DIRECT TORQUE CONTROL BASED INDUCTION MOTOR DRIVE

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ECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

It is hereby declared that the thesis entitled **“DIRECT TORQUE CONTROL BASED INDUCTION MOTOR DRIVE”** contains literature survey and original research work by the undersigned candidate, as part of her degree in Master of Nuclear Engineering.

All the information in this document has been obtained and presenter in accordance with academic rules and ethical conduct.

It is also declared that all the materials and results, not original to this work have been fully cited and referred throughout this thesis, according to rules of ethical conduct.

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ABSTRACT

This work deals with, how to control both the stator flux and electromagnetic torque of induction motor simultaneously in a low speed operation. That is the basic idea of direct torque control method(DTC).

Both torque and flux of DTC based drive are controlled in the manner of closed loop system without using current loops in comparison with the conventional vector controlled drives.

Moreover, the DTC-based drives do not require fulfilling the coordinate transformation between stationary frame and synchronous frame, in comparison with the conventional vector-controlled drives. Since a DTC-based drive selects the inverter switching states using switching table, pulse-width modulation (PWM) modulator is not required, thereby providing fast torque response.

Simulation and experimental results has proved the effectiveness of the proposed speed estimation technique at low and zero speed regions, and good robustness with respect to parameter variations, measurement errors and noises are obtained.

Keywords: Induction Motor, Direct torque control(DTC), control,speed estimation, vector or field oriented control.

Table of Contents

LIST OF FIGURES

NOMENCLATURE

Variable	**Description**
$V_A, V_{B,}V_C$	Instantaneous values of the stator phase voltages.
$i_{A,}i_B,i_C$	Flux linkage of the stator flux.
$\varphi_{A,}\varphi_{B,}\varphi_C$	Flux linkage of the stator phase windings.
k	Arbitrary phase variables.
$\psi_{A,}\psi_B,\psi_C$	Stator magnetic fluxes [Wb]
R_S	Stator phase resistant[Ohm]
R_r	Rotor phase resistance[Ohm]
L_s	Stator phase inductance[H]
L_r	Rotor phase inductance[H]
L_m	Mutual(stator or rotor) inductance [H]
ω/ω_s	Electrical rotor speed/synchronous speed[rad/sec]
P	Number of pole pairs
τ_e	Electromagnetic torque[]Nm
f	Frequency
P_{md}	Mechanical power developed.
E_2	Rotor phase voltage[V]

R_2	Rotor phase resistance[Ohm]
X_2	Rotor phase inductance[H]

Chapter 1

Introduction

• BACKGROUND AND OBJECTIVE

Speed information is very important for the operation of vector controlled induction motor drives. The objective of the paper is control the speed of Induction motor in some specific circumstances i.e. the costs, limitations, applications, product availability and other benefits.

Theory of direct torque control (DTC) technique is basically similar with the field-oriented control (FOC) and direct self control (DSC) techniques. In the DTC technique, all power elements are switched based on the electromagnetic state of the motor. Similar with the FOC technique, the DTC technique controls flux and torque independently.

The main disadvantages of these model based estimators is their insufficient performance at low speeds and parameter machine sensitivity. In order to overcome the problems of these model based estimators, signal injection based methods are now widely used. Although the signal injection based methods perform well at low and zero speed regions but, they suffer from computational complexity, the need of external hardware for signal injection and adverse effect of injecting signal on the machine performance.

Therefore, due to the simplicity, direct torque control methods are untilthe most widely used speed estimation methods. Direct torque control(DTC)

has emerge recently as a viable control method for high performance motor drives because it minimizes the use of machine parameters and reduce complexity of the algorithm involved in FOC and feedback linearization method.

Different from FOC, DTC does not try to reproduce the electromechanical behavior of a dc motor, but is aimed at the flux- and torque-producing capability of an induction motor fed by an inverter. The produced torque of a DTC induction motor relies on effectively constructing the stator flux.

This work proposes a field oriented control (FOC) induction motor drive based on a new DTC method. First, the modeling of induction motor is described. Then a new and advanced DTC rotor speed observer is designed in Matlab/Simulink. Finally simulation results are discussed.

- **DYNAMIC MODEL OF INDUCTION MOTOR**

Research interest in induction motor sensorless drive has grown significantly over the past few years as, the speed sensor spoil the ruggedness and simplicity of the induction motors. In the meanwhile, the speed sensorless system has a lot of advantages such as it can cut down the system cost and the installation and maintenance is simple. It is well known that the implementation of high performance control depend on the right estimation of the rotor flux and rotor speed.

The dynamic model of a three phase induction motor can be described in the synchronous reference frame by the voltage equations.

The electromagnetic torque equation is given by,

$$\hat{\tau}_e = (\frac{3}{2})(\frac{P}{2})\frac{L_m}{L_r}(I_{sq}\hat{\psi}_{rd} - I_{sd}\hat{\psi}_{rq})\ (1.1)$$

• SPEED CONTROL STRATEGY

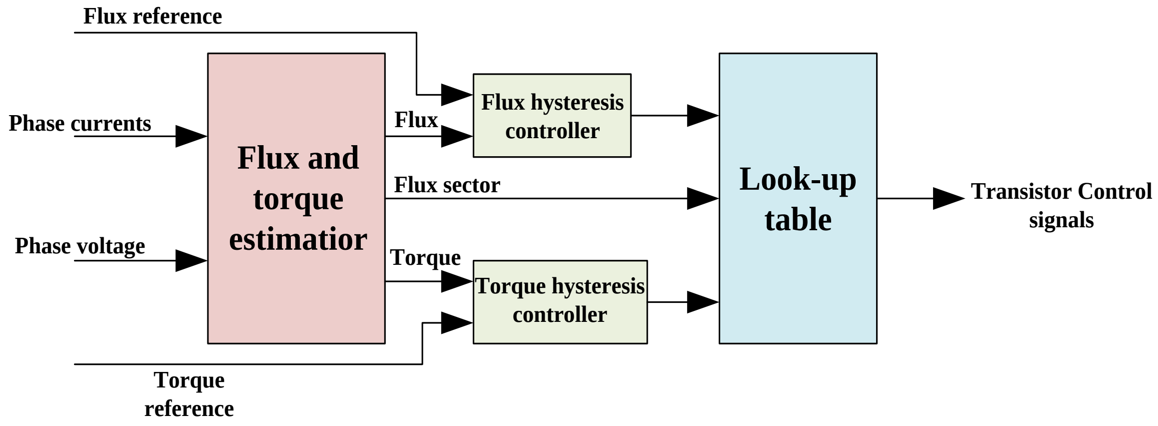
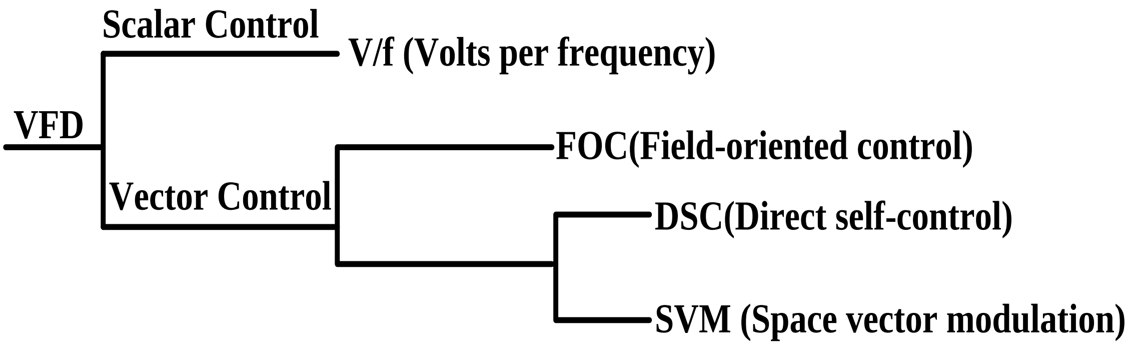


Figure.1.1.Block diagram of flux and torque control scheme (taken from public domain).

The objective of vector control or rotor flux orientation is to decouple the stator current into flux and torque producing components regulated separately, to obtain a good performance of the induction motor drive. The rotor flux is oriented on the d-axis and the stator flux is oriented on the q-axis.

Overview of key competing VFD (Variable Frequency Drive) control platform



• DIRECT TORQUE CONTROL(DTC) CONCEPT

Theory of direct torque control (DTC) technique is basically similar with the field-oriented control (FOC) and direct self-control (DSC) techniques. In the DTC technique, all power elements are switched based on the electromagnetic state of the motor. Similar with the FOC technique, the DTC technique controls flux and torque independently. Although classical DTC technique, similar with the FOC, offers a high dynamic performance, it produces a large ripple in the steady state. It also operates with a variable inverter switching frequency, which is regarded as disadvantage. Furthermore, an accurate stator flux estimate is necessary, which can require an accurate motor model and fast sampling **.**Simple structure and easy assembling of the DTC technique is regarded as advantage. Although speed samples are necessary in control routine, a speed sensor is not required and speed is estimated.

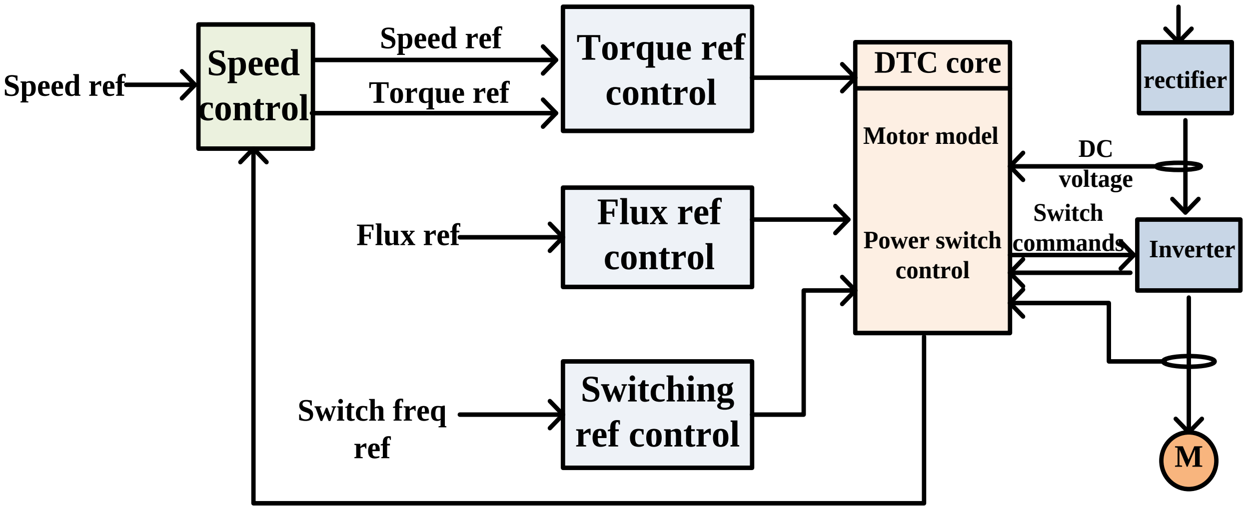


Fig 1.2 Simplified block diagram showing the basic sections of the DTC control and power circuits.

LITERATURE REVIEW

Speed control of induction motor by DTC technique is not something that has been invented recently but it, in fact, one of the technologies mankind has been using since ages in India.

Since its mid-**1980**s introduction applications, DTC have been used to advantage because of its simplicity and very fast torque and flux control response for high performance induction motor (IM) drive applications.

DTC was patented by **Manfred Depenbrock**in the US and in Germany, the latter patent having been filed on October 20, **1984**, both patents having been termed direct self-control (DSC).

However**, Isao Takahashi and Toshihiko Noguchi** described a similar control technique termed DTC in an IEEJ paper presented in September 1984 and in an IEEE paper published in late **1986**. The first major successful commercial DTC products, developed by **ABB**, involved traction applications late in the **1980**s for German DE502 and DE10023 diesel-electric locomotives and the **1995** launch of the ACS600 drives family. ACS600 drives has since been replaced by ACS800 and ACS880 drives. **Vas, Tiitinen et al**. and **Nash** provide a good treatment of ACS600 and DTC.

DTC techniques for the interior permanent magnet synchronous machine (IPMSM) were introduced in the late 1990s and synchronous reluctance motors (SynRM) in the **2010**s.

DTC was applied to doubly fed machine control in the early **2000**s. Doubly fed generators are commonly used in 1-3 MW wind turbine applications.

Since its introduction in **1985**, the direct torque control (DTC) (or direct self control (DSC)) principle was widely used for IM drives with fast dynamics. Several solutions with modified DTC are presented in the literature. Due to its simple structure, DTC can be easily integrated with an artificial intelligence control strategy.

There are several methods which are relevant for controlling speed in induction motor. **Taguchi's Method** - The Taguchi's method is an effective analysis technique to find out the dominant control factor and its associated level, which significantly affect the experimental results.

James N. Nash proposed several applications in induction motor vector-control without an encoder. By using an inner-current control loop, the dc drive can directly control torLikewisethe

Chapter-2

Theory of induction motor drives

2.1. INTRODUCTION

An induction motor also known as “asynchronous motor” is an ac electric motor in which the electric current flowing in the rotor windings produces torque which is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor can therefore be made without electrical connections to the rotor.

Three phase induction motors are the most popular type of ac motors and are widely used as industrial drives because of the following advantages:

a. Robust in construction

b. Reliable

c. Efficient

d. Economical

Single phase induction motors are used extensively for smaller loads such as household appliances like fan.

Although traditionally used in fixed speed service, induction motors are now increasingly being used with variable frequency drives (VFDs) in various variable speed applications.

VFDs offer especially important energy saving opportunities for existing and prospective induction motors in variable torque centrifugal fan, pumps, and compressor load applications.

2.2. CONSTRUCTION

A three phase induction motor essentially consists of two parts:-

a) The Stator
b) The Rotor

- ### The Stator:

The stator is the stationary part of an induction motor through which energy flows to the rotating part of the system. It is built up of high grade alloy steel laminations (to reduce eddy current losses) which are slotted on the inner periphery and are insulated from each other. They are supported on a stator frame of cast iron or fabricated steel plate. The insulated stator conductors are placed in these slots and the conductors are connected to form a three phase winding which may be either star or delta connected.

- **The Rotor:**

The rotor is the rotating part of an induction motor whose rotation is due to the interaction between the rotor windings and magnetic field produced in the stator which produces a torque around the rotor axis. It is also built up of thin laminations of the same material as stator. The laminated cylindrical core is mounted directly on the shaft or a spider carried by the shaft. These laminations are slotted on their outer periphery to receive the rotor conductors.

The induction motors are classified into types based on rotor construction:-

a) Squirrel cage rotor induction motor

b) Phase wound or slip ring induction motor

2.3. PRINCIPLE OF OPERATION

In a dc motor supply is needed to be given to the stator winding as well as the rotor winding. But in case of an induction motor only the stator winding is fed with an acsupply. When a three-phase balanced supply is given to the stator of an induction motor, a **rotating magnetic field (RMF)** of constant magnitude is produced. This rotating magnetic field rotates at a constant speed known as **synchronous speed**. The relative speed between stator RMF and rotor conductors causes an induced emf in the rotor conductors according to **"Faraday's laws of electromagnetic induction".** The rotor conductors are short circuited and hence rotor current is produced due to induced emf. That is why such motors are known as induction motors.

Now induced current in rotor will also produce alternating flux around it and this rotor flux lags behind the stator flux. The direction of induced rotor current, according to **Lenz's Law** is such that it will tend to oppose the cause of its production. As the cause of production of rotor current is the relative velocity between rotating stator flux and the rotor, the rotor will try to catch up with the stator RMF. Thus the rotor rotates in the same direction as that of stator flux to minimize the relative velocity. However, the rotor never succeeds in catching up the synchronous speed. This is the basic working principle of an induction motor.

2.4. SPEED AND SLIP

The rotational speed of the stator RMF is called as synchronous speed. However, an induction motor cannot run at the synchronous speed. Let us consider for a moment that the rotor is rotating at the synchronous speed. Under this condition, there would be no cutting of flux by the rotor conductors, and thus there would be no generated voltage, no current and hence no torque.

Hence, the rotor speed is slightly less than the synchronous speed. Thus an induction motor may also be called as “Asynchronous motor” as it does not run at the synchronous speed. The difference between the synchronous speed and the actual rotor speed is known as slip speed. Thus the slip speed express the speed of rotor relative to stator magnetic field.

If N_s = synchronous speed (rpm), then,

$$N_s = \frac{120f}{P} \quad (2.4.1)$$

Where, f= supply frequency

P= no of poles

If, Nr = actual rotor speed (rpm), then,

$$\text{Slip speed} \cong = \frac{N_s - N_r}{N_s} \text{ (p.u)} (2.4.2)$$

$$\text{Percentage slip} \cong = \frac{N_s - N_r}{N_s} \times 100 \quad (2.4.2)$$

2.5. TORQUE OF AN INDUCTION MOTOR

The developed torque or induced torque in an induction motor is actually the torque generated by the internal electromechanical power conversion. Hence the torque is also known as **electromagnetic torque.** The developed torque is given by-

$$\tau_d = \frac{Mechinacal\ power\ developed}{Mechanical\ angular\ Velocity\ of\ rotor} = \frac{P_{md}}{\omega_r} \quad (2.5.1)$$

Where, $P_{md} = (1 - s)P_g$(2.5.2)

$\omega_r = (1 - s)\omega_s$(2.5.3)

Hence, $\tau_d = \frac{P_g}{\omega_s}$ (2.5.4)

Where, P_g = air gap power

ω_s= synchronous speed

Hence, the electromagnetic torque of induction motor can be expressed as,

$$\tau_d = k\frac{sE_2^2R_2}{R_2^2+s^2X_2^2} \quad (2.5.5)$$

Where, $k = \frac{3}{2\pi N_s}$ = a constant

2.6. TORQUE-SLIP CHARACTERISTICS:

The torque-slip characteristics of an induction motor gives us the information about the variation of torque with slip. The variation of slip can be obtained with the variation of speed i.e, when speed varies the slip will also vary and the torque corresponding to that speed will also vary. The torque-slip characteristics curve can be divided roughly into three regions:-

1. Low slip region
2. Medium slip region
3. High slip region

The curve shown below shows the torque-slip characteristics of the induction motor:

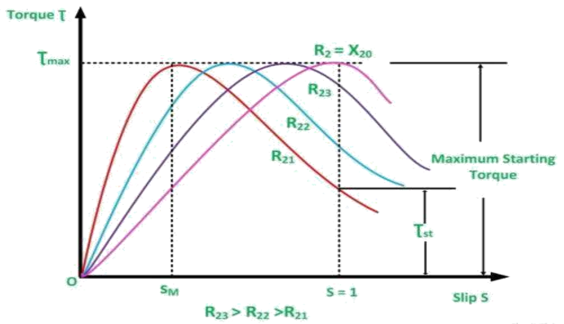


Fig.2.1. Torque-slip characteristics (Figure is taken from public domain)

2.7. TORQUE-SPEED CHARACTERISTICS

The torque speed characteristics of an induction motor are the curves plotted between the torque and speed of the induction motor. It is seen that although the maximum torque is independent of rotor resistance, yet the exact location of $\tau_{d\max}$ is dependent on it.Thus, greater the value of R_2 , greater is the value of slip at which maximum torque occurs. It is

also seen that as the rotor resistance is increased, the pull out speed of the motor decreases, but the maximum torque remains constant. The curve shown below represents the torque-speed characteristics.

Fig.2.2. Torque-speed characteristics (Figure is taken from public domain).

2.8. SPEED CONTROL OF INDUCTION MOTOR

A three phase induction motor is practically a constant speed motor. That means for the entire loading range change in the speed of motor is quite small. Hence, it is somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low power factor. The speed of rotor of an induction motor is given by-

$$N_r = (1-s)N_s \qquad (2.8.1)$$

Where, $N_s = \frac{120f}{P}$ (2.8.2)

$$\therefore N_r = \frac{120f}{P}(1-s) \qquad (2.8.3)$$

Hence, the various methods for the speed control of induction motor are-

(1) V/f control or frequency control

(2) Stator pole changing

(3) Variable supply voltage control

(4) Variable rotor resistance control

(5) Cascade control

(6) Slip power recovery

(7) Vector or field oriented control

2.9 CONCEPT OF INDUCTION MOTOR DRIVE

The control and estimation of induction motor drives constitute a vast subject and the technology has further advanced in recent years. Induction motor with cage type have been the work horses in industry for variable speed applications in a wide-power range that covers from fractional horsepower to multi-mega watts. These applications includes pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, machine tools and robotics, home appliances, heat pumps and air conditions, rolling mills, wind generation systematic. In addition to process control the energy saving aspect of variable frequency drives is getting a lot of attention nowadays.

The control and estimation of ac drives in general is more complex than those of ac drives and this complexity increases substantially if high performance are demanded. The main reason for this complexity are the need of variable frequency, harmonically optimum converter power supplies, the complex dynamics of a ac machines, machine parameter variations, and the difficulties of processing a feedback signals in the presence of harmonics. This technology has claimed to have nearly comparable performance with vector controlled drives. Recently, the scheme was introduced in commercial products by a major company and therefore created wide interest. Direct torque and flux control is a very efficient control technique of induction motor drives.

2.10. OVERVIEW OF DIRECT TORQUE CONTROL

In the mid-1980s, an advanced scalar control technique, known as direct torque and flux control (DTFC OR DTC) or direct self-control (DSC) was introduced for voltage fed PMW induction motor drives. The technique has claimed to have nearly comparable performance with vector controlled drives. Recently the scheme was introduced in commercial products by a major company and therefore created wide interest.The scheme as the name indicates, is the direct control of the torque and stator flux of a drive by inverter voltage space vector selection through a look-up table. Firstly a torque expression has been developed as a function of the stator and rotor fluxes, before explaining the control principle of DTC.

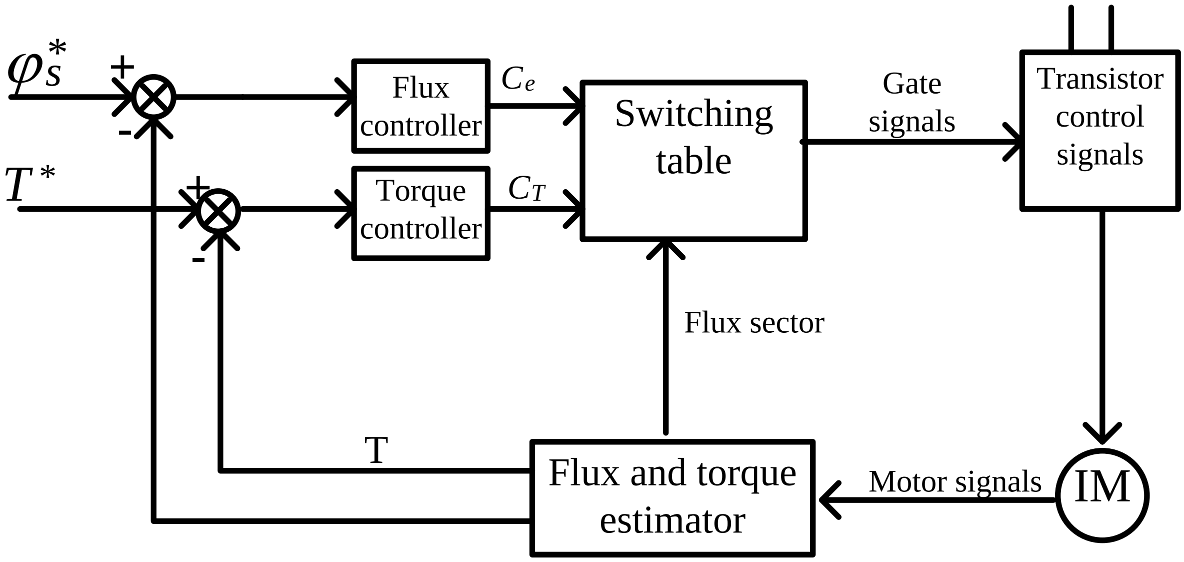


Figure 2.3: An overview of direct torque control scheme.

2.11. TORQUE EXPRESSION WITH STATOR AND ROTOR FLUXES

The torque expression can be expressed in vector forms as,

$$\overrightarrow{T_e} = \frac{3}{2}\left(\frac{P}{2}\right)\overrightarrow{\varphi_s}\,\mathrm{X}\overrightarrow{I_s} \qquad (2.11.1)$$

Where, φ_s= stator flux

$I_{s=}$ Stator current

And, $\overrightarrow{\varphi_s}$= φ_{qs}^s-jφ_{ds}^s and $\overrightarrow{I_s}$= i_{qs}^s-ji_{ds}^s. In that equation $\overrightarrow{I_s}$ is to be replaced by rotor flux $\overrightarrow{\varphi_r}$. In the complex form of $\overrightarrow{\varphi_s}$ and $\overrightarrow{\varphi_r}$ can be expressed as a function of currents as-

$$\overrightarrow{\varphi_s} = L_s\overrightarrow{I_s} + L_m\overrightarrow{I_r} \qquad (2.11.2)$$

$$\overrightarrow{\varphi_r} = L_r\overrightarrow{I_r} + L_m\overrightarrow{I_s} \qquad (2.11.3)$$

Eliminating $\overrightarrow{I_r}$ from equation (2.11.2), we get,

$$\overrightarrow{\varphi_s} = \frac{L_m}{L_r}\overrightarrow{\varphi_r}L_s'\overrightarrow{I_s} \qquad (2.11.4)$$

Where, L_s' = $L_sL_r - L_m^2$.

The corresponding expression of $\overrightarrow{I_s}$ is,

$$\overrightarrow{I_s} = \frac{1}{L_s'}\overrightarrow{\varphi_s} - \frac{L_m}{L_rL_s'}\overrightarrow{\varphi_r} \qquad (2.11.5)$$

Substituting equation (2.11.5) in equation (2.11.1) and simplifying yields,

$$\overrightarrow{T_e} = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_rL_s'}\overrightarrow{\varphi_r} \times \overrightarrow{\varphi_s} \qquad (2.11.6)$$

So, the magnitude of torque is,

$$\overrightarrow{T_e} = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_rL_s'}|\varphi_r||\varphi_s|\sin\gamma \qquad (2.11.7)$$

Where γ is the angle between the fluxes.Figure () shows the phasor (or vector) diagram for equation

(2.11.6), indicating the vectors $\overrightarrow{\varphi_s}$,$\overrightarrow{\varphi_r}$ and $\overrightarrow{I_s}$ for the positive developed torque. If the rotor flux remains constant and the rotor flux is changed incrementally by stator voltage $\overrightarrow{V_s}$ as shown and the corresponding change of γ angle is $\Delta\gamma$,the incremental torque $\Delta\overrightarrow{T_e}$ can be expressed by,

$$\overrightarrow{T_e} = \frac{3}{2}\left(\frac{P}{3}\right)\frac{L_m}{L_r L_s'}|\overrightarrow{\varphi_r}||\overrightarrow{\varphi_s} + \Delta\overrightarrow{\varphi_s}| \sin\Delta\gamma \qquad (2.11.8)$$

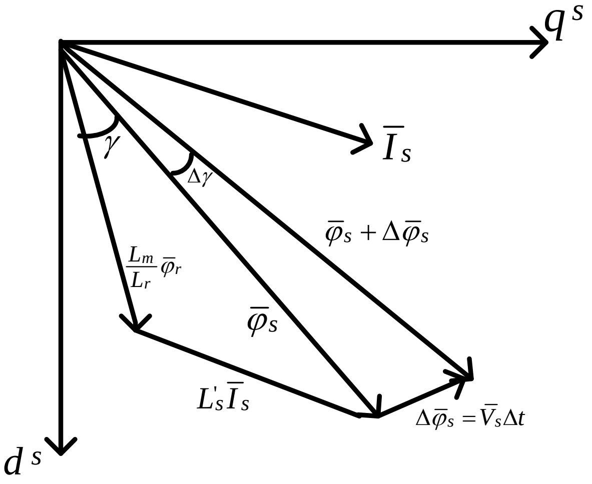


Figure.2.4.stator flux, rotor flux and stator current vectors on $d^s - q^s$ plane.

(stator resistant is neglected)

2.12. CONTROL STRATEGY OF DTC

The block diagram of direct torque and flux control is shown in figure (2.5) and figure (2.6) explain the control strategy.Any variation of the stator flux space vector leads to a variation of the torquedue to both the amplitude variation and the phase angle variation between the stator and rotor flux space vectors.

The switching configuration selection block set the state of the inverter switches on the basics of the instantaneous error of torque ΔT and flux $\Delta\varphi$. With the switching table strategy, inverter voltage space vector is selected for each sampling period- in order to maintain the torque and stator flux amplitude within the limits of two hysteresis band. The selection is carried out on the basics of the error in the torque and in the stator flux.

