PERFORMANCE EVALUATION OF HYBRID CONVERTER SYSTEM FOR LARGE INDUCTION MOTOR DRIVE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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(With Specialization in Power Apparatus and Electric Drives)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this dissertation report, entitled **"Performance Evaluation of Hybrid converter system for large induction motor drive"** is submitted in partial fulfillment of the requirements for the award of the degree of Master of Technology with specialization in **"Power Apparatus and Electric Drives"** to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, is an authentic record of my own work under the esteemed guidance of **Dr. Pramod Agarwal, Department of Electrical Engineering, Indian Institute of Technology Roorkee,** Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University/Institute.

Dated: 26 June 2008

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CERTIFICATE

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

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ABSTRACT

In industries, conventional drives such as Voltage source inverter (VSI) and Current source inverter (CSI) drives are used for control of small to medium induction motor drives. CSI drive is simple in structure it has many inherent weaknesses in high power applications problems related with output capacitors like resonance phenomena and inherent instability in high frequency region. Similarly VSI drive has very efficient control techniques, for high power induction motor; they face problems like constraints of device ratings.

Recent researches in the field of large induction motor drives are going on in multilevel converter system drives and hybrid converter system drives. Multilevel inverter system overcomes weaknesses of VSI by using different series combinations of devices with latest PWM techniques. Hybrid converter system drive uses VSI parallel to CSI. This strategy allows the operation of the CSI with a safe commutation angle provided by the VSI, regardless of the load speed and torque. By eliminating the requirement of the output capacitors for the conventional CSI-based induction motor drive, this system is quite free from all problems caused by the conventional CSI drives, such as resonance problem and inherent instability. In addition, sinusoidal motor currents and voltages as well as faster response are obtained with this system. It thus removes all difficulties raised by use of output capacitor in high power applications.

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Chapter 1

Introduction

1.1 Overview

High power induction motors presently use conventional drives like Voltage source inverter (VSI) based drives or Current source inverter (CSI) based drives . The VSI ensures a simple and effective motor control over wide ranges of load frequency and voltages. But, the VSI has shown intrinsic weakness for high power application due to substantial switching losses [32]. It also has constraints of device ratings with respect to large induction motor.

In order to overcome problems faced by VSI drive which is, in normal sense, two level drive, a concept of multilevel power conversion was first introduced in 1981[5]. The general concept involves utilizing a higher number of active semiconductor switches to perform the power conversion in small voltage steps. This drive removed all difficulties of a simple two-level drive as smaller voltage steps lead to the production of higher power quality waveforms and also reduce the *dv/dt* stresses on the load [36]. In multilevel inverter devices are connected in series, which allows operation at higher voltages. However, the series connection is typically made with clamping diodes, which eliminates over voltage concerns. Furthermore, since the switches are not truly series connected, their switching can be staggered, which reduces the switching frequency and thus the switching losses.

Multilevel inverter drive have major disadvantages which are increase in total number of devices, which with cost, also increase the complexity of control of devices. There is also problem of balanced voltage for each level.

The CSI is popularly used for high power application, because it is economical and reliable current source inverter using thyristors and the rugged induction motors. It provides simplicity, robustness, cost effectiveness, and very low switching losses, resulting in a favorable topology in high-power areas. And also CSI has inherent advantages such as embedded short-circuit protection, improved converter reliability [15].

CSI based drive has shown some difficulties. CSI has switching devices which requires safe self commutation which demands that the CSI be faced with a leading power factor over all of the operating regions. For this output capacitor is needed for providing the leading power factor for safe commutation [20]. But using output capacitor leads to other disadvantages in high power applications. The size of output capacitor increases with increase in total power output, which is quite tedious and expensive proposition and also they are not reliable. Also output capacitor with inductance in induction motor can lead to resonance, which may lead to instability in high frequency region.

Hybrid converter system drive is developed, which is an assembly of a CSI, a VSI, and a dc-to-dc converter [32], to rectify difficulties raised by using output capacitor in CSI. The VSI generates the leading power factor for the CSI commutation and compensates the harmonic and reactive power to the motor. In all operating regions, the safe commutation of the CSI is ensured from active angle control by the VSI, rather than the passive capacitor commutation in the conventional CSI drive. Therefore, all drawbacks caused by the output capacitor in the conventional CSI-based induction motor drives can be eliminated. Also the rating of VSI is controlled to keep it to minimum required value so as to reduce the overall cost of the drive as the cost of VSI is much more than CSI. One of the major advantages of using hybrid converter is that the induction motor input voltage and current are sinusoidal which leads to better performance of large induction motors. This is not the case for output of CSI drives.

Hybrid converter system drive has some disadvantages, like there is marginal increase in number of devices used and also this in turn increases the complexity of control system for the drive. So, with marginal increase of cost there is substantial improvement in performance of drive.

1.2 Literature Review

Induction motors have become a very integral portion of industry today, with its different applications growing day by day. So control of induction motor is very crucial. There are many drive strategies discussed in literature suitable for induction motor for high power application. These drives have been discussed in following categories.

Voltage Source Inverter (VSI) drive and various modulation techniques

There are many different Pulse Width Modulation (PWM) techniques which are being implemented in controlling VSI drive

Jegathesan. V., Jerome. J. in 2007 [1] proposed an efficient and reliable evolutionary programming-based algorithm for specific harmonic elimination (SHE) switching pattern. This method eliminates the considerable amount of lower order line current harmonics in Pulse Width Modulation (PWM) inverter.

In 2007 Nandhakumar. R., Jeevananthan. S.[2] proposed a novel natural sampled Pulse Width Modulation (PWM) switching strategy for Voltage Source Inverