PERFORMANCE EVALUATION & HARDWARE IMPLEMENTATION OF VARIOUS SPEED CONTROL TECHNIQUES FOR IM DRIVE

A DISSERTATION

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Submitted by:

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CANDIDATE'S DECLARATION

I, Mr. Chinmay Ravindra Tigade, Roll No. 2K16/C&I/07 student of M. Tech. Control & Instrumentation, hereby declare that the project Dissertation titled "**Performance Evaluation & Hardware Implementation of Various Speed Control Techniques for IM Drive**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Performance Evaluation & Hardware Implementation of Various Speed Control Techniques for IM Drive**" which is submitted by Mr. Chinmay Ravindra Tigade, Roll No 2K16/C&I/07 Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Induction motor is extensively used in industry and in household applications due to numerous advantages, where it is operated at various speed and load torque. As a result, substantial amount of energy is consumed by induction motors. Hence, various efficient speed control techniques of induction motor drive need to be used for optimal use of energy.

In this thesis, performance of various speed control techniques such as open-loop and closed-loop V/f method, direct and indirect vector control method and direct torque control method of three phase induction motor drive is examined using Simulation and Experimental results. The goal of this study is to identify various advantages and disadvantages of each speed control technique.

Simulation of scalar speed control method, vector control method and direct torque control method is performed in MATLAB Simulink and their performance is analyzed under various operating condition. The hardware implementation of open-loop and closed-loop V/f method is performed to test the performance of these method in real world. These methods are implemented on laboratory prototype using dSPACE DS1104 on a 3Hp, 415V, 50Hz Induction Motor.

The performance of scalar technique is also observed using real-time Full Spectrum Simulator (FSS) and it is compared with the MATLAB simulation results to study its performance using two different simulation tool. FSS is advanced easily configurable controller which has a capability of performing offline and real-time simulation. It is also having hardware in loop capability which enable us to test new power electronic systems.

It is found that open-loop V/f system is very easy to implement and its response is satisfactory when precise speed control is not required whereas closed-loop V/f system provides precise speed control. The response of vector control method is fast as compared to scalar control method and it also provides performance like separately excited dc motor thus we can control flux and torque independently. Direct torque control method is very advance speed control technique and its performance is superior than all other methods and provides independent control of flux and torque like vector control. The disadvantage of vector control method and direct torque control is that they are totally dependent on voltage, current and speed feedback signals which makes the system complex and expensive. The experimental results of both scalar control techniques compared with the simulation results and it is observed that the experimental results almost match with the corresponding simulation results.

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CHINMAY TIGADE

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS

V_s – Stator Voltage

ω_s – Stator Supply frequency in rad/sec

ω_r – Rotor Electrical Speed rad/sec

ω_m – Rotor Mechanical Speed rad/sec

ω_{sl} – Slip frequency in rad/sec

F_a – Armature flux

F_f – Field flux

F_r – Rotor Flux

F_s – Stator Flux

i_{ds}, i_{qs} – Stator current components in synchronously rotating frame

i_{dr}, i_{qr} – Rotor current components in synchronously rotating frame

i_{ds}^s, i_{qs}^s – Stator current components in stationary frame

i_{dr}^s, i_{qr}^s – Rotor current components in stationary frame

L_m – Mutual Inductance

L_s, L_r – Stator and Rotor self-inductance

V_{ds}, V_{qs} – Stator voltage components in stator frame

V_{ds}^s, V_{qs}^s – Stator voltage components in stationary frame

F_{ds}, F_{qs} – stator flux vector signal in synchronously rotating frame

F_{dr}, F_{qr} – Rotor flux vector signal in synchronously rotating frame

F_{ds}^s, F_{qs}^s – Stator flux vector signal in stationary frame

F_{dr}^s, F_{qr}^s – Rotor flux vector signal in stationary frame

R_s – Stator Resistance

R_r – Rotor Resistance

L_{ls} / X_{ls} – Stator Leakage Inductance / Reactance

L_{lr} / X_{lr} – Rotor Leakage Inductance / Reactance

CHAPTER 1

INTRODUCTION

1.1 Introduction

The induction motors are used in huge volume all over the world due to countless advantages it has. IM are trustworthy, extremely tough, cheap to run and they need less maintenance. Thus, IM are preferred in variety of commercial and domestic applications [1]. It is estimated that more than 50% of total electric energy generated all over the world is utilized by induction motors. Hence it is very important to efficiently control the induction motor drive to reduce environmental pollution and for economical saving [2].

The various speed control techniques of three-phase squirrel cage induction motors are open-loop and closed-loop V/f method, direct and indirect vector control method and direct torque control method [3]. The V/f method also known as scalar control method as only the magnitude of control variable is changed. In this stator voltage is changed in proportion with the frequency in order to keep stator flux constant. The V/f method is further categorized as open-loop V/f and closed-loop V/f method. The main advantage of scalar control method is that it is very easy to implement [4]. The response of scalar control method is somewhat sluggish due to inherent coupling effect i.e. both torque and flux are dependent on voltage and frequency [3]. This problem can be resolved using vector control method, also known as field oriented control (FOC) method, which provide independent control of both torque and flux. The vector control methods are classified into two methods on the basis of how unit vector is generated. The first method is called as direct vector control also known as feedback method and other is called as indirect vector control method. In direct vector control method unit vector is obtain using estimating flux vector. There are two method of flux estimation, the first one is called voltage model estimation, in which machine terminal voltage and current are sensed for estimation while second one is called current model estimation which only uses current signal for estimation. In indirect vector control method unit vector is obtained by estimating slip frequency ω_{sl} and adding it with rotor frequency ω_r. Thus, high performance vector control method is very popular in industrial applications. Direct Torque Control (DTC) allow us to directly control torque and stator flux by using space vector selection from lookup table [3]. It is easy to use as compared to vector control drive and its response is fast at various speed levels [5]. It provides indirect control of stator current and voltages [6]. Also, there is absence of co-ordinate transformation and its torque response time is very small. In DTC, machine terminal voltage and current are sensed to estimate flux and torque which is compared with desired flux and torque then appropriate inverter state is selected from look up table. The performance of these speed control techniques is examined under different operating conditions using simulation tools such as MATLAB and FSS. Also, to test the real world performance of open-loop and closed-loop V/f method experimental results are also obtained using laboratory setup.

1.2 MATLAB Simulink

MATLAB Simulink is a graphical programming environment used for modeling, simulating and analyzing multi-domain dynamical system. Simulation is extremely important tool during designing phase for analysis of system behavior under different operating condition. There are two types of simulation viz. offline and real-time. Simulink offers a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. Due to its simplicity it is widely used all over the world for modeling and offline simulation.

1.3 Full Spectrum Simulator

The Full Spectrum Simulator is an advanced Digital Signal Processing device that has a facility of performing offline and real-time simulation in which library components can be easily configured for custom applications. Offline simulation is largely carried out using MATLAB Simulink, SABER etc. These software's permits great flexibility in designing, but there are some restrictions such as components present in library are encoded and they are not accessible for alteration. In offline simulators, the simulation time is mostly much higher than the physical time. However, in real time simulator physical time and simulation time is identical hence it allows us to examine system in real-time which is very helpful for performing “Hardware in the loop” simulation [1], [7]. As a result, FSS is very valuable instrument for Power System and Power Electronics related research activities. Fig. 1.1 shows miniature FSS hardware. The benefit of using it is that it contains several types of components in its library which can be used for developing new control schemes. Also, user can create new component that can be incorporated in system library and can be used for countless application [8]. In FSS, program is written in ‘C’ language with the help of notepad and file is saved with ‘.in’ extension. This file is used for offline as well as real-time simulation by making few alterations [9]. The file is termed as circuit file and it comprises of following sections;

1. Circuit Section: This section explains various components used for designing the system and their interconnection. Moreover, it includes numerous input and output variables of each component and their value.
2. Solver Section: It contains information of simulation time, discrete time step and method of solving.
3. Target Section: In this section we need to specify the target whether it is HOST_PC (for offline simulation) or FSS (for real-time simulation) it then generates ‘C’ code for chosen target.

Figure 1.1 Miniature Full Spectrum Simulator

1.4 dSPACE Controller

dSPACE DS1104 is a controller board which is used for real-time implementation of different control strategies. This board upgrades a PC to a development system for rapid control prototyping. In this research work it is used for implementing open-loop and closed-loop speed control technique.

1.5 Thesis Organization

This thesis consists of seven chapters. Chapter 1 includes introduction of the various speed control techniques and Full Spectrum Simulator. Chapter 2 includes the literature review. Chapter 3 covers in-depth explanation of various concepts and mathematical equations. How the Simulation of various speed control techniques is performed using MATLAB Simulink and FSS which is explained in chapter 4. Chapter 5 includes information regarding hardware implementation. The output waveforms obtained by simulation and hardware implementation are included in chapter 6. Chapter 6 also includes comparison and detailed discussion of various speed control techniques regarding their performance. Chapter 7 summarizes the thesis with conclusion. References and list of publications are mentioned at the end.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

To carry out this research work number of books, research articles and other resources are used. This chapter provides a description and summary of the material used for solving research problem being investigated.

2.2 Importance of Efficient IM Drive

The three-phase squirrel cage induction motors are frequently used in many applications, the reason behind it is their good performance, quite operation and low cost maintenance. These motors are used in the pumps, compressor, conveyors, fans, automated processes and various mechanical systems [1]. It is estimated that the energy consumed by electric machines all over the world is more than 50% of total energy generated. Thus, it is very important that the efficient operation of induction motor drive is ensured. Traditionally for example the flow of fluid coming out of pipe is controlled by manually adjusting the control valve and keeping the pump running at rated speed. The efficiency of such type of control technique used for various applications is very low. Thus to solve this problem various efficient speed control methods were discovered over a period of time such as open-loop V/f, closed-loop V/f, direct vector control, indirect vector control, direct torque control and many more [3].

2.3 Speed Control Techniques

The open-loop V/f method is low-cost speed control technique which is very easy to implement. It uses parameters which does not depend on each other. But the performance of this methodology is very poor [4]. If frequency is reduced keeping voltage constant then flux starts increasing, that results into increase in eddy current of winding which causes heating problem. Hence, to adjust the speed voltage and frequency are altered proportionally in V/f method [5]. Also, at low frequency the voltage drop across the stator resistance might cause flux reduction. The simple method used to compensate this voltage drop is consisting of boosting the stator voltage [7]. The problem observed in this method is that the speed of motor cannot be controlled precisely that is because only the frequency of stator supply is controlled i.e. only the synchronous speed is controlled and the rotor speed is always slightly less than synchronous speed. This problem is resolved in closed-loop V/f method in which speed of motor is measured and it is compared with desired speed. The error is processed by PI controller to set the stator supply frequency [10].

Although scalar control method is simple and economical it does not allow us to control flux and torque independently like separately excited DC motor. In vector control, coordinate transformation theory is used in which motor control is considered in synchronously rotating reference frame [11]. The three-phase stator current is transformed into direct axis component and quadrature axis components which allows independent control of flux and torque respectively [12]. The unit vector is used for 2φ to 3φ transform or 3φ to 2φ transform of stator current. Depending on the method used for finding the unit vector it is classified as direct vector control and indirect vector control. The unit vector can be obtained using number of permutation such as stator flux orientation, rotor flux orientation and air gap flux orientation. Estimation of flux vector using stator flux oriented vector control has advantage that the accuracy of estimating flux vector is affected only by the stator resistance [13]. In direct vector control unit vector is obtained using current or voltage model flux estimation method by taking current and voltage feedback signal. As it involves number of sensors it is bit costly and tuning of sensors is bit tedious. However, in indirect vector control unit vector is obtained in feedforward manner by using speed signal thus it reduces the cost of system. Also, if any fault occurs in sensor, the stability of system gets affected and reliability of system is reduced [15]. The tuning of PI controller in vector control required exact knowledge of rotor resistance and mutual inductance. The value of rotor resistance varies with temperature and frequency whereas value of mutual inductance changes with magnitude of stator current. Thus, tuning of PI controller is bit time consuming [16]. The cost of vector control drive can be reduced by employing speed sensor less vector control method. In sensor less vector control speed is determined by calculating slip frequency [17].

The DTC is advanced scalar speed control technique introduced in mid-1980s by Isao Takahashi and T. Noguchi. It allows direct control of stator flux and torque by selecting inverter voltage space vector from lookup table [3]. During transient state highest torque response can be obtain in DTC by selecting fastest accelerating voltage vector. Also, during steady state torque can be maintained constant by selecting accelerating voltage vector and zero vector alternatively [18].

Over the years many researchers have explored advanced, accurate and efficient speed control techniques of induction motor. In this thesis, inference taken from above material is used to examine performance of various speed control techniques. The next chapter explain principle and working of each speed control technique in detail.

2.4 Conclusion

Literature review includes summery of various research papers, books and other material used for performing this research work.

CHAPTER 3

CONTROL OF INDUCTION MOTOR DRIVE

3.1 Introduction

This chapter illustrates the block diagram of each speed control technique that describes the principle and operation of each technique. It covers mathematical equations required for implementation. The working of SPWM and hysteresis band current controller will be discussed. The chapter also describes the different flux estimation methods.

3.2 Scalar Control

The scalar control method also known as V/f method is very popular speed control technique used in industry due to its simplicity. In this method, magnitude of control variable is altered to change the speed of motor hence termed as scalar control. The flux of IM can be controlled by adjusting voltage whereas torque can be controlled by changing frequency. If we neglect the voltage drop across stator resistance, the stator flux is given as $F_s = V_s/f_s$ where V_s is stator voltage and f_s is stator supply frequency. Thus, if we keep voltage constant and reduce frequency to decrease speed of motor then flux will saturate causing excess of stator current which might harm the motor permanently. Now if we increase the frequency above rated value to increase the speed the flux will decrease as voltage cannot be increased beyond rated value. This region of operation is called as field weakening region. Hence, to operate the motor at rated flux both frequency and voltage need to vary in proportion. There are two types of scalar control techniques viz. open-loop and closed-loop V/f.

3.2.1 Open-loop V/f Method

It is most simple and economical speed control technique of three-phase induction motor. Fig. 3.1 shows block diagram of open-loop V/f method. The desired speed ω_m^* command is given as input to the system which is converted into corresponding frequency command f and fed to V/f controller. The corresponding voltage is calculated by multiplying frequency f with V_{rated}/f_{rated} ratio as shown in figure. The three phase stator voltages are then computed as shown in block diagram. These voltages are given as input to the Sinusoidal Pulse Width Modulator (SPWM) which compares it with high frequency triangular wave to generate pulses for switching of inverter as shown in Fig. 3.2. The IM is connected to the inverter whose output is variable voltage variable frequency supply depending upon input speed command. The speed of motor in open-loop method will never be exactly equal to the given speed command as IM can never run at synchronous speed. Also, there is significant drop in motor speed when load torque is applied. The absence of any feedback signal makes this method very simple but at the same time it makes the system prone to instability. If there is any disturbance in the system or speed of motor, system cannot rectify it but still it can be used in the applications where high precision is not required.

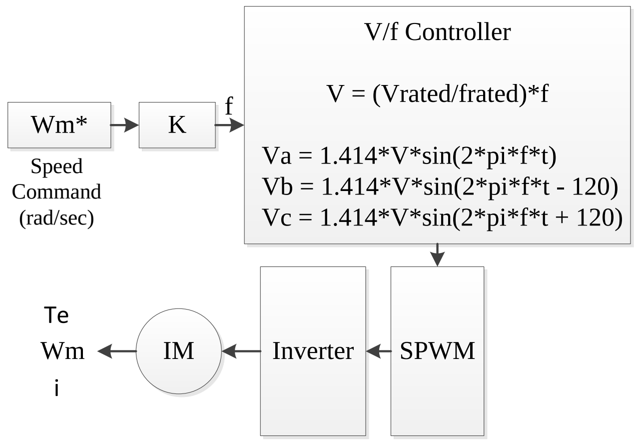

Figure 3.1 Block diagram of Open-loop Scalar Control Technique

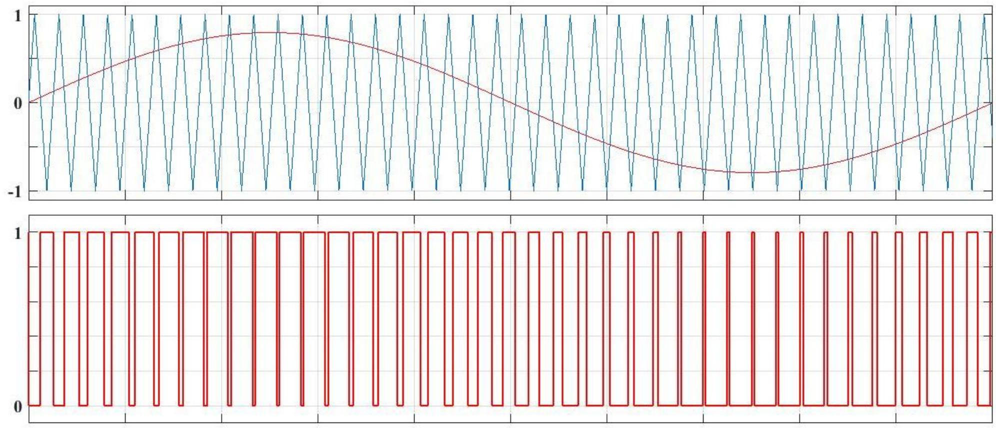

Figure 3.2 Principle of SPWM for Three-phase Voltage Fed Inverter

3.2.2 Closed-loop V/f Method

The issues involved in open-loop method are solved by including speed control loop. Desired speed command ω_m^* is converted into electrical rotor speed ω_r^* and compared with instantaneous speed ω_r and error is processed by PI controller which generated slip frequency command ω_{sl}^*. The addition of slip frequency and instantaneous speed gives desired stator frequency ω_s^* as $\omega_{sl} = \omega_s - \omega_r$. This frequency is then fed to V/f controller which then computes the corresponding voltages. The remaining operation is same as the open-loop method. The speed control loop amends ω_{sl} whenever there is drop in speed due to application of load torque or any disturbance and maintains it at desired speed command. Block diagram of closed-loop V/f method is as shown in Fig. 3.3.

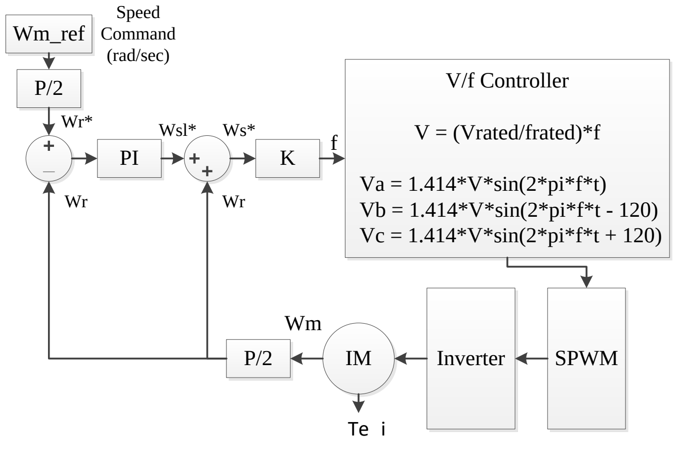

Figure 3.3 Block diagram of Closed-loop Scalar Control Technique

3.3 Vector or Field Oriented Control

Although scalar control is easy to implement and affordable it has certain limitation due to which it can be used only for limited number of application. Since, the flux and torque are functions of voltage and frequency it causes coupling problem in V/f method which makes response of scalar control technique less accurate and slow. Thus this problem can be resolved by controlling the induction motor like separately excited DC motor by using vector or field oriented control technique. In a dc machine torque is given as,

$$T_e = KI_aI_f \tag{3.1}$$

Where, I_a is armature current and I_f is field current

The dc machine is constructed in such a way that the flux F_a produce by I_a is perpendicular to the flux F_f produced by the I_f. Due to this if we alter I_a to control torque, F_f is not affected and when field current I_f is changed only the field flux gets affected. This theory can be used for induction motor if we control the machine by considering it in synchronously rotating reference frame where sinusoidal variables appear like DC quantities at steady state. The stator current of induction motor in synchronously rotating reference frame are called as direct axis component i_{ds} and quadrature axis component i_{qs} which are analogous to field current I_f and armature current I_a of dc motor i.e to control flux i_{ds} is controlled and to control torque i_{qs} is changed. This dc motor like performance is possible only when i_{ds} is aligned with rotor flux F_r and i_{qs} is perpendicular to it. Thus, torque can be expressed as,

$$T_e = K'i_{qs}i_{ds} \tag{3.2}$$

In vector control method, i_{ds} and i_{qs} stator current are converted into three-phase current with the help of unit vector and 2φ to 3φ transformation. This desired three-phase current command is fed to hysteresis band current controller where they are compared with instantaneous values of three-phase stator current. Whenever instantaneous current exceeds the hysteresis band it generates pulses that results into PWM signal which is used to control the inverter voltage and frequency. The operation of hysteresis band current controller is as shown in Fig. 3.4. Depending upon how unit vector is obtain the FOC is classified as direct vector control also known as feedback control method and indirect vector control known as feedforward method.

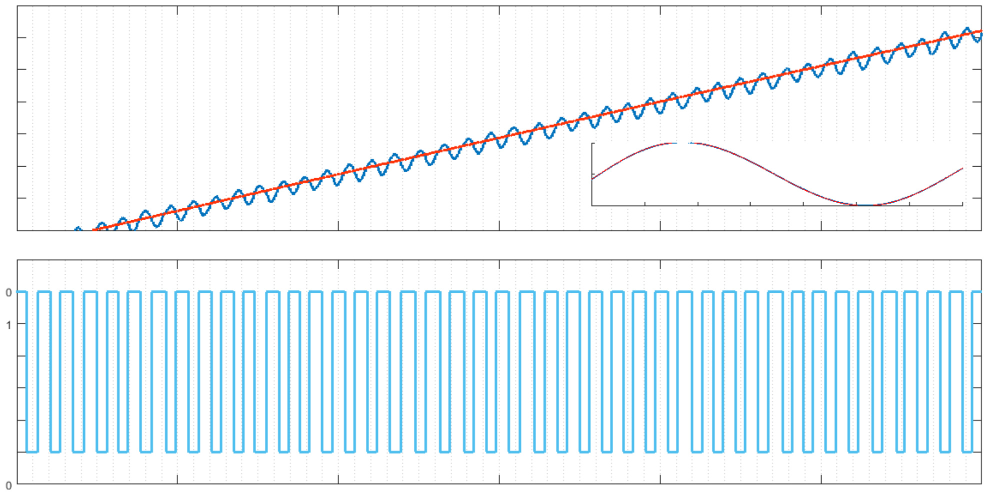

Figure 3.4 Working of Hysteresis Band Current Controller

The redline is the desired current command and blue one is actual current which is oscillating within the hysteresis band generating pulses as shown in the figure.

3.3.1 Direct Vector Control

In direct vector control desired speed ω_m^* and flux F_r^* is given as input which are compared with corresponding instantaneous values. The speed control loop gives error signal to PI controller which gives torque component i_{qs}^* and flux control loop gives flux component i_{ds}^*. Both these components are dc values in synchronously rotating reference frame. These current are then converted into stationery frame with help of unit vectors $\cos(\theta_s)$ and $\sin(\theta_s)$ generated from flux vector signals F_{dr}^s and F_{qr}^s. These vector signals are obtain using Voltage Model Estimator or Current Model Estimator which makes use of machine terminal voltage and current. The schematic diagram of direct vector control is as shown in Fig. 3.5.

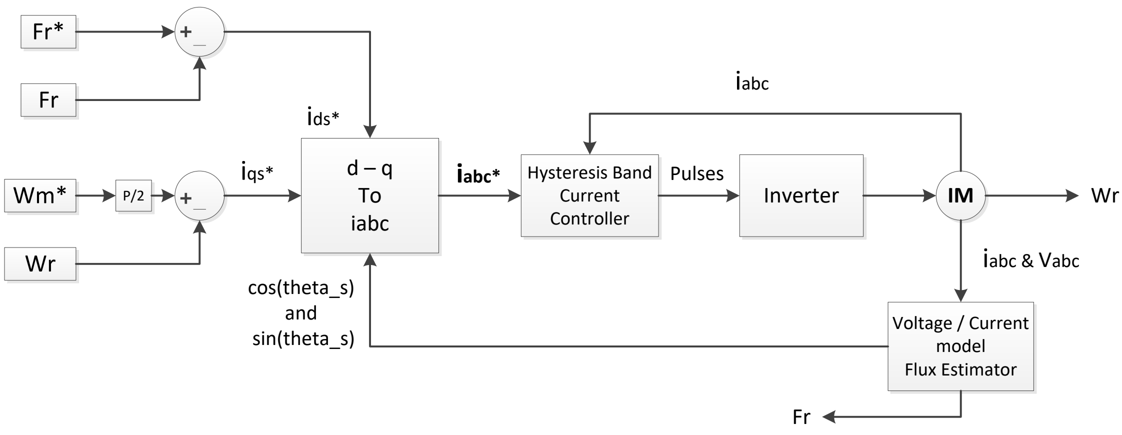

Figure 3.5 Block Diagram of Direct Vector Control

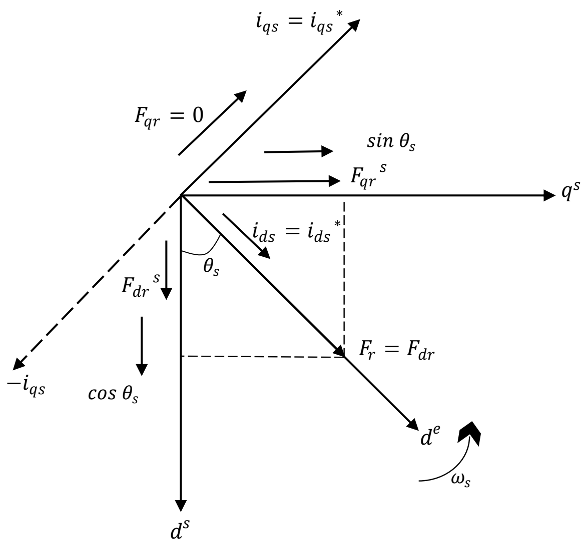

Figure 3.6 $d^s - q^s$ and $d^e - q^e$ phasors showing correct rotor flux orientation

In vector control it is very important that i_{ds} is perfectly aligned with F_r and i_{qs} is perpendicular to it. This can be achieved as follows. Fig. 3.6 shows alignment of stationary fame flux vector $F_{dr}{}^s$ and $F_{qr}{}^s$ obtain from voltage model or current model estimator. The $d^e - q^e$ frame is rotating at synchronous speed ω_s with respect to $d^s - q^s$ stationary frame. The angular position of rotating frame from stationary frame at any instant is $\theta_s = \omega_s t$. From figure we can write the equations as follows.

$$F_{dr}{}^s = F_r \cos\theta_s \tag{3.3}$$

$$F_{qr}{}^s = F_r \sin\theta_s \tag{3.4}$$

Therefore,

$$\cos\theta_s = \frac{F_{dr}{}^s}{F_r} \tag{3.5}$$

$$\sin\theta_s = \frac{F_{qr}{}^s}{F_r} \tag{3.6}$$

$$F_r = \sqrt{(F_{dr}{}^s)^2 + (F_{qr}{}^s)^2} \tag{3.7}$$

When these unit vectors ($\cos(\theta_s)$ and $\sin(\theta_s)$) are used to transform i_{ds}^* and i_{qs}^* into stationary frame it perfectly aligns i_{ds}^* along F_r and i_{qs}^* perpendicular to it. Since, these unit vectors are derived using flux vector which are obtain from feedback voltage and current signals it is called as feedback method. There are two methods to estimate flux vector signal viz. Voltage Model and Current Model estimator.

1. Voltage Model Estimator –

In this technique, stator terminal voltage and current are sensed and using d – q equivalent circuit of an Induction Motor in stationary frame flux vector are derived to obtain unit vectors.

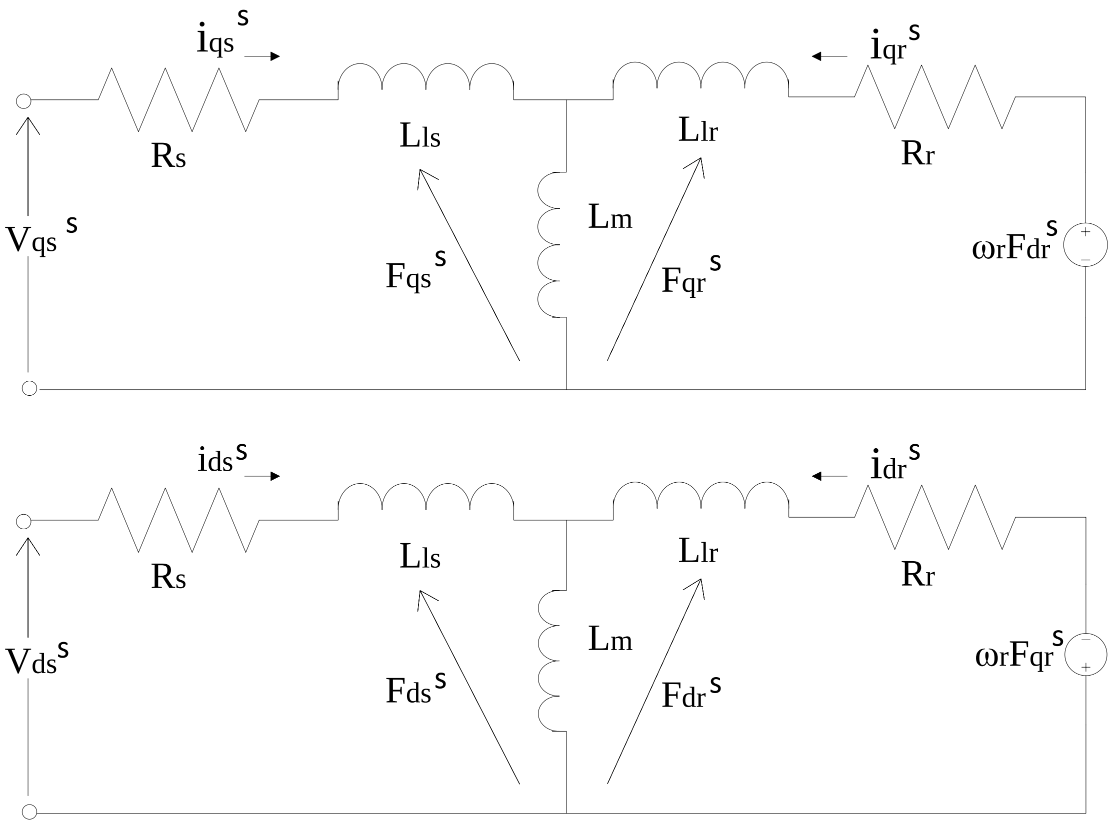

Figure 3.7 d - q equivalent Circuit of Induction Motor in Stationary Frame

Considering Fig. 3.7 we can obtain unit vector as follows:

$$i_{qs}{}^{s} = \frac{2}{3}i_a - \frac{1}{3}i_b - \frac{1}{3}i_c = i_a \quad (3.8)$$

$$i_{ds}{}^{s} = -\frac{1}{\sqrt{3}}i_b + \frac{1}{\sqrt{3}}i_c \quad (3.9)$$

Since, $i_c = -(i_a + i_b)$ for isolated neutral load we can write $i_{ds}{}^{s}$ as

$$i_{ds}{}^{s} = -\frac{1}{\sqrt{3}}(i_a + 2i_b) \quad (3.10)$$

$$V_{qs}{}^{s} = \frac{2}{3}V_a - \frac{1}{3}V_b - \frac{1}{3}V_c \quad (3.11)$$

$$V_{ds}{}^{s} = -\frac{1}{\sqrt{3}}V_b + \frac{1}{\sqrt{3}}V_c \quad (3.12)$$

$$F_{ds}{}^{s} = \int (V_{ds}{}^{s} - R_s i_{ds}{}^{s})dt \quad (3.13)$$

$$F_{qs}{}^{s} = \int (V_{qs}{}^{s} - R_s i_{qs}{}^{s})dt \quad (3.14)$$

$$F_s = \sqrt{F_{ds}{}^{s^2} + F_{qs}{}^{s^2}} \tag{3.15}$$

$$F_{dm}{}^s = F_{ds}{}^s - L_{ls}i_{ds}{}^s = L_m(i_{ds}{}^s + i_{dr}{}^s) \tag{3.16}$$

$$F_{qm}{}^s = F_{qs}{}^s - L_{ls}i_{qs}{}^s = L_m(i_{qs}{}^s + i_{qr}{}^s) \tag{3.17}$$

$$F_{dr}{}^s = L_m i_{ds}{}^s + L_r i_{dr}{}^s \tag{3.18}$$

$$F_{qr}{}^s = L_m i_{qs}{}^s + L_r i_{qr}{}^s \tag{3.19}$$

Substituting equation (3.18) – (3.19) into 3.16 and 3.17 we get,

$$F_{dr}{}^s = \frac{L_r}{L_m}F_{dm}{}^s - L_{lr}\, i_{ds}{}^s \tag{3.20}$$

$$F_{qr}{}^s = \frac{L_r}{L_m}F_{qm}{}^s - L_{lr}\, i_{qs}{}^s \tag{3.21}$$

Using equation (3.20) – (3.21) and (3.5) – (3.7) we can obtain unit vectors.

2. Current Model Estimator –

At low frequency flux vectors can be obtain more easily using current model estimator hence whenever it is desire to operate motor at low speed current model is used. Considering Fig. 3.7 we can obtain flux vector using following equation:

$$\frac{dF_{dr}{}^s}{dt} + R_r i_{dr}{}^s + \omega_r F_{qr}{}^s = 0 \tag{3.22}$$

$$\frac{dF_{qr}{}^s}{dt} + R_r i_{qr}{}^s - \omega_r F_{dr}{}^s = 0 \tag{3.23}$$

Adding term $(L_m Rr/L_r)i_{ds}{}^s$ and $(L_m Rr/L_r)i_{qs}{}^s$ respectively, on both side of the above equations we get,

$$\frac{dF_{dr}{}^s}{dt} + \frac{R_r}{L_r}(L_m i_{ds}{}^s + L_r i_{dr}{}^s) + \omega_r F_{qr}{}^s = \frac{L_m R_r}{L_r} i_{ds}{}^s \tag{3.24}$$

$$\frac{dF_{qr}{}^s}{dt} + \frac{R_r}{L_r}\left(L_m i_{qs}{}^s + L_r i_{qr}{}^s\right) - \omega_r F_{dr}{}^s = \frac{L_m R_r}{L_r} i_{qs}{}^s \tag{3.25}$$

Substituting equation (3.18) and (3.19) in above equation we get,

$$\frac{dF_{dr}{}^s}{dt} = \frac{L_m}{T_r} i_{ds}{}^s - \omega_r F_{qr}{}^s - \frac{1}{T_r}F_{dr}{}^s \tag{3.26}$$

$$\frac{dF_{qr}{}^s}{dt} = \frac{L_m}{T_r} i_{qs}{}^s + \omega_r F_{dr}{}^s - \frac{1}{T_r}F_{qr}{}^s \tag{3.27}$$

Where $T_r = L_r/R_r$ is rotor time constant. By sensing stator currents and speed we can determine flux vectors and unit vectors using equation (3.26) and (3.27). Since, it only uses current signals for flux estimation it is called as current model.

3.3.2 Indirect Vector Control

In indirect vector control unit vectors are generated in feedforward manner using following principle. Consider Fig. 3.8 the $d^s - q^s$ axes are fixed to stator and $d^r - q^r$ axes are fixed to rotor. The rotor axes $d^r - q^r$ are moving at an angular speed ω_r. the synchronously rotating $d^e - q^e$ axes are rotating ahead of $d^r - q^r$ axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl}. Since, rotor poles are directed on the d^e axis and $\omega_s = \omega_r + \omega_{sl}$, we can write

$$\theta_s = \int \omega_s \, dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \tag{3.28}$$

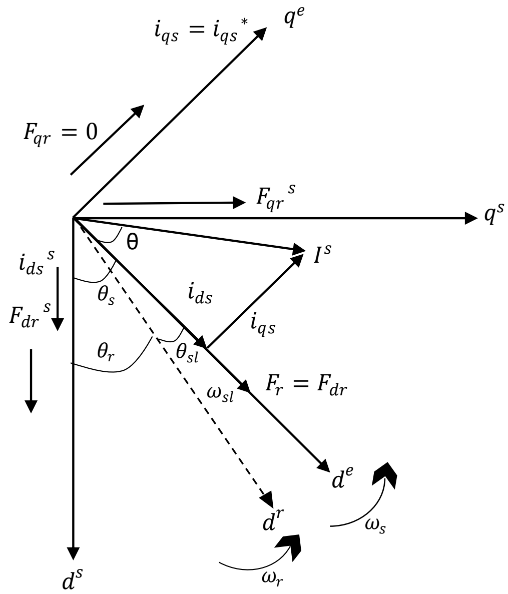

Figure 3.8 Phasor Diagram Explaining concept of Indirect Vector Control

Note that rotor pole position is not fixed, but it is lipping with respect to rotor at an angular frequency ω_{sl}. For decoupling control stator flux component i_{ds} should be align along d^e axis and torque component i_{qs} should be align along q^e axis. This can be achieved by deriving indirect vector control equation with the help of $d^e - q^e$ equivalent circuit of an induction motor as shown in Fig. 3.9.

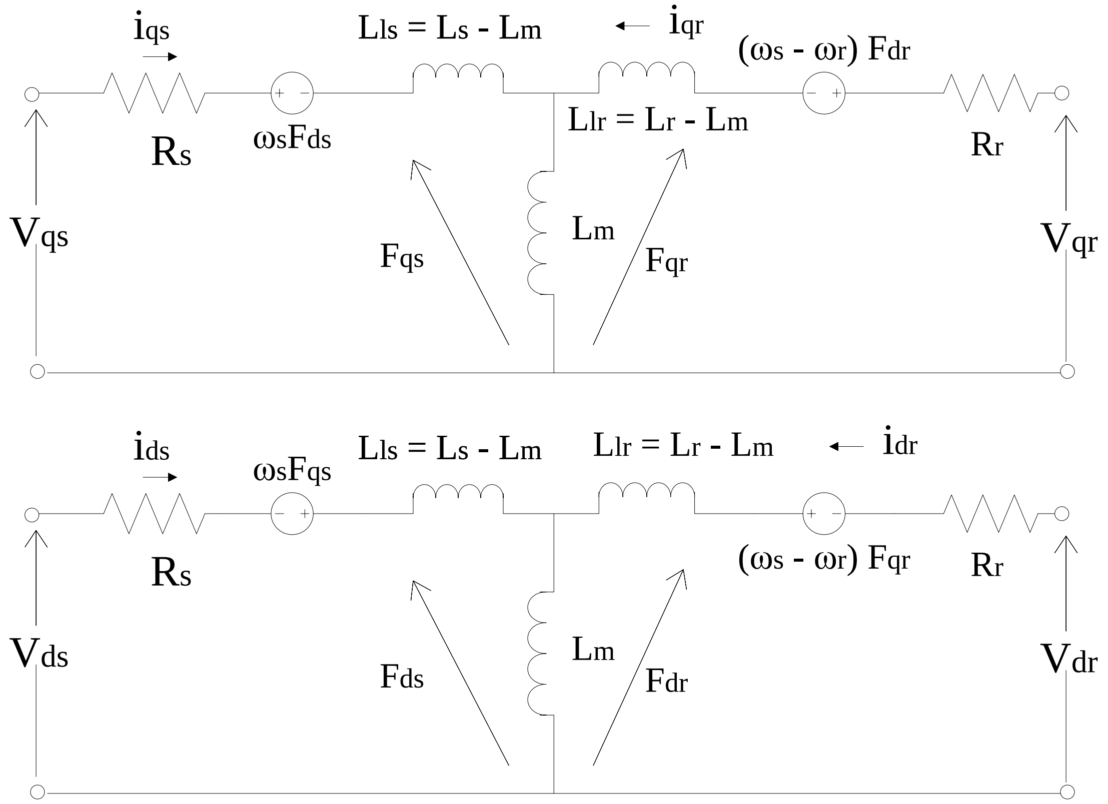

Figure 3.9 Dynamic d^e – q^e Equivalent Circuit of Induction Motor

$$\frac{dF_{dr}}{dt} + R_r i_{dr} - (\omega_s - \omega_r)F_{qr} = 0 \tag{3.29}$$

$$\frac{dF_{qr}}{dt} + R_r i_{qr} + (\omega_s - \omega_r)F_{dr} = 0 \tag{3.30}$$

The rotor flux linkage equation can be written as,

$$F_{dr} = L_r i_{dr} + L_m i_{ds} \tag{3.31}$$

$$F_{qr} = L_r i_{qr} + L_m i_{qs} \tag{3.32}$$

From above equation we can write

$$i_{dr} = \frac{1}{L_r} F_{dr} - \frac{L_m}{L_r} i_{ds} \tag{3.33}$$

$$i_{qr} = \frac{1}{L_r} F_{qr} - \frac{L_m}{L_r} i_{qs} \tag{3.34}$$

The rotor current in equation (3.29) and (3.30) can be eliminated using equation (3.33) and (3.34)

$$\frac{dF_{dr}}{dt} + \frac{R_r}{L_r} F_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl} F_{qr} = 0 \tag{3.35}$$

$$\frac{dF_{qr}}{dt} + \frac{R_r}{L_r} F_{qr} - \frac{L_m}{L_r} R_r i_{qs} + \omega_{sl} F_{dr} = 0 \tag{3.36}$$

Where $\omega_{sl} = \omega_s - \omega_r$

For decoupling control, F_r should be aligned with d^e axis which is possible when

$$F_{qr} = 0 \quad (3.37)$$

therefore,

$$\frac{dF_{qr}}{dt} = 0 \quad (3.38)$$

Substituting equations (3.37) and (3.38) in equation (3.35) and (3.36) we get

$$\frac{L_r}{R_r}\frac{dF_r}{dt} + F_r = L_m i_{ds} \quad (3.39)$$

$$\omega_{sl} = \frac{L_m R_r}{F_r L_r} i_{qs} \quad (3.40)$$

Where $F_r = F_{dr}$

Since rotor flux F_r is constant derivative of it becomes zero, thus

$$F_r = L_m i_{ds} \quad (3.41)$$

That is the rotor flux is directly proportional to current i_{ds} in steady state. The indirect vector control can be implemented using equation (3.28), (3.39) and (3.40) as shown in Fig. 3.10.

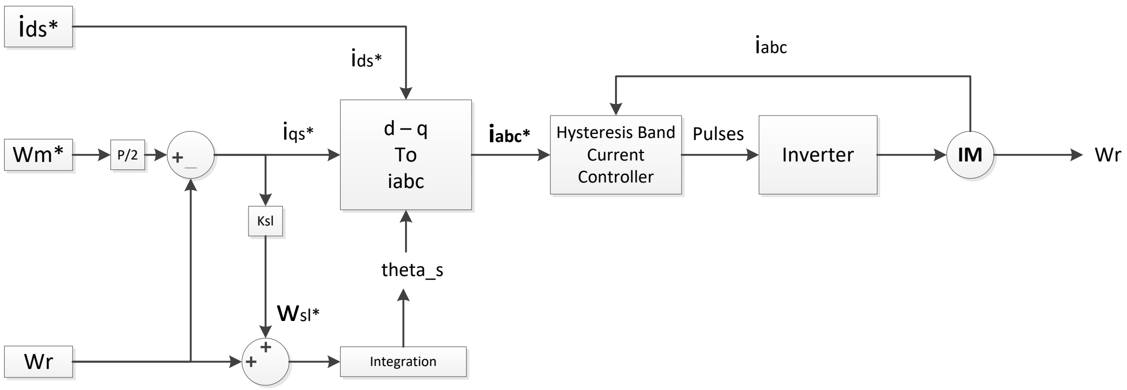

Figure 3.10 Block Diagram of Indirect Vector control

3.4 Direct Torque Control

The direct torque control technique is advanced scalar speed control method that provides superior performance like vector control methods. It allows direct control of torque and stator flux by selecting inverter voltage space vector from lookup table. The voltage and current of machine are sensed to estimate stator flux using equations (3.8) to (3.15) whereas the torque of motor can be obtained using follows equation.

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(F_{ds}{}^{s} i_{qs}{}^{s} - F_{qs}{}^{s} i_{ds}{}^{s}\right) \quad (3.42)$$

In DTC, the desired stator flux is compared with estimated flux value and error is given to hysteresis band flux controller. Similarly, the estimated torque is compared with desired torque obtain from speed control loop and error is passed to hysteresis band torque controller as shown in Fig. 3.11.

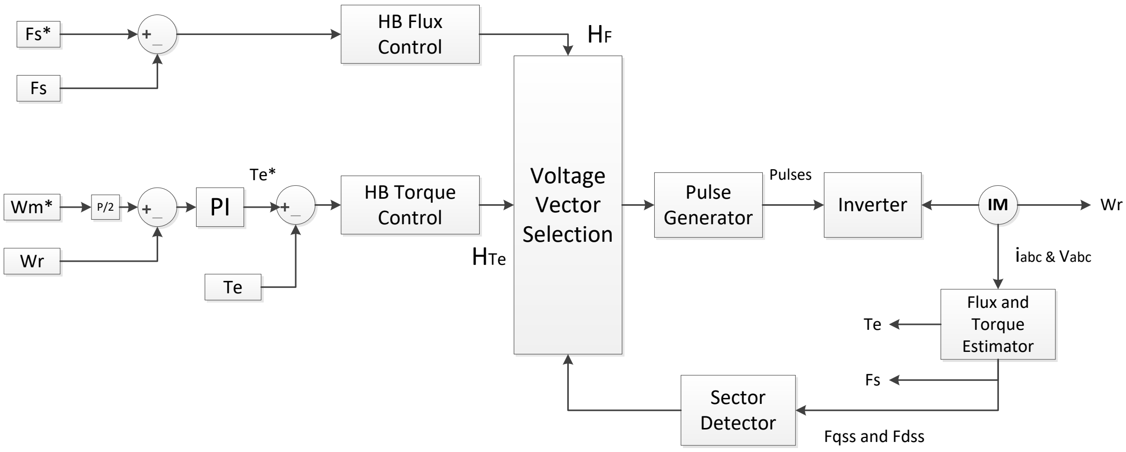

Figure 3.11 Block Diagram Of Direct Torque Control

The flux controller is having two digital output states according to following relations:

$$H_F = 1 \quad \text{for} \quad E_F > +HB_F \tag{3.43}$$

$$H_F = 0 \quad \text{for} \quad E_F < -HB_F \tag{3.44}$$

Where $2HB_F$ = total hysteresis bandwidth of Flux controller.

Whereas torque controller is having three digital output states which are as follows:

$$H_{Te} = +1 \quad \text{for} \quad E_{Te} > +HB_F \tag{3.45}$$

$$H_{Te} = -1 \quad \text{for} \quad E_{Te} < -HB_{Te} \tag{3.46}$$

$$H_{Te} = 0 \quad \text{for} \quad -HB_{Te} < E_{Te} < +HB_{Te} \tag{3.47}$$

The sector detector determines sector number in which flux vector Fs lies. The voltage vector selection block receives the signal H_F, H_{Te} and sector number and selects the appropriate voltage vector from lookup table, which is shown in Table 4 for controlling the flux or torque. This voltage vector is then given as input to pulse generator block which gives the switching states corresponding to that voltage vector to the inverter. The flux can be increased by using voltage vectors V_1, V_2 and V_6, whereas it can be decreased by using vectors V_3, V_4 and V_5. Similarly, the torque is increased by vector V_2, V_3 and V_4 but decreased by V_1, V_5 and V_6 vectors. Table 2 summarizes the effect of different voltage vectors on magnitude and direction of flux and torque. The zero vectors (V_0 and V_7) short-circuit the machine terminals and keeps the flux and torque unchanged.

Table 1 Switching Table of Inverter Voltage Vectors

H_F	H_{Te}	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_5	V_6	V_1	V_2	V_5	V_4

Table 2 Effect of Voltage Vectors on Magnitude and Direction of Flux and Torque

Voltage Vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0 or V_7
F_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

Consider, for example if flux vector is in sector 3 and flux is higher than the desired value that means $H_F = 0$ and if torque is very low then $H_{Te} = 1$. Now as per the table 1 the corresponding vector for this condition is V_3 which will decrease the flux and increase the torque. Thus, it results into very fast torque and speed response. The advantages of using DTC are it does not involve feedback current control, it does not use traditional PWM algorithm and it does not involve any vector transformation.

3.5 Conclusion

In this chapter working of scalar control, vector control and direct torque control technique is discussed in depth. Due to the simplicity of scalar control method it is widely used in the industry. The vector control methods and direct torque control method are very complex and requires voltage and current sensors for implementation. As these technique involves lot of calculation for feedback signal estimation high speed DSP is required. Different flux vector estimation techniques also discussed in this chapter.

CHAPTER 4

MODELING AND SIMULATION

4.1 Introduction

In this chapter the Simulink model of each speed control technique will be discussed in detail. The chapter also covers detail explanation of development of Full Spectrum Simulator (FSS) program for open-loop and closed-loop method.

4.2 Simulation Using MATLAB Simulink

The MATLAB Simulink is graphical block diagram environment which is widely used throughout the world due to its simplicity. In MATLAB Simulink different control techniques can be easily tested using different library component available [22]. The real-time implementation of any developed control strategy is possible by interfacing Simulink with advanced DSP kit such as dSPACE. The simulation of different speed control techniques of induction motor is performed as follows –

1. Open-loop V/f Method –

Fig. 4.1 shows MATLAB Simulink model of open-loop V/f method. The main components of this method are DC voltage source and PWM voltage source inverter. The desired speed command ω_m^* is given as input to the system which is then multiplied by V_s/ω_s ratio to obtain corresponding desired voltage and θ_s is obtain by integrating ω_s. The desired three- phase voltages are then calculated as shown in model which are fed to Sinusoidal Pulse Width Modulator (SPWM) which compares it with triangular carrier wave to generate pulses which are given to IGBT switches of three-phase inverter. The output of inverter is given to the motor.

