage sensors connected to the any two phases of the motor terminals. For current sensing there should be two current sensors

connected on any two phases of the motor terminals. Offset in the measurements of DC-link voltage and the stator currents might happen, because for current and voltage sensing, however, temperature sensitive devices, such as operational amplifiers, are normally used which can introduce an unwanted DC offset. This offset may introduce large drifts in the stator flux linkage computation (estimation) thus creating an error in torque estimation (torque is proportional to the flux value) which can make the system become unstable.

- The stator flux linkage estimation has a stator resistance, so any variation in the stator resistance introduces error in the stator flux linkage computation, especially at low frequencies. If the magnitude of the applied voltage and back-EMF are low, then any change in the resistance will greatly affect the integration of the back-EMF.
- Because of the constant energy provided from the permanent magnet on the rotor the rotor position of motor will not necessarily be zero at start up. To successfully start the motor under the DTC scheme from any position (without locking the motor at a known position), the initial position of the rotor magnetic flux must be known. Once it is started properly, however, the complete DTC scheme does not explicitly require a position sensor.

3.7 SUMMARY:

In this chapter a theoretical review of DTC for applying to a induction motor is given. An algorithm for implementation of Direct Torque control technique for a two level inverter driving induction motor is developed. The key elements like torque estimation, flux estimation and voltage vector selection table is also given.

Chapter 4

Vector Control of IM Drive

Chapter 4

Vector control of IM drive

4.1 INTRODUCTION:

During the last few years the field of controlled electrical drives has undergone rapid expansion due mainly to the advantages of semiconductors in both power and signal electronics and culminating in micro-electronic microprocessors and DSPs[2]. These technological improvements have enabled the development of really effective AC drive control with ever lower power dissipation hardware and ever more accurate control structures. The electrical drive controls become more accurate in the sense that not only are the DC current and voltage controlled but also the three phase currents and voltages are managed by so-called vector controls. This document describes the most efficient form of vector control scheme: the Field Orientated Control. It is based on three major points: the machine current and voltage space vectors, the transformation of a three phase speed and time dependent system into a two co-ordinate time invariant system and effective Pulse Width Modulation pattern generation. Thanks to these factors, the control of AC machine acquires every advantage of DC machine control and frees itself from the mechanical commutation drawbacks.

4.2 Field Orientated Control:

The Field Orientated Control (FOC) [1][3] consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. The FOC thus solves the classic scheme problems, in the following ways:

- the ease of reaching constant reference (torque component and flux component of the stator current)

- the ease of applying direct torque control because in the (d,q) reference frame the expression of the torque is:

$$T_e = K_t \Psi_r i_{qs} \tag{4.1}$$

$$T_e = K_t' i_{ds} i_{qs} \tag{4.2}$$

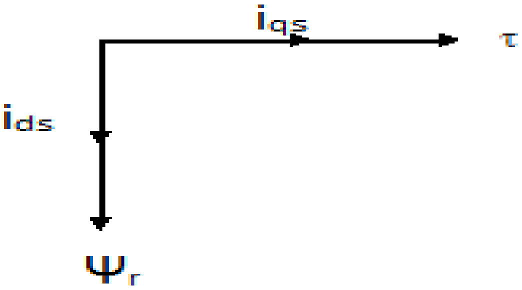

Fig.4.1 Vector controlled induction motor

In the case of induction machines, the control is normally performed in a reference frame aligned to the rotor flux space vector. To perform the alignment on a reference frame revolving with the rotor flux requires information on the modulus and the space angle (position) of the rotor flux space vector.

In order to estimate the rotor flux vector is possible to use two different strategies:

- **DFOC** (Direct Field Oriented Control): rotor flux vector is either measured by means of a flux sensor mounted in the air-gap or measured using the voltage equations starting from the electrical machine parameters.
- **IFOC** (Indirect Field Oriented Control): rotor flux vector is estimated using the field oriented control equations (current model) requiring a rotor speed measurement. The usual terminology "*Sensor less"* specifies that no position/speed feedback devices are used. With these algorithms, the stator currents of the induction machine are separated into flux and torque producing components by utilizing transformation to the d-q coordinate system.

On this reference frame the torque component is on the q axis and the flux component is on the d axis. The vector control system requires the dynamic model equations of the induction motor and returns to the instantaneous currents and voltages in order to calculate and control the variables. Indirect vector control of the rotor currents can be implemented using the following data:

- Instantaneous stator phase currents, i_a, i_b, and i_c .
- Rotor mechanical position.
- Rotor electrical time constant.

The motor must be equipped with sensors to monitor the three-phase stator currents and a rotor position feedback device. An encoder is normally mounted on the shaft rotor for this purpose but in order to have a cheaper solution is possible to use a speed feedback device such as a tachometer.

The key for understanding how vector control works is to explain the coordinate reference transformation process[5]. From the perspective of the stator, a sinusoidal input current is forced to the stator. This time variant signal causes the generation of a rotating magnetic flux. The speed of the rotor is a function of the rotating flux vector. From a stationary perspective, the stator currents and motor and the rotating flux vector look like AC quantities. Keep in mind that the rotor flux speed is not equal to the revolving magnetic field, produced by the stator phase windings, during the transient conditions. Looking at the motor from this perspective during steady state conditions, the stator currents become constant.

By maintaining the amplitude of the rotor flux (Ψ_r) at a fixed value we have a linear relationship between torque and torque component (i_{qs}). We can then control the torque by controlling the torque component of stator current vector.

4.3 Space Vector definition and projection:

The three-phase voltages, currents and fluxes of AC-motors can be analyzed in terms of complex space vectors. With regard to the currents, the space vector can be defined as follows. Assuming that i_a, i_b, i_c are the instantaneous currents in the stator phases, then the complex stator current vector i_S is defined by

$$i_S = \mathrm{i}_a + \alpha \mathrm{i}_b + \alpha^2 \mathrm{i}_c \qquad (4.3)$$

Where $\alpha = e^{j2\pi/3}$ and $\alpha^2 = e^{j4\pi/3}$ represent the spatial operators. The following diagram shows the stator current complex space vector:

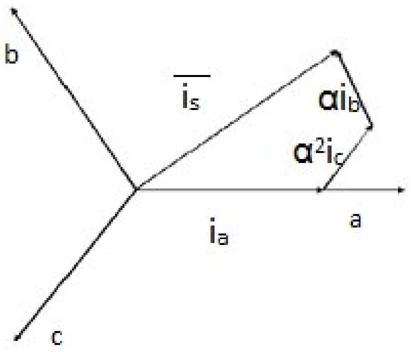

Fig.4.2 Stator current space vector and its components in (a,b,c).

where (a,b,c) are the three phase system axes. This current space vector depicts the three phase sinusoidal system. It still needs to be transformed into a two time invariant co-ordinate system. This transformation can be split into two steps:

- **(a,b,c) to (α,β)**(the Clarke transformation) which outputs a two co-ordinate time variant system
- **(α,β) to (d,q)**(the Park transformation) which outputs a two co-ordinate time invariant system

4.3.1 The (a,b,c) to (α,β) projection (Clarke transformation):

The space vector can be reported in another reference frame with only two orthogonal axis called (α,β).:

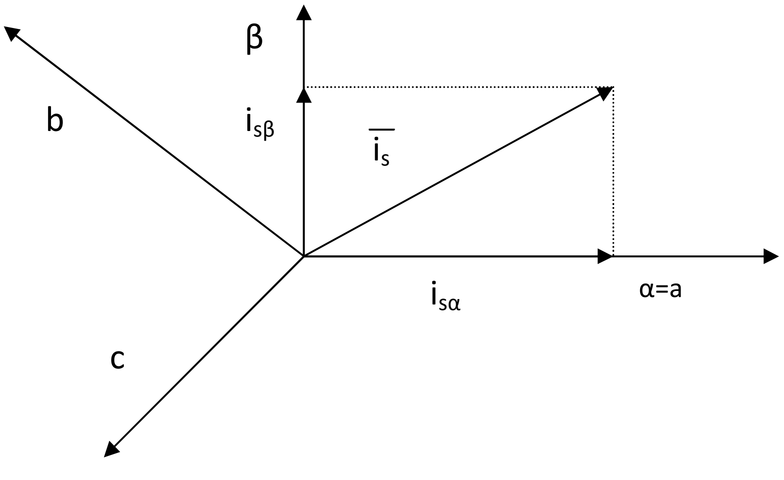

Fig.4.3 Stator current space vector and its components in (α,β).