The speed control loop and the flux program as a function of speed as shown as usual and will not be discussed. The command stator flux $\overrightarrow{\varphi_s^*}$ and torque $\overrightarrow{T_e^*}$magnitudes are compared with the respective estimated values, and the errors are processed through hysteresis band and controllers as shown

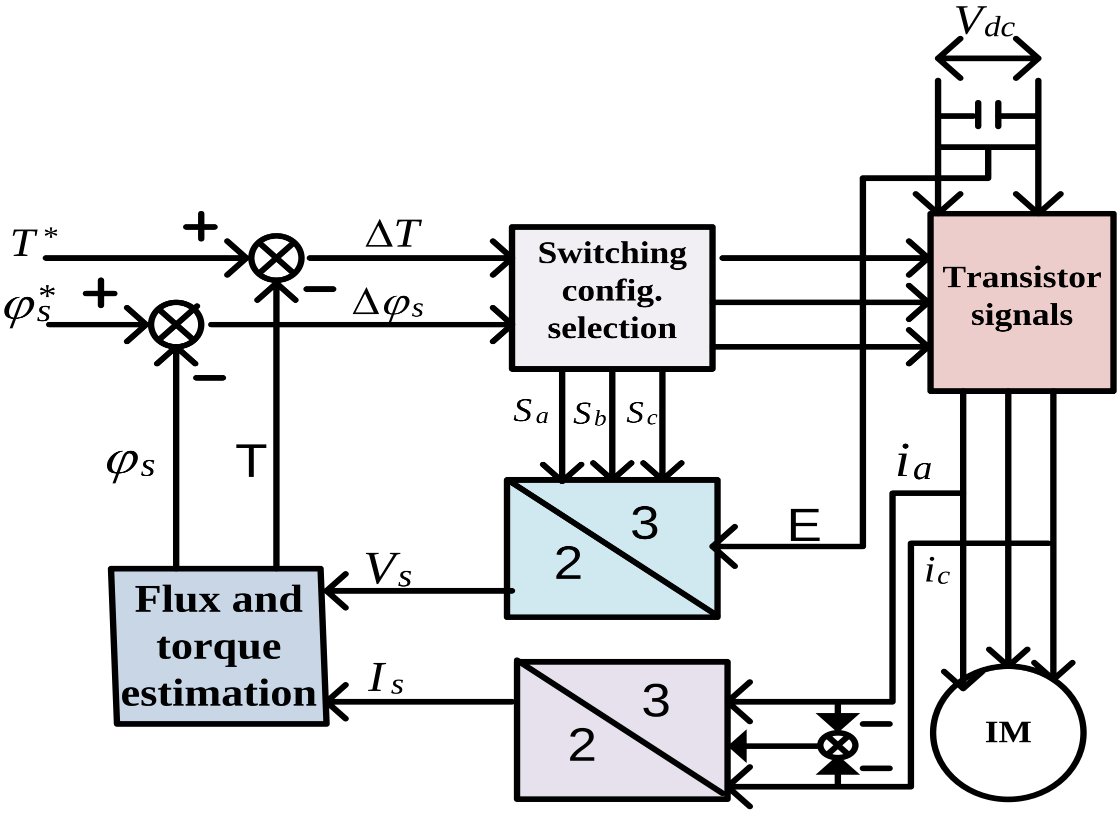


Figure 2.5 Direct torque and flux control block diagram.

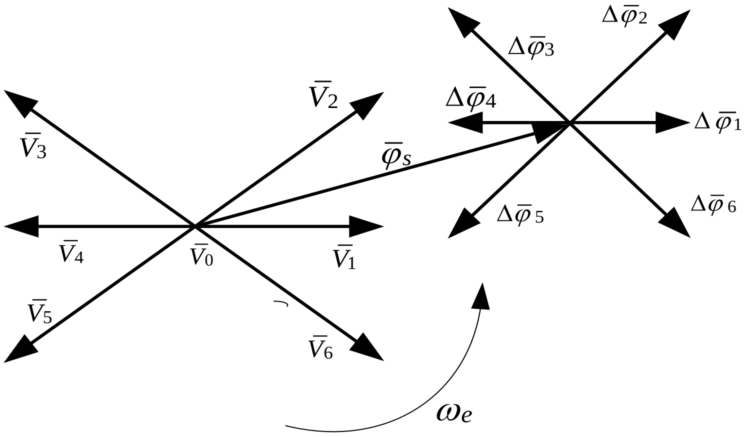


Figure.2.6.Inverter voltage vector and corresponding stator flux variation in time Δt.(taken from public domain).

here are some circumstances which should be noted,

- In order to increase the magnitude of voltage space vector $\overrightarrow{V_1}$, $\overrightarrow{V_2}$ and $\overrightarrow{V_6}$ can be selected.
- Conversely, the decrement of stator flux can be obtained by selecting $\overrightarrow{V_3}$, $\overrightarrow{V_5}$ and $\overrightarrow{V_4}$.
- The voltage space vectors are utilized to control the stator flux which also affects the torque.

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

Figure.2.7.Flux and torque variations due to applied voltage vector in figure.2.6.

(arrow indicates magnitude and directions)

The torque response of the drive is claimed to be comparable with that of a vector controlled device.The feedback flux and torque are calculated from the machine termial voltages and currents.There are a few special features of DTC control that can be summerized as follows,

1. No feedback current control.
2. No traditional PWM algorithm is applied.
3. No vector transformation as in vector control.
4. Feedback signal processing is somewhat similar to stator flux oriented vector control.
5. Hysterisis-band control generates flux and torque ripple and switching frequency is not constant(like hysterisis-band current control).

2.13.IMPLEMENTATION OF MODIFIED DTC METHOD

Let, $\psi_{rd},\hat{\psi}_{rd}$ = measured and estimated value of rotor flux respectively along d-axes.

$\psi_{rq},\hat{\psi}_{rq}$ = measured and estimated value of rotor flux respectively along q-axes.

$\psi_{r},\hat{\psi}_{r}$ = measured and estimated value of total rotor flux respectively.

$\tau_{e},\hat{\tau}_{e}$ = measured and estimated value of electromagnetic torque respectively.

$\omega_{r},\hat{\omega}_{r}$ =actual and estimated value of rotor speed respectively.

- **MATHEMATICAL EXPRESSION OF ψ_{rd} & ψ_{rq}**

We know from basic theory of induction motor,

$$\psi_r = L_r I_r + L_m I_s \qquad (2.13.1)$$

And, $$\psi_s = L_s I_s + L_m I_r \qquad (2.13.2)$$

$$\therefore I_r = \frac{\psi_s - L_s I_s}{L_m} \qquad (2.13.3)$$

Now putting the value of I_r in the equation (4.1) we obtain-

$$\psi_r = \frac{L_r}{L_m}(\psi_s - L_s I_s) + L_m I_s$$

$$\psi_r = \frac{L_r}{L_m}[\psi_s - (1 - \frac{L_m^2}{L_s L_r}) L_s I_s]$$

Or, $$\psi_r = \frac{L_r}{L_m}(\psi_s - \sigma L_s I_s) \qquad (2.13.4)$$

Hence, ψ_{rd} & ψ_{rq} can be expressed as,

$$\psi_{rd} = \frac{L_r}{L_m}(\psi_{sd} - \sigma L_s I_{sd}) \qquad (2.13.5)$$

$$\psi_{rq} = \frac{L_r}{L_m}(\psi_{sq} - \sigma L_s I_{sq}) \qquad (2.13.6)$$

MATHEMATICAL EXPRESSION OF $\hat{\psi}_{rd}$ & $\hat{\psi}_{rq}$

From theory of vector control of induction motor,

$$R_r I_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} = 0 \qquad (2.13.7)$$

And, $$R_r I_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} = 0 \qquad (2.13.8)$$

Also from equation (4.1) we can write-

$$I_r = \frac{\psi_r - L_m I_s}{L_r} \qquad (2.13.9)$$

Hence we can express I_{rd} & I_{rq} as-

$$I_{rd} = \frac{\psi_{rd} - L_m I_{sd}}{L_r} \qquad (2.13.10)$$

$$I_{rq} = \frac{\psi_{rq} - L_m I_{sq}}{L_r} \qquad (2.13.11)$$

Substituting value of I_{rd} in equation (4.1) we obtain,

$$\frac{R_r}{L_r}(\psi_{rd} - L_m I_{sd}) + \frac{d\psi_{rd}}{dt} - \omega_r \psi_{rq} = 0$$

$$\therefore \frac{d\psi_{rd}}{dt} = \frac{L_m}{T_r} I_{sd} - \frac{1}{T_r}\psi_{rd} + \omega_r \psi_{rq} \quad (2.13.12)$$

Similarly, $\frac{R_r}{L_r}(\psi_{rq} - L_m I_{sq}) + \frac{d\psi_{rq}}{dt} + \omega_r \psi_{rd} = 0$

$$\therefore \frac{d\psi_{rq}}{dt} = \frac{L_m}{T_r} I_{sq} - \frac{1}{T_r}\psi_{rq} - \omega_r \psi_{rd} \qquad (2.13.13)$$

Hence the estimated quantities of rotor flux be expressed as –

$$\hat{\psi}_{rd} = \int \left(\frac{L_m}{T_r} I_{sd} - \frac{1}{T_r}\hat{\psi}_{rd} - \hat{\omega}_r \hat{\psi}_{rq}\right) dt \qquad (2.13.14)$$

$$\hat{\psi}_{rq} = \int \left(\frac{L_m}{T_r} I_{sq} - \frac{1}{T_r}\hat{\psi}_{rq} - \hat{\omega}_r \hat{\psi}_{rd}\right) dt \qquad (2.13.15)$$

- **MATEMATICAL EXPRESSION OF τ_e & $\hat{\tau}_e$**

The electromagnetic torque in terms of d & q axes components can be expressed as-

$$\tau_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r}\left(I_{sq}\psi_{rd} - I_{sd}\psi_{rd}\right) \qquad (2.13.16)$$

Hence the estimated value of electromagnetic torque in terms of d & q axes-

$$\hat{\tau}_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\frac{L_m}{L_r}\left(I_{sq}\hat{\psi}_{rd} - I_{sd}\hat{\psi}_{rd}\right) \qquad (2.13.17)$$

Chapter-3

Proposed work

3.1.INTRODUCTION

The simulation is one of the key steps in the validation of the deign process of the motor drive system, which eliminate the desigining mistakes and the resulting errors in the prototype construction and testing. The model of induction motor in direct and quadrature axes can be derived from fundamental equations of transformations. The analysis of symmetrical induction motor in an arbitrary reference frame has been intensively used as a standard simulation approach from which any particular mode of operation may be developed.

Matlab/Simulink has an advantage over other machine simulators in modeling the induction motors. Generally modeling of these equations is considered difficult but in this paper they are presented in their simplified form. The transformations used at various steps are based on simple trigonometric relationships obtained as projections on a set of axes. The model is used to obtain transient responses, small signal equations, and a transfer function of induction motor. The mathematical modeling of induction motor are done in order to have a better understanding of the behavior of induction motor in both transient and steady state.

The mathematical modeling sets all the mechanical equations for torque and speed versus time. It also models all the differential voltage, current and flux linkages between the stationary stator and the moving rotor. This mathematical model has been done by using Matlab/Simulink which represents the three-phase induction motor including a three phase to d-q axes transformation. The main advantages of using Matlab/Simulink is that the electromechanical model can be accomplished in a simple way and it can be simulated faster using simulation blocks.

3.2. MODELLING OF 3-PHASE DTC INDUCTION MOTOR IN MATLAB

Here we use DTC Induction motordrive from mathworks which consists various circuits and parameters. Basically this high level schematic is built from six main blocks. The induction motor, the three phase inverter and the three phase diode rectifier models are provided with the simpscape power system library from matlab. We also use the speed controller, braking chopper and other dtc controller models.

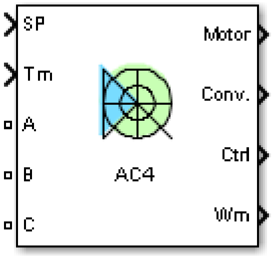


Figure.3.1. DTC induction motor drive from matlab

The DTC Induction Motor Drive (AC4) block represents an improved scalar control drive for induction motors with direct torque and flux control. This drive features closed-loop speed control using hysteresis-band torque and flux controllers. The speed control loop outputs the reference electromagnetic torque and stator flux of the machine. The torque and flux references are compared with their estimated values, respectively, and the errors are fed to hysteresis-band controllers. The outputs of the hysteresis-band controllers are then used to obtain the required gate signals for the inverter through an optimal switching table.

The main advantage of this drive compared to other scalar-controlled drives is its improved dynamic response. This drive can reduce the impact of torque variation on the flux and conversely through an optimal switching table. Therefore, this drive is less sensitive to the inherent coupling effect (between the torque and flux) present in the machine. However, this drive requires similar signal processing as in vector-controlled drives, which makes its implementation complex compared to closed-loop Volts/Hertz controlled drives.

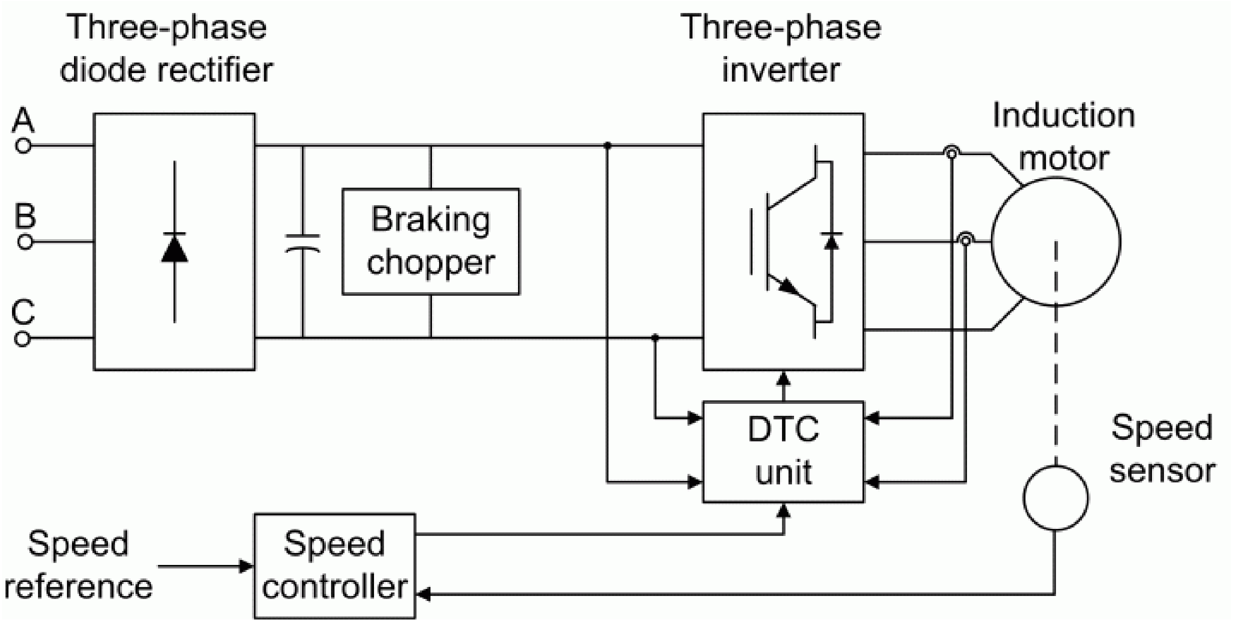


Figure.3.2. High-level schematic diagram of DTC induction motor drive

3.2.1.CONTROLLERS OF DTC INDUCTION MOTOR DRIVE

The DTC induction motor drive block uses three blocks from electric drive-

- Speed controller(AC)
- Direct torque controller
- DC bus
- Inverter(three-phase)

This model is discrete. Good simulation result have been obtained with a 2 μs time step. In order to simulate a digital controller device, the control system has two different sampling time-

- The speed controller sampling time
- The DTC controller sampling time

The speed controller sampling time has to be a multiple of DC sampling time. The latter sampling time has to be a multiple of the simulation time step. The simulink schematic diagram looks like-

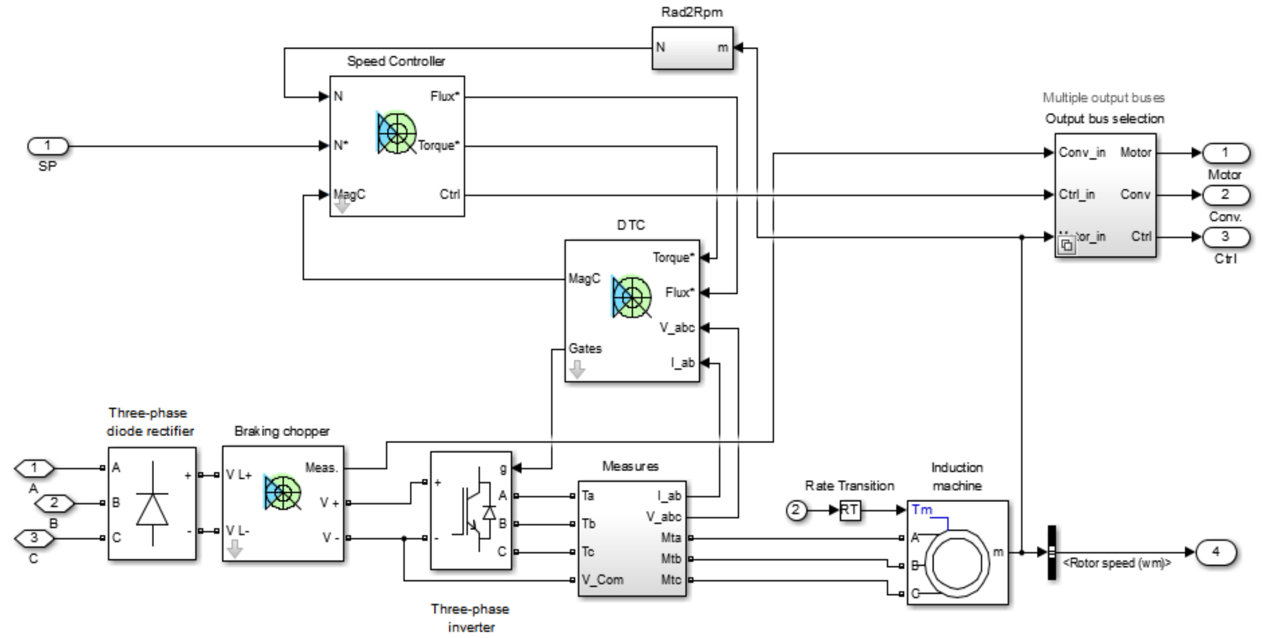


Figure.3.3.Simulink schematic diagram of DTC induction motor drive

From the diagram we can see that DTC induction motor is made of three major sections. Such as-speed controller, DTFC controller and braking chopper.

- **Speed controller**

The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the DTC controller block.

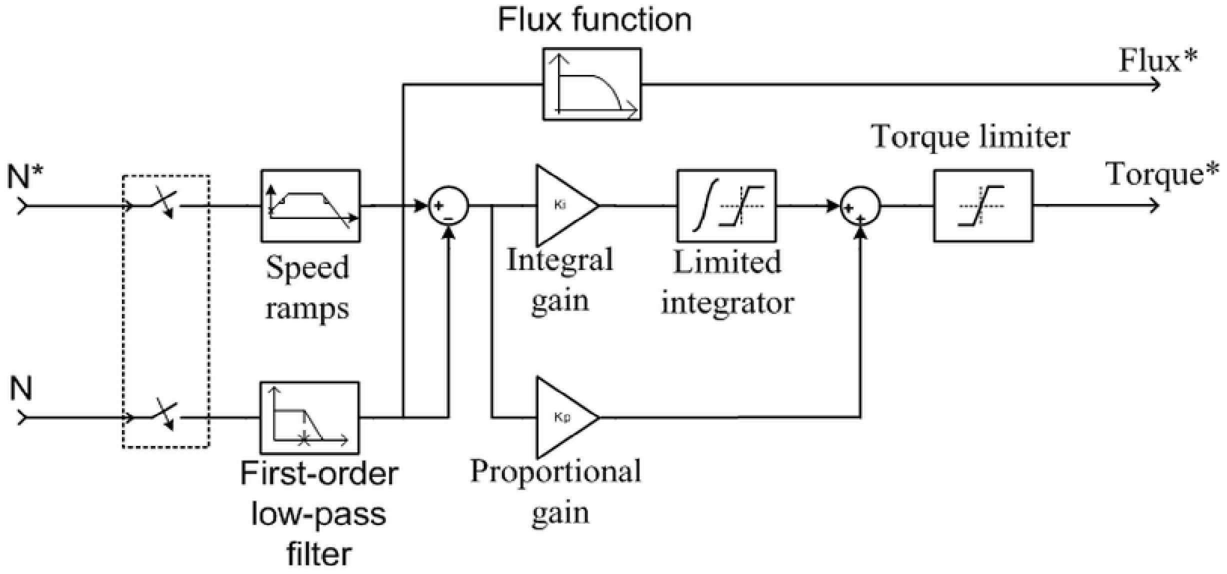


Figure.3.4.Schematic block diagram of speed controller.

- **DTFC controller**

The Direct Torque and Flux Control (DTFC) controller contains five main blocks, shown below. These blocks are described below.

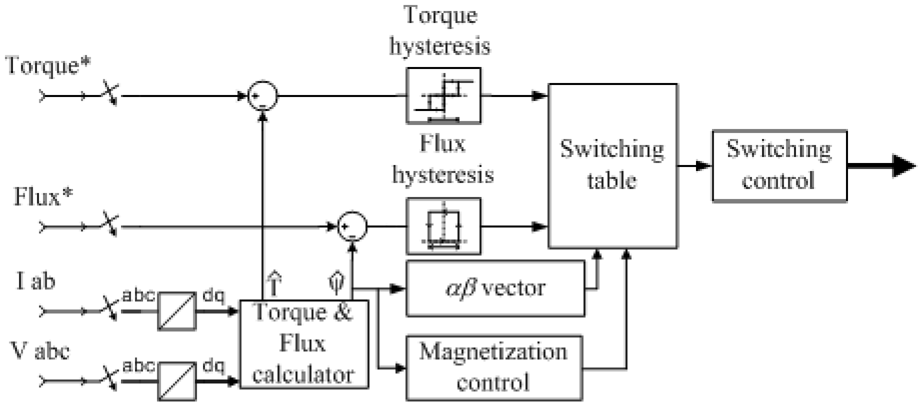


Figure.3.5.Schematic block diagram of DTFC controller.

The Torque & Flux calculator block is used to estimate the motor flux αβ components and the electromagnetic torque. This calculator is based on motor equation synthesis.

The *αβ* vector block is used to find the sector of the αβ plane in which the flux vector lies. The αβ plane is divided into six different sectors spaced by 60 degrees.

The Flux & Torque Hysteresis blocks contain a two-level hysteresis comparator for flux control and a three-level hysteresis comparator for the torque control. The description of the hysteresis comparators is available below.

The Switchingtable block contains two lookup tables that select a specific voltage vector in accordance with the output of the Flux & Torque Hysteresis comparators. This block also produces the initial flux in the machine.

The Switching control block is used to limit the inverter commutation frequency to a maximum value specified by the user.

- **Braking chopper**

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration.

3.2.2.DIALOG BOX

Dialog box in which we put the respective values of controller parameters can be briefly categorized into three groups-

- Asynchronous machine tab
- Converters and DC bus tab
- Controller tab

We will discuss about the parameters and features of these three tabs,

- **ASYNCHRONOUS MACHINE TAB**

The Asynchronous Machine tab displays the parameters of the Asynchronous Machine block of the Fundamental Blocks library.

1. **Output bus mode**

   Select how the output variables are organized. If you select **Multiple output buses**, the block has three separate output buses for motor, converter, and controller variables. If you select **Single output bus**, all variables output on a single bus.

2. **Mechanical input**

   Select between the load torque, the motor speed, and the mechanical rotational port as mechanical input. If you select and apply a load torque, the output is the motor speed according to the following differential equation that describes the mechanical system dynamics:

$$T_e = J\frac{d}{dt}\omega_r + F\omega_r + T_m \tag{3.1}$$

   This mechanical system is included in the motor model.

If you select the motor speed as mechanical input, then you get the electromagnetic torque as output, allowing you to represent externally the mechanical system dynamics. The internal mechanical system is not used with this mechanical input selection and the inertia and viscous friction parameters are not displayed.

For the mechanical rotational port, the connection port S counts for the mechanical input and output. It allows a direct connection to the simscape environment. The mechanical system of the motor is also included in the drive and is based on the same differential equation

- **CONVERTERS AND DC BUS TAB**

Converters and dc bus tab can be discussed in different sections,

1. **Rectifier Section**

The rectifier section of the Converters and DC Bus tab displays the parameters of the rectifier block of the Fundamental Blocks library.

2. **Inverter Section**

The inverter section of the Converters and DC Bus tab displays the parameters of the Inverter block of the Fundamental Blocks library.

3. **DC-Bus Capacitance**

The DC bus capacitance (F).

4. **Braking Chopper section: Resistance**

The braking chopper resistance used to avoid bus over-voltage during motor deceleration or when the load torque tends to accelerate the motor (Ω).

5. **Braking Chopper section: Frequency**

The braking chopper frequency (Hz).

6. **Braking Chopper section: Activation Voltage**

The dynamic braking is activated when the bus voltage reaches the upper limit of the hysteresis band. The following figure illustrates the braking chopper hysteresis logic.

7. Braking Chopper section: Shutdown Voltage

The dynamic braking is shut down when the bus voltage reaches the lower limit of the hysteresis band. The Chopper hysteresis logic is shown below:

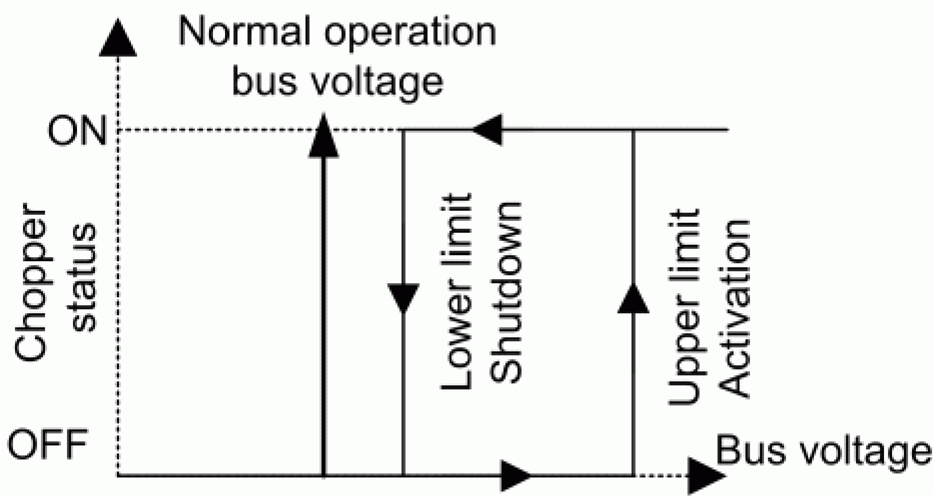


Figure.3.6.Hysterisis logic in braking chopper.

- **CONTROLLER TAB**

I. Regulation type

This parameter allows you to choose between speed and torque regulation.

II. Schematic

When you press this button, a diagram illustrating the speed and current controllers schematics appears.

III. Speed Controller section

I. Speed cut-off frequency

The speed measurement first-order low-pass filter cut off frequency (Hz). This parameter is used in speed regulation mode only.

II. Speed controller sampling time

The speed controller sampling time (s). The sampling time must be a multiple of the simulation time step.

III. Speed Ramps — Acceleration

The maximum change of speed allowed during motor acceleration (rpm/s). An excessively large positive value can cause DC bus under-voltage. This parameter is used in speed regulation mode only.

IV. Speed Ramps — Deceleration

The maximum change of speed allowed during motor deceleration (rpm/s). An excessively large negative value can cause DC bus overvoltage. This parameter is used in speed regulation mode only.

V. PI Regulator — Proportional Gain

The speed controller proportional gain. This parameter is used in speed regulation mode only.

VI. PI Regulator — Integral Gain

The speed controller integral gain. This parameter is used in speed regulation mode only.

VII. Torque output limits — Negative

The maximum negative demanded torque applied to the motor by the current controller (N.m).

VIII. Torque output limits — Positive

The maximum positive demanded torque applied to the motor by the current controller (N.m)

IV. DTC Controller Section

I. Maximum switching frequency

The maximum inverter switching frequency (Hz).

II. Initial machine flux

The desired initial stator flux established before the DTC drive module begins to produce an electromagnetic torque. This flux is produced by applying a constant voltage vector at the motor terminals (Wb).

III. DTC sampling time

The DTC controller sampling time (s). The sampling time must be a multiple of the simulation time step.

IV. Hysteresis bandwidth — Torque

The torque hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the torque set point (N.m). The following figure illustrates a case where the torque set point is $T_e^*$and the torque hysteresis bandwidth is set to dT_e.

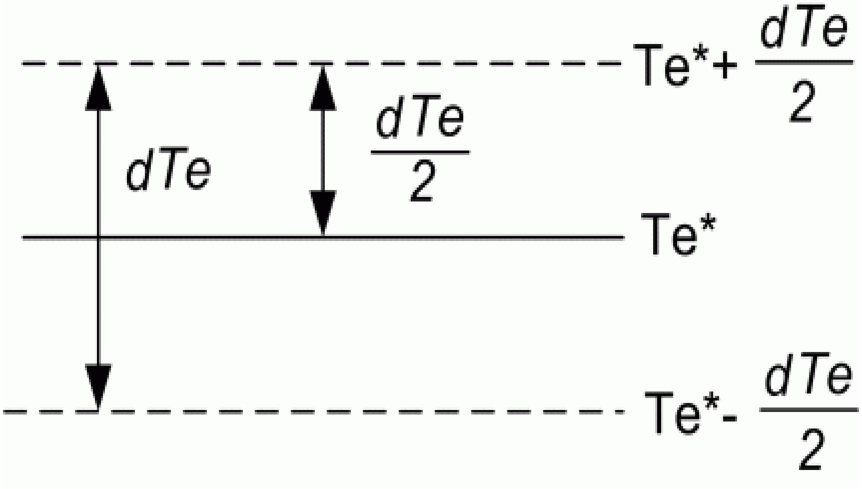


Figure.3.7.Hysteresis bandwidth(torque)

V. Hysteresis bandwidth — Flux

The stator flux hysteresis bandwidth. This value is the total bandwidth distributed symmetrically around the flux set point (Wb). The following figure illustrates a case where the flux set point is ψ^* and the torque hysteresis bandwidth is set to dψ.

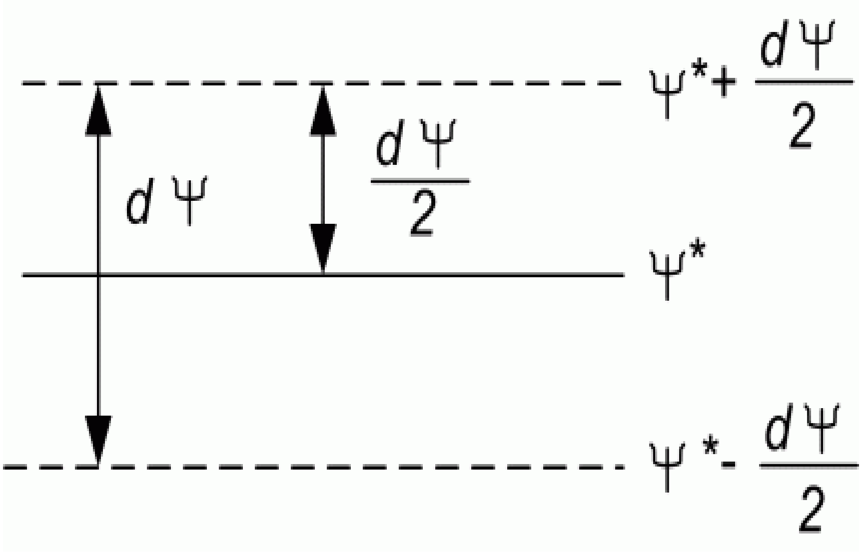
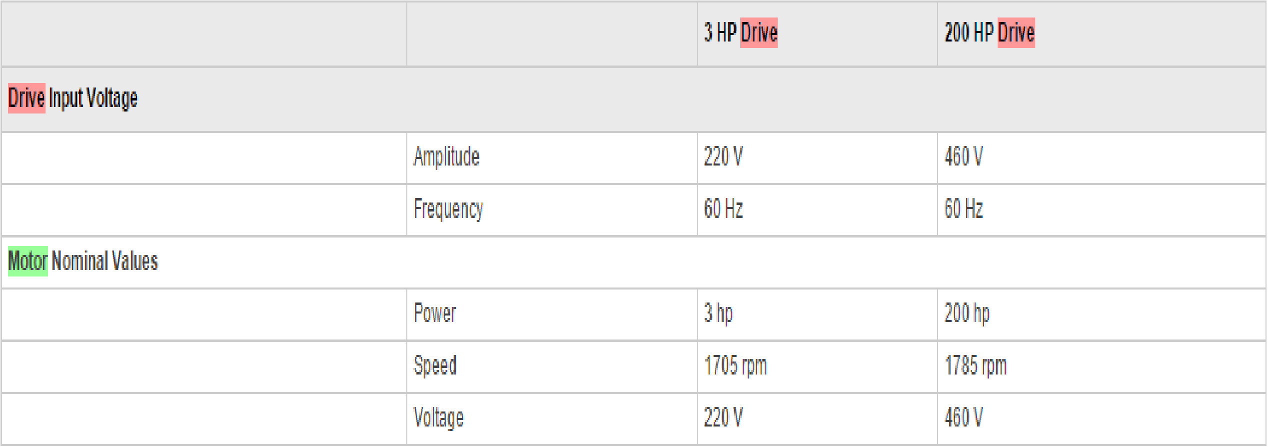


Figure.3.8.Hysteresis bandwidth(flux)

3.2.3.MODEL SPECIFICATION

The library contains a 3 hp and a 200 hp drive parameter set. The specifications of these two drives are shown in the following table.

Drive Specifications



		3 HP Drive	200 HP Drive
Drive Input Voltage			
	Amplitude	220 V	460 V
	Frequency	60 Hz	60 Hz
Motor Nominal Values			
	Power	3 hp	200 hp
	Speed	1705 rpm	1785 rpm
	Voltage	220 V	460 V

An example has been considered in whichAt time t = 0 s, the speed set point is 500 rpm. As shown in the following figure, the speed precisely follows the acceleration ramp. At t = 0.5 s, the nominal load torque is applied to the motor. At t = 1 s, the speed set point is changed to 0 rpm. The speed decreases to 0 rpm. At t = 1.5 s., the mechanical load passes from 792 N.m to −792 N.m.

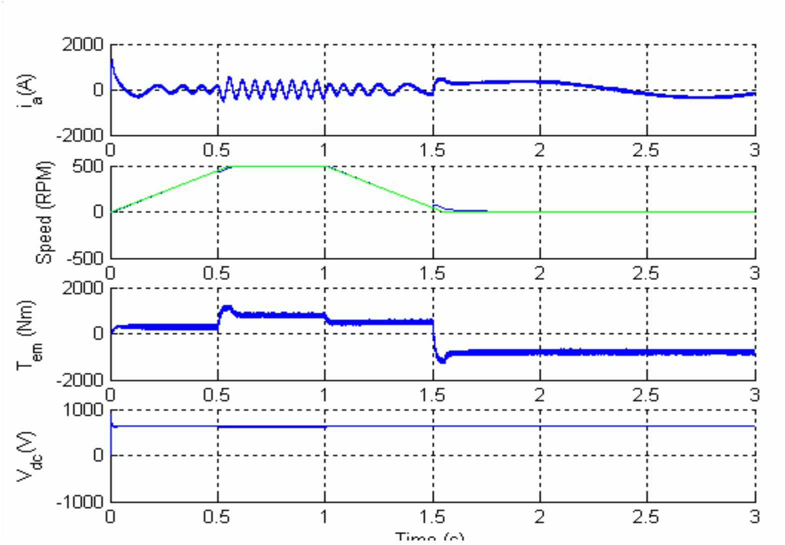


Figure.3.9.Difference in speed, torque, current and dc voltage with respect to time.

3.3.MATLAB MODULATION WITH DTC INDUCTION MOTOR DRIVE

In the SP (speed and torque set point) input and the load torque Tm, which is a mechanical input of DTC induction motor drive, a **stair generator** has been putted. In the 1st stair generator which is putted in the SP port, the value of amplitude is 500 and it will be operated at 0 second. In the 2nd stair generator which is putted in the Tm port, the value of amplitudes are 0, 792,-792 and it will be calculated at 0, 0.5,1.5 seconds.

A three phase source is connected to the three phase terminal of the motor drive. On the other hand in motor port which is motor measurement vector, a dc bus is connected in which there are seven measuring parameters are connected. They are stator current for three different phases, mechanical rotor speed, mechanical electromagnetic torque, stator flux in d-q phases. Stator fluxes of d-q planes are connected together with an x-y graph and also they are put together in the scope to measure the stator flux waveform. Stator currents of different phases are put together to measure the three phase current waveform from the scope. Rotor speed along with the gain is connected to a dc bus with the ctrl port of DTC induction motor drive and the bus’s output is connected to the scope to measure the waveform of the rotor speed. The electromagnetic torque waveform is also measured by the same process. DC bus voltage waveform can also be seen from the conv. port of DTC induction motor drive. A terminator is connected to the Wm port which is a mechanical output port.

3.4.INDUCTION MOTOR SPECIFICATIONS

DC bus voltage(V)	700
Motor Voltage(V)	460
Power(KW)	150
Frequency(Hz)	60
Phase	3
Pole	4
Stator resistance(ohm)	$14.85e^{-3}$
Rotor resistance(ohm)	$9.295e^{-3}$
Leakage inductance(H)	$0.3027e^{-3}$
Mutual inductance(H)	$10.46e^{-3}$
Type	Squirrel cage
DC bus capacitance	$7500e^{-6}$

Figure.3.11.Matlab modulation of DTC induction motor drive without load.

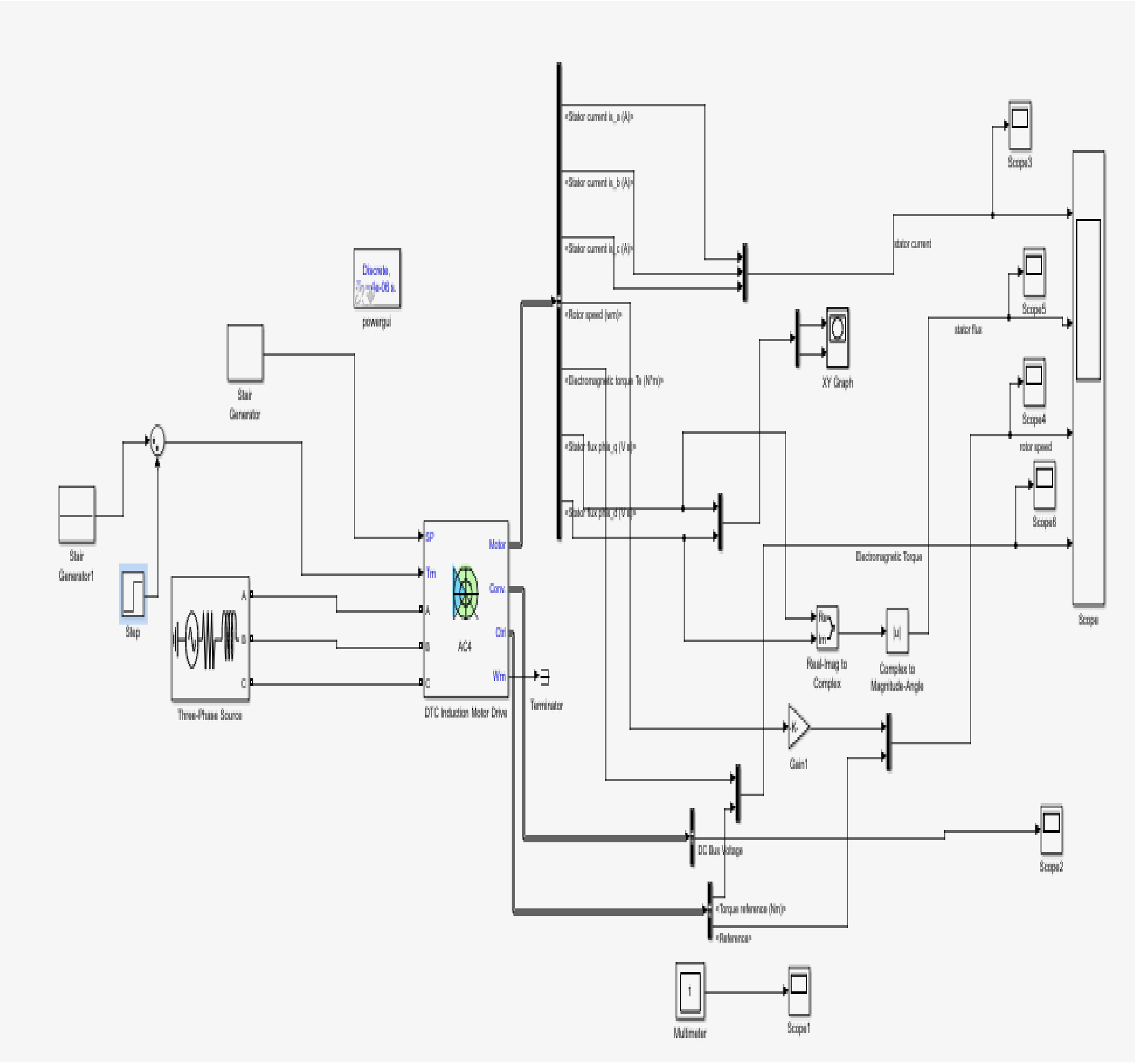


Figure.3.12.Matlab modulation of DTC induction motor drive with load.

Chapter-4

Simulation results

4.1.INTRODUCTION

Field oriented or vector control of induction motors have been widely used in high performance ac drives. To orient the injected stator current vector and to establish speed loop feedback, a knowledge of rotor speed is necessary in these applications. The speed estimate is mandatory when feedback is employed and also when decoupling is intended in the current regulation loops of the synchronous reference frame.

Another control technique for induction motor drivesfor an excellent performance, known as direct torquecontrol (DTC) was introduced more than a decade ago. Nowadays, speed control of induction motor drives usingdirect torque control(DTC) method have become increasinglypopular in the industrial drives due to the simplicity in controlstructure and high dynamic performance of instantaneouselectromagnetic torque. Since DTC for induction motor wasintroduced in 1980’s, Field Orientation Control and DirectTorque Control methods are most popular for electric machine vectors control methods.

The main disadvantages of FieldOrientation Control method is high dynamic performance,switching frequency, low torque ripples and maximumfundamental component of stator current, but field orientedcontrol method suffer severe disadvantages. i.e. requirementof two co-ordinate transformations and current controllers,high machine parameter sensitivity. Comparing with field
Orientated control, DTC has very simple control scheme andalso less computational requirements.

In case of Direct Torque Control method, current controller and coordinate transformations are not required. The operation of the conventional DTC is very simple but it produce high ripple in torque do to the non-linear hysteresis controllers. Sampling frequency of conventional DTC is

4.2.WAVEFORM OF MATLAB MODEL

The waveform of three-phase currents, rotor speed, stator flux and electromagnetic torque can be shown from the graph obtained from matlab simulation model. This experiment is done in two different speed like 1000 rpm and 100 rpm. So the shape of waveformof low speed region can be easily compared to that of the high speed region.

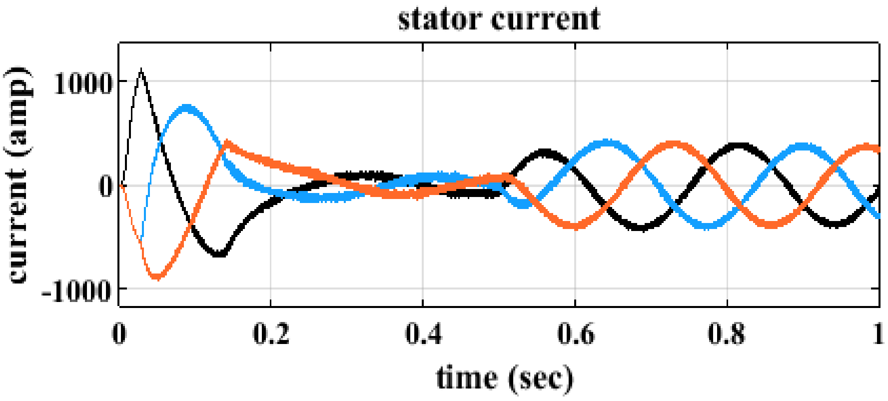


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Figure.4.1.stator currents of three phase induction motor drive at 100 rpm.

[y axis-current (1 unit of y axis = 500A),

X axis- time (1 unit of y axis =0.5 sec)]

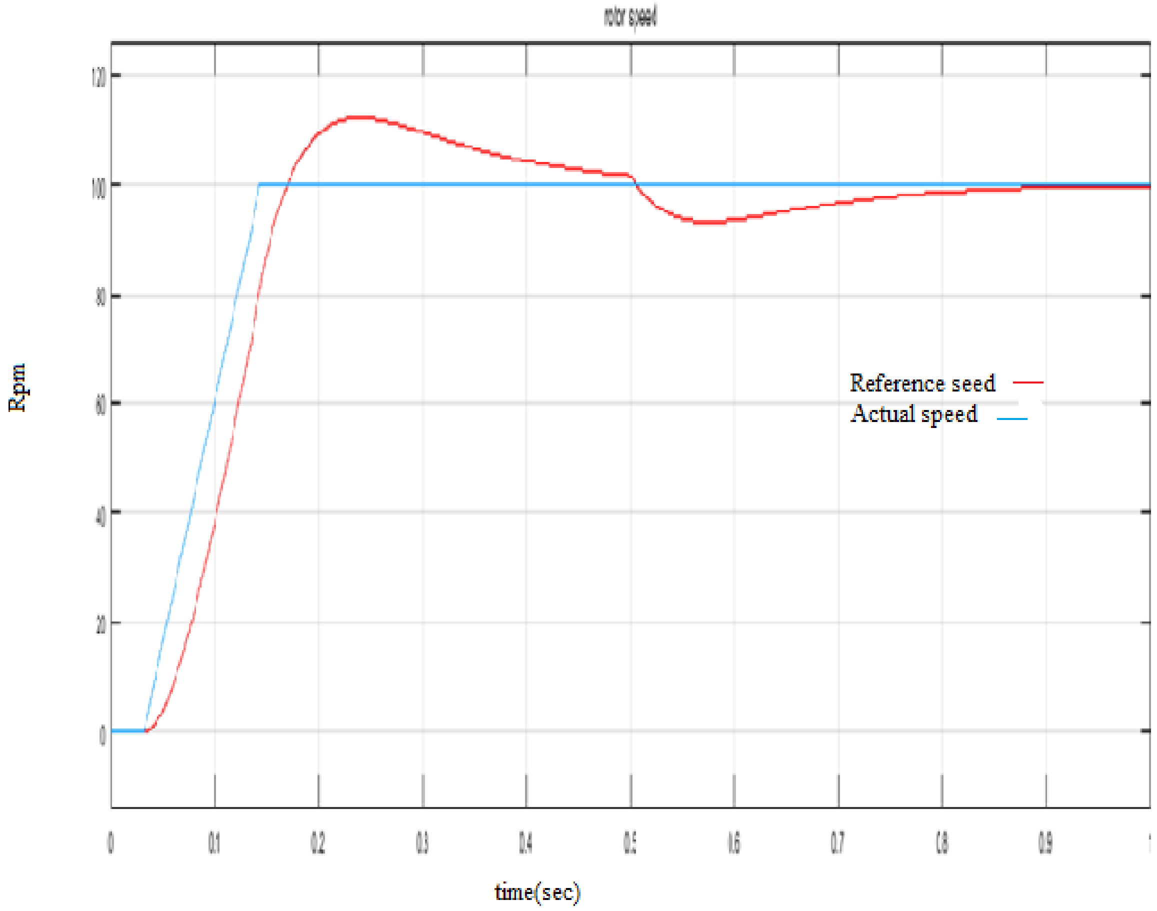

Figure.4.2.Waveform of rotor speed of induction motor drive at 100 rpm.

[y axis- voltage(1 unit of voltage = 100V),

x axis – time(1 unit of time= 0.1sec)]

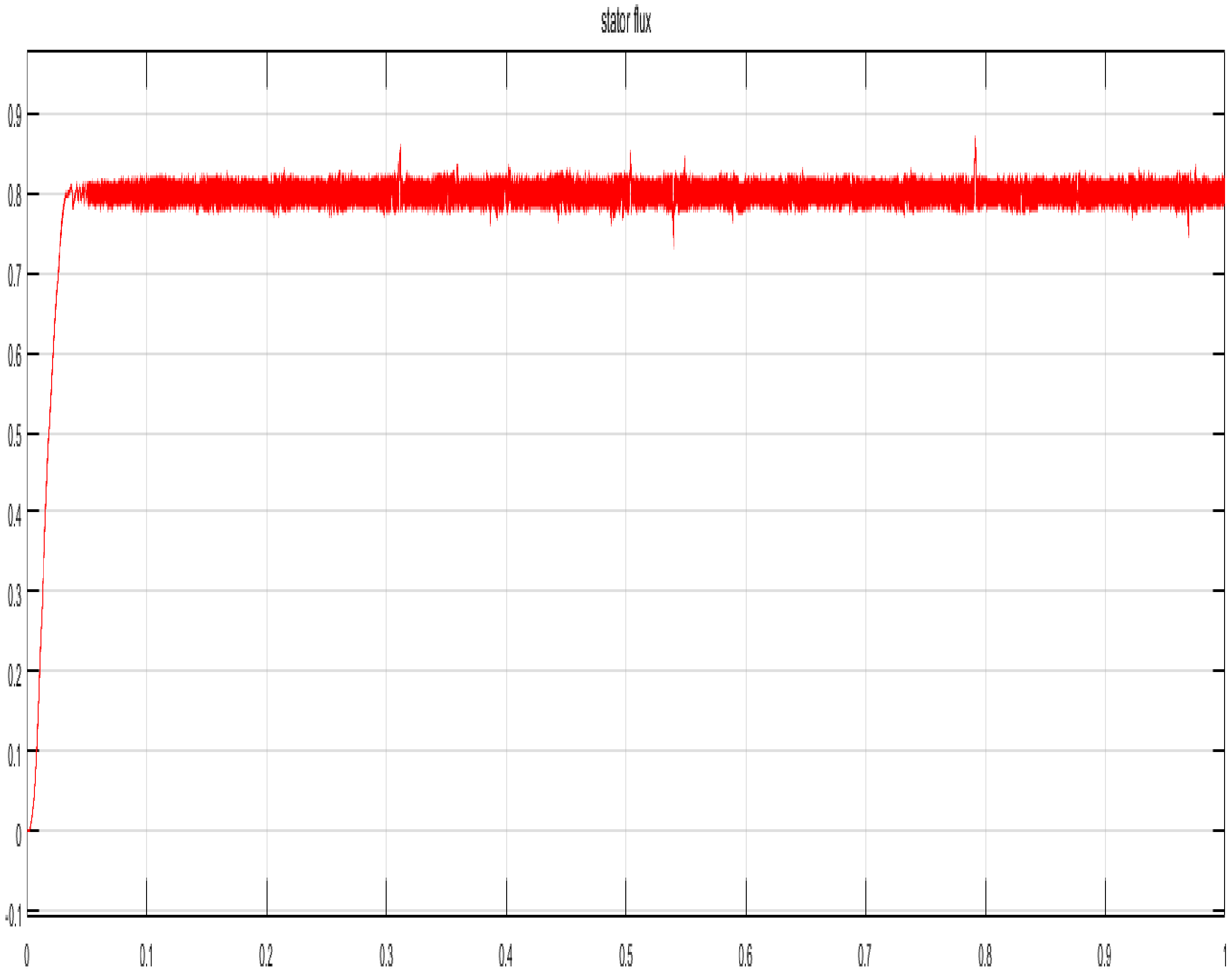

Figure.4.3Waveform of stator flux of induction motor drive at 100 rpm.

[y axis-angular frequency(1 unit of y axis= 0.2rad/sec)

x axis-time(1 unit of time= 0.1 sec)]

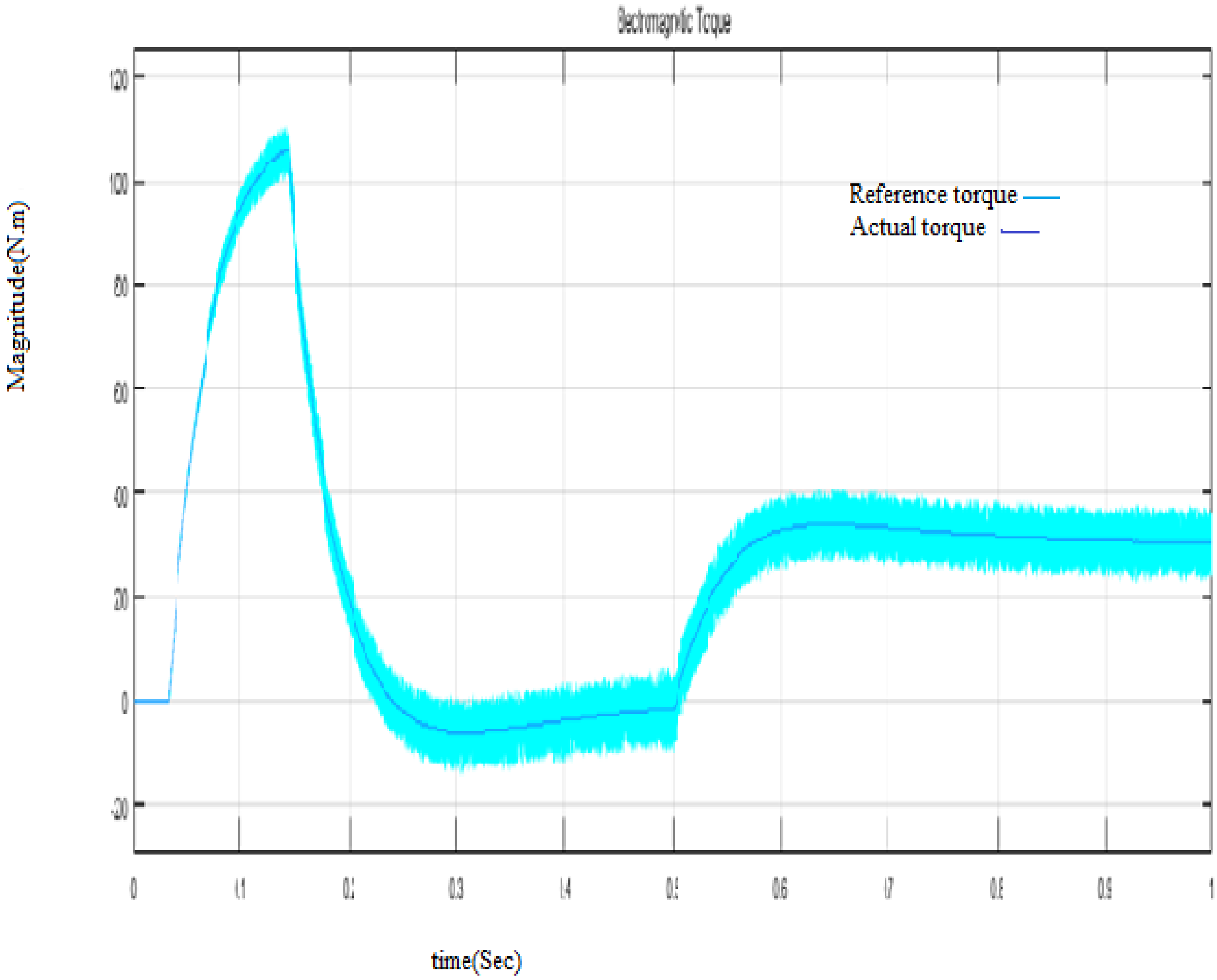

Figure.4.4.Electromagnetic torque of induction motor drive at 100 rpm
[y axis – magnitude(1 unit of y axis=500N.m), x axis – time(1 unit of x axis=0.5 sec)]

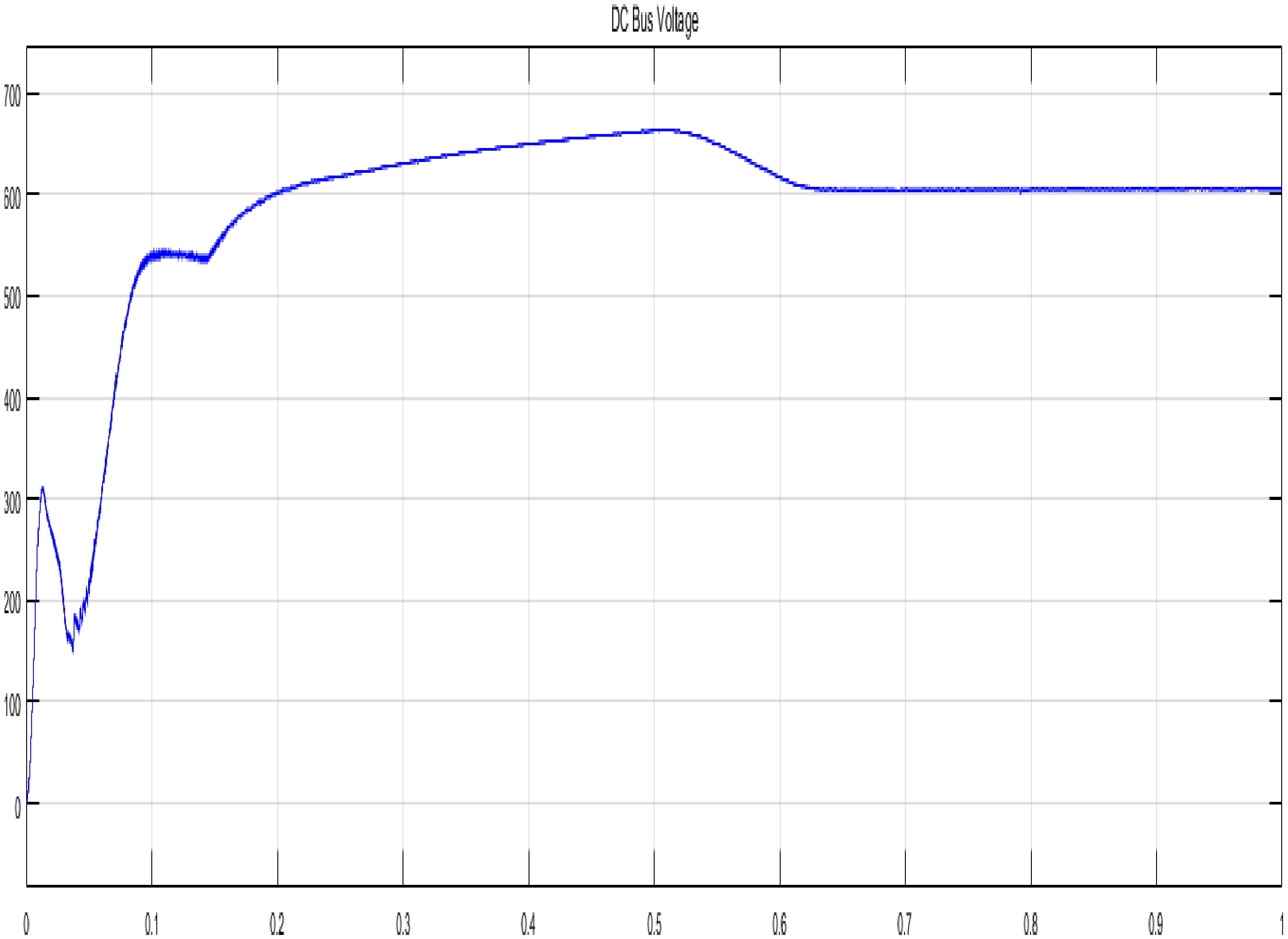

Figure.4.5.DC bus voltage of induction motor drive at 100 rpm.

[x axis-time(1 unit of x axis =0.5 sec),y axis-voltage(1 unit of y axis=100V)]

Figure.4.6. comparative waveform of stator current, stator flux, rotor speed, electromagnetic torque with respect to time and magnitude at 100 rpm. (Low speed)

[Stator current-{y axis- current (1 unit of y axis = 1000A)

x axis-time(1 unit of x axis = 0.1 sec)}

Stator flux - {y axis-Wb(1 unit of y axis = 0.2 Wb)

X axis-time(1 unit of x axis = 0.1 sec)}

Rotor speed-{y axis-Rpm(1 unit of y axis = 200 rpm)

x axis-time(1 unit of x axis = 0.1 sec)}

Electromagnetic torque-{y axis-magnitude (1 unit of y axis =500N.m)

x axis- time(1 unit of time = 0.1 sec)}

in that graph, if stator flux , rotor speed and electromagnetic torque are compare to each other, the it is shown that initially the rotor speed is increasing but at 0.55 sec the speed get saturated. If electromagnetic torque is also being considered then it is shown from the fig.(4.6) it is increasing

upto0.1 sec then it get saturated up to 0.55 sec ,then it fell to 0 , after that it will oscillate around 500N.m.

Thus from the above fig. 4.6, we can say that after small variations finally the speed estimation error is very small and very quickly converge to zero at the low speed region. Hence it confirms the better efficiency of our speed estimation technique.

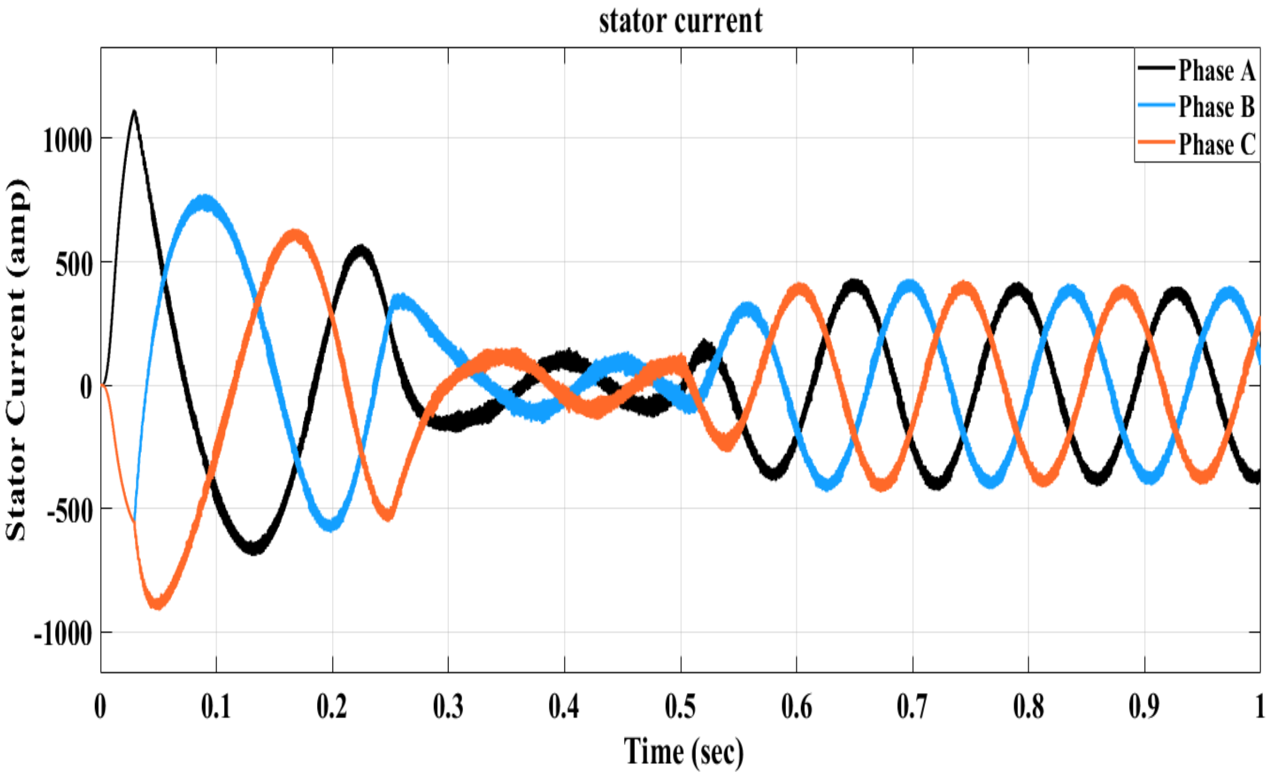

Figure.4.7. Stator current of three phase induction motor drive at 200 rpm with no load.

[y axis – Current(1 unit of y axis=500 A)

X axis – Time(1 unit of x axis=0.1 sec)]

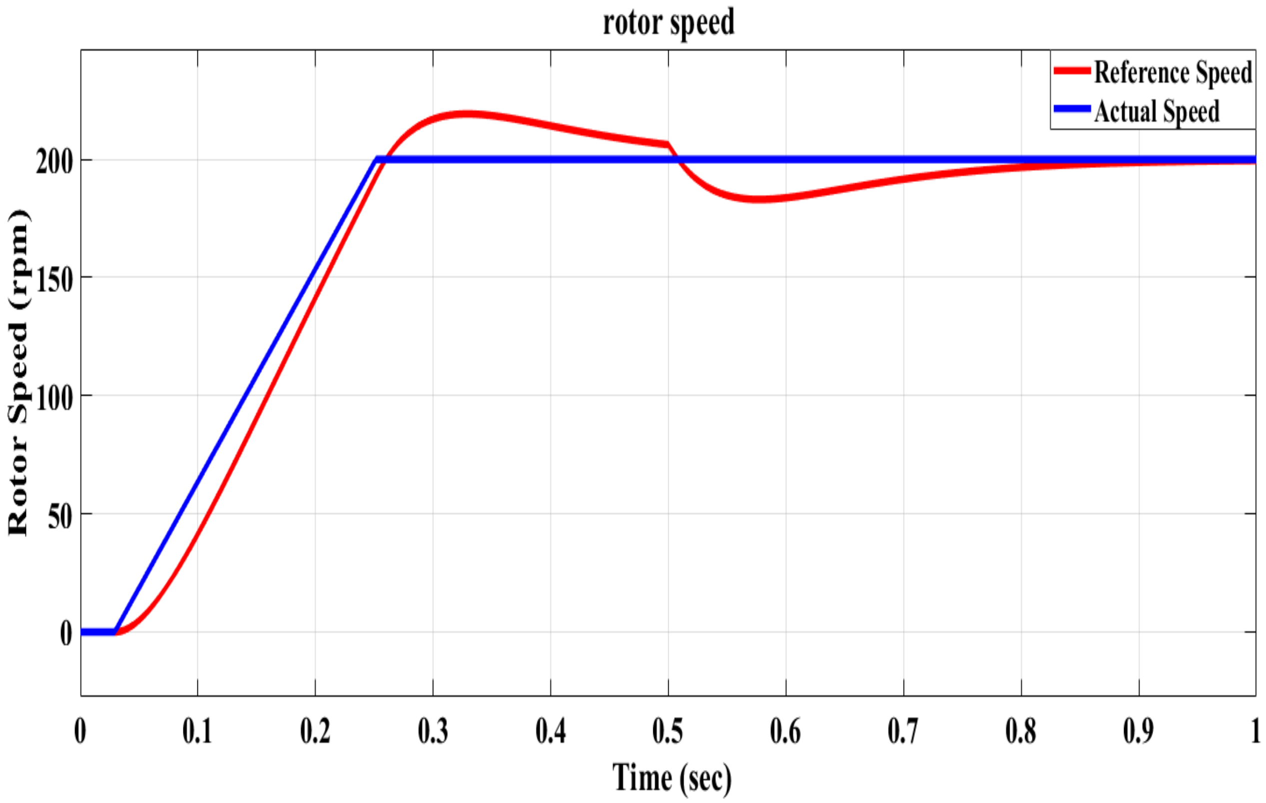

Figure4.8. Rotor speed of DTC induction motor drive at 200 rpm with no load.

[Y axis- Rpm (1 unit of y axis=100 rpm)

X axis- Time (1 unit of x axis=0.1S Sec)]

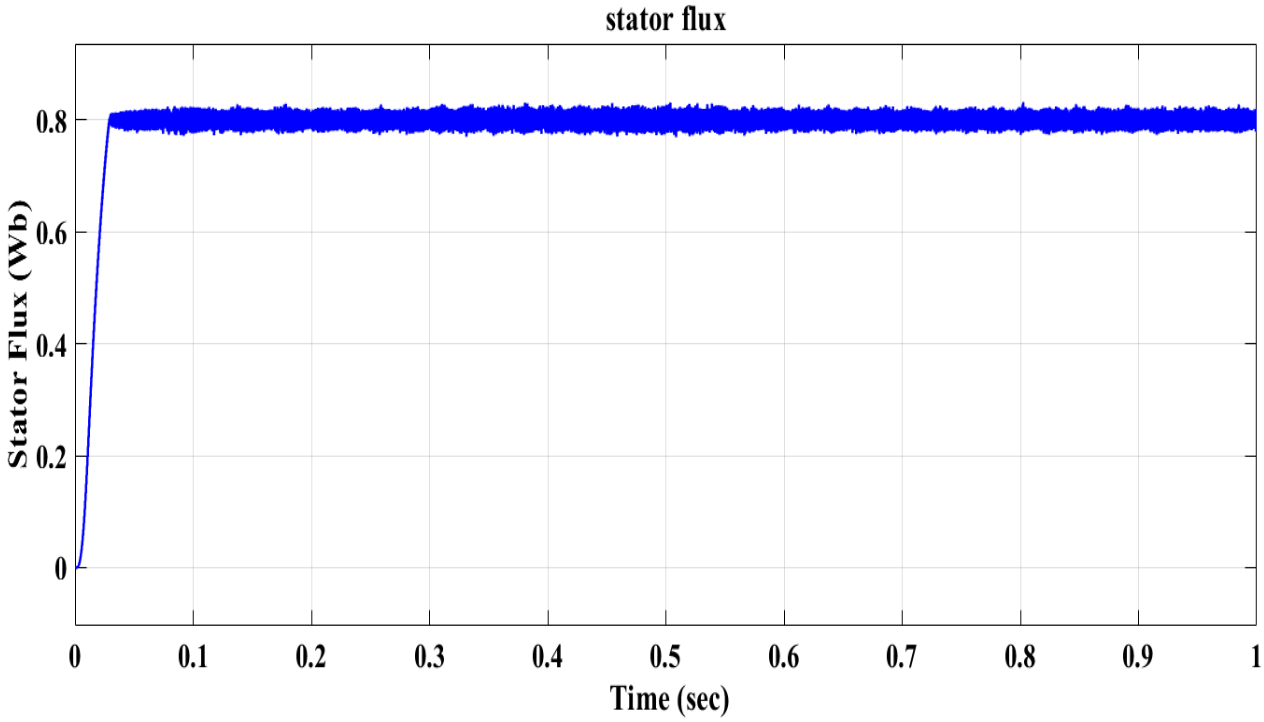

Figure 4.9. Stator flux of DTC induction motor drive at 200 rpm with no load.

[Y axis – Wb(1 unit of y axis=0.1 Wb)

X axis – Time(1 unit of x axis=0.1 Sec)]

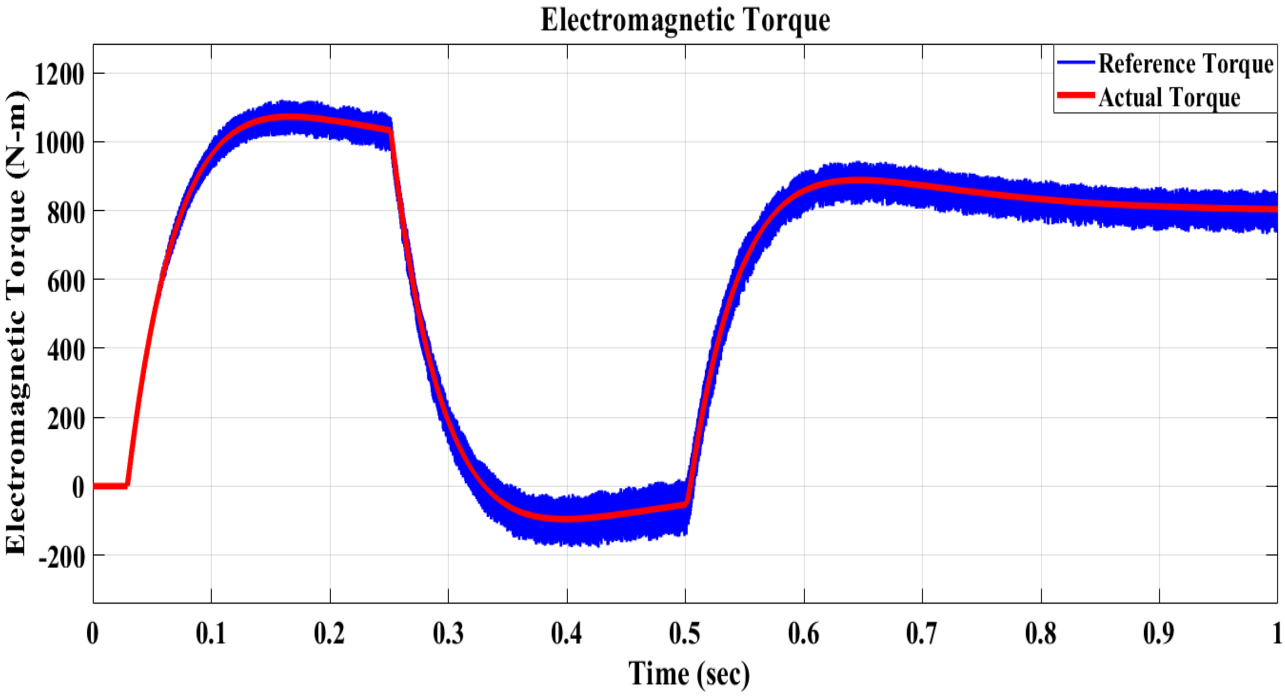

Figure 4.10. Electromagnetic torque of DTC induction motorat 200 rpm with no load.

[y axis = N.m(1 unit of y axis = 200 N.m)

X axis - Time(1 unit of x axis = 0.1 Sec)]

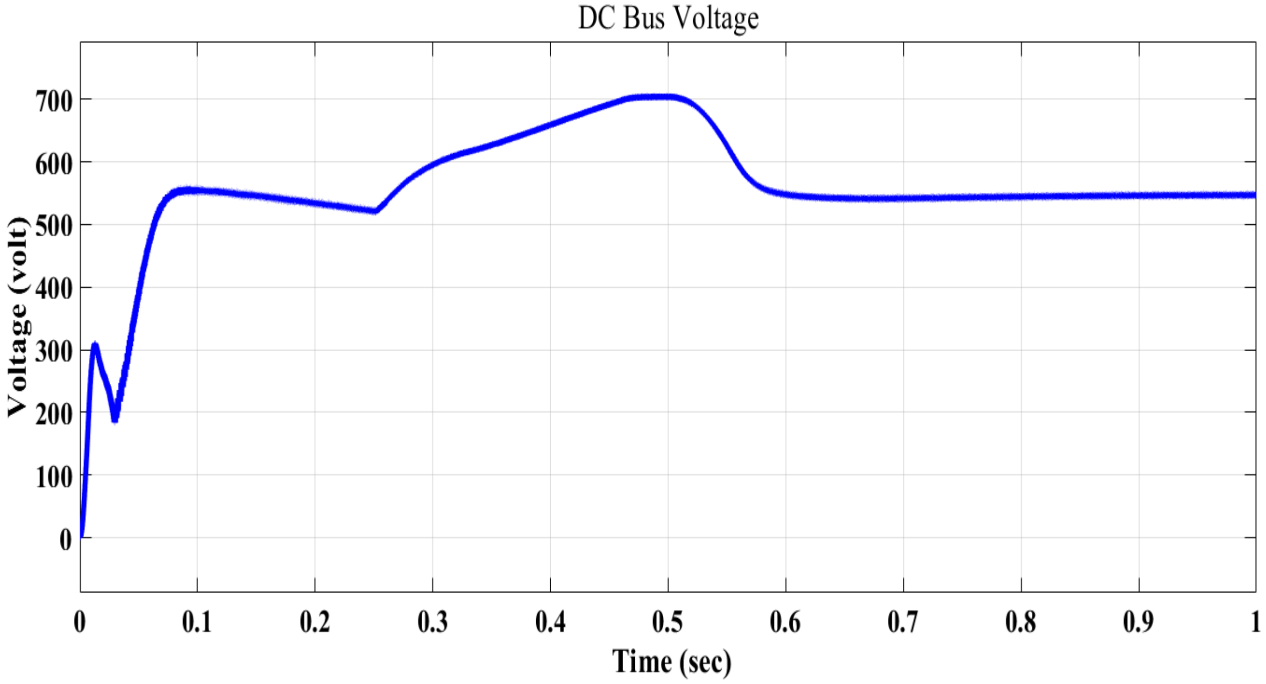

Figure 4.11. DC bus voltage of DTC induction motor at 200 rpm with no load.

[y axis-Voltage(1 unit of y axis=100 V)

X axis- Time (1 unit of x axis= 0.1 Sec)]

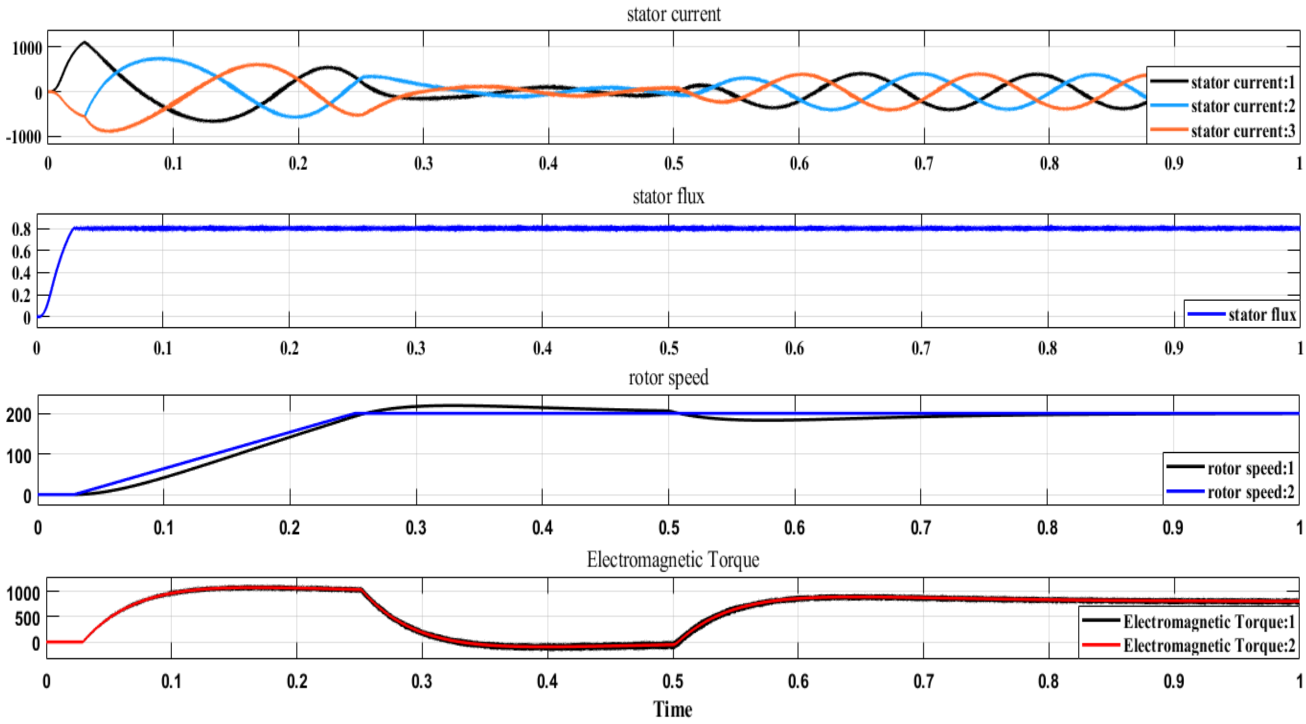

Figure.4.12. comparative waveform of stator current, stator flux, rotor speed, electromagnetic torque with respect to time and magnitude at 200 rpm. (High speed) with no load.

[Stator current-{y axis- current (1 unit of y axis = 1000A)

X axis- time (1 unit of x axis = 0.1 sec)}

Stator flux- {y axis-Wb(1 unit of y axis = 500 Wb)

X axis- time (1 unit of x axis = 0.1 sec)}

Rotor speed-{y axis- Rpm (1 unit of y axis = 500 rpm)

X axis-time (1 unit of x axis = 0.1 sec)}

Electromagnetic torque-{y axis- magnitude (1 unit of y axis = 500N.m)

X axis- time (1 unit of time = 0.1 sec)}.Here it is shown that the torque is falling at 0.6 sec.

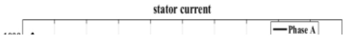

Figure.4.7. Stator current of three phase induction motor drive at 500 rpm with load.

[Y axis – Current(1 unit of y axis=500 A)

X axis – Time(1 unit of x axis=0.1 sec)]

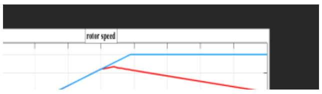

Figure4.8. Rotor speed of DTC induction motor drive at 500 rpm with load.

[Y axis- Rpm (1 unit of y axis=100 rpm), X axis- Time (1 unit of x axis=0.1S Sec)]

Figure 4.9. Stator flux of DTC induction motor drive at 500 rpm with load.

[Y axis – Wb(1 unit of y axis=0.1 Wb)

X axis- Time (1 unit of x axis=0.1 Sec)]

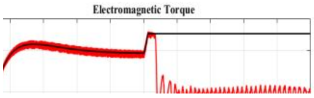

Figure 4.10. Electromagnetic torque of DTCinduction motorat 500 rpm with load.

[y axis=N.m(1 unit of y axis=200 N.m), X axis-Time(1 unit of x axis=0.1 Sec)]

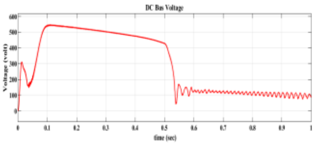

Figure 4.11. DC bus voltage of DTC induction motor at 500 rpm with load.

[Y axis-Voltage(1 unit of y axis=100 V)

X axis- Time(1 unit of x axis= 0.1 Sec)]

Figure.4.12. comparative waveform of stator current, stator flux, rotor speed, electromagnetic torque with respect to time and magnitude at 500 rpm. (High speed) with load.

[Stator current-{y axis- current (1 unit of y axis = 1000A)

X axis- time (1 unit of x axis = 0.1 sec)}

Stator flux-{y axis – Wb(1 unit of y axis = 500 Wb)

X axis-time (1 unit of x axis = 0.1 sec)}

Rotor speed-{y axis-Rpm (1 unit of y axis = 500 rpm)

X axis-time (1 unit of x axis = 0.1 sec)}

Electromagnetic torque-{y axis-magnitude (1 unit of y axis = 500N.m)

X axis- time (1 unit of time = 0.1 sec.]

- **COMPARISON OF WAVEFORMS BETWEEN HIGH SPEED AND LOW SPEED OPERATION**

1) The stator flux is same in both the cases, it rises from 0 to 0.8 wband get saturation.
2) In case of rotor speed for the first case i.e. for 100 rpm, actual speed rises from 0 to 100 rpm then get saturated but the reference speed starts from 0 and rises to 120rpm then it decreases to 90rpm and finally after some distortion it will meet to the actual speed waveform. On the other hand for 500 rpm the actual and reference speed starts from 0 and rises to 500 rpm but after that actual speed continue rising to 500 rpm but distortion is shown in the reference speed.
3) In case of 100 rpm, the electromagnetic torque starts from 0 and it rises up to 100N.m but after 100 N-m it falls to 0 and continue for few seconds until the load is putted. The reference and actual waveform overlap with each other. But in case of 500 rpm the reference and actual torque follow the same path up to 500N.m. after that the reference torque falls to 100N.m.
4) For DC bus voltage the cineraria is different for both cases. In case of 100 rpm it starts from 0 and rises to 300V, then it falls to 200 after that it rises again to 500V. So its distortion is very high. Distortion in DC bus voltage waveform is also high when the motor run at 500 rpm.

4.3CONCLUSION

In this work a field oriented control induction motor is used whose speed is estimated by an advanced speed estimation technique that is based on DTC strategy in order to improve the performance of motor at low speed region. The simulation results proved that the proposed DTC method is able to estimate the rotor speed accurately at low speed regions also. Also the robustness of the proposed observer regarding load torque and stator resistance variation is much better. The ac drive controllers using the DTC technologies will be available later this year. The first units will be single-quadrant designs - motoring in one direction. Later in the year, four-quadrant units will be in production. These will offer motoring in both directions and the ability to regenerate power back to the ac power line.

Moreover, the estimated speed must be generated which one can see through the oscilloscope. By using 40-MHz DSPs, the control circuit starts to react to a change in 25 msec. This gives a torque loop response of 300 ms to 5 ms, depending on the magnitude of the needed change. Digital signal processors (DSPs) combined with application specific integrated circuit (ASIC) technology. From this work it is shown that controlling speed of an induction motor is very easy at low speed region with the help of DTC technique. Cost and limitations of this method are very low compare to efficiency of this method.

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