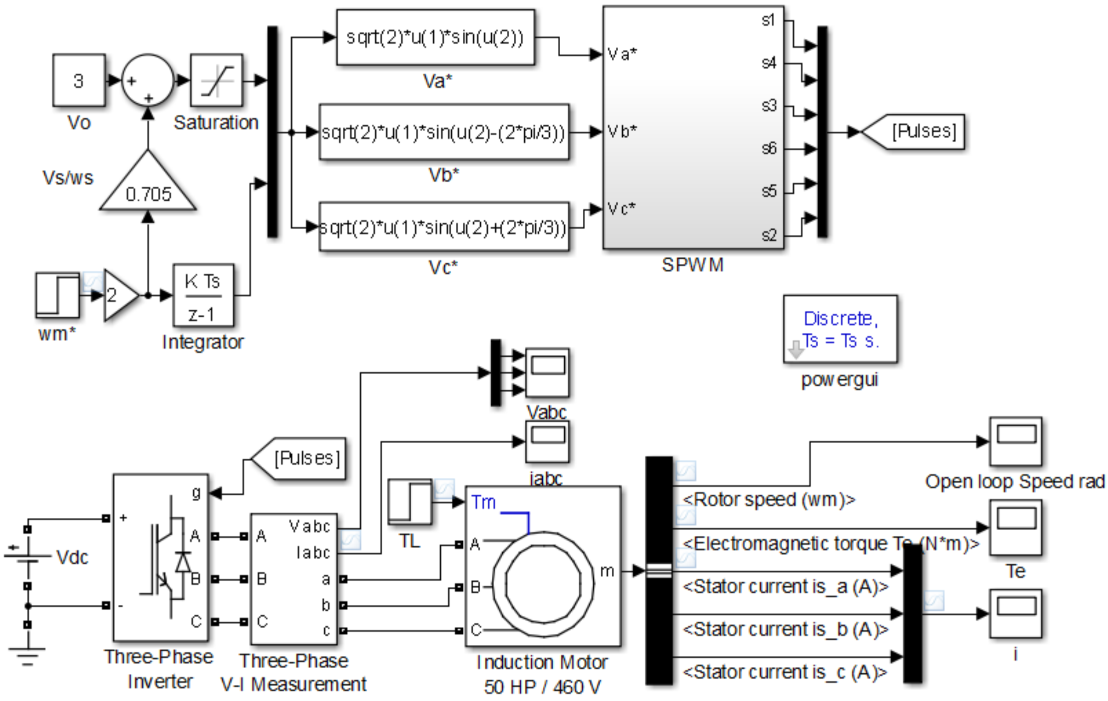

Figure 4.1 Open-loop V/f MATLAB Simulink Model

2. Closed-loop V/f Method –

The closed-loop V/f method is similar to the open-loop method it overcomes problems associated with it. In closed-loop method actual speed of motor is compared with desired speed of motor and error is fed to PI controller which calculated slip frequency ω_{sl}^* and then it is added with ω_r to obtain stator supply frequency ω_s^*, the remaining operation is same as open-loop method. When load torque is applied speed of motor reduces, PI controller then detects the reduction in speed and takes the corrective action by increasing ω_{sl}^* to maintain motor at desired speed. Fig. 4.2 shows MATLAB Simulink model of closed-loop method.

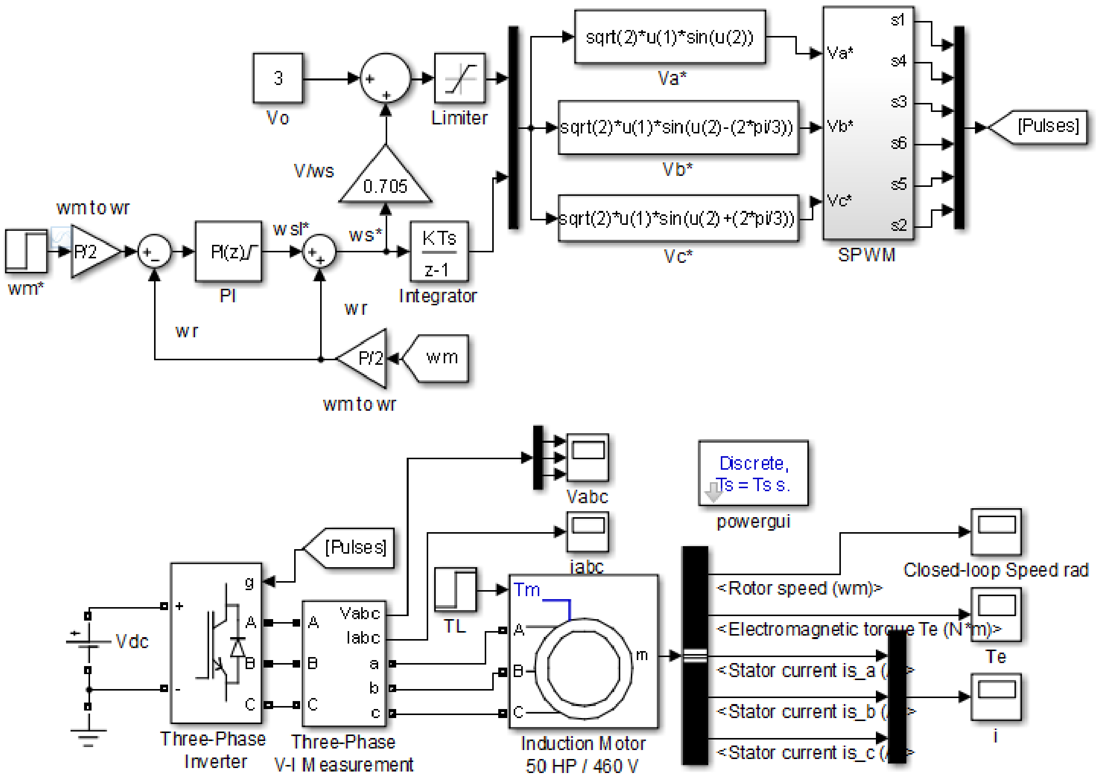

Figure 4.2 Closed-loop V/f MATLAB Simulink Model

3. Direct Vector Control –

Fig. 4.3 shows Simulink model of Direct Vector Control. The desired speed command ω_r^* is compared with instantaneous value of ω_r and passed to PI controller that generates stator quadrature axis component i_{qs}^*. The flux and unit vectors can be estimated with the help of current model estimator or using voltage model estimator as shown in Fig. 4.4 and 4.5 respectively. The estimated flux is compared with desired flux and fed to PI controller which generates stator direct axis component i_{ds}^*. These two rotating frame current are first converted into stationary frame using unit vector generated in feedback manner and finally into three-phase current. Current regulator i.e. hysteresis band current controller compares this three-phase current with corresponding instantaneous stator current in order to obtain PWM signal which is used to controller the inverter output voltage and frequency.

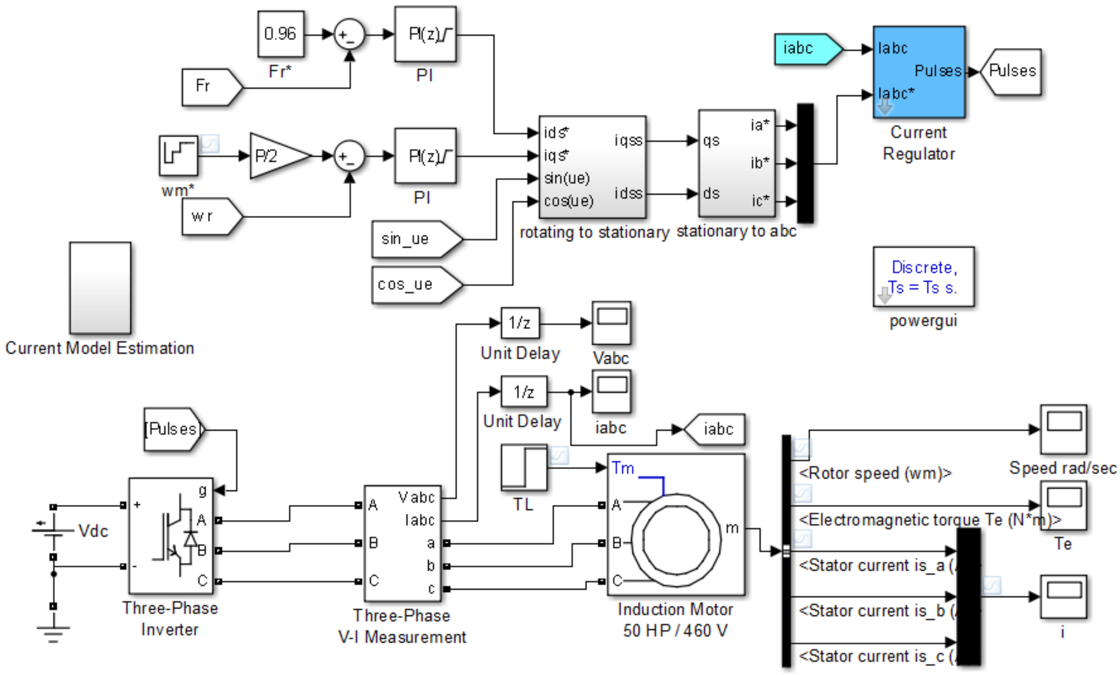

Figure 4.3 Direct Vector control MATLAB Simulink Model

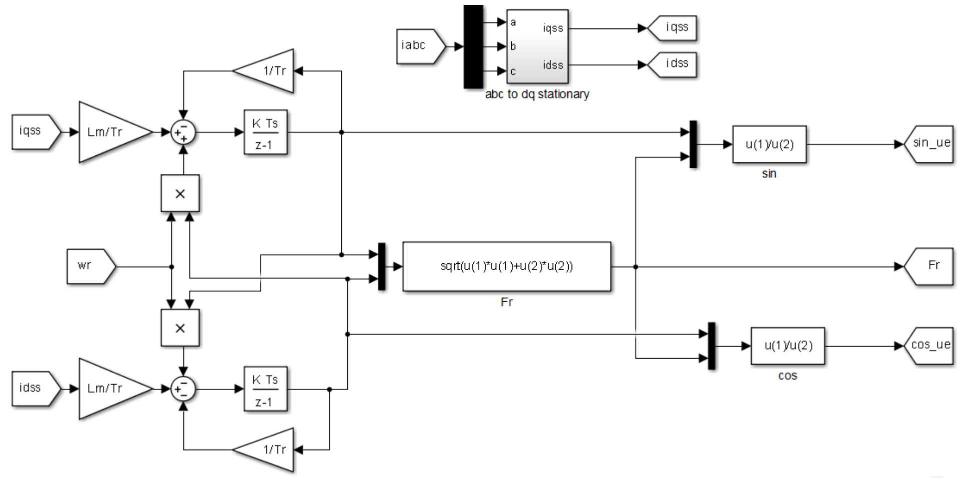

Figure 4.4 Current Flux Estimation MATLAB Simulink Model

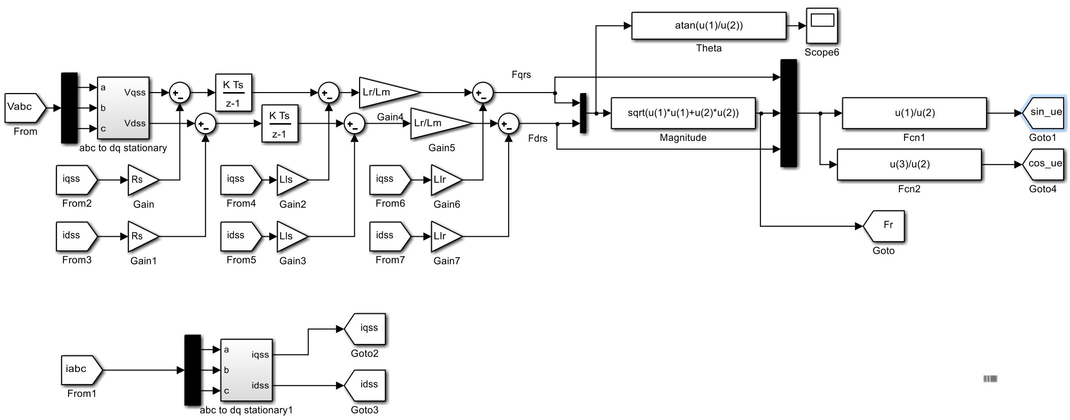

Figure 4.5 Voltage Flux Estimation MATLAB Simulink Model

4. Indirect Vector Control –

In indirect vector control, direct axis component of stator current i_{ds}^* is calculated using equation 3.40 and it is maintained constant for simplicity. The quadrature axis component i_{qs}^* is generated by speed control loop as shown in Fig. 4.6. In indirect vector control, slip frequency ω_{sl}^* is determined using equation 3.39 which is added with instantaneous value of ω_r that gives angular frequency ω_s. It is then integrated to get θ_s which is used to obtain unit vector signal $\cos(\theta_s)$ and $\sin(\theta_s)$.

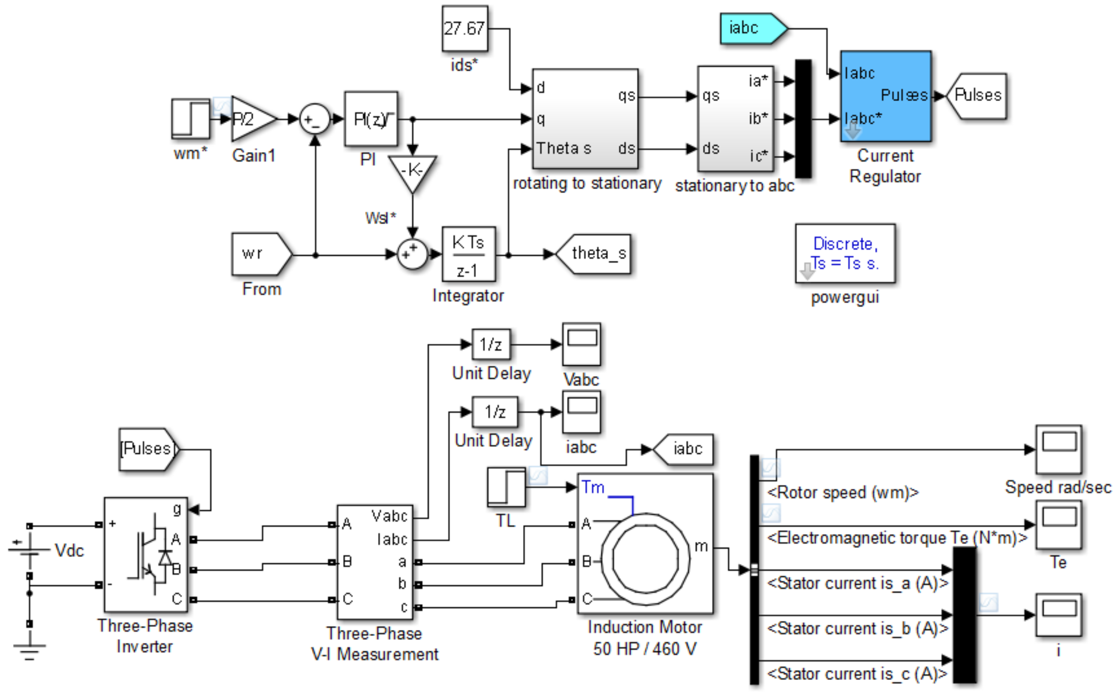

Figure 4.6 Indirect Vector Control MATLAB Simulink Model

5. Direct Torque Control –

In DTC, the flux and torque are directly controlled by inverter space vector selection through a look up table. In DTC flux and torque are estimated with the help of equation (3.8) – (3.15) by sensing machine terminal voltage and current. Desired flux is compared with instantaneous value and error is fed to flux control block which generates output 1 or 0 whenever error value exceeds the hysteresis band. Desired torque obtained from speed control loop is compared with actual torque of motor and error is passed to torque control block. As torque error exceeds the hysteresis band torque control block generates output 1 or 0 or -1. Considering the values obtained from flux control block, torque control block and sector in which flux vector is present the appropriate voltage vector is selected from lookup table. Pulses are then given to the inverter based on selected vector.

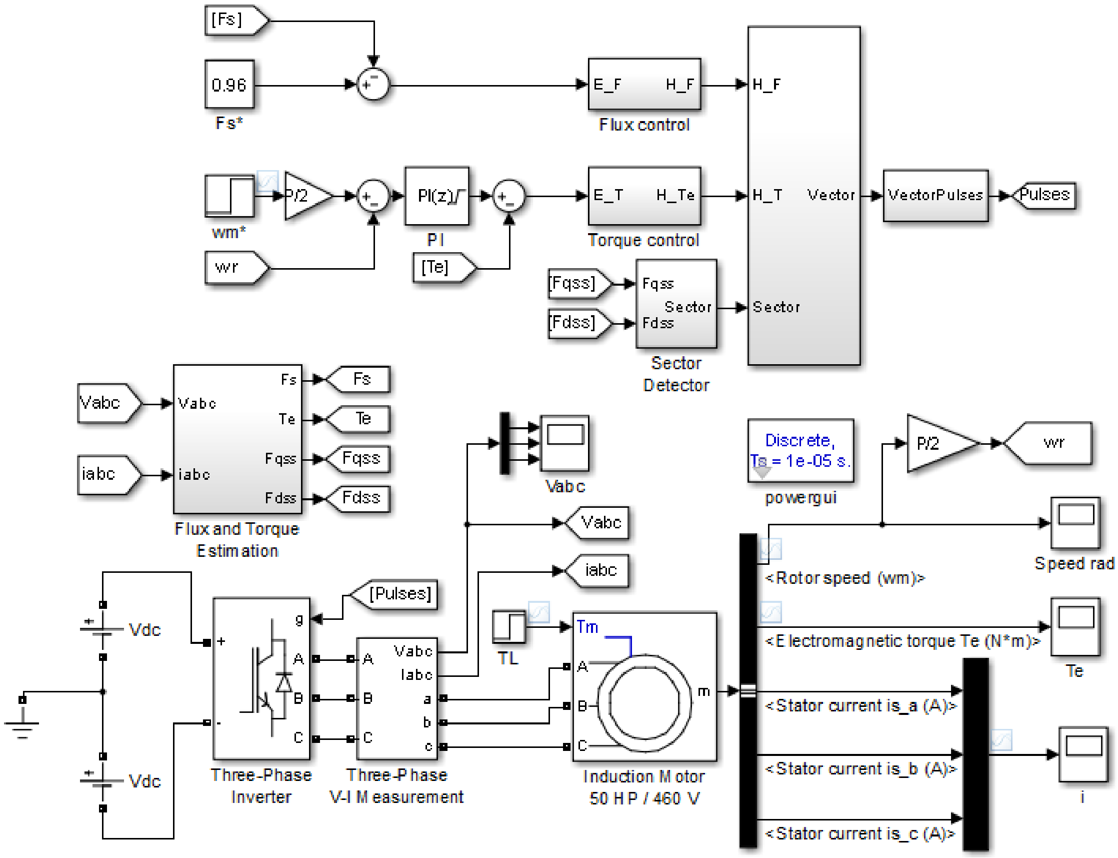

Figure 4.7 DTC MATLAB Simulink Model

4.3 Simulation Using FSS

FSS is an advanced real-time simulator that can be used to perform offline and real-time simulation by writing program in "C" language. For performing simulation, the program has to be written in specified format given by the manufacturer as shown in following programs. Before performing real-time simulation, the offline simulation result of written program should be examined and once this result is satisfactory the same program can be used for real-time simulation.

1. Open-loop V/f Method –

The simulation of open-loop V/f method is performed by writing program in "C" language and executing it using FSS software. The program is written as per the block diagram shown in Fig. 3.1. In FSS simulation we have to call various required elements from library in program by using command "gelement type". The program for open-loop V/f method is given in Appendix 1. In this program to give step speed command “pulse” element is used which initially give command of 100 rad/sec then at t = 1 sec speed is increased to 150 rad/sec. The speed command is then given to “v_and_f_control” element which calculates desired three-phase voltage as shown in block diagram. These voltages are then given to SPWM block which consists of “triangle_3” element that generates triangular carrier wave of given frequency and comparator element “cmprtr_1a”. The PWM signal is then given to inverter element “invrtr_3ph” to which induction motor is connected. The load torque command is also given using “pulse” element which increases the load to 190 N.m. at t = 2 sec. The speed, torque and current response is observed using “out_port” element. Simulation time, discrete sampling time and solver is mentioned in the “solve block” section.

2. Closed-loop V/f Method –

To perform the simulation of closed-loop V/f the program is written as per block diagram shown in Fig. 3.3. The program is similar to the open-loop method except it includes speed control loop. The actual speed of motor is fed back using element “feedback_gain”. The desired speed and actual speed are compared using element “diff_2” and error is given to PI controller element “picntrl” which gives slip frequency ω_{sl}. It is then added with actual motor speed to obtain supply frequency which is given to “v_and_f_control”. The remaining operation of closed-loop method is same as the open-loop method. The program of closed-loop V/f method is given in Appendix 2.

4.4 Conclusion

It is observed that developing speed control techniques in MATLAB Simulink was bit easy when only offline simulation is required. The FSS offered great flexibility in developing new control strategy or during designing new components as per requirement but its programing is bit tiresome. The real-time simulation capability of FSS is valuable when it comes to testing any prototype.

CHAPTER 5

HARDWARE IMPLEMETATION USING DSPACE

5.1 Introduction

This chapter describes the different equipment's used in the implementation of open-loop and closed-loop speed control strategies. The pros and cons of various voltage level shifting circuit will be discussed in detail. The test conducted to find parameters of IM will be discussed. The steps involved in the implementation of any control strategy using dSPACE have been described. The Simulink model used for implementation will also be discussed in this chapter.

5.2 Component Details

Open-loop and closed-loop V/f speed control methods are implemented on a laboratory prototype using dSPACE. The laboratory setup consists of a 3 phase induction motor of rating 3HP, 415V, 50Hz fed by a VSI. The block diagram of laboratory setup is as shown in Fig. 5.1 whereas Fig. 5.2 shows the experimental setup used for implementation of these technique. The switching signals for the switches of VSI is obtained using SPWM technique and given through DS1104 dSPACE controller.

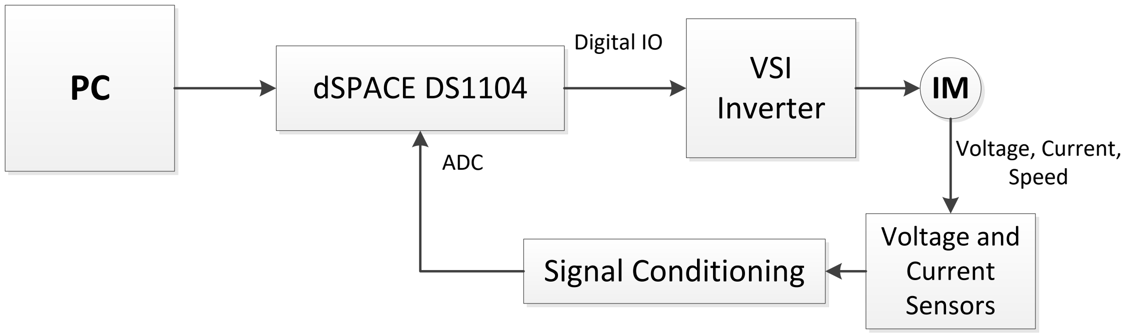

Figure 5.1 Block Diagram of Laboratory Setup

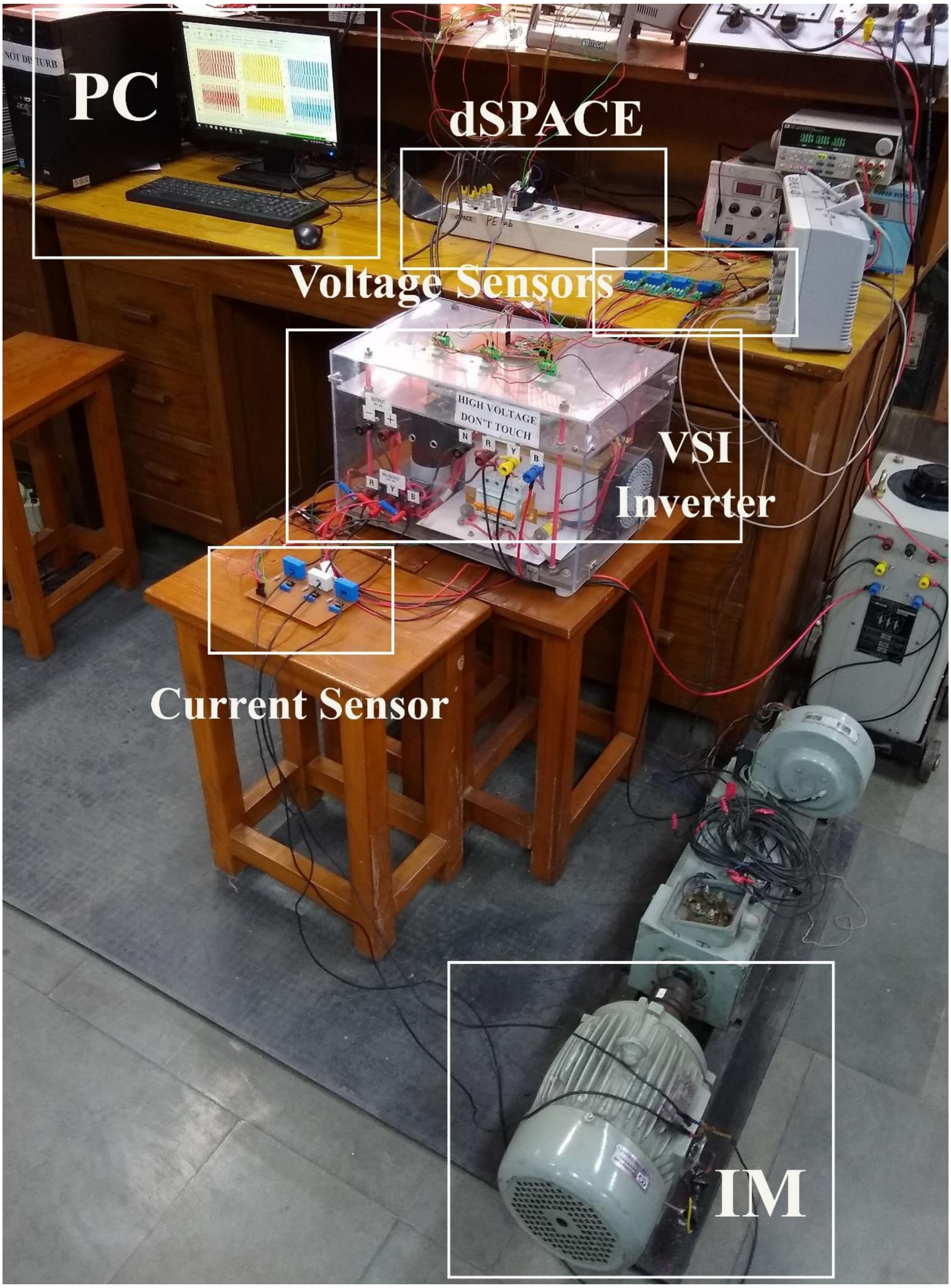

Figure 5.2 Experimental Setup

The specification of various components and equipment's used for the hardware setup is as follows –

1. dSPACE DS 1104 –

The dSPACE with following specification is used for hardware implementation of various speed control techniques [23].

Table 3 Specification of dSPACE

Processor	64-bit 250 MHZ
Memory	32 MB SDRAM
Timer	Four 32-bit Down Counters, one 64-bit Up Counter
A/D Converter	4 Multiplexed 16-bit Channel, 4 parallel 12-bit Channel. The input voltage range is +/- 10V
D/A Converter	Eight 16-bit Channels. The output voltage range is +/- 10V
Digital I/O	20-bit parallel I/O
Digital Encoder Interface	2 Channels 24-bit resolution
Serial Interface	Single UART, RS232/RS422/RS485 Compatible
Slave DSP	10 PWM outputs, 4 Capture inputs, 1 Serial Peripheral Interface

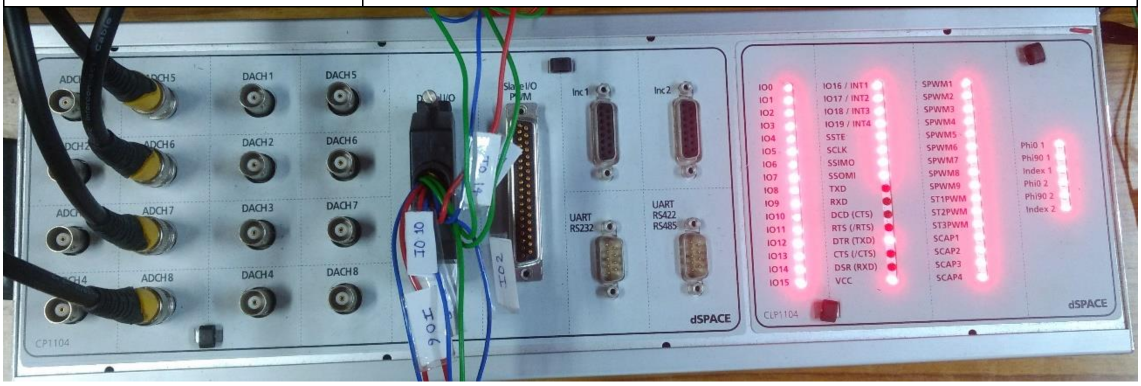

Figure 5.3 dSPACE DS 1104

2. 3 Hp Crompton Three-Phase Squirrel-Cage Induction Motor Coupled with 3 Hp Kirloskar DC Generator and Tachogenerator.

Figure 5.4 Induction Motor Coupled with DC generator and Tachogenerator

3. Semikron Three-Phase Rectifier and Inverter –

It consists of following components –

- Silicotronics B6U100A three-phase bridge module whose voltage rating is 2500V and 100A output DC current.
- SKM75GB12T4 half bridge IGBT module whose maximum collector emitter voltage is 1200V and 75A collector current. The IGBT module can be used for switching frequency up to 20KHz.
- Skyper 32 gate driver is used which has two output channels. It provides various protections such as under voltage protection, driver interlock top/bottom, dynamic short circuit protection [24].

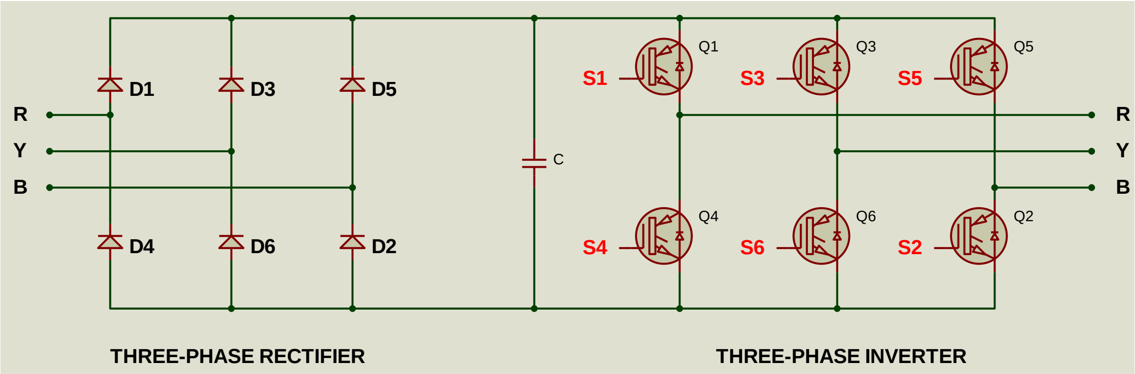

Figure 5.5 Block Diagram of Semikron Three-Phase Rectifier and Inverter

Figure 5.6 SKYPER 32 Gate Driver Module

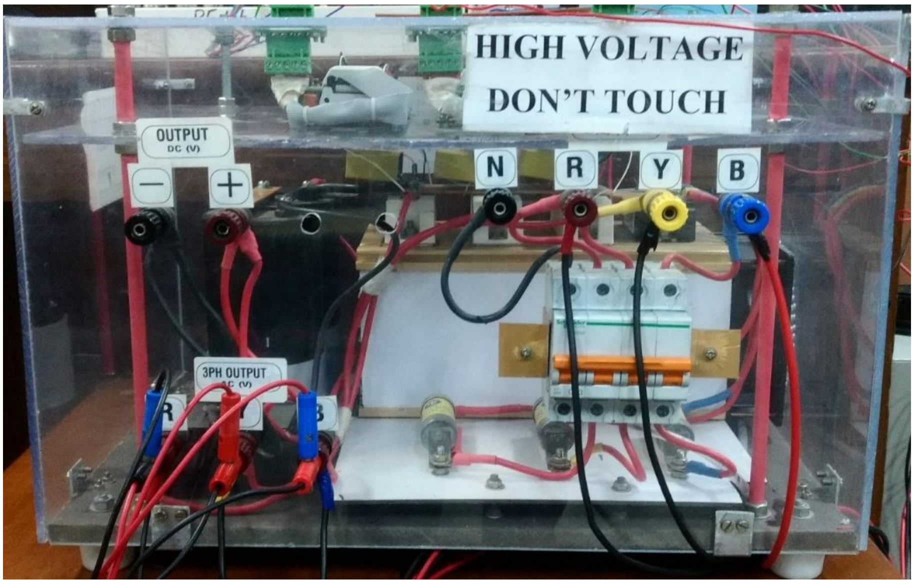

Figure 5.7 Semikron Three-phase Rectifier and Inverter

4. LV25-P/SP2 Voltage Sensor –

This sensor is designed to measure high DC/AC voltage. It is capable of measuring voltage up to 1500V. It provides galvanic isolation between primary side (high voltage side) and secondary side (electronic circuit side). Its working is based on hall effect. It has high accuracy, good linearity, high immunity to external interference and low response time [25].

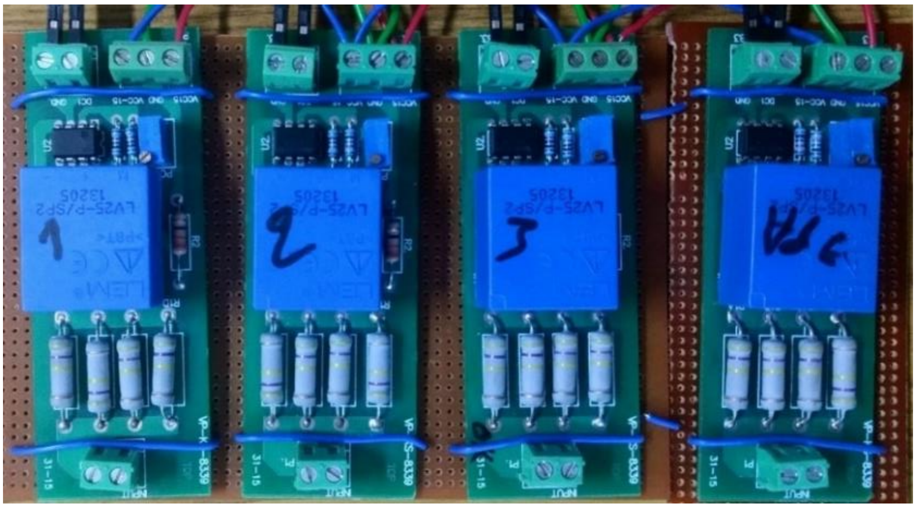

Figure 5.8 LV 25 – P / SP2 Voltage Sensor

5. LA 55-P Current Sensor –

This sensor is designed for the measurement of high DC/AC current. It also provides galvanic isolation like voltage sensor. It operates on the principle of hall effect and it is capable of measuring current up to 50A. It provides high accuracy, good linearity optimized response time, and has high immunity to external interference [26].

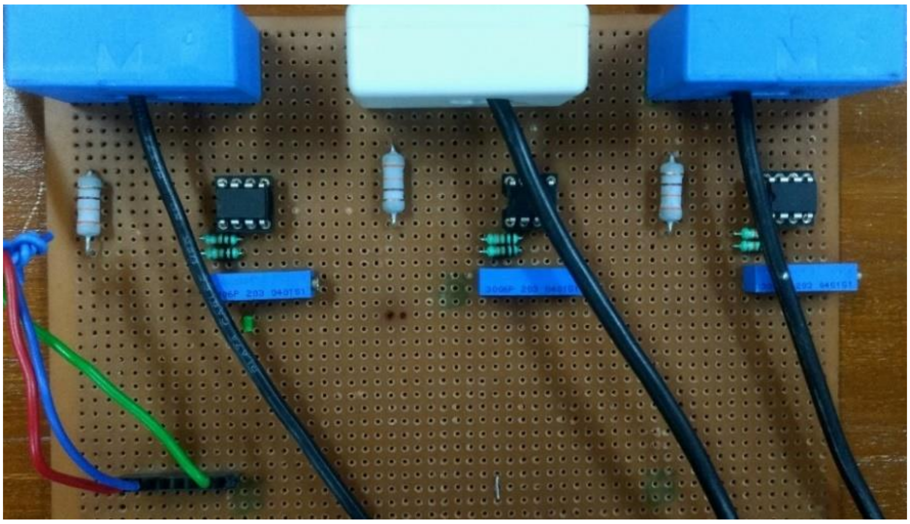

Figure 5.9 LA 55-P Current Sensor

6. Voltage Level Shifting circuit using IC 7406 and Transistor 2N2222 –

The signal obtain from dSPACE is amplified to 15V from 5V using following circuit. The detail of this circuit is mentioned in next section.

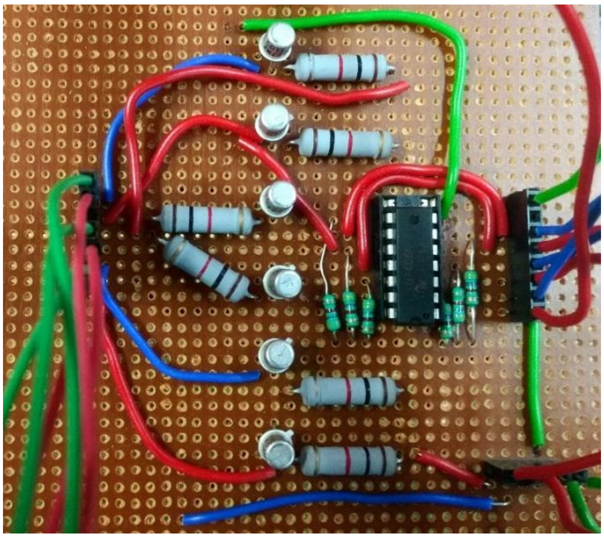

Figure 5.10 Voltage Level Shifting Circuit on Zero PCB

5.3 Voltage Level Shifting circuit for Gate Driver Circuit

Digital I/O ports of dSPACE are used to obtain pulses for controlling the switching of IGBT's of inverter. The output voltage of digital I/O ports is +5V and 0V representing logic 1 and logic 0 respectively. However, the driver circuit used for switching of IGBT's need +15V supply. The IGBT gate driver is used to offer various protections. Thus, voltage level shifting circuit is used to give switching signals to this driver. The various voltage level shifting circuit tested while performing experiment are as follows –

1. Using hex Inverter IC 7406 and Transistor 2N2222 –

IC 7406 is 14 pin IC which is having high source current and sink current capability. It is consisting of 6 hex inverter buffer. It has high voltage open collector output which allows us to interface with high voltage and high current circuits such as IGBT. The output of hex inverter is given to base of transistor 2N2222 using 4.7K pull up resistor. As transistor is capable of carrying collector current up to 800mA it is used in this circuit. The output of transistor is given to SKYPER 32 driver circuit of the IGBT inverter.

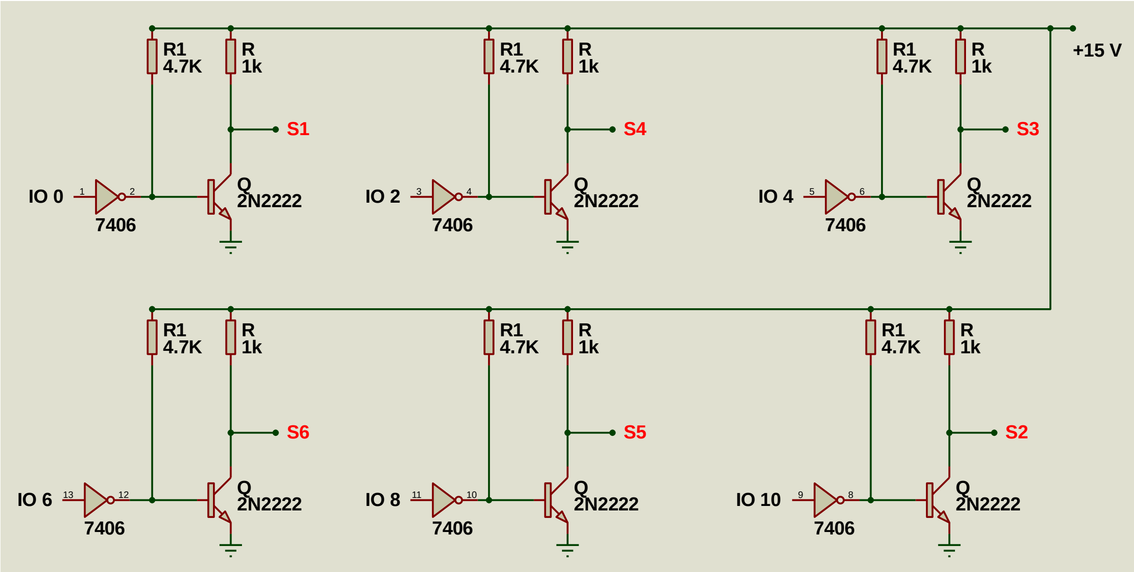

Figure 5.11 Voltage Level Shifting Circuit using IC 7406

2. Circuit using TLP 250 –

TLP 250 is 8-lead DIP package IGBT gate Driver IC which provides optical isolation between controller and IGBT. It consists of light emitting diode and integrated photodetector. The signal from controller is given to LED of IC which is detected by detector. The output of detector is given to totem pole configuration of transistor. The output is then taken from pin number 6 and given to the IGBT. The advantage of using it is it has sourcing and sinking current capability up to 1.5 A. Since, SKYPER 32 gate driver circuit providing various protection and isolation there is no need of using this gate driver circuit.

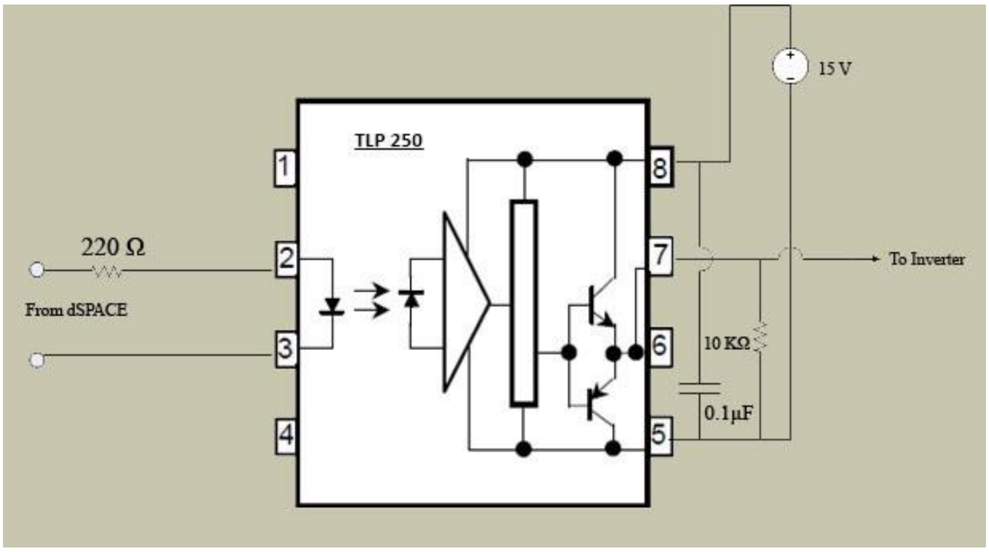

Figure 5.12 Voltage Level Shifting Circuit using TLP 250

3. Circuit Using Transistor –

It is very simple circuit tested during performing experiment. The problem with this circuit is that there is no isolation between dSPACE digital I/O port and transistor circuit. This might damage these ports permanently hence mostly this circuit is not used.

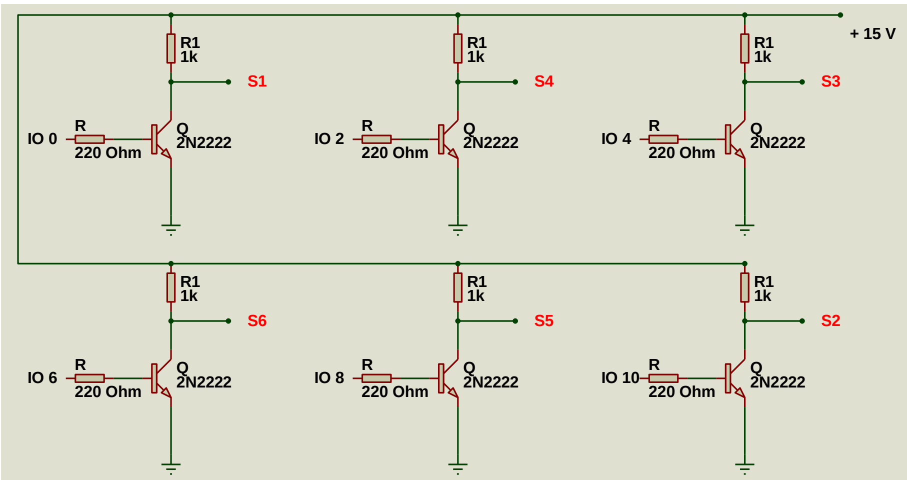

Figure 5.13 Voltage Level Shifting Circuit Using Transistor

4. Circuit using IC 6N137 and UA741 –

In this circuit the signal from dSPACE is given to the Optocoupler IC 6N137 to provide isolation. The output is then fed to Op-amp IC UA741 to amplify the voltage. The problem with this circuit is that it does not provide high source and sink current capability.

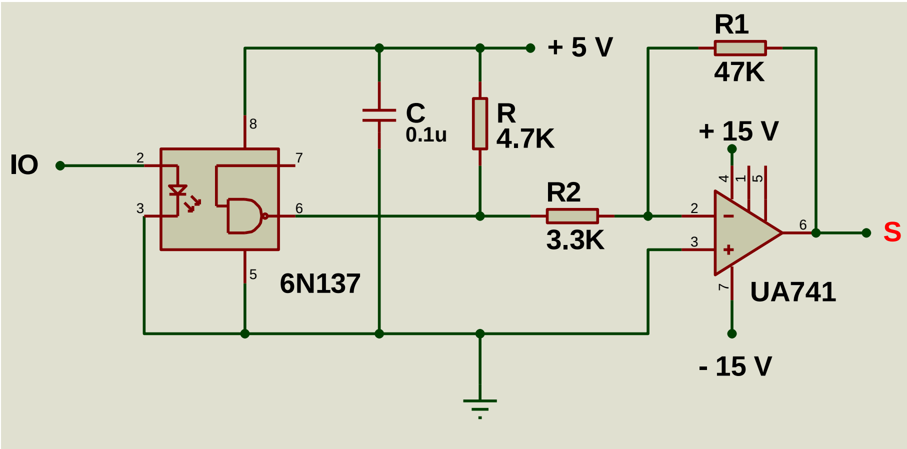

Figure 5.14 Voltage Level Shifting Circuit Using IC 6N137 and UA741

5.4 Calculation of Induction Motor Parameters

The equivalent circuit parameters of three-phase induction motor for hardware implementation are determined by performing No Load Test, Blocked Rotor Test and DC test [27] – [28].

1. No Load Test –

The no load test is performed to obtain the value of magnetizing inductance by supplying 415V (line-line), 50 Hz supply to balanced three-phase stator winding under no load. Phase Voltage (V_{nl}), Phase Current (I_{nl}) and per phase input power (P_{nl}) are measured using power analyzer whose readings are as shown in Fig. 5.15 and 5.16.

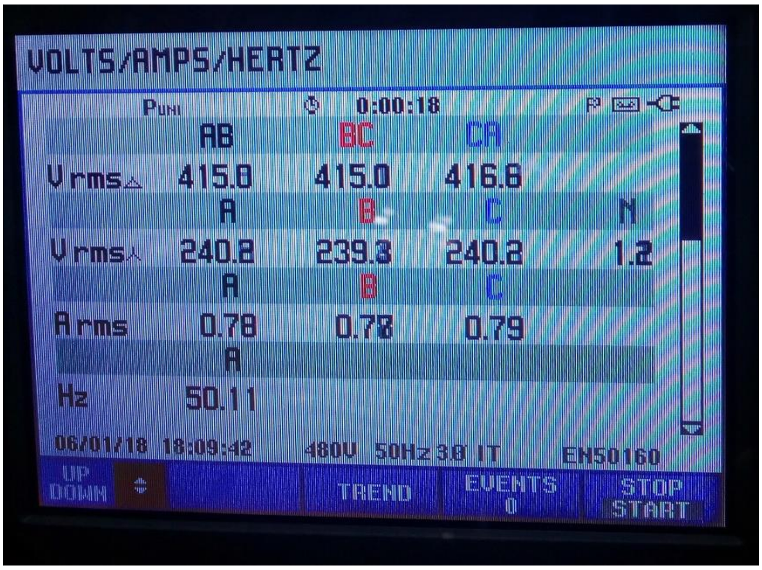

Figure 5.15 No Load Test Voltage and Current Reading

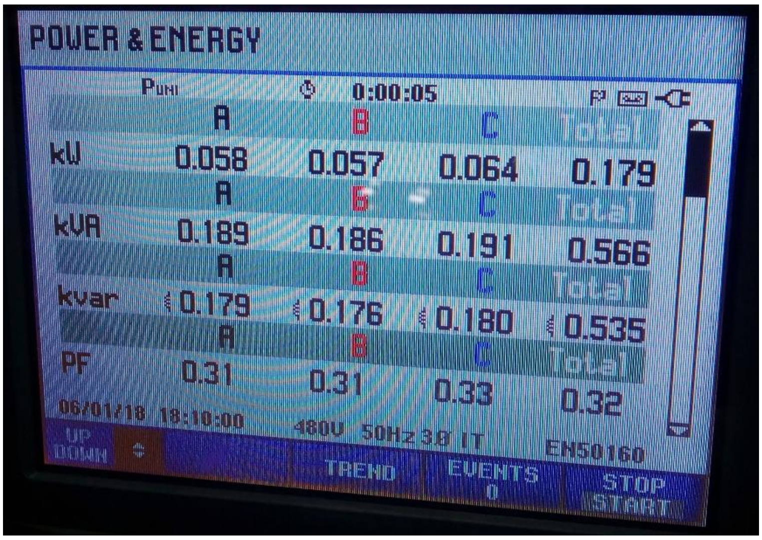

Figure 5.16 No Load Test Power Reading

From No Load Test,

V_{nl} = 240 V, I_{nl} = 0.8 A, P_{nl} = 60 W

$$Z_{nl} = \frac{V_{nl}}{I_{nl}} \tag{5.1}$$

$$\therefore\ Z_{nl} = \frac{240}{0.8} = 300\ \Omega$$

$$R_{nl} = \frac{P_{nl}}{{I_{nl}}^2} \tag{5.2}$$

$$\therefore\ R_{nl} = \frac{60}{0.8^2} = 93.75\ \Omega$$

$$X_{nl} = \sqrt{{Z_{nl}}^2 - {R_{nl}}^2} \tag{5.3}$$

$$\therefore\ X_{nl} = \sqrt{300^2 - 93.75^2} = 284.97\ \Omega$$

2. Blocked Rotor Test –

Blocked rotor test is carried out to find the value of rotor resistance and leakage inductance of stator and rotor. This test is performed by blocking rotor using hand and slowly increasing the voltage till the current flowing through the stator is equal to the rated value. Similar to no load test Phase Voltage (V_{br}), Phase Current (I_{br}) and per phase input power (P_{br}) are measured using power analyzer whose reading are as shown in Fig. 5.17 and 5.18.

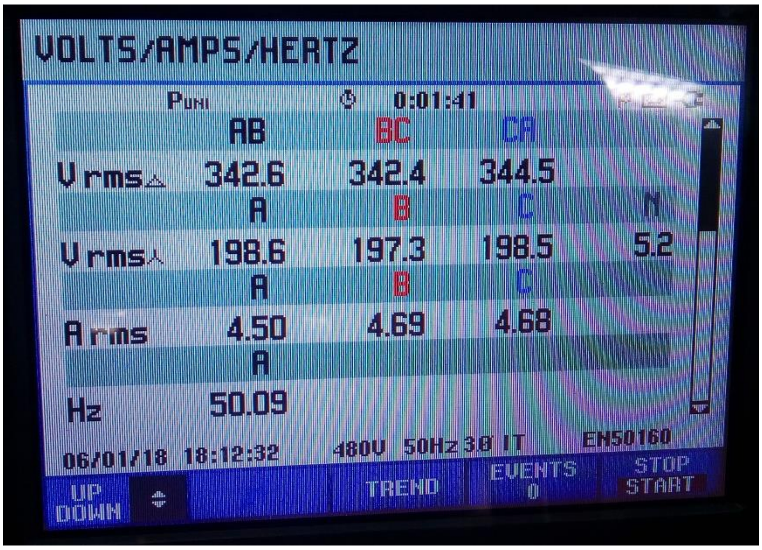

Figure 5.17 Blocked Rotor Voltage and Current Reading

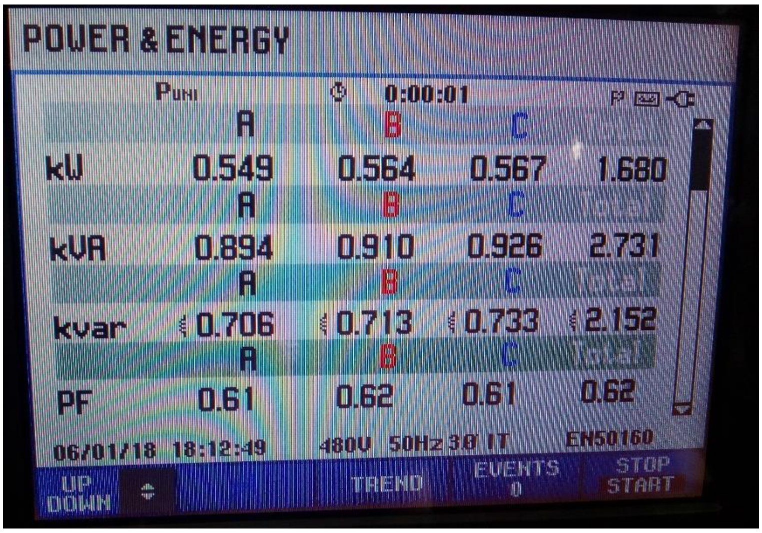

Figure 5.18 Blocked Rotor Power Reading

From Blocked Rotor Test,

V_{br} = 198 V, I_{br} = 4.7 A, P_{br} = 567 W

$$Z_{br} = \frac{V_{br}}{I_{br}} \tag{5.4}$$

$$\therefore \; Z_{br} = \frac{198}{4.7} = 42.12\,\Omega$$

$$R_{br} = \frac{P_{br}}{{I_{br}}^2} \tag{5.5}$$

$$\therefore \; R_{br} = \frac{567}{4.7^2} = 25.66\,\Omega$$

$$X_{br} = \sqrt{{Z_{br}}^2 - {R_{br}}^2} \tag{5.6}$$

$$\therefore \; X_{br} = \sqrt{42.12^2 - 25.66^2} = 33.40 \, \Omega$$

$$X_{ls} = X_{lr} = \tfrac{1}{2} X_{br} \quad (5.7)$$

$$\therefore \; X_{ls} = X_{lr} = \frac{1}{2} * 33.40 = 16.7 \, \Omega$$

$$\therefore \; L_{ls} = L_{lr} = \frac{16.7}{2 * 3.14 * 50} = 0.05318 \, H$$

$$X_m = X_{nl} - X_{ls} \quad (5.8)$$

$$\therefore \; X_m = 284.97 - 16.7 = 268.27 \, \Omega$$

$$\therefore \; L_m = \frac{268.27}{2 * 3.14 * 50} = 0.85 \, H$$

$$X_r = X_m + X_{lr} \quad (5.9)$$

$$\therefore \; X_r = 268.27 + 16.7 = 284.97 \, \Omega$$

3. DC Test –

DC test is performed to determine the stator resistance by passing rated current through the two terminals of stator winding. Then the current flowing through stator winding and voltage across them is measured. Since motor is star connected when we supply rated current through two terminals two phases of stator winding appears in series. Thus, stator resistance is given as follows

$$R_s = \frac{1}{2} \frac{V_{dc}}{I_{dc}} \quad (5.10)$$

$$R_s = \frac{1}{2} * \frac{112}{4.8} = 11.66 \, \Omega$$

$$R_r = (R_{br} - R_s) * \left(\frac{X_r}{X_m}\right)^2 \quad (5.11)$$

$$R_r = (25.66 - 11.66) * \left(\frac{284.97}{268.27}\right)^2 = 15.79 \, \Omega$$

The equivalent circuit parameters of induction motor used for hardware implementation obtained from above calculation are tabulated below.

Table 4 Parameters of Induction Motor used for Hardware Implementation

Stator Resistance (R_s)	11.66 Ω
Rotor Resistance (R_r)	15.79 Ω
Stator and Rotor Leakage Inductance (L_{ls}, L_{lr})	0.05318 H
Magnetizing Inductance (L_m)	0.85 H

5.5 Steps Before Building Simulink Model

After successfully testing the developed control strategy using MATLAB simulation it can be used for hardware implementation. When first time building the developed control technique for real-time implementation the following steps should be taken otherwise the model will show different types of errors [29] – [32].

1. Open MATLAB and select dSPACE RTI Platform Support RTI 1104 –

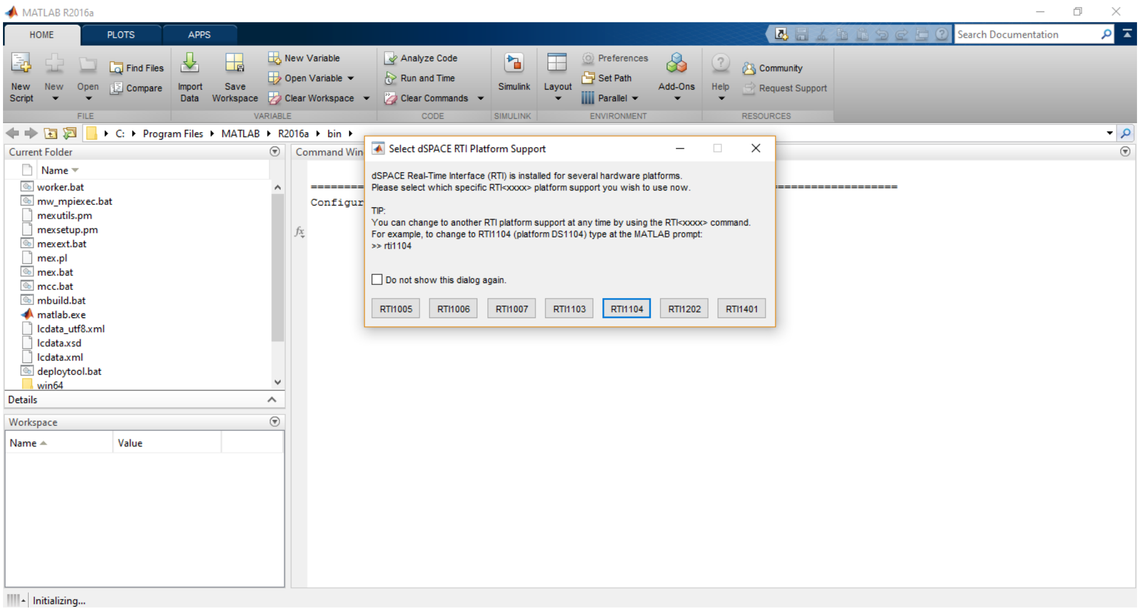

Figure 5.19 Step One Selecting RTI Platform for Building Simulink Model

2. Open Simulink Model –

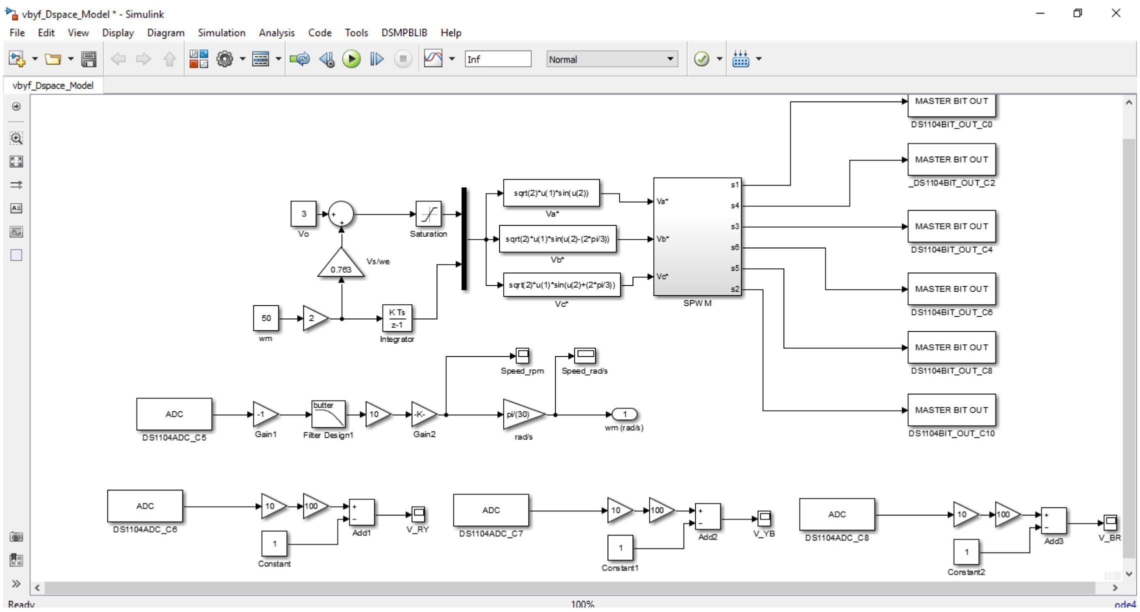

Figure 5.20 Step Two Opening Simulink Model

3. Open Configuration Parameter Window –

Change stop time to infinite, make solver type as fixed step and select solver from list. Set fixed-step size 100 μsec.

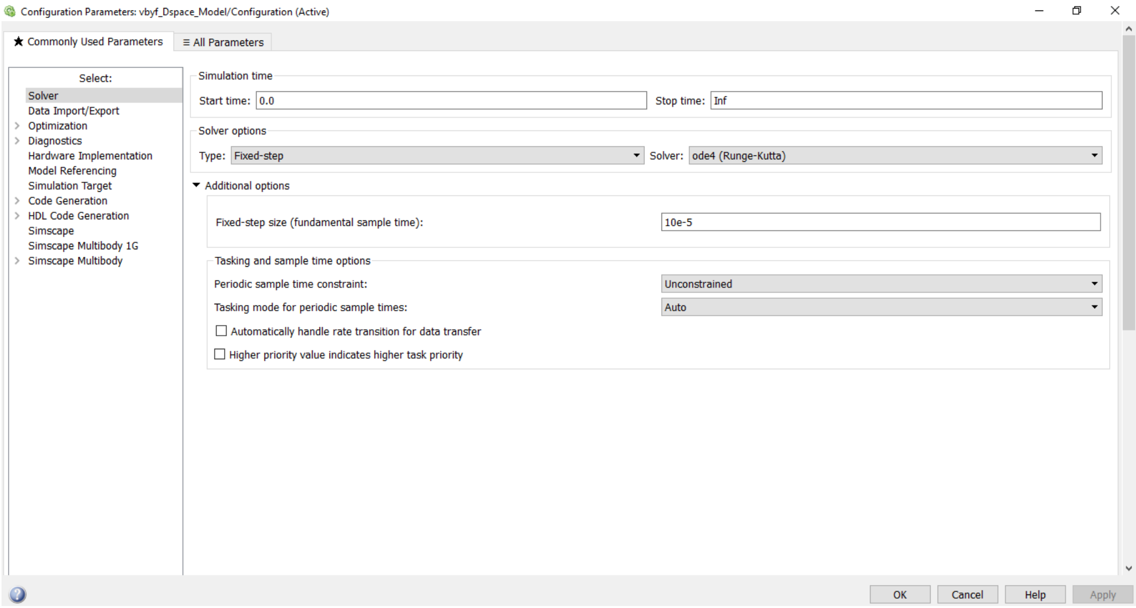

Figure 5.21 Step Three Change Configuration Parameter

4. Select Code Generation and set System Target file –

Set system target file to "rti1104.tlc".

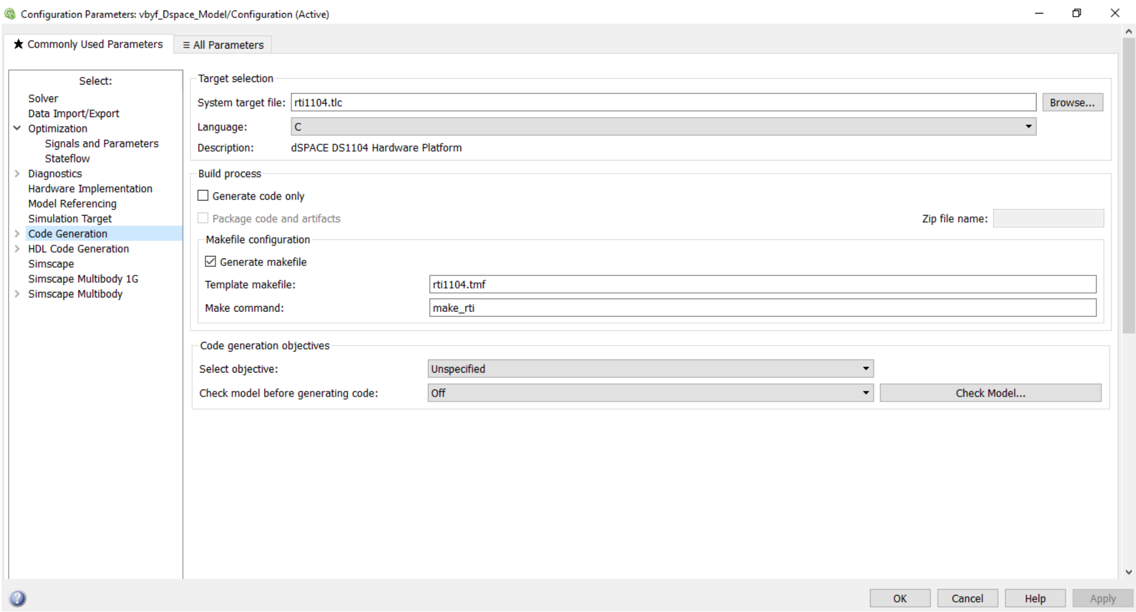

Figure 5.22 Step Four Selecting System Target File

5. Go to RTI Load Option –

Uncheck load application after build.

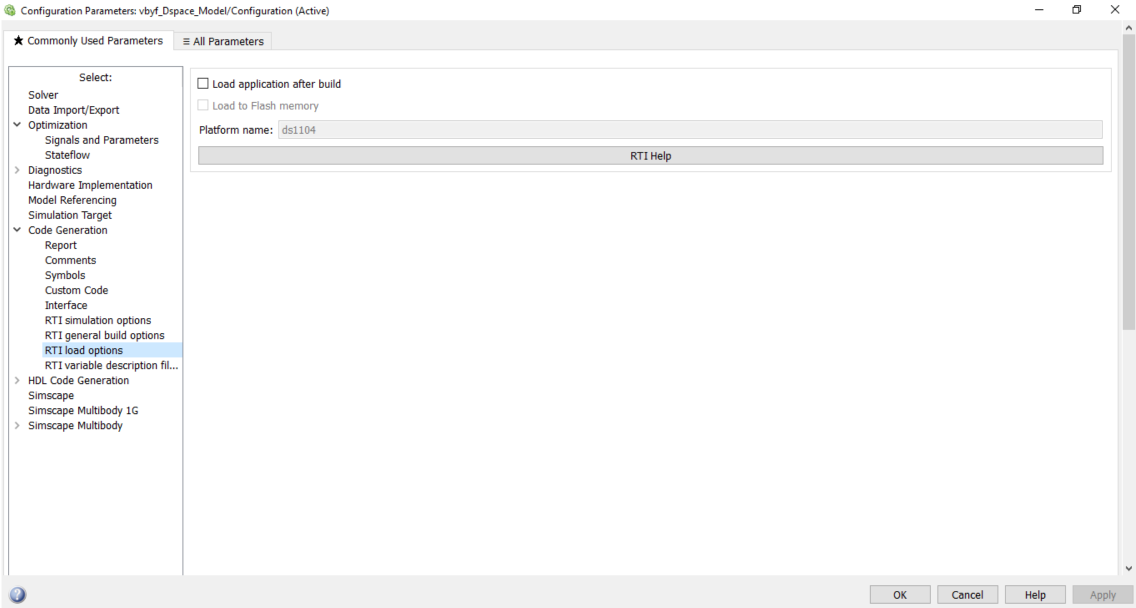

Figure 5.23 Step Five Setting RTI Load Options

6. Go to All Parameter tab and select optimization category –

Uncheck Block reduction, Conditional input branch execution and Signal Storage Reuse.

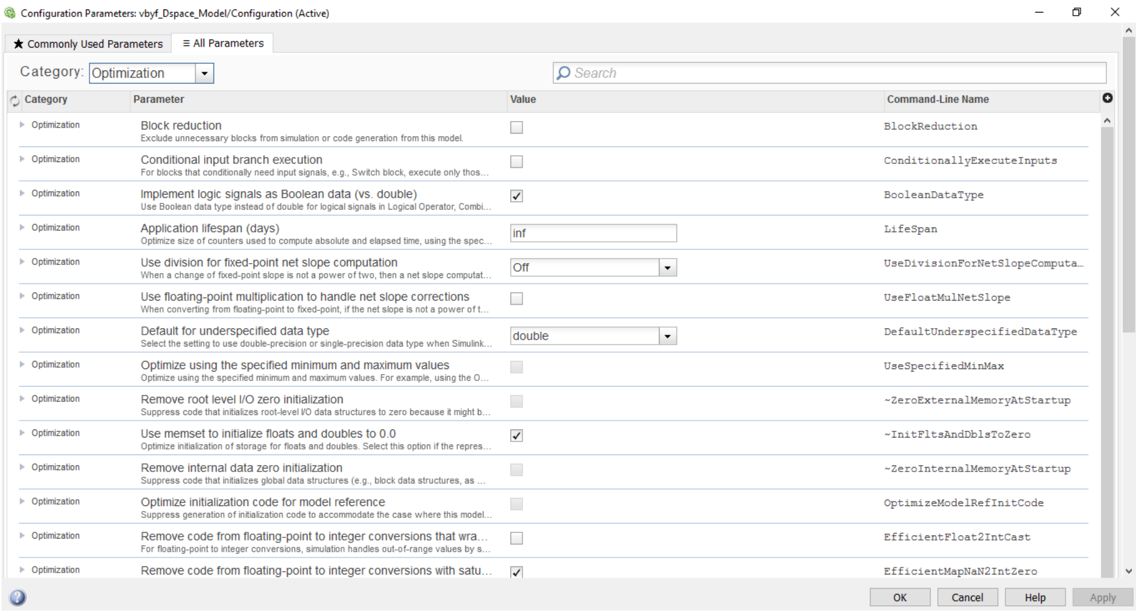

Figure 5.24 Step Six Unchecking Optimization Parameters

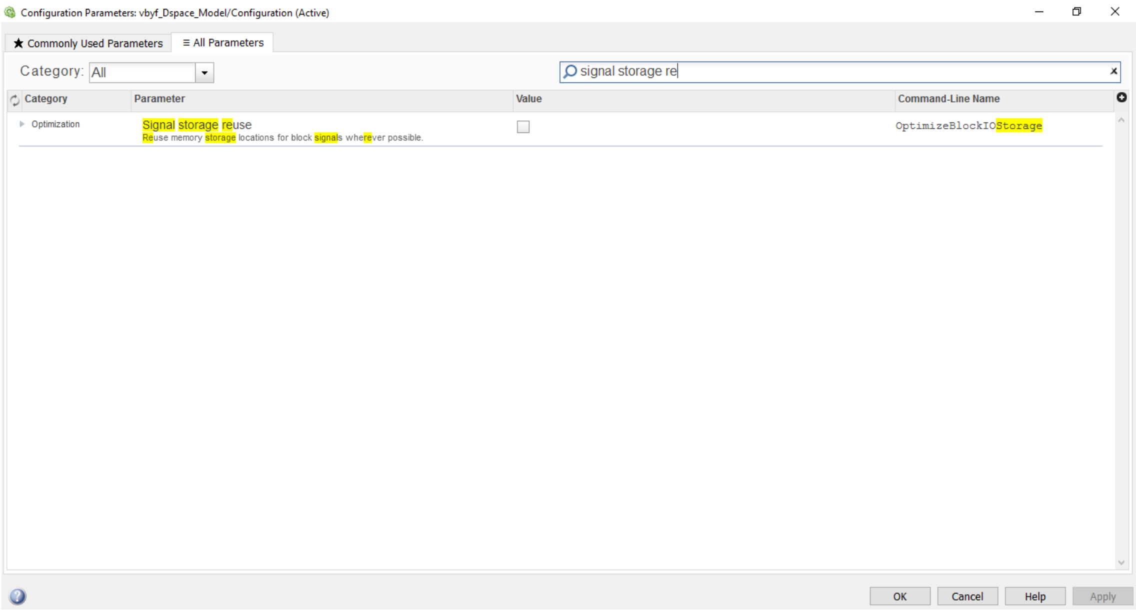

Figure 5.25 Step Six Unchecking Signal Storage Reuse

Once steps 1 to 6 are completed click on build model and see the diagnostic result. When build process is complete ".sdf" file is generated in set directory folder. Open this ".sdf" file in Control Desk software and create required layout. Now to star program execution click on "Go Online" button then click on "Start Measuring" button to start measurement of various parameters.

5.6 Simulink Model for Hardware Implementation

For using the Simulated model for real-time implementation some modifications are done in the Simulink model. The open-loop and closed-loop model used for real-time implementation are given in this section.

1. Open-loop V/f Method –

For hardware implementation, the SPWM switching signals are obtained using MASTER BIT OUT terminal of dSPACE using channel 0, 2, 4, 6, 8, 10 and given to the IGBT switches of three-phase inverter to get variable voltage variable frequency supply. To observe speed of motor the output of Tachometer generator is given to the voltage sensor which is then fed to ADC channel 5 of dSPACE. The signal given to ADC channel gets divided by 10 internally hence we multiply the ADC output obtain in Simulink by 10. Also, since the output obtained gets affected by noise we use low pass Butterworth filter to filter out noise. Fig. 5.26 and 5.27 shows open-loop V/f model used for hardware implementation and Control Desk layout used for controlling speed of motor. Time plotter shows mechanical speed of motor in rad/sec. The speed can be changed using slider or by typing value in variable array window.

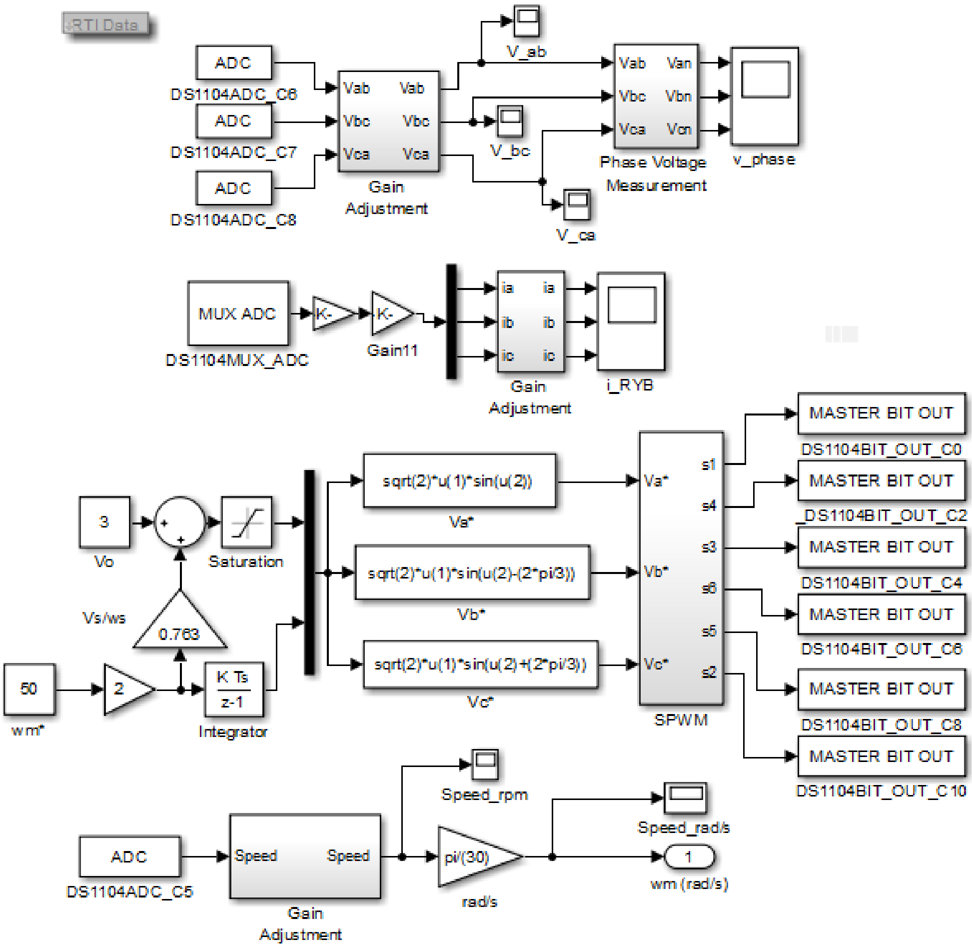

Figure 5.26 Open-Loop V/f Simulink Model for Hardware Implementation

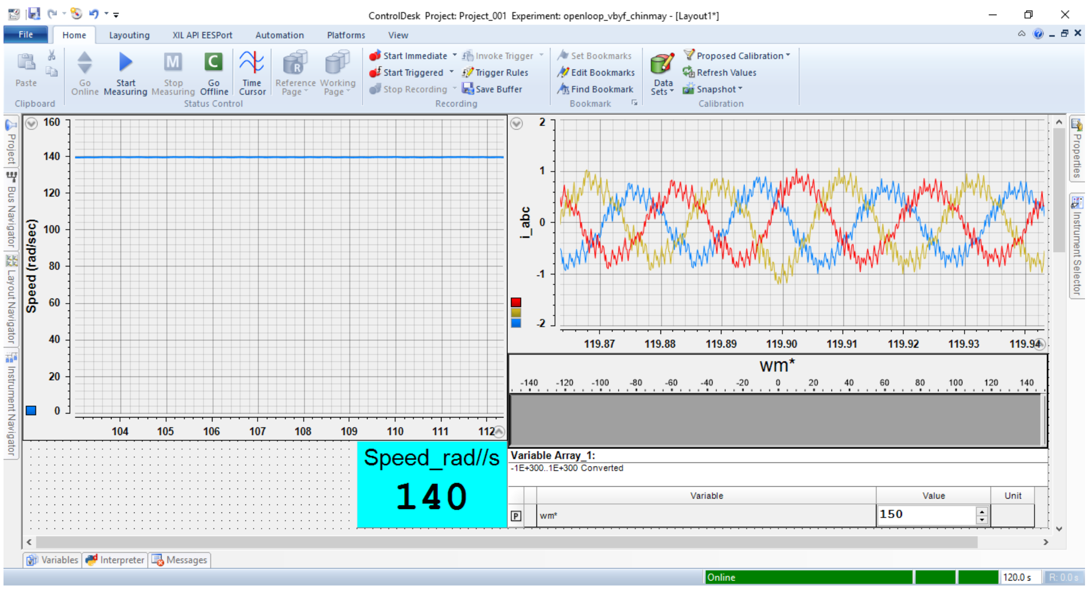

Figure 5.27 Control Desk for Open-loop V/f Method

2. Closed-loop V/f Method

Similar to open-loop V/f method the SPWM signal is obtain using MASTER BIT OUT as shown in Fig. 5.28. Speed signal is converted into rad/sec and fed back to the speed control loop. The control desk for closed-loop V/f is as shown in Fig. 5.29. Similar to open-loop V/f method we can alter speed using slider or by typing value.

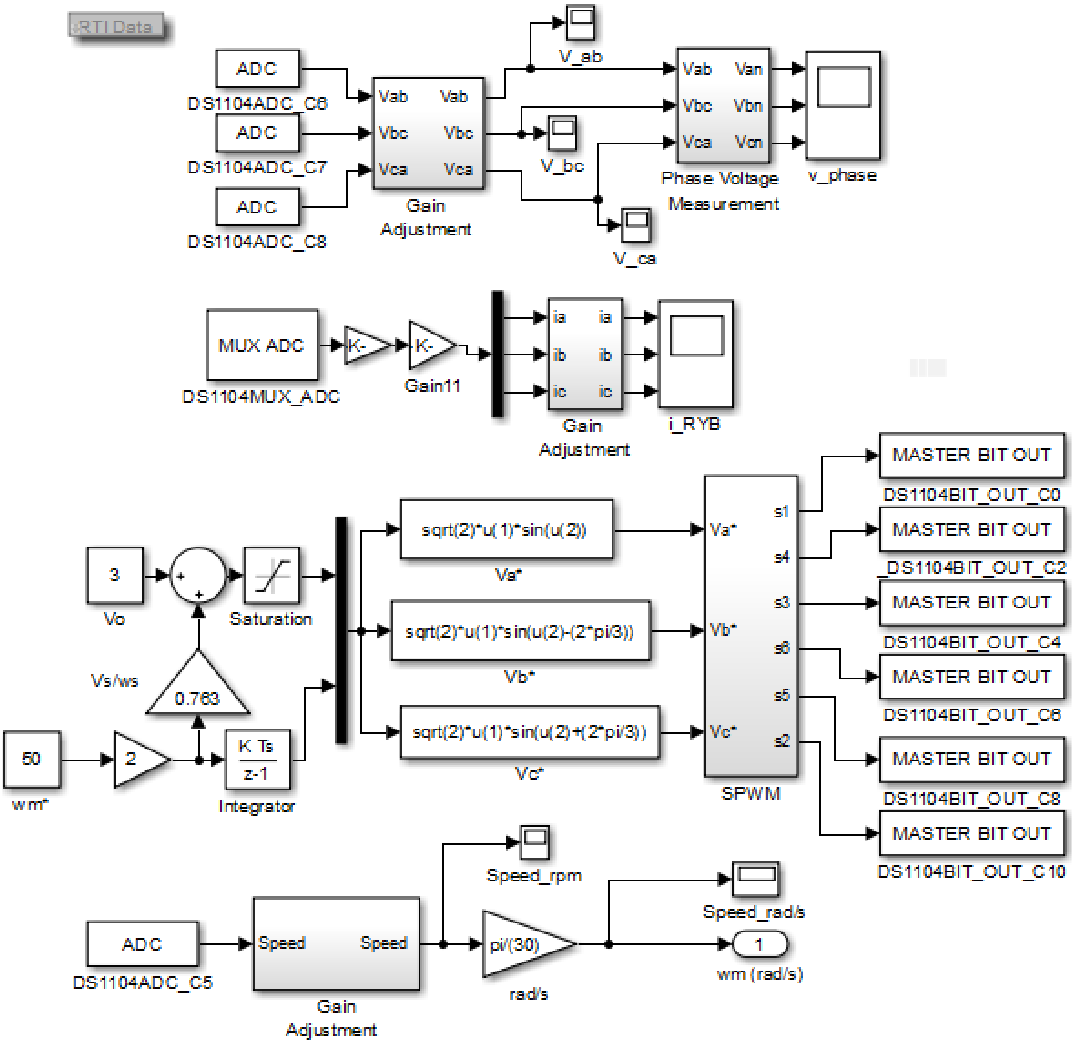

Figure 5.28 Closed-loop V/f Simulink Model for Hardware Implementation

Figure 5.29 Control Desk for Closed-loop V/f Method

5.7 Conclusion

The different components involved in the experimental implementation of speed control technique were discussed in detail. The problems involved in implementation of voltage level shifting circuit were reviewed and best circuit to satisfy the requirement is determined. The modification made to Simulation model of MATLAB for hardware implementation were also covered in this chapter.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Introduction

The objective of this chapter is to study how each speed control technique such as open-loop V/f, closed-loop V/f, direct vector control, indirect vector control and direct torque control behaves under different operating condition. In this chapter, detail discussion of MATLAB and FSS simulation results of various speed control strategies will be covered. The experimental results of open-loop and closed-loop V/f method are also included in this chapter.

6.2 Simulation Results Using MATLAB Simulink

The simulation of various speed control techniques of a three-phase squirrel cage induction motor is performed using parameters mentioned in table 5. Fig. 6.1, 6.3, 6.5, 6.6 and 6.7 show the speed, torque and current response of various speed control techniques of induction motor for step change in speed and load torque.

Table 5 Parameters of Induction Motor used for Simulation

Rated Power	50 Hp
Rated Voltage	460 V
Rated Current	46.8 A
Rated Frequency	60 Hz
Stator Resistance (R_s)	0.087 Ω
Rotor Resistance (R_r)	0.228 Ω
Stator Leakage Reactance (X_{ls})	0.302 Ω
Rotor Leakage Reactance (X_{lr})	0.302 Ω
Mutual Reactance (X_m)	13.08 Ω
Inertia (J)	1.662 $Kg.m^2$
Friction (F)	0.1 N. m. s.
Number of Poles (P)	4

Initially under no load, speed command of 100 rad/sec is given then at time t = 1 sec speed is increased to 150 rad/sec. The load torque is increased to 190 N.m. at time t = 2 sec. The desired speed and torque is represented by red line and actual response is represented in blue color.

1. Open-loop V/f Method –

It is found that when speed command is given, speed of motor increases gradually and settle down close to desired speed. Lot of oscillations are observed during starting of motor using open-loop V/f method. When motor is tuned on it takes approximately 0.75 secs to reach speed of 100 rad/sec and 0.5 secs to reach speed of 150 rad/sec from 100 rad/sec. When load is applied, motor draws more current to satisfy the load torque requirement. It is witnessed that, on application of load torque the speed of motor decreases significantly and there is no corrective action taken by the system to maintain it at desired speed command.

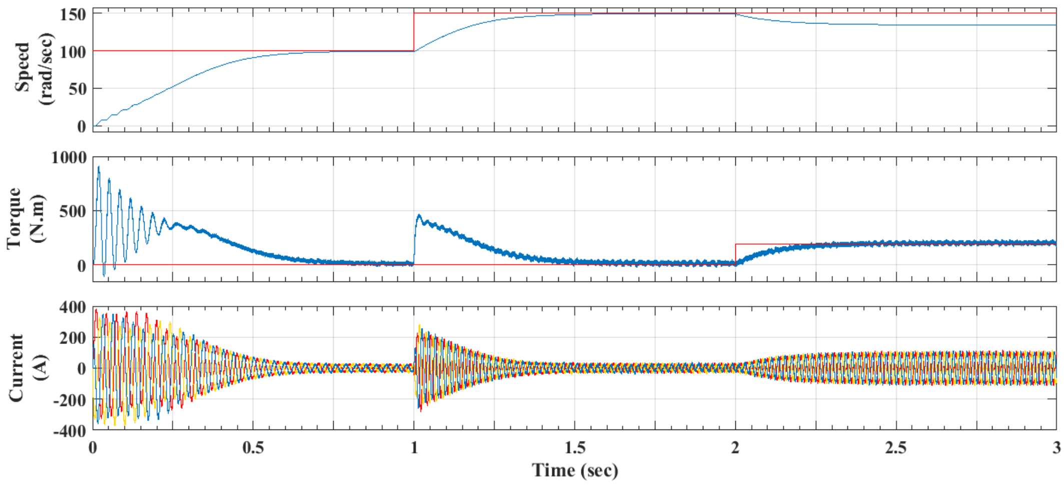

Figure 6.1 Open-loop V/f MATLAB Simulation Result

Before doing hardware implementation of open-loop V/f method its simulation is performed using the parameters of induction motor mentioned in table 4. The initial speed command of 50 rad/sec is given to motor, then the speed is increased to 100 rad/sec and 150 rad/sec at time t = 1 sec and t = 2 sec respectively. Finally, at t = 3 sec speed is reduced to 100 rad/sec. It is observed that the speed of motor is 47 rad/sec, 94 rad/sec and 140 rad/sec corresponding to given speed command.

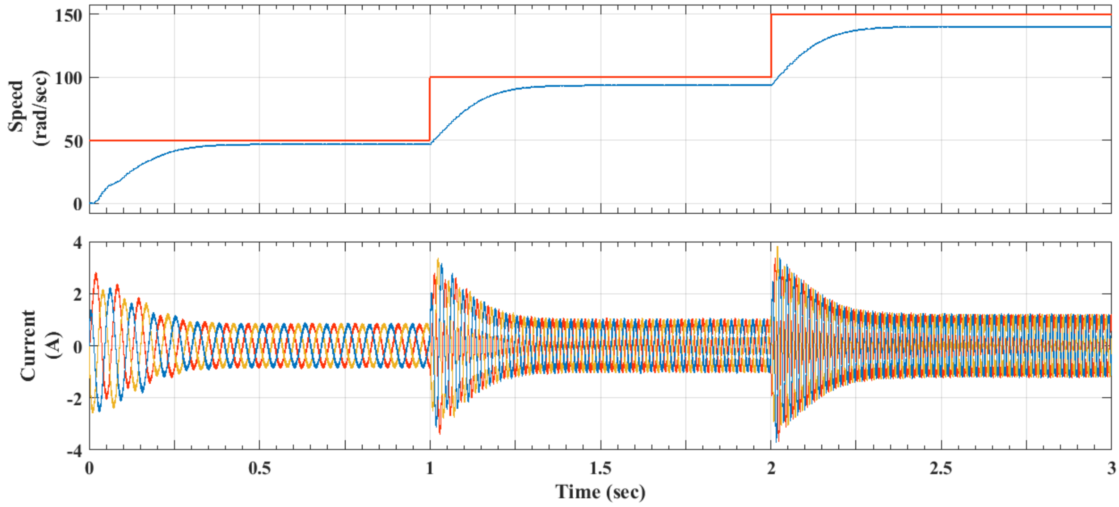

Figure 6.2 Open-loop V/f MATLAB Simulation Result of 3HP IM

2. Closed-loop V/f Method –

In case of closed-loop system the speed of motor increases linearly and more quickly than open-loop system. It takes around 0.45 sec to reach speed of 100 rad/sec when motor starts from zero and around 0.3 secs to reach 150 rad/sec from 100 rad/sec. When load torque is given current drawn by motor increases and it is found that speed control loop increases the slip frequency to maintain the motor at desired speed.

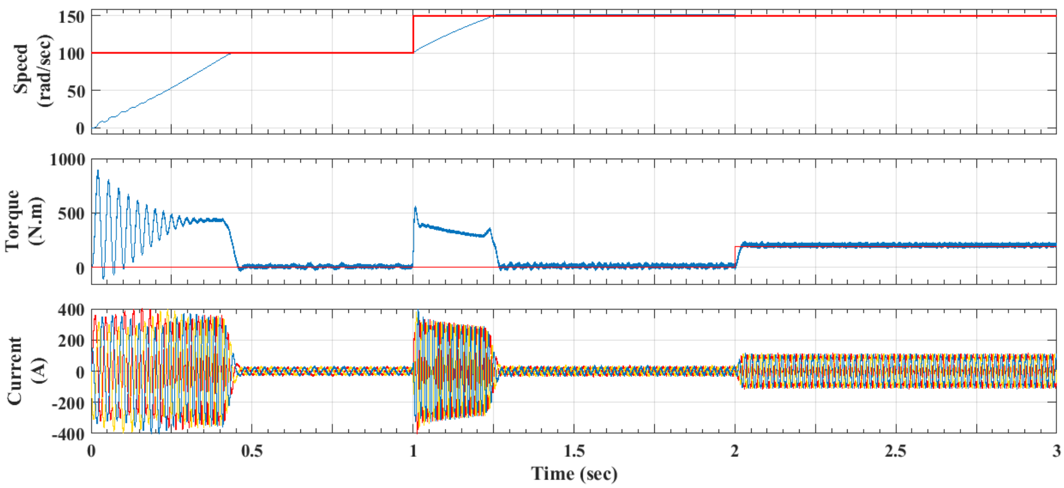

Figure 6.3 Closed-loop V/f MATLAB Simulation Result

The simulation of closed-loop method also performed using parameters of IM mentioned in table 4. The initial speed command of 50 rad/sec is given to motor, then the speed is increased to 100 rad/sec and 150 rad/sec at time t = 1 sec and t = 2 sec respectively. Finally, at t = 3 sec speed is reduced to 100 rad/sec. It is observed that the speed of motor is 50 rad/sec, 100 rad/sec and 150 rad/sec corresponding to given speed command.

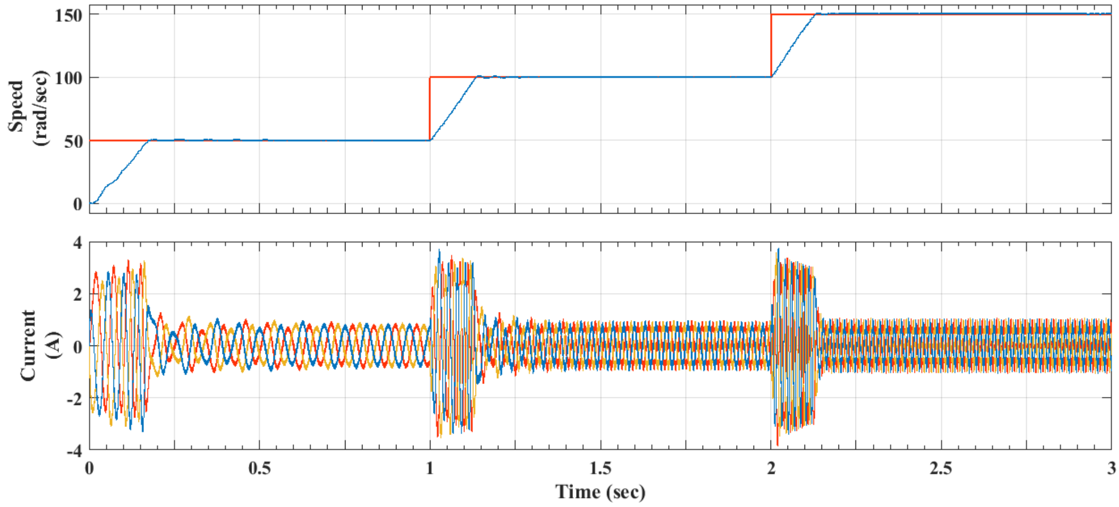

Figure 6.4 Closed-loop V/f MATLAB Simulation of 3HP IM

3. Direct Vector Control Method –

Simulation is carried out to investigate performance of IM using direct vector control method under the same operating conditions. There is significant change in torque and speed response of vector control method. In case of direct vector control the torque response is very smooth and there are no oscillations during startup. The speed of motor increases linearly and it takes around 0.4 secs to reach initial speed command. It takes less than 0.25 sec when there is step change in speed command. There is increase in quadrature axis component of stator current to satisfy the load torque requirement. The system maintains motor at desired speed even after change in load.

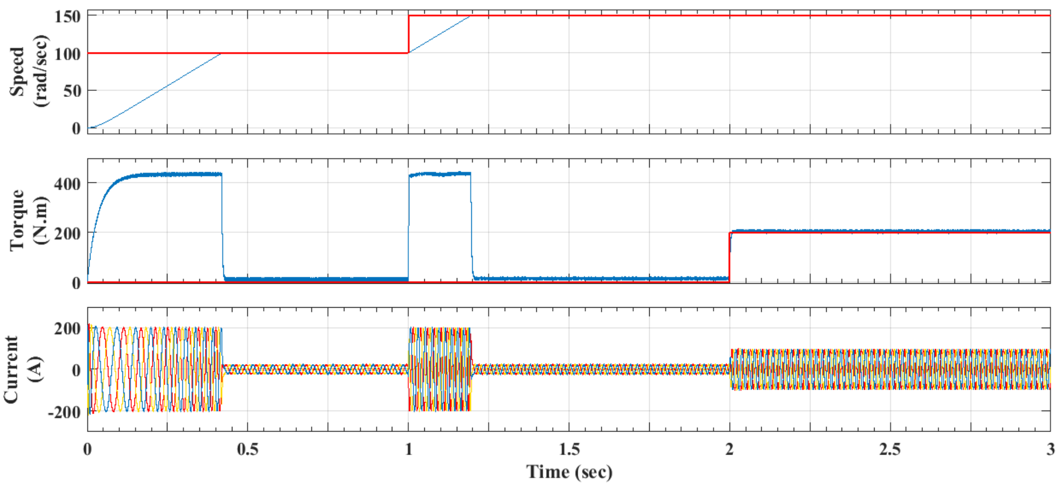

Figure 6.5 Direct Vector Control MATLAB Simulation Result

4. Indirect Vector Control Method –

Simulation is carried out to examine performance of IM using indirect vector control method under the same operating conditions. In case of indirect vector control it is observed that, during startup there is sharp increase and decrease in the torque of motor which causes some oscillations in speed response when motor is turned on. The motor achieves speed of 100 rad/sec in approximately 0.45 sec and when speed command is changed it is noticed that the speed increases linearly taking only 0.25 sec to reach desired speed. Similar to the direct vector control method it also maintains the motor at desired speed when load on motor increased.

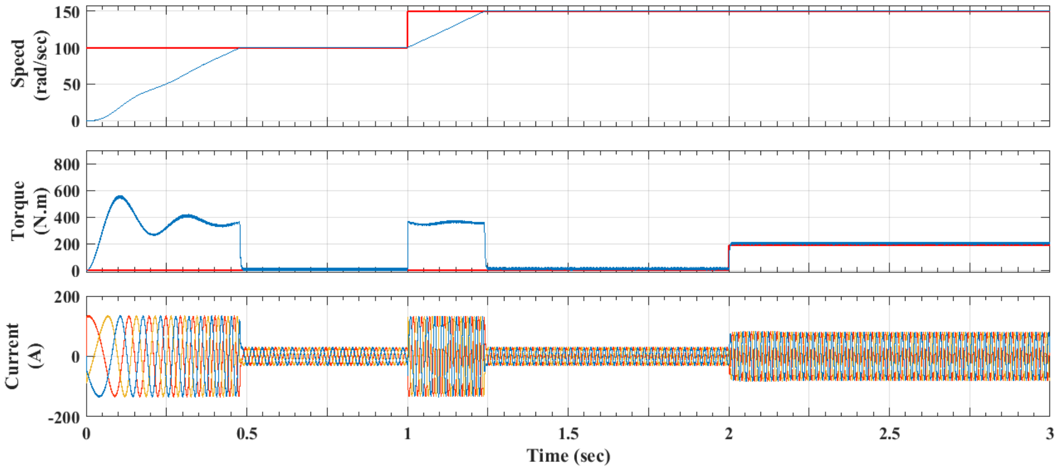

Figure 6.6 Indirect Vector Control MATLAB Simulation Result

5. Direct Torque Control Method

It is most advanced speed control technique among all above methods. Simulation is carried out to investigate performance of IM using direct torque control method under the same operating conditions. The speed response is very linear and fast. It takes 0.35 sec to achieve initial speed command and around 0.2 sec when there is step change in speed. Torque response is smooth and there are no oscillations during startup or when speed change command is given. Like all other methods this control system also maintains desired speed of motor when load is increased.

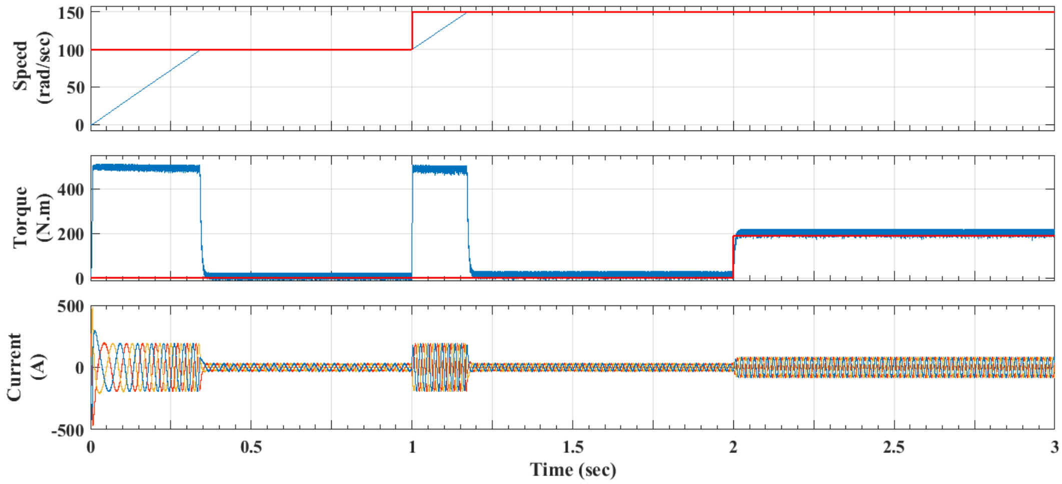

Figure 6.7 Direct Torque Control MATLAB Simulation Result

6.3 Simulation Results Using FSS

The simulation of open-loop and closed-loop V/f method is performed using miniature real-time Full Spectrum Simulator (FSS). The parameters of induction motor mentioned in table 5 are used to analyze performance of both these speed control techniques of induction motor. The system response is examined for step change in speed and load torque. Initially under no load speed command of 100 rad/sec is given then at time t = 1 sec it is increased to 150 rad/sec and finally at t = 2 sec load torque of 190 N.m. is applied. The red line represents desired response whereas actual response is represented by blue color.

1. Open-loop V/f Method –

It is found that the time taken by motor to settle down to initial speed command of 100 rad/sec is 0.75 sec which is slightly more than the simulation result obtained using MATLAB. Also, when speed is increased it takes 0.5 sec to reach speed of 150 rad/sec which is 0.4 sec in case of MATLAB Simulation. In FSS Simulation, when load torque is applied the speed of motor is reduced to 132 rad/sec, however in MATLAB Simulation it is observed that the motor speed decreases to 134 rad/sec. During startup it is observed that amplitude of oscillations of torque response is higher in MATLAB Simulation than in FSS Simulation.

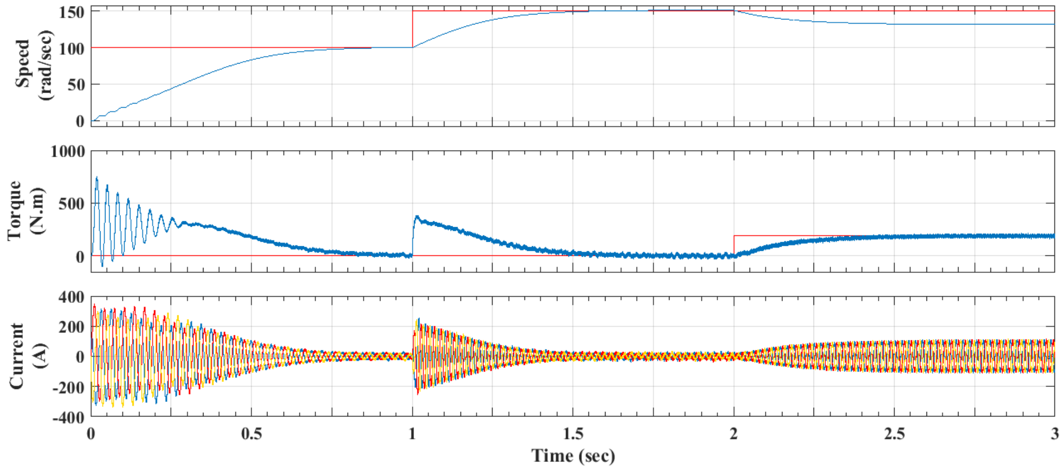

Figure 6.8 Open-loop V/f FSS Simulation Result

2. Closed-loop V/f Method –

Similarly, in case of closed-loop method it is found that the time taken by motor to reach desired speed command is more than the time taken in MATLAB. In FSS motor takes 0.55 sec to reach initial speed command and when speed command is increased it takes 0.30 sec to achieve new desired speed whereas for the same command in MATLAB this time is 0.45 sec and 0.25 sec respectively. During steady state torque response seen in FSS Simulation result contains high oscillations as compared to MATLAB Simulation result.

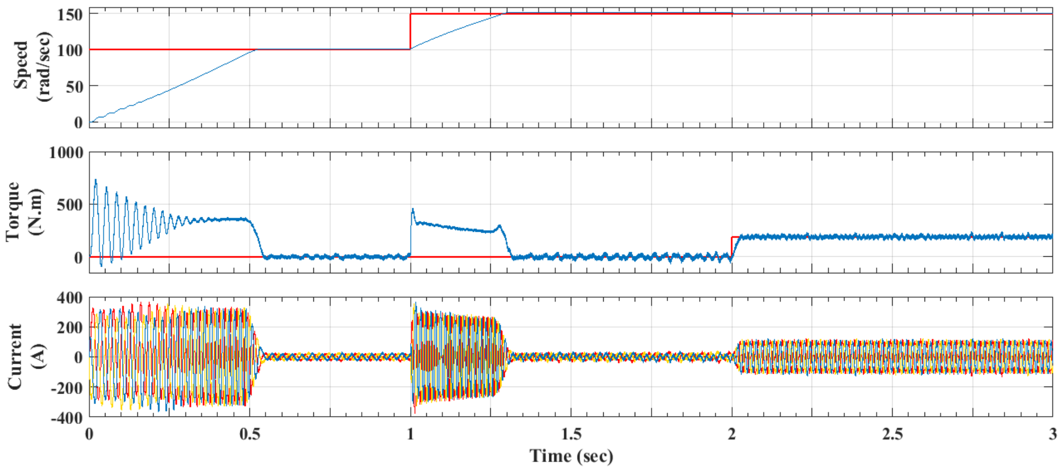

Figure 6.9 Closed-loop V/f FSS Simulation Result

6.4 Experimental Results

The experimental results of open-loop and closed-loop methods are obtained using Control Desk. The performance of both methods is observed for step change in speed. Initially speed command of 50 rad/sec is given to motor then it is increase to 100 rad/sec and finally it is raised to 150 rad/sec. The speed of motor is then reduced to 100 rad/sec. The results of both these methods are as follows –

1. Open-loop V/f Method –

Fig. 6.10 and 6.11 displays control desk view and actual speed response of induction motor to step change in speed. The scope on left side of screen shows actual speed of motor and right scope shows current waveform. It is observed that speed of motor is 48 rad/sec, 92 rad/sec and 140 rad/sec when speed command is 50 rad/sec, 100 rad/sec and 150 rad/sec respectively. The speed response of motor also verified by observing output on DSO as shown in Fig. 6.12. Fig. 6.13 shows current response when speed is increased from 100 rad/sec to 150 rad/sec whereas Fig. 6.14 shows current response when speed is reduced to 100 rad/sec from 150 rad/sec. It is found that when speed change command is given current increases and then reduces gradually as motor attains desired speed. Fig. 6.15 and 6.16 show change in frequency of supply voltage when speed command is given. It is observed that when speed command is changed then frequency of stator supply voltage changes quickly to desired value and there is no fluctuation in frequency.

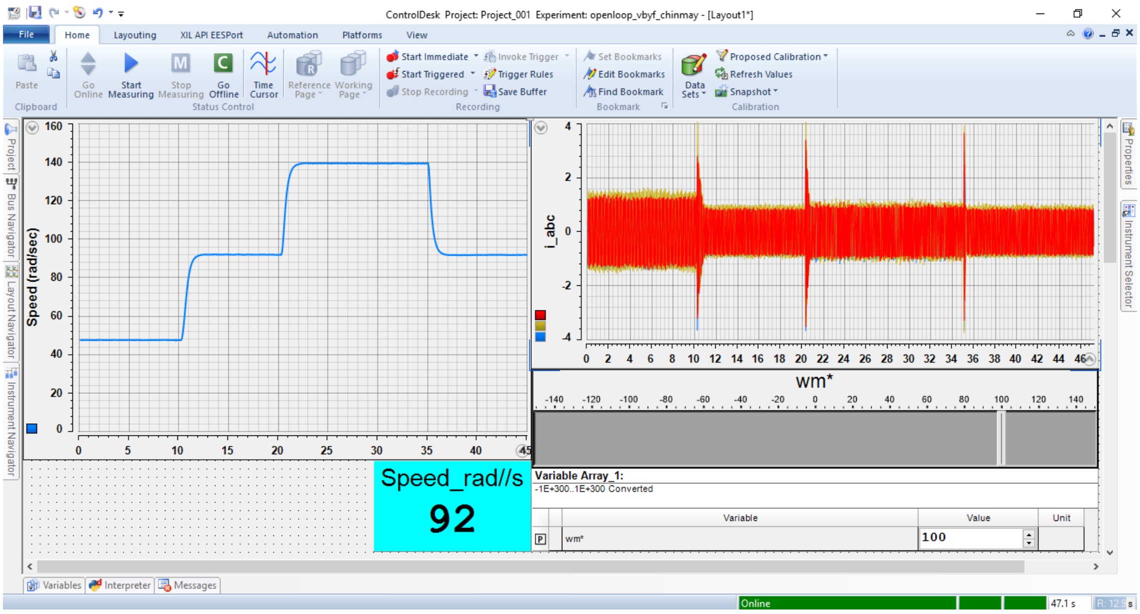

Figure 6.10 Control Desk view of Open-loop V/f method for Speed Change Command

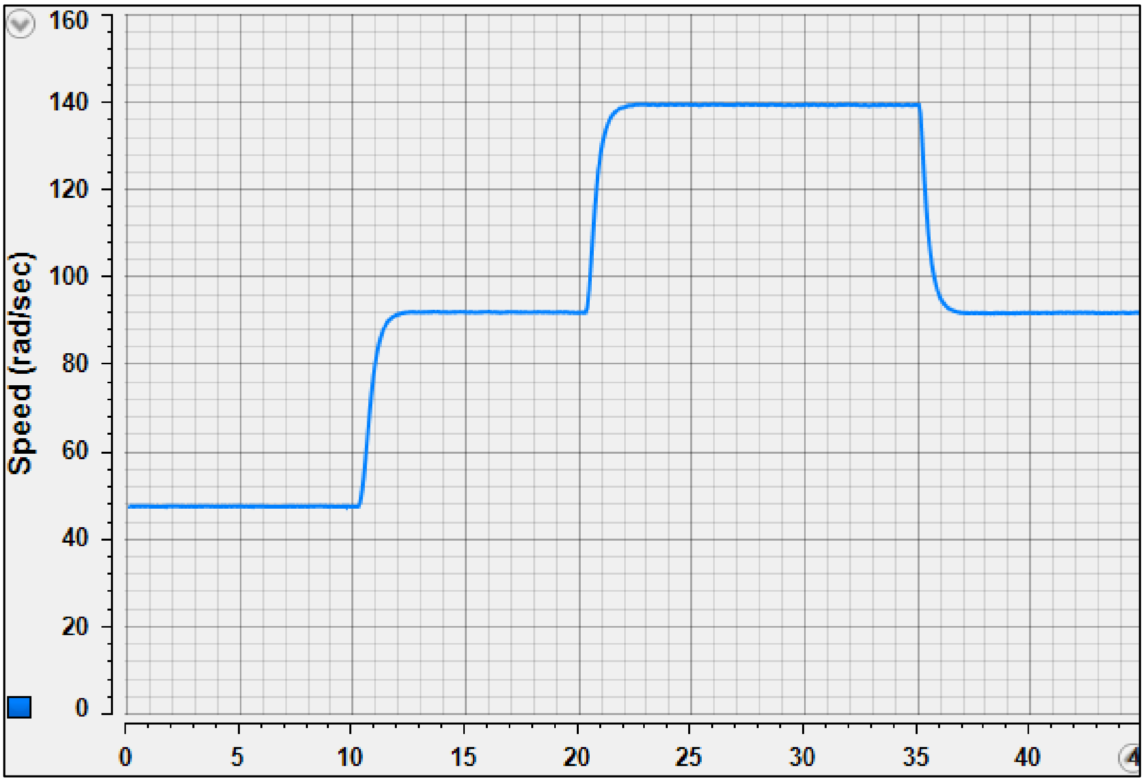

Figure 6.11 Experimental Result of Speed response of Open-loop V/f Method

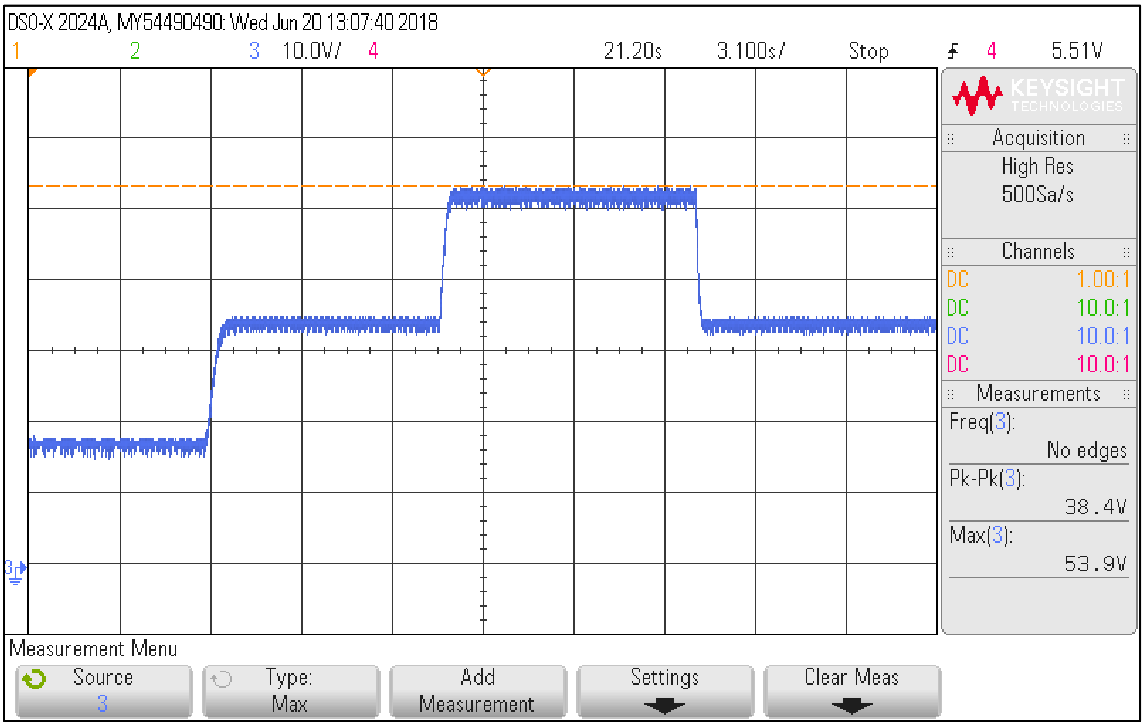

Figure 6.12 Speed Response of Open-loop V/f Observed on DSO

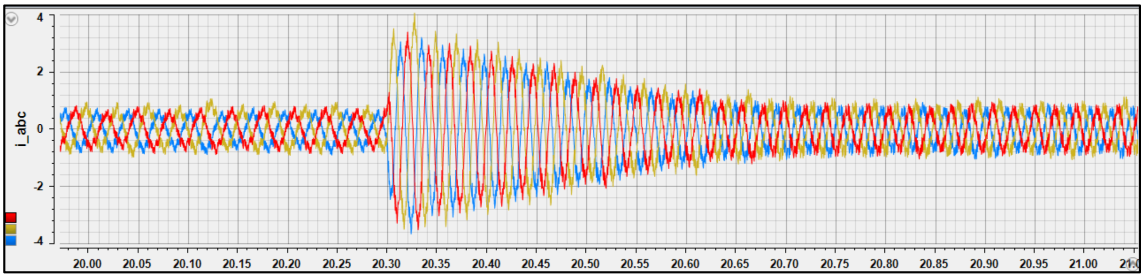

Figure 6.13 Current Response of Open-loop V/f When Speed is Increase

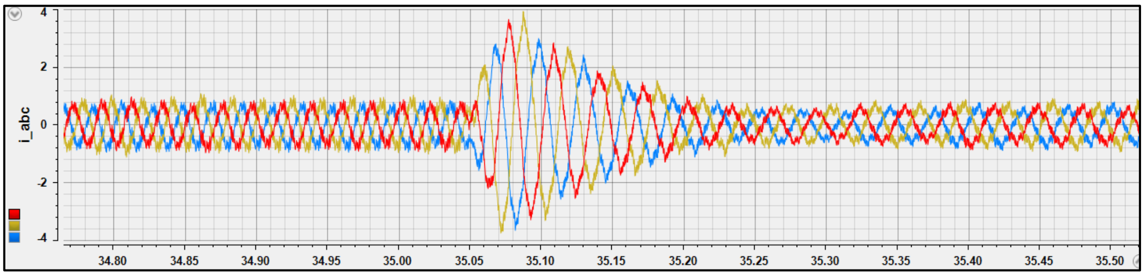

Figure 6.14 Current Response of Open-loop V/f When Speed is Reduced

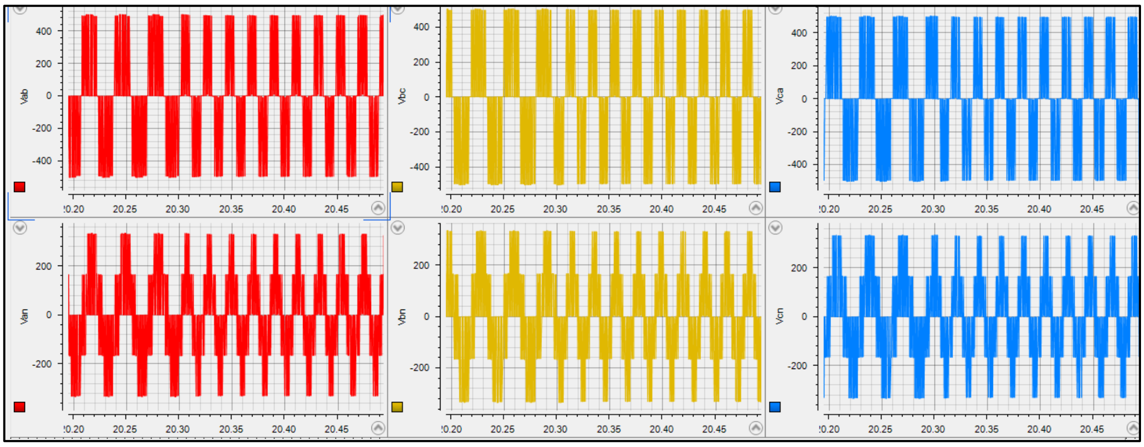

Figure 6.15 Voltage Response of Open-loop V/f When Speed is Increased

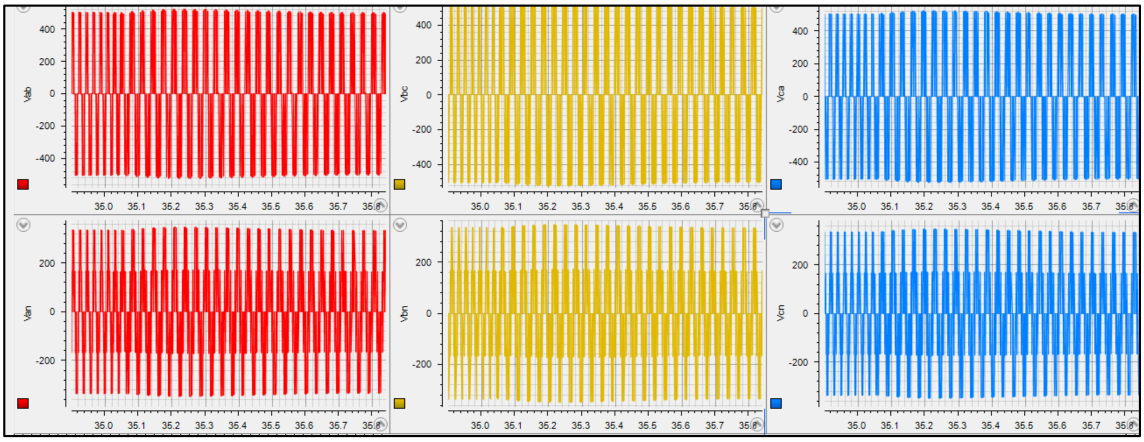

Figure 6.16Voltage Response of Open-loop V/f When Speed is Reduced

2. Closed-loop V/f Method

Similarly, in case of closed-loop method speed is increased in step. It is found that, when speed command is given, speed increased linearly and after minute transients it settled to desired speed. Fig. 6.17 and 6.18 shows control desk view and actual speed response of motor to speed command of 50 rad/sec, 100 rad/sec and 150 rad/sec. The speed response of closed-loop V/f observed on DSO is shown in Fig. 6.19.

Figure 6.17 Control Desk view of Closed-loop V/f Method for Speed Change Command

Fig. 6.20, 6.21, 6.22 and 6.23 shows current and voltage response when speed is increased from 100 rad/sec to 150 rad/sec and when speed is reduced from 150 rad/sec to 100 rad/sec. It is observed that when speed is changed current increases and after few transients it settles to steady state value when motor reaches desired speed. The sharp increase in frequency of stator voltage is observed when speed is increased. When speed is reduced it is observed that the frequency of supply reduced significantly and then it increases to desired value which results in fast speed response.