The projection that modifies the three phase system into the (α,β) two dimension orthogonal system is presented below.

$$i_{s\alpha} = i_a \tag{4.4}$$

$$i_{s\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \tag{4.5}$$

4.3.2 The (α,β) to (d,q) projection (Park transformation):

This is the most important transformation in the FOC. *In* fact, this projection modifies a two phase orthogonal system (α, β)in the d,q rotating reference frame. If we consider the d axis aligned with the rotor flux, the next diagram shows, for the current vector, the relationship from the two reference frame:

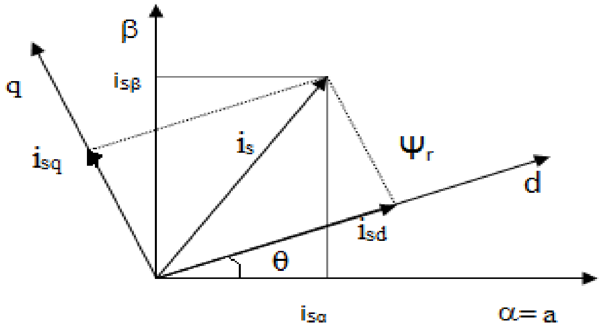

Fig.4.4 Stator current space vector and its component in (α,β) and in the d,q rotating reference frame.

where θ is the rotor flux position. The flux and torque components of the current vector are determined by the following equations:

$$i_{sd} = i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta \tag{4.6}$$

$$i_{sq} = -i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta \tag{4.7}$$

These components depend on the current vector (α,β) components and on the rotor flux position; if we know the right rotor flux position then, by this projection, the d,q component becomes a constant. We obtain a two co-ordinate system

$$\begin{pmatrix} i_{Sd} \\ i_{Sq} \end{pmatrix}$$

with the following characteristics:

- two co-ordinate time invariant system
- with i_{Sd} (flux component) and i_{Sq} (torque component) the direct torque control is possible and easy.

4.3.3 The (d,q) to (α,β) projection (inverse Park transformation):

Here, we introduce from this voltage transformation only the equation that modifies the voltages in d,q rotating reference frame in a two phase orthogonal system:

$$V_{s\alpha ref} = V_{sdref}\cos\theta - V_{sqref}\sin\theta \qquad (4.8)$$

$$V_{s\beta ref} = V_{sdref}\sin\theta + V_{sqref}\cos\theta \qquad (4.9)$$

The outputs of this block are the components of the reference vector that we call V_r ;V_r is the voltage space vector to be applied to the motor phases.

The basic scheme for the FOC:

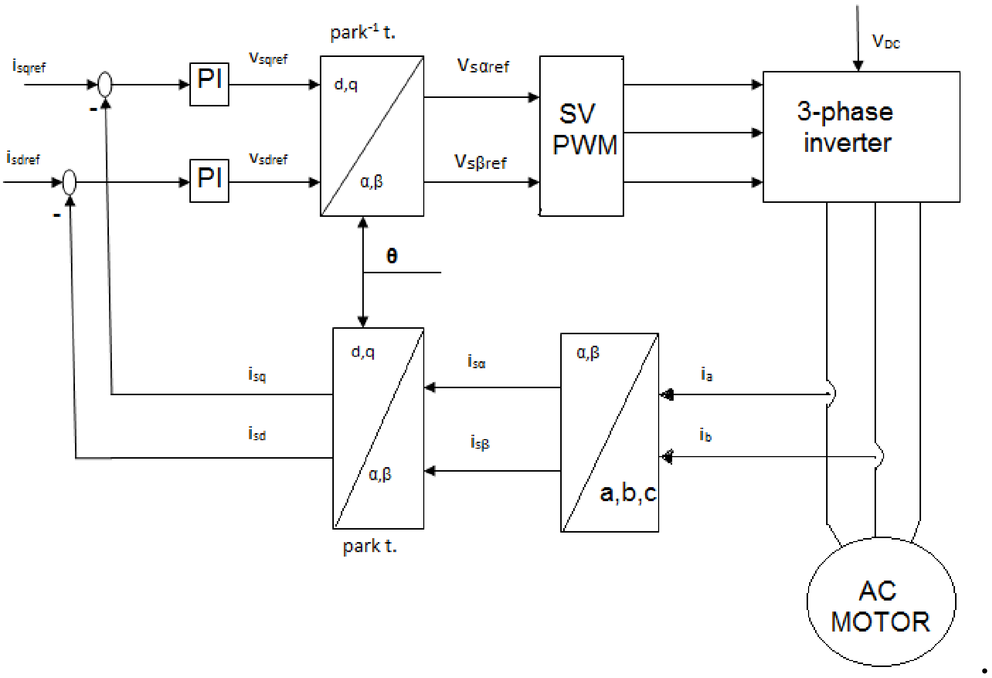

Fig.4.5 Basic scheme of FOC for AC-motor.

4.3.4 Torque equation in vector control:

$$T_e = \frac{3PLm}{4Lr'}\left(\Psi_{dr}^{'e} i_{qs}^{'e} - \Psi_{qr}^{'e} i_{ds}^{'e}\right) \tag{4.10}$$

The rotor flux components can be expressed as:

$$\Psi_{dr}^{'e} = L_r^{'e} I_{qr}^{'e} + L_m I_{qs}^{e} \tag{4.11}$$

$$\Psi_{qr}^{'e} = L_r^{'e} I_{dr}^{'e} + L_m I_{ds}^{e} \tag{4.12}$$

Where P is the number of poles, L_m is the magnetizing inductance, $\Psi_{qr}^{'e}$,$\Psi_{dr}^{'e}$,$i_{ds}^{'e}$, $i_{qs}^{'e}$ are the rotor flux and stator current direct (*d*)and quadrature (*q)* components, respectively, and

$$L_r' = L_m + L_{lr}' \tag{4.13}$$

L_{lr}' being the rotor equivalent leakage inductance.

Two motor phase currents are measured. These measurements feed the Clarke transformation module. The outputs of this projection are designated $i_{s\alpha}$ and $i_{s\beta}$. These two components of the current are the inputs of the Park transformation that gives the current in the d,q rotating reference frame[2] .The i_{Sd} and i_{Sq} components are compared to the references i_{Sdref} (the flux reference) and i_{Sqref} (the torque reference). At this point, this control structure shows an interesting advantage: it can be used to control either synchronous or induction machines by simply changing the flux reference and obtaining rotor flux position. As in synchronous permanent magnet motors , the rotor flux is fixed (determined by the magnets) there is no need to create one. Hence, when controlling a PMSM, i_{Sdref} should be set to zero. As induction motors need a rotor flux creation in order to operate, the flux reference must not be zero. This conveniently solves one of the major drawbacks of the "classic" control structures: the portability from asynchronous to synchronous drives. The torque command i_{Sqref} could be the output of the speed regulator when we use a speed FOC. The outputs of the current regulators are v_{Sdref} and v_{Sqref}; they are applied to the inverse Park transformation. The outputs of this projection are $v_{S\alpha ref}$ and $v_{S\beta ref}$ which are the components of the stator vector voltage in the α, β stationary orthogonal reference frame. These are the inputs of the Space Vector PWM. The outputs of this block are the signals that drive the inverter. Note that both Park and inverse Park transformations need the rotor flux position.

4.4 Input for the FOC:

Fundamental requirements for the FOC are a knowledge of two phase currents (as the motor is star-connected, the third phase current is also known, since ia + ib + ic = 0), and the rotor flux position.

4.4.1 Current sampling:

The measured phase currents ia and ib are sampled and converted by an A/D converter. The correct working of the FOC depends on the true measurement of these currents. Type of analog to digital converter depends on sampling period. Current sampling is done between the motor output currents and voltage space vectors.

4.4.2 Rotor flux position:

Knowledge of the rotor flux position is the core of the FOC. In fact if there is an error in this variable the rotor flux is not aligned with d-axis and iSd and iSq are incorrect flux and torque

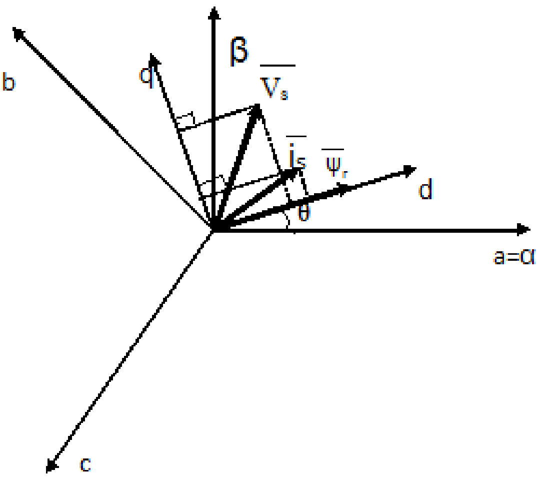

Fig.4.6 Current, voltage and rotor flux space vectors in the d,q rotating reference frame and their relationship with a,b,c and α,β stationary reference frame.

components of the stator current.The above diagram shows the (a,b,c), (α,β) and (d,q) reference frames, and the correct position of the rotor flux, the stator current and stator voltage space vector that rotates with d,q reference at synchronous speed.

The measure of the rotor flux position is different if we consider synchronous or induction motor.

- In the synchronous machine the rotor speed is equal to the rotor flux speed. Then q (rotor flux position) is directly measured by position sensor or by integration of rotor speed .
- In the induction machine the rotor speed is not equal to the rotor flux speed (there is a slip speed), then it needs a particular method to calculate q. The basic method is the use of the current model which needs two equations of the motor model in d,q reference frame.

Fig. 4.7 AC Vector Control Drive

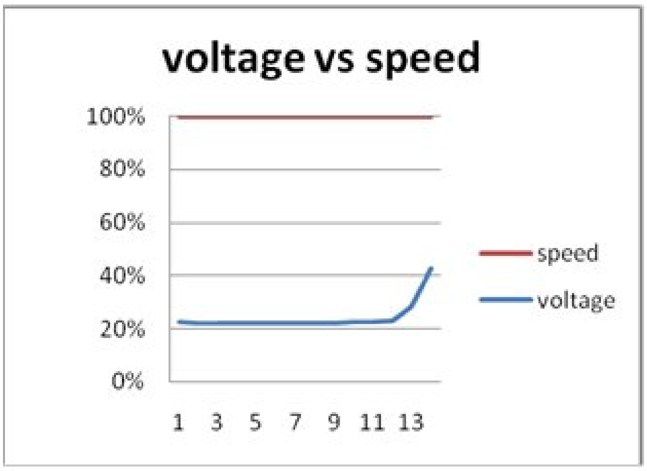

Fig. 4.8 Voltage Vs Speed

Hardware setup for control drive consists of :

Induction motor = 3Hp, 3Φ,400V

Voltmeter = 500V ac

Tachometer → Non contact type

AC VC DRIVE- Siemens

Table 4.1 Hardware Vector Control Motor Drive

Applied Voltage(V)	Speed (r.p.m)
413.5	1478
400.28	1428
380.00	1354
360.00	1280
340.00	1200
320.00	1126
300.00	1062
280.00	992.8
260.00	910.6
240.00	827
220.00	756
200.00	665
160.00	505
100.00	267.7

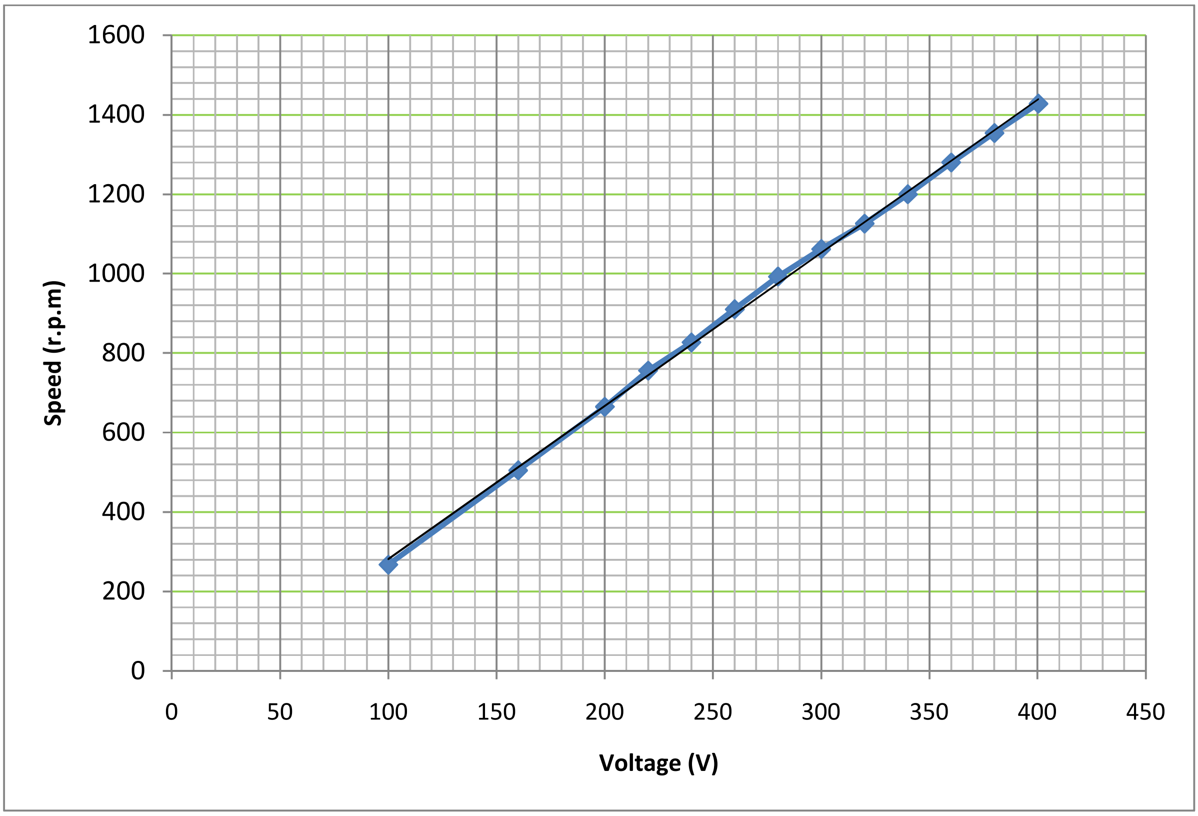

Fig 4.9 Graph Speed Vs Voltage

4.5 Summary:

In this chapter a theoretical review of Vector control applying to a induction motor is given. By performing the experiment using Vector Controlled Induction Motor Drive available in our Power Electronics and Drives lab the above results are obtained. The key elements like torque estimation, flux estimation and voltage and speed table is also given.

Chapter 5

Simulation Results

Chapter 5

SIMULATION RESULTS

5.1 INTRODUCTION:

The control system block diagrams shown in Fig 3.7 and Fig 4.3 and simulated for Induction Motor in the MATLAB/Simulink environment. The SimPowerSystem is used for this modeling work. The advantage of the SimPowerSystem is that it has extensive libraries for machines and power electronics circuits. In first section the Simulink model for the induction motor is given, in the next section the simulation results of DTC technique are implemented

The motor parameters used for simulation are:

Stator resistance = 2.45 Ω

Rotor resistance = 7.94Ω

Stator self inductance = 0.0125 mH

Rotor self inductance = 0.0125 mH

Mutual inductance = 0.265 mH

Motor Moment of Inertia = 0.059 kg-m^2

Damping coefficient = 0 kg-m^2/s

Number of poles = 6

5.2 MATLAB/Simulink model for IM :

The Induction motor is modeled in MATLAB/Simulink using the modeling equations eqns 2.19 – 2.25 derived in chapter 2. The V_d and V_q voltages are obtained from the park's transformation of the stator abc voltages. The model is given below.

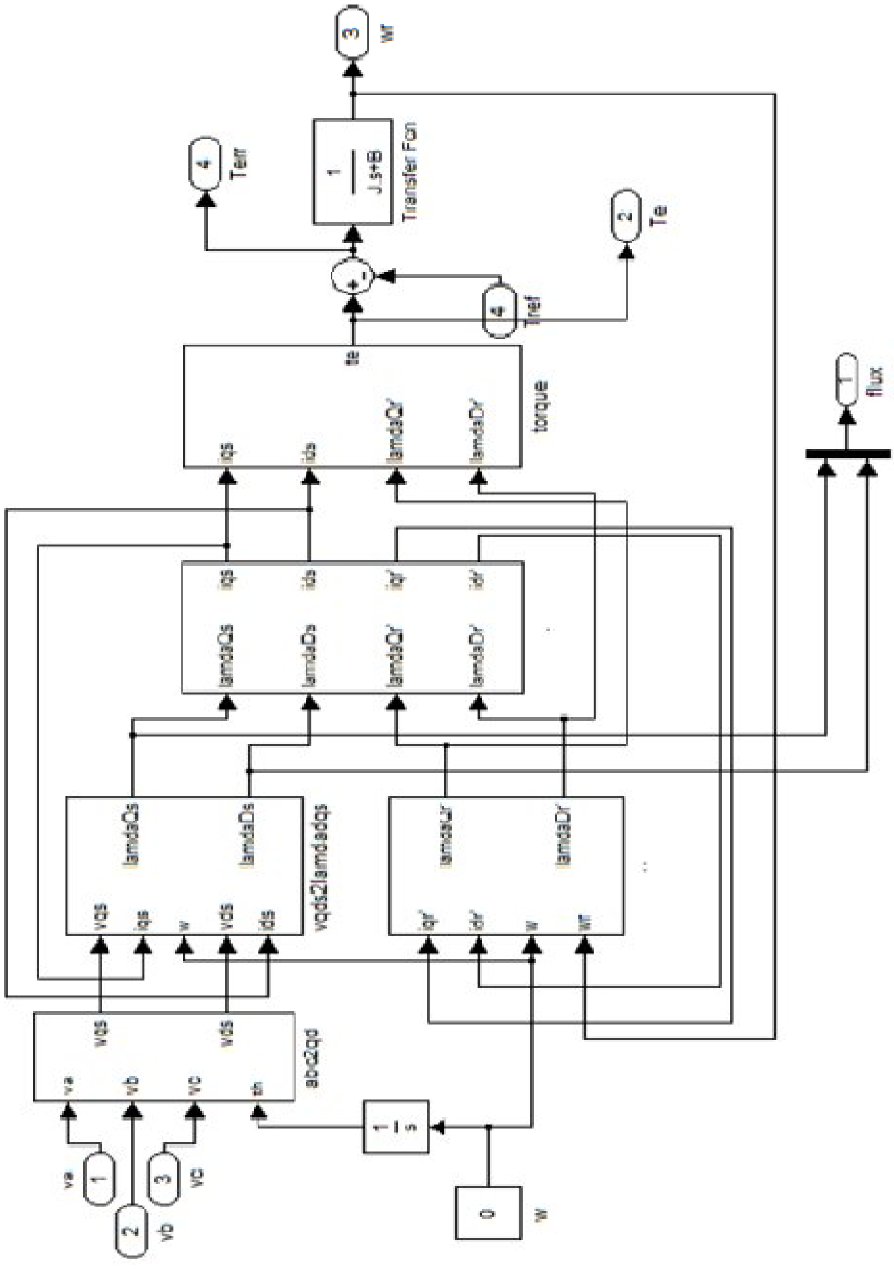

Fig. 5.1 Simulink model of Induction Motor.

Park's transformation converts stator abc 3-phase voltages to equivalent 2-phase dq-reference frame i.e. to the rotor reference frame.

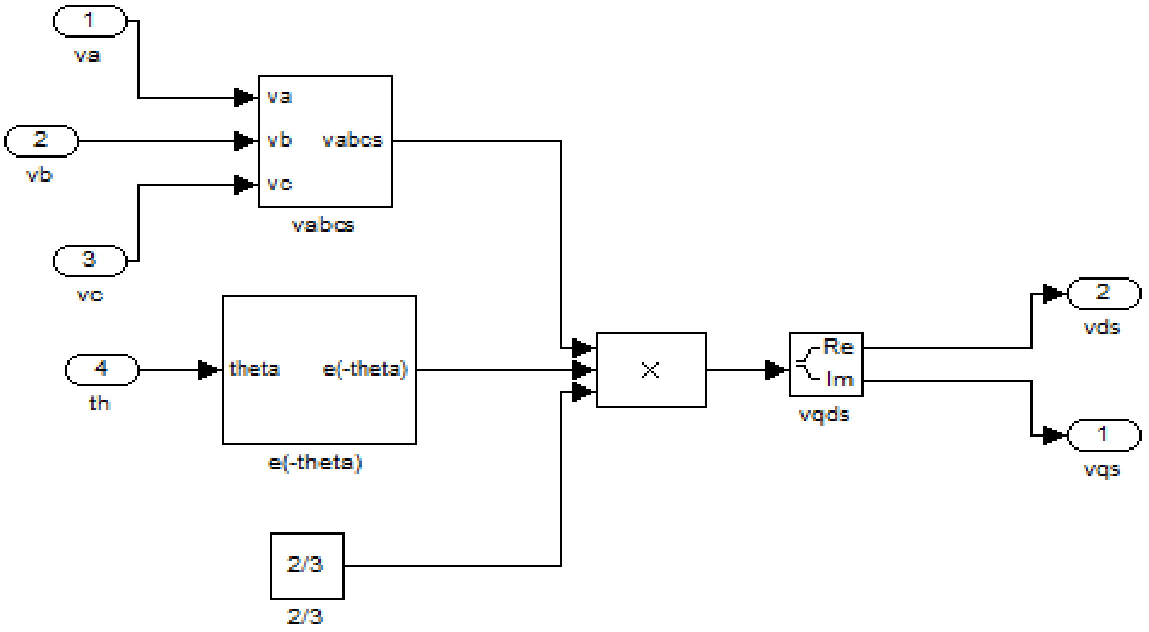

Fig. 5.2 Park's Transformation block.

5.3 DTC TECHNIQUE:

The control technique shown in fig 3.7 is implemented in MATLAB environment. With reference to the fig 5.3 the whole model can be divided into

IM motor model

Two level Inverter

Voltage vector selection table

Torque estimator and flux estimator

The torque and flux values are estimated from the eqns 3.18 and 3.19 and are compared with the reference values, the error is compared in hysteresis comparator and the output of the comparators along with the flux sector (θ) are together used in Switching table to determine the appropriate voltage vector. The vector selected from the Switching table is then applied to the Voltage Source Inverter (VSI). The voltages V_α, V_β are estimated from the switching state of the each leg in the inverter and the simulink model is given below

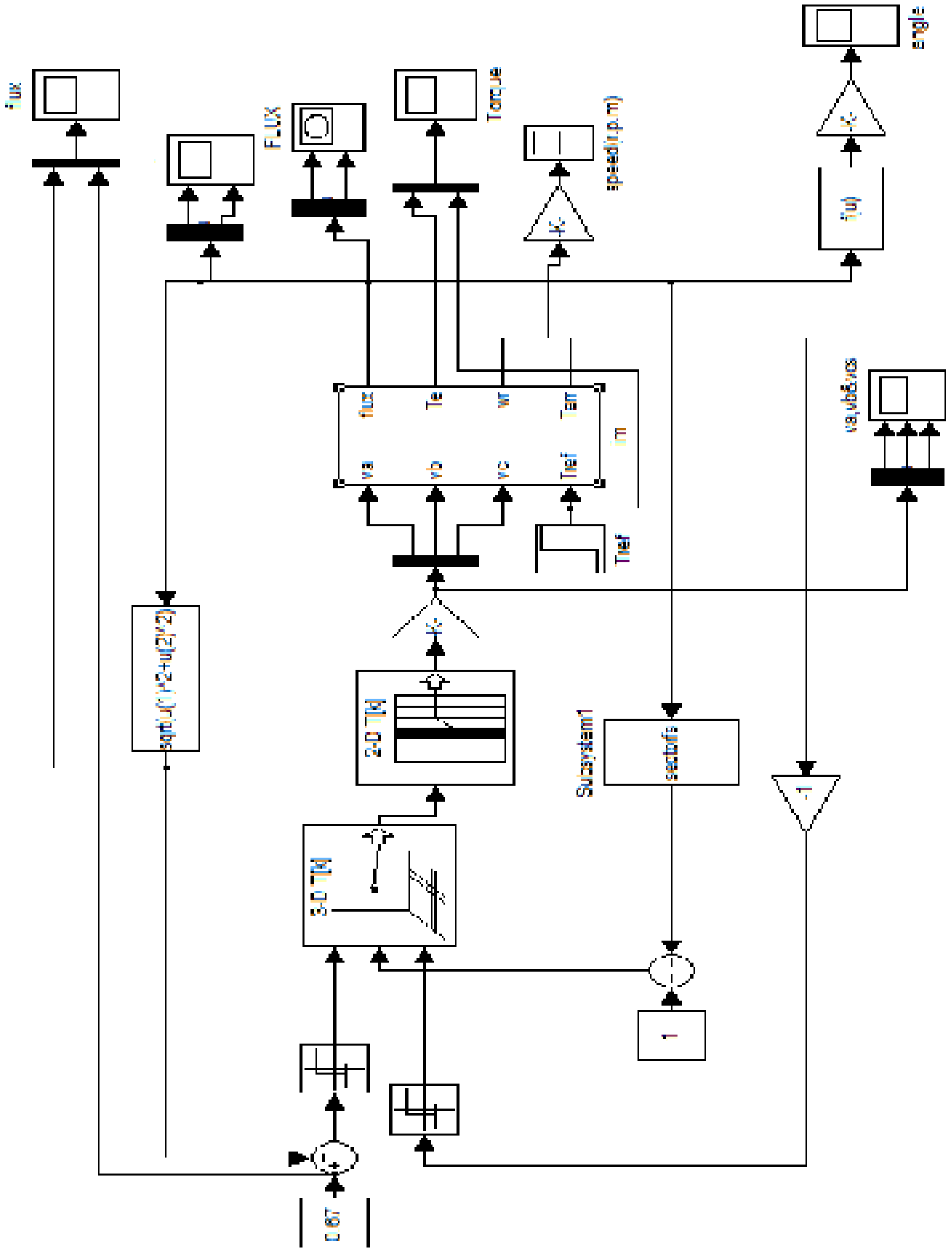

Fig. 5.3 DIRECT TORQUE CONTROL

The results for the above control technique for 220V are given below:

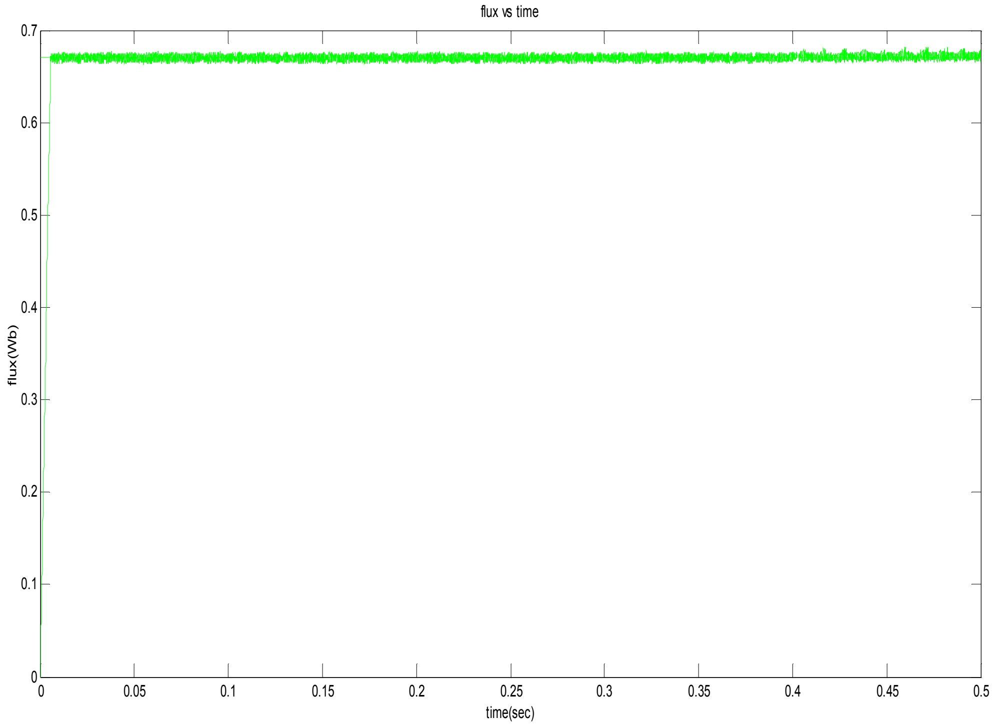

Fig. 5.4 Flux response of DTC for 220V

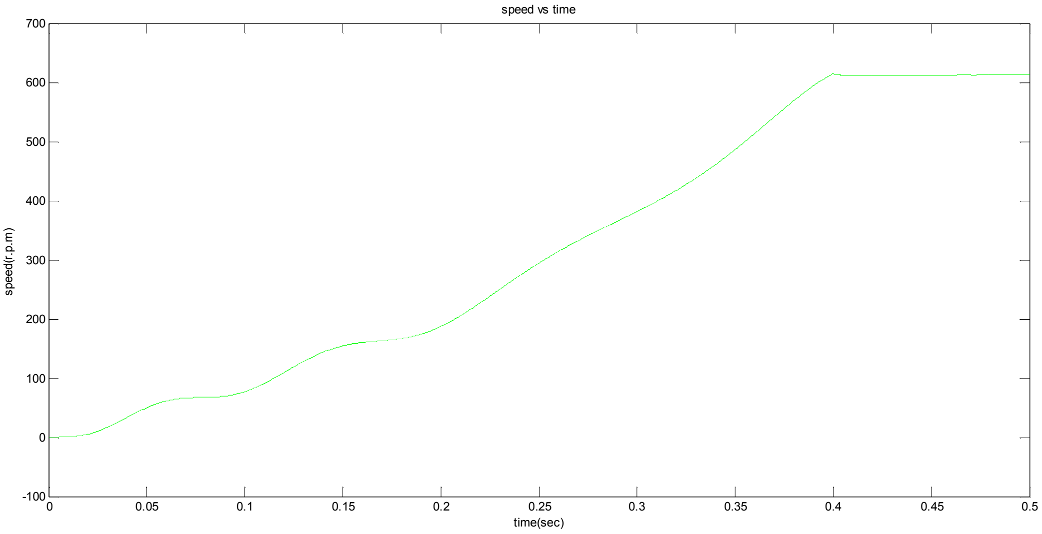

Fig. 5.5 Speed response of DTC for 220 V

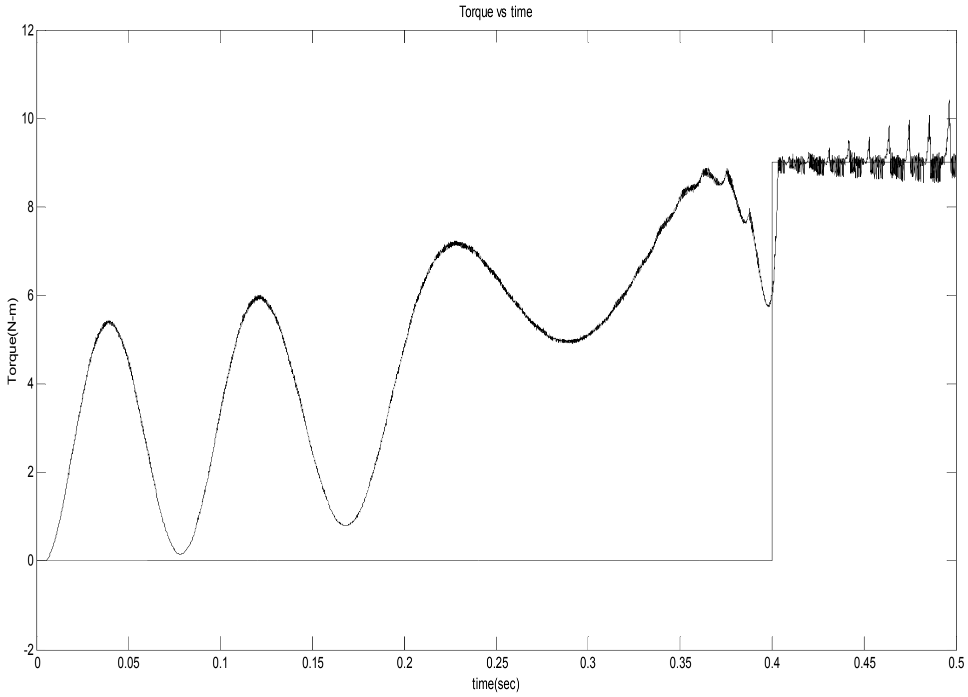

Fig. 5.6 Torque response of DTC for 220 V

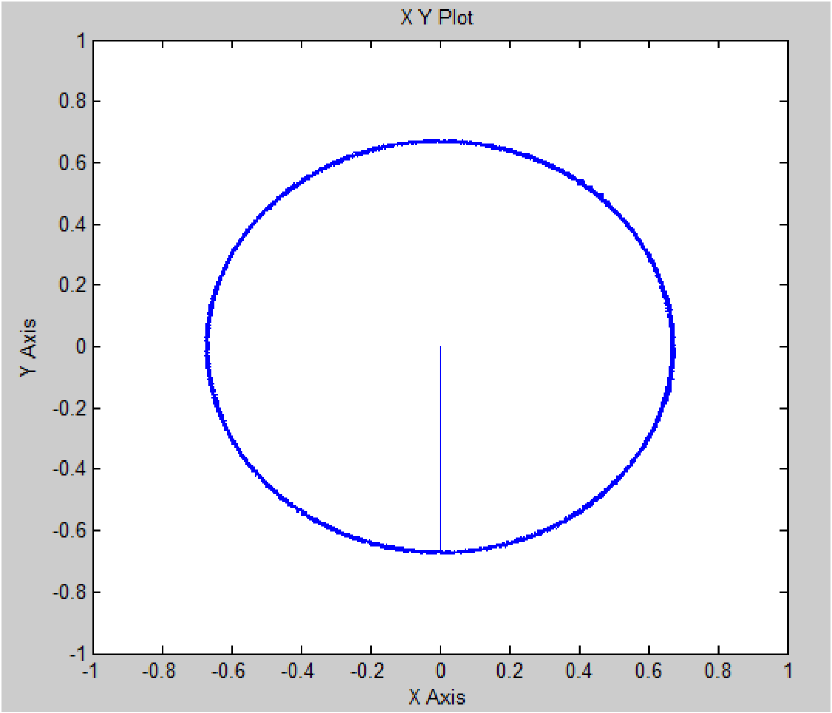

Fig. 5.7 Flux trajectory for 220 V

The results for the above control technique for 100V are given below:

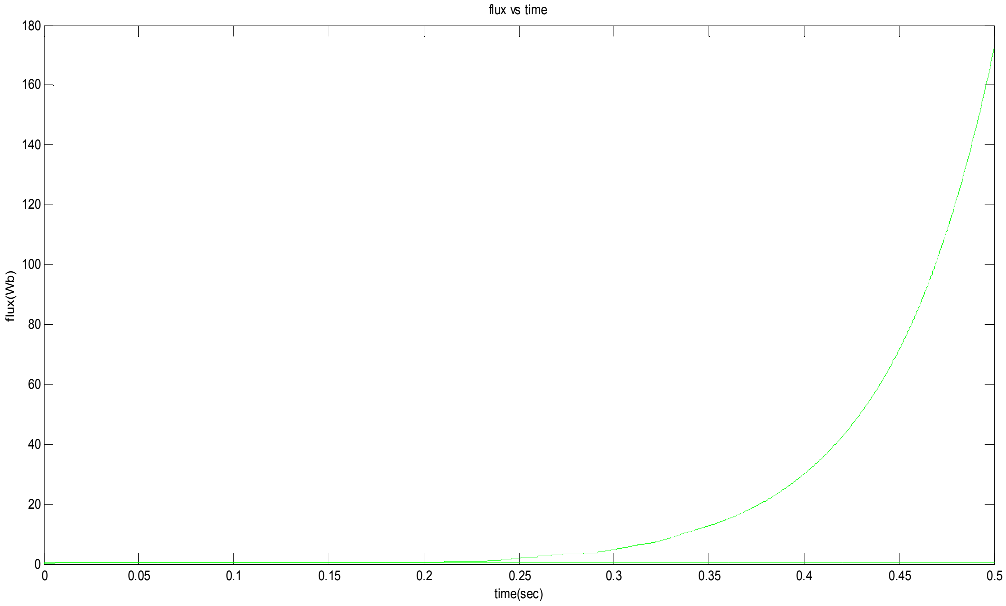

Fig. 5.8 Flux response of DTC

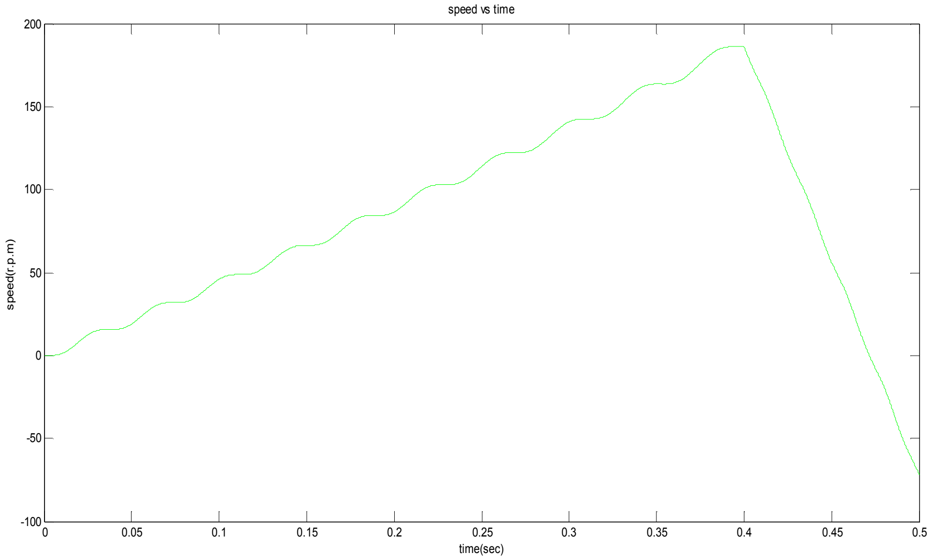

Fig.5.9 Speed response of DTC

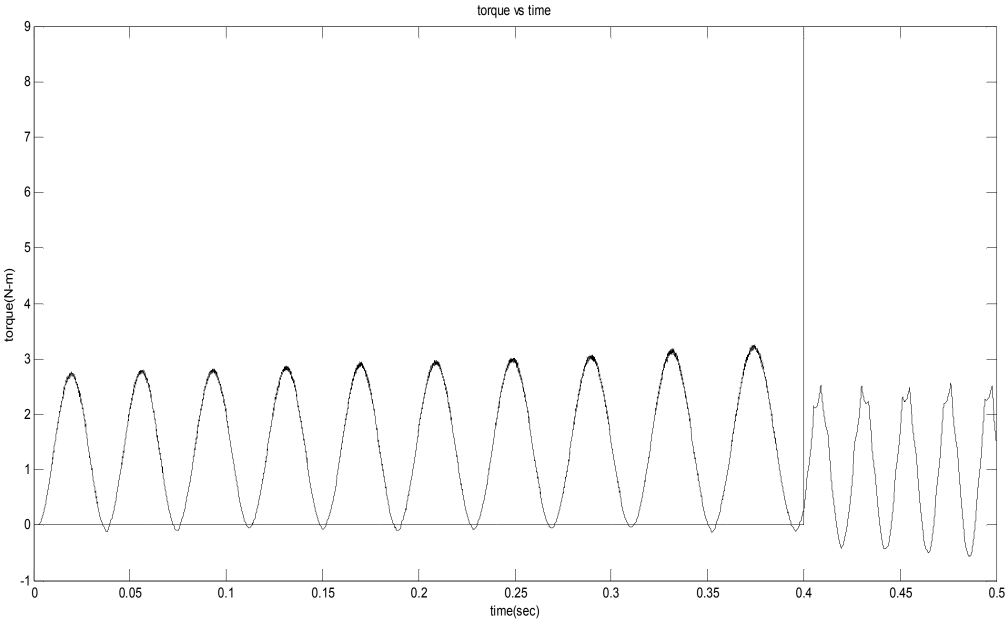

Fig. 5.10 Torque response of DTC

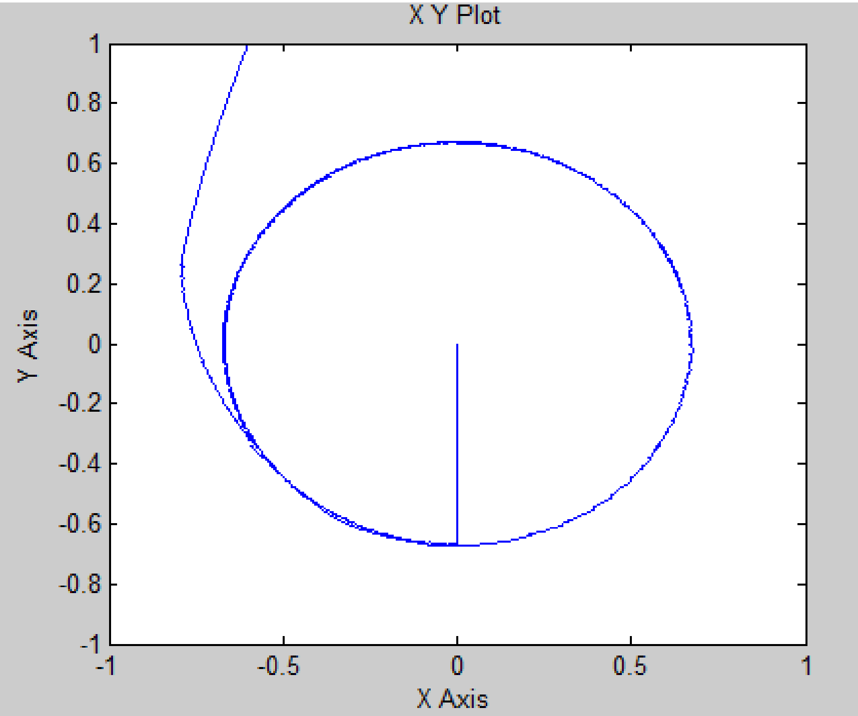

Fig. 5.11 Flux trajectory

The results for the above control technique for 413.5V are given below:

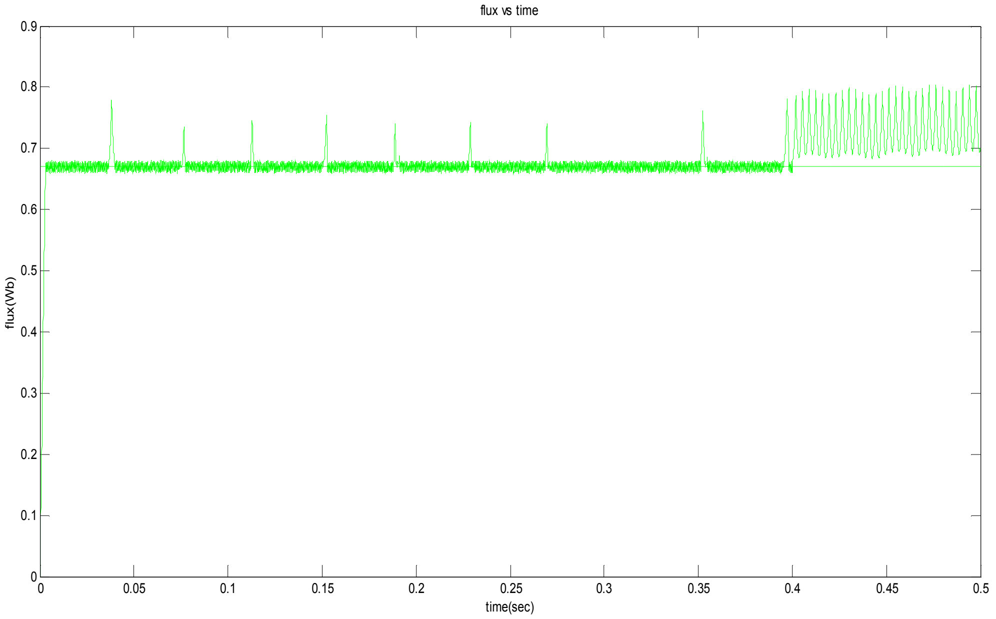

Fig. 5.12 Flux response of DTC

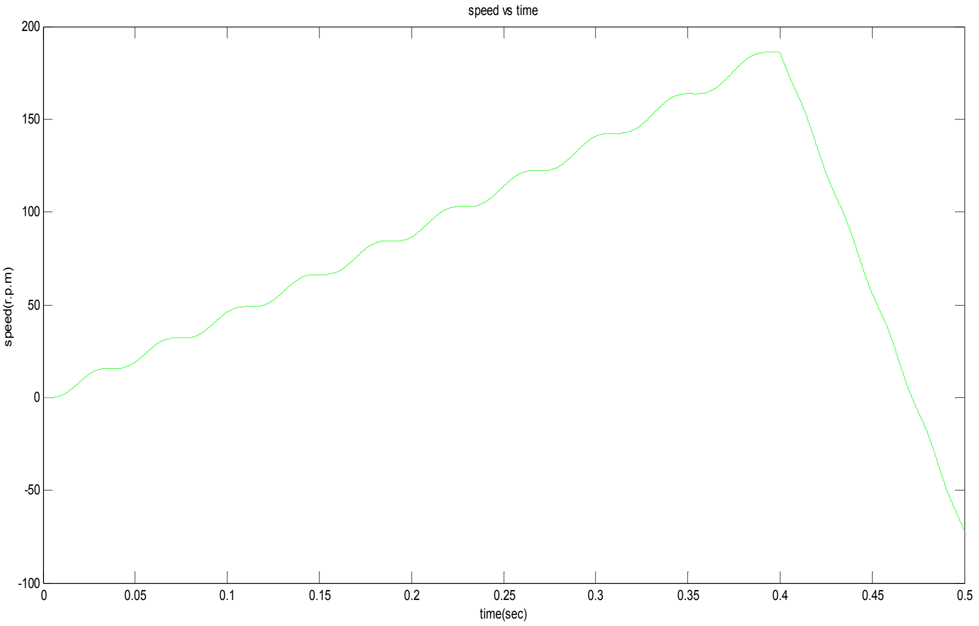

Fig. 5.13 Speed response of DTC

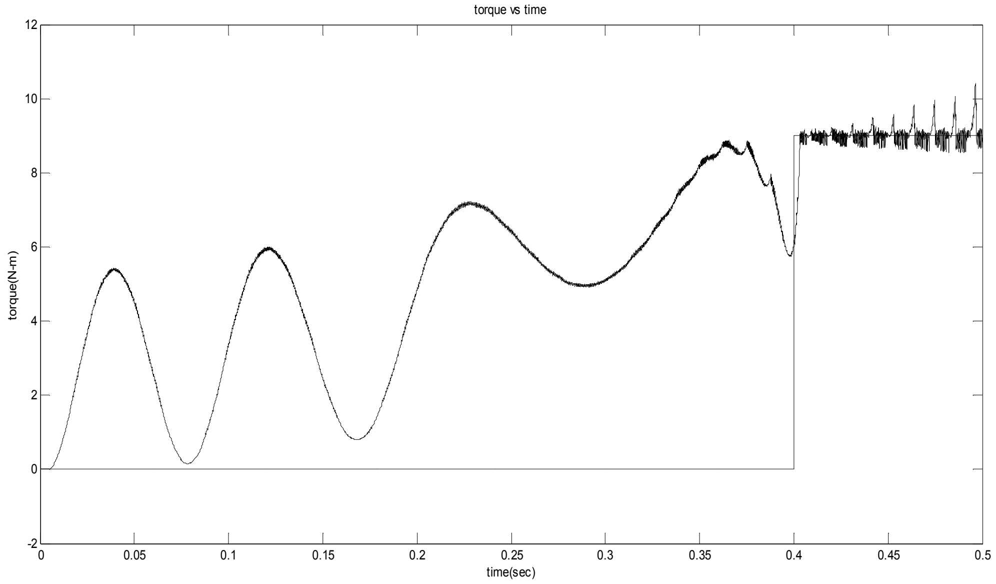

Fig. 5.14 Torque response of DTC

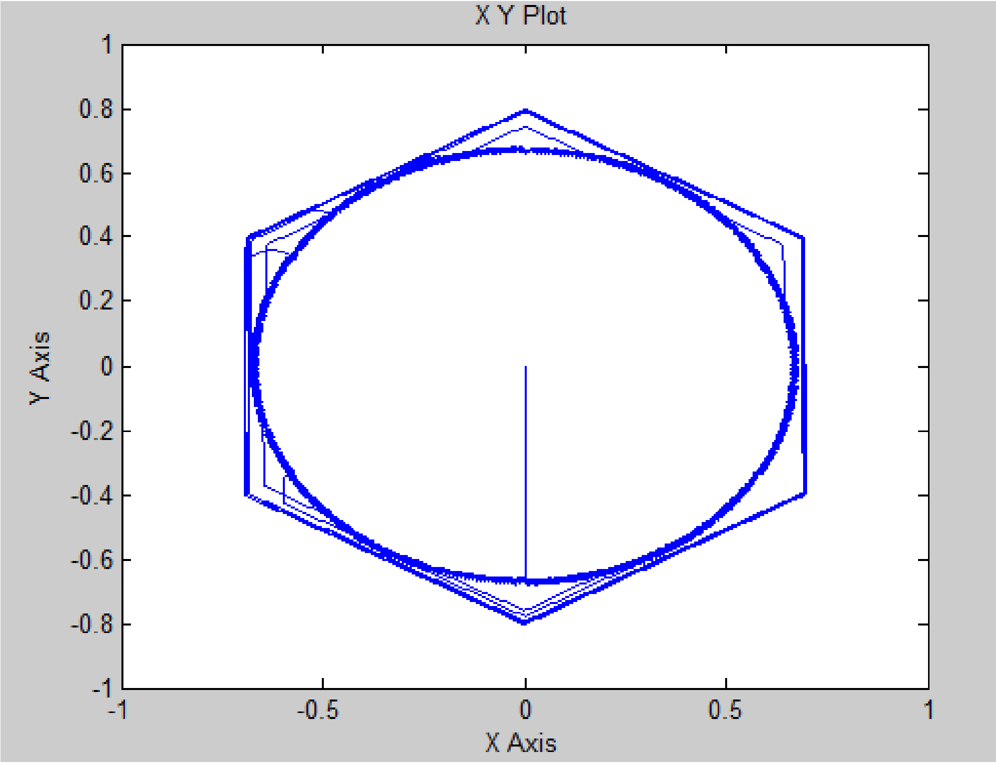

Fig. 5.15 Flux trajectory

5.4 Summary:

The Simulink model induction motor of variable speed control of induction motor is realized using Simulink and Sim Power System blocks. The SVM strategy provides fast torque response and better speed accuracy. Steady State torque ripples as well as the flux ripple are considerably reduced.

Chapter 6

Conclusion and Recommendations

Chapter 6

CONCLUSION AND RECOMMENDATIONS

Motor criteria such as durability, high performance, high power factor, easy and cheap control, low maintenance demands have led to a new type of motor excited by induction motors. In this thesis, by means of space vector theory, a mathematical model for the Induction Motor is developed and implemented in MATLAB/Simulink

DTC is intended for an efficient control of the torque and flux without changing the motor parameters and load. Also the flux and torque can be directly controlled with the inverter voltage vector in DTC. Two independent hysteresis controllers are used in order to satisfy the limits of the flux and torque. In the performed simulation, certain stator flux and torque references are compared to the values estimated from the motor parameters and errors are sent to the hysteresis comparators. The outputs of the flux and torque comparators are used in order to determine the appropriate voltage vector and stator flux space vector.

In this thesis, DTC technique for a two level fed induction motor is explained and is simulated in MATLAB/Simulink environment. The simulation results are analyzed and found that the torque obtained from the motor is having a large amount of ripple content. Direct Torque Control Technique of induction motor with a two level inverter can be implemented in Real-Time environment and the results can be validated with the obtained simulation results. Torque ripples can also be reduced by applying the duty ratio controller. The performance of the classical DTC can be improved by neural network based DTC schemes. SVPWM switching patterens can be analysed and fed to VSI fed induction motor drive and proposed technique can be implemented in DSP TMS320LF2407 Processor.

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