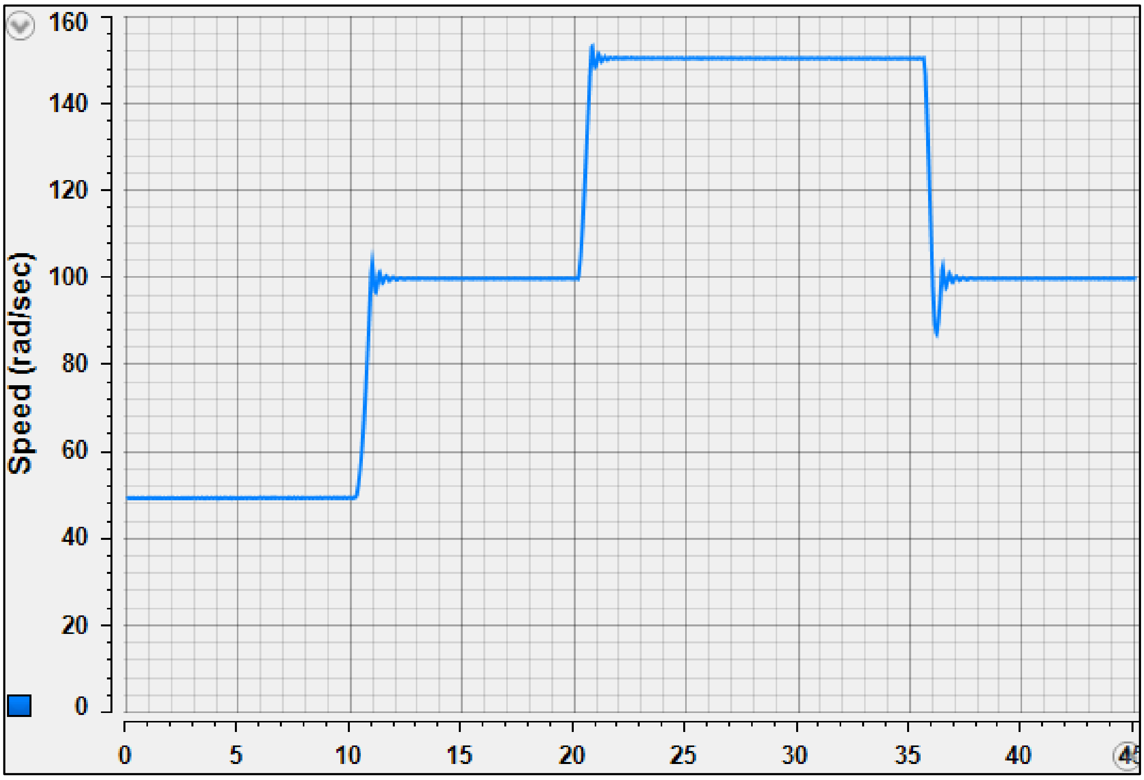

Figure 6.18 Experimental Result of Speed Response of Closed-loop Method

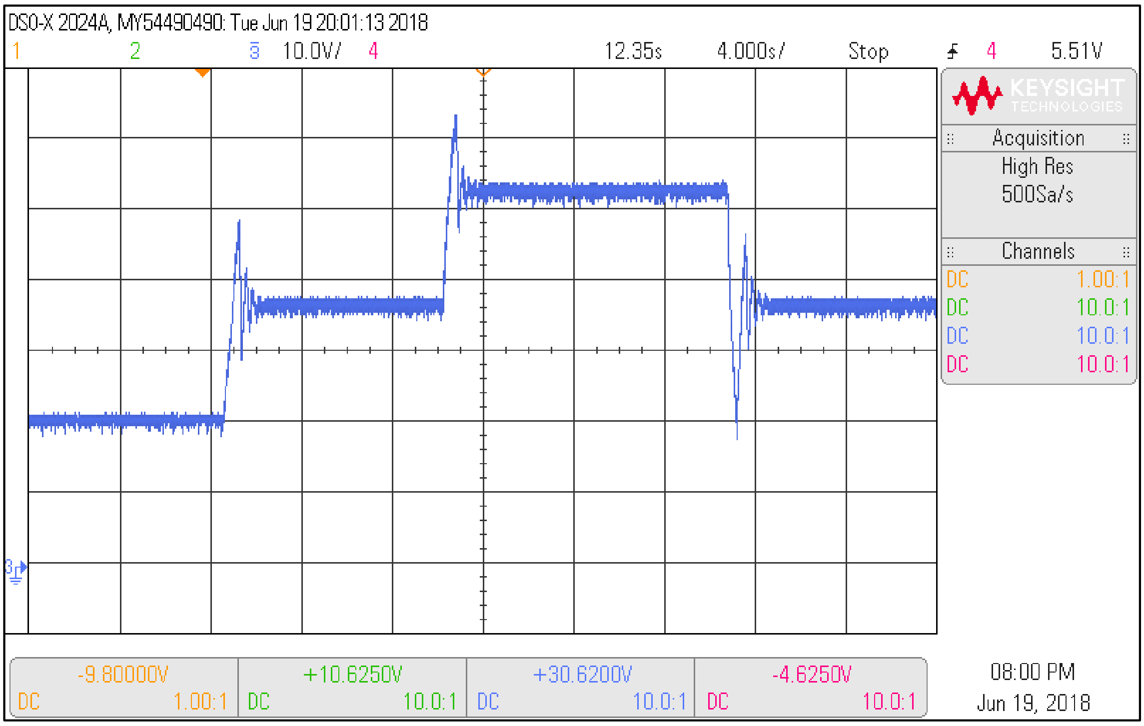

Figure 6.19 Speed Response of Closed-loop V/f Observed on DSO

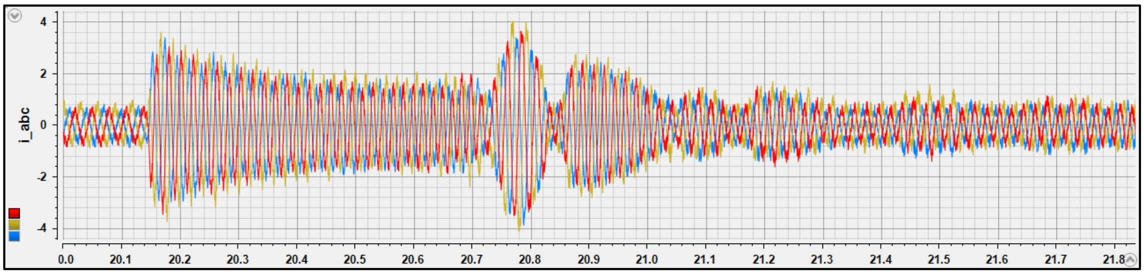

Figure 6.20 Current Response of Closed-loop V/f When Speed is Increased

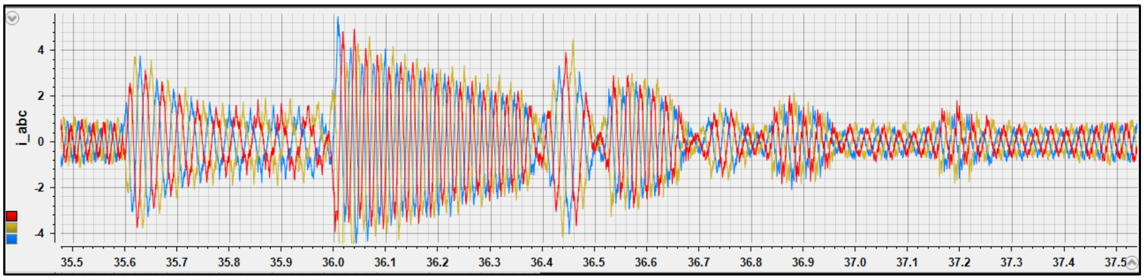

Figure 6.21 Current Response of Closed-loop V/f When Speed is Reduced

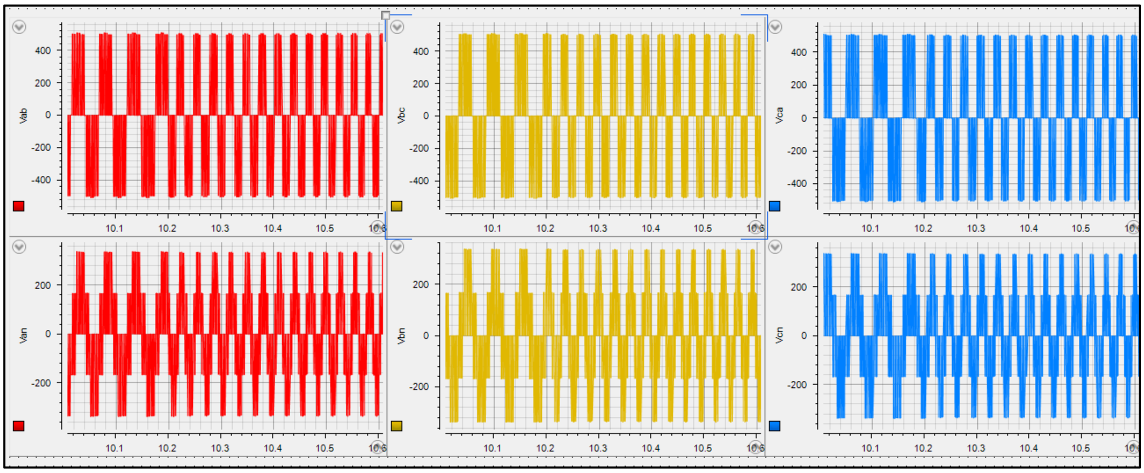

Figure 6.22 Voltage Response of Closed-loop V/f When Speed is Increased

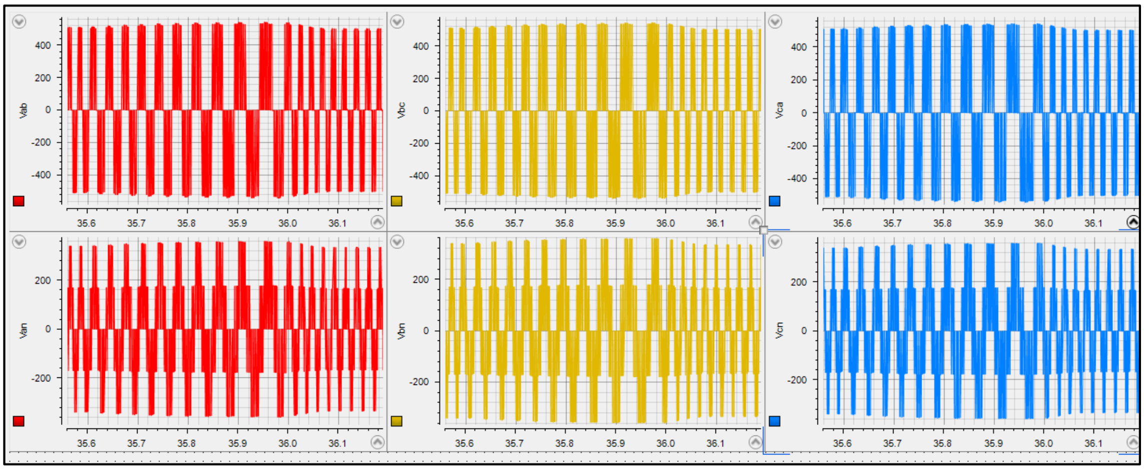

Figure 6.23 Voltage Response of Closed-loop V/f When Speed is Reduced

6.5 Conclusion

The performance of each speed control technique is explored by comparing their starting performance, reaction to speed change command and their torque response with and without load. The MATLAB and FSS simulation results of open-loop and closed-loop V/f are examined and discussed. It is found that the experimental results of open-loop and closed-loop V/f almost matches with the simulation results obtained.

CHAPTER 7

SUMMARY AND CONCLUSION

In this thesis, performance analysis of different speed control techniques of three-phase squirrel cage induction motor is performed. Since induction motor is extensively used all over the world for numerous application it is very important to use efficient and cost-effective speed control technique of IM to reduce energy consumption. The performance of open-loop V/f, closed-loop V/f, direct vector control, indirect vector control and direct torque control is studied using MATLAB Simulink under different operating condition such as step change in speed and torque.

It found that in open-loop and closed-loop method there are lot of oscillations in torque during starting. In open-loop method when load torque is applied there is significant drop in speed whereas in case of closed loop speed is maintained constant at desired speed command. Direct vector control speed response is faster than both scalar control methods and there are no fluctuations in torque response. Indirect vector control is simple than the direct vector control as there is no requirement of sensing terminal voltage and current of machine to estimating flux vector which are used to obtain unit vector, thus reduces the complexity. Also, in direct vector control there is need of tuning two PI controllers which took lot of time whereas in indirect vector control tuning of only one PI controller is required. Its response is analogous to direct vector control but there are few undulations in torque response during starting. The performance of direct torque control is better than all other speed control method. It is observed that its speed response is faster and more linear and torque response does not contain oscillations.

The simulation of open-loop and closed-loop V/f method is also performed using Full Spectrum Simulator (FSS). The performance results acquired from FSS Simulation of these technique is compared with MATLAB Simulation results. It is found that the time taken by motor to reach desired speed command in FSS Simulation was more than that observed in MATLAB Simulation. FSS result shows that the starting current and magnitude of starting torque is somewhat less as compared to MATLAB Simulation result. The FSS is very advance controller that can be used for offline and real-time simulation but it involves writing of code in “C” language which is bit tedious process. Despite this time consuming process it offers lot of flexibility when developing a new system.

The speed of 3Hp, 460V, 50Hz induction motor is controlled by implementing scalar speed control strategies using dSPACE DS1104. The simulation result of open-loop V/f and closed-loop V/f nearly matches with the hardware results. In open-loop V/f, it is found that speed of motor is less than the given speed command when operated under load whereas in closed-loop method the speed is maintained equal to desired speed. The experimental results prove the effectiveness of both speed control methods.

Thus, this thesis shows the advantages and disadvantages of various speed control techniques. It is found that scalar control technique can be used where cost effective speed control solution is required and high accuracy of system is not required. Vector control techniques and direct torque control methods are cutting-edge speed control techniques that provides fast and precise speed control. The torque response of these methods is also very smooth and contains very less undulations.

APPENDICES

Appendix 1

```
# Header
title: Open Loop V by f method

# CircuitBlock
begin_circuit
gelement type=v_and_f_control name=vbyf rt_id=0 fref=fc va=van vb=vbn vc=vcn vrated=460 frated=60 vrs=3
gelement type=pulse name=wm rt_id=0 y=fc1 t1=1 t2=2 val1=100 val2=150 val3=150
gelement type=multscl name=wm_to_f rt_id=0 x=fc1 y=fc a=0.32

gelement type=multscl name=vas rt_id=0 x=van y=van1 a=0.0013
gelement type=multscl name=vbs rt_id=0 x=vbn y=vbn1 a=0.0013
gelement type=multscl name=vcs rt_id=0 x=vcn y=vcn1 a=0.0013

gelement type=triangle_3 name=carrier rt_id=0 y=vcar g_high=1 g_low=-1 f_hz=1980 t0=0
gelement type=cmprtr_1a name=a_phase rt_id=0 x1=van1 x2=vcar y1=g1 y2=g2 g_high=1
gelement type=cmprtr_1a name=b_phase rt_id=0 x1=vbn1 x2=vcar y1=g3 y2=g4 g_high=1
gelement type=cmprtr_1a name=c_phase rt_id=0 x1=vcn1 x2=vcar y1=g5 y2=g6 g_high=1

gelement type=vsrcdc name=Vdc rt_id=0 p=p m=m vdc=600
gelement type=invrtr_3ph name=Inverter rt_id=0 p=p m=m g1=g1 g2=g2 g3=g3 g4=g4 g5=g5 g6=g6 a=a b=b c=c g_high=0.5

gelement type=indmc_free name=indmc rt_id=0 a=a b=b c=c tl=tl wrm=wr tem=tem ia=ia ib=ib ic=ic P=4 rs=0.087 lls=0.0008 lm=0.0347 llr=0.0008 rr=0.228 j=1.662
gelement type=pulse name=loadtorque rt_id=0 y=tl t1=1 t2=2 val1=0 val2=0 val3=190

gelement type=out_port name=Speed rt_id=0 x=wr scl=200 ch=0
gelement type=out_port name=torque rt_id=0 x=tem scl=100 ch=1
gelement type=out_port name=currenta rt_id=0 x=ia scl=500 ch=2
gelement type=out_port name=currentb rt_id=0 x=ib scl=500 ch=3
gelement type=out_port name=currentc rt_id=0 x=ic scl=500 ch=4
```

```
end_circuit

#Solve Blocks#Solve Block 1#
begin_solve
solve_type=trns
method: t_start=0
method: t_end=3
method: delt_const=0.00001
begin_output
filename=output.dat limit_lines=1000000 append=no fourier=no +
sweep_format=reverse
variables: v0 vin v1 v2 vf1 vf2
end_output
method: back_euler=yes
end_solve
target: HOST_PC
end_cf
```

APPENDIX 2

```
# Header
title: Closed Loop V by f method

# CircuitBlock
begin_circuit
gelement type=v_and_f_control name=vbyf rt_id=0 fref=fc va=van vb=vbn vc=vcn vrated=460 frated=60 vrs=3
gelement type=feedback_gain name=spdfed rt_id=0 x=wrm y=wr
gelement type=multscl name=wrmtowre rt_id=0 x=wr y=wre a=2

gelement type=pulse name=wm rt_id=0 y=wm_ref t1=1 t2=2 val1=100 val2=150 val3=150
gelement type=multscl name=wm_to_wr rt_id=0 x=wm_ref y=wr_ref a=2
gelement type=diff_2 name=wr_dif rt_id=0 x1=wr_ref x2=wre y=wr_diff
gelement type=picntrl name=trq_cntrl rt_id=0 x=wr_diff y=wrcntrl kp=12 ki=0.55
gelement type=lmtr name=trq_lmtr rt_id=0 x=wrcntrl y=slip xmin=-180 xmax=180
gelement type=sum_2 name=spd_addr rt_id=0 x1=slip x2=wre y=we
gelement type=multscl name=wetofe rt_id=0 x=we y=fc a=0.16

gelement type=multscl name=vas rt_id=0 x=van y=van1 a=0.0013
gelement type=multscl name=vbs rt_id=0 x=vbn y=vbn1 a=0.0013
gelement type=multscl name=vcs rt_id=0 x=vcn y=vcn1 a=0.0013

gelement type=triangle_3 name=carrier rt_id=0 y=vcar g_high=1 g_low=-1 f_hz=1980 t0=0
gelement type=cmprtr_1a name=a_phase rt_id=0 x1=van1 x2=vcar y1=g1 y2=g2 g_high=1
gelement type=cmprtr_1a name=b_phase rt_id=0 x1=vbn1 x2=vcar y1=g3 y2=g4 g_high=1
gelement type=cmprtr_1a name=c_phase rt_id=0 x1=vcn1 x2=vcar y1=g5 y2=g6 g_high=1

gelement type=vsrcdc name=Vdc rt_id=0 p=p m=m vdc=600
gelement type=invrtr_3ph name=Inverter rt_id=0 p=p m=m g1=g1 g2=g2 g3=g3 g4=g4 g5=g5 g6=g6 a=a b=b c=c g_high=0.5
```

```
gelement type=indmc_free name=indmc rt_id=0 a=a b=b c=c tl=tl wrm=wrm tem=tem
ia=ia ib=ib ic=ic P=4 rs=0.087 lls=0.0008 lm=0.0347 llr=0.0008 rr=0.228 j=1.662
gelement type=pulse name=loadtorque rt_id=0 y=tl t1=1 t2=2 val1=0 val2=0 val3=190

gelement type=out_port name=Speed rt_id=0 x=wrm scl=200 ch=0
gelement type=out_port name=torque rt_id=0 x=tem scl=100 ch=1
gelement type=out_port name=currenta rt_id=0 x=ia scl=500 ch=2
gelement type=out_port name=currentb rt_id=0 x=ib scl=500 ch=3
gelement type=out_port name=currentc rt_id=0 x=ic scl=500 ch=4
end_circuit

# Solve Blocks# Solve Block 1#
begin_solve
solve_type=trns
method: t_start=0
method: t_end=3
method: delt_const=0.00001
begin_output
filename=output.dat limit_lines=1000000 append=no fourier=no
+sweep_format=reverse
variables: v0 vin v1 v2 vf1 vf2
end_output
method: back_euler=yes
end_solve
target: HOST_PC
end_cf
```

REFERENCES

[1]. Martinez-Hernandez M.A., “A speed performance comparative of field oriented control and scalar control for induction motors,” *in 2016 IEEE Conference on Mechatronics, Adaptive and Intelligent Systems (MAIS)*. Hermosillo, Mexico, 20 October 2016. Hermosillo, Mexico: IEEE.

[2]. Hussein Sarhan, “Energy Efficient Control of Three-Phase Induction Motor Drive,” Energy and Power Engineering, vol. 3, pp. 107-112, 2011.

[3]. B.K. Bose, *Power Electronics and AC Drives*, Prentice-Hall, New Delhi, 2002.

[4]. J. M. Peña and E. V. Diaz, “Implementation of V/f scalar control for speed regulation of a three-phase induction motor,” *in 2016 IEEE ANDESCON*. Arequipa, Peru, 19 October 2016.

[5]. R. K. Bindl and I. Kaur, “Comparative Analysis of Different Controlling Techniques using Direct Torque Control on Induction Motor,” *in 2016 2nd International Conference on Next Generation Computing Technologies (NGCT – 2016).* Dehradun, India, 14 - 16 October 2016.

[6]. A. A. Pujol, Direct Torque Control Principles and Generalities, Available at: https://www.tdx.cat/bitstream/handle/10803/6317/07Chapter2.PDF?...7 (Accessed: 12 January 2018).

[7]. H. Akroum, M. Kidouche and A. Aibeche, “Scalar Control of Induction Motor Drives Using dSPACE DS1104,” *in International Conference on Systems, Control and Informatics*. Rhodes (Rodos) Island, 16-19 July. 322-327.

[8]. CDAC. 2018. *Miniature Model of Full Spectrum Simulator (FSS MINI)*. [ONLINE] Available at: https://www.cdac.in/index.aspx?id=pe_pe_PEG_FSSMINI (Accessed: 20 November 2017).

[9]. H. Mohan, R. Singh, K. Agrawal, B. Kumar and T. R. Chelliah, “Energy Conservation on Induction Motors Drives with Immune Control Strategy using Full Spectrum Simulator,” *in 2017 International Conference on Computer Communication and Informatics (ICCCI -2017),* Coimbatore, INDIA, 5 - 7 January 2017.

[10]. P. K. Behera, M. K. Behera, A. K. Sahoo, “Speed Control of Induction Motor using Scalar Control Technique,” *in International Conference on Emerging Trends in Computing and Communication (ETCC – 2014), Journal of Computer Application,* (0975-8887), pp. 37-39.

[11]. Amit Kumar and T. Ramesh, “Direct Field Oriented Control of Induction Motor Drive,” *in 2015 Second International Conference on Advances in Computing and Communication Engineering (ICACCE – 2015),* Dehradun, India, 1 May 2015.

[12]. B. S. Naik, "Comparison of Direct and Indirect Vector Control of Induction Motor," *in International Journal of New Technologies in Science and Engineering*, Vol. 1, Issue. 1, Jan. 2014

[13]. Paul C. Krause, Oleg Wasynczuk and Scott D. Sudhoff, *Analysis of Electric Machinery and Drive Systems,* 2nd edn., Wiley, Delhi, 2013.

[14]. X. Wang, Y. Yang and W. Liu, "Simulation of vector controlled adjustable speed System of induction motor based on Simulink," *in 2011 International Conference on Computer Science and Service System (CSSS)*, Nanjing, China, 27 June 2011.

[15]. D. Karthik and T. R. Chelliah, "Analysis of Scalar and Vector control based Efficiency-Optimized Induction Motors subjected to Inverter and Sensor faults," *in 2016 International Conference on Advanced Communication Control and Computing Technologies (ICACCCT),* Ramanathapuram, Tamilnadu, India, 25 May 2016.

[16]. Ramu Krishnan, *Electric Motor Drives: Modeling, Analysis and Control*, Pearson Education, Delhi, 2003.

[17]. Dhiya Ali Al-Nimma and S. Ibrahim Khather, "Modeling and Simulation of a Speed Sensor Less Vector Controlled Induction Motor Drive System," *in The 24th Annual Canadian Conference on Electrical and Computer Engineering (CCECE – 2011),* Niagara Falls, Canada, 8 – 11 May 2011.

[18]. Isao Takahashi and T. Noguchi, "A new quick response and high efficiency control strategy of an induction motor," *in IEEE Trans. 1nd. Appl.*, vol. 22, no. 5, pp. 820-827, 1986.

[19]. P. Palpandian, E. Arunkumar and K. S. J. Paul, "Efficiency Improvement of 3 Phase Induction Motor," *in International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 1, Issue 3, September 2012.

[20]. Mini Sreejeth, M. Singh and P. Kumar, "Efficiency Optimization of Vector Controlled Induction Motor Drive," *in 38th Annual Conference on IEEE Industrial Electronics Society (IECON - 2012),* Dec 2012, pp. 1758-1763

[21]. Mini Sreejeth, M. Singh and P. Kumar, "Efficient operation of IM drive through selection of optimal V/f ratio," *in Power India International Conference (PIICON - 2014),* Dec 2014.

[22]. HOANG Le-Huy, "Modeling and Simulation of Electrical Drives using MATLAB/Simulink and Power System Blockset," *in The 27th Annual Conference of the IEEE Industrial Electronics Society (IECON - 2001),* Denver, Colorado, USA, 29 Nov. to 2 Dec. 2001.

[23]. dSPACE (2018) dSPACE Catalogue, Available at: https://www.dspace.com/shared/data/pdf/2018/dSPACE_DS1104_Catalog2018.pdf (Accessed: 12 May 2018).

[24]. Semikron (2014). "SKYPER 32 PRO Datasheet," Available at: https://www.semikron.com/dl/service-support/downloads/download/semikron-datasheet-skyper-32-pro-r-l6100202/ (Accessed: 10 May 2018).

[25]. Europower Components (2018) Voltage Transducer LV 25-P/SP2 - Europower Components Ltd, Available at: http://www.europowercomponents.com/media/uploads/LV25-P-SP2.pdf (Accessed: 15 May 2018).

[26]. Farnell (2018) IPN = 50 A Current Transducer LA 55-P/SP1 - Farnell, Available at: http://www.farnell.com/datasheets/1639877.pdf (Accessed: 15 May 2018).

[27]. P. S. Bhimbhra, *Electrical Machinery*, 7th edn., Khanna Publishers, Delhi, 2014.

[28]. A. E. Fitzgerald, C. Kingsley, Jr., and S. D. Umans, *Electric Machinery*, 5th edn., McGraw-Hill,New York, 1990.

[29]. The University of Utah (2016) ECE 5671/6671 – Lab 1 dSPACE DS1104 Control Workstation & Simulink Tutorial, Available at: http://www.ece.utah.edu/~bodson/5671/Labs/Lab%201%20-%20Handout.pdf (Accessed: 7th May 2018).

[30]. Cleveland State University (2018) Setting up a real-time digital data acquisition and control interface in dSPACE, Available at: http://academic.csuohio.edu/richter_h/courses/mce484/dspace_guide.pdf (Accessed: 7th May 2018).

[31]. Azad Ghaffari (2012) “dSPACE and Real-Time Interface in Simulink,” Available at: http://flyingv.ucsd.edu/azad/dSPACE_tutorial.pdf (Accessed: 7th May 2018).

[32]. Nicanor Quijano and Kevin Passino (2002) “A Tutorial Introduction to Control Systems Development and Implementation with dSPACE,” Available at: http://www2.ece.ohio-state.edu/~passino/dSPACEtutorial.doc.pdf (Accessed:7th May 2018).

LIST OF PUBLICATIONS

1. Chinmay Tigade**,** Mini Sreejeth, Ambrish Devanshu (2018), "Comparative Study of Speed Control Techniques of a Three-phase Induction Motor", *International Conference on Electrical, Electronics, Computers, Communication, Mechanical and Computing (EECCMC).*

2. Chinmay Tigade, Mini Sreejeth, Madhusudhan Singh (2018), "Performance Analysis of a Three-Phase Induction Motor Drive Using Miniature Full Spectrum Simulator and MATLAB Simulink", *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT 2018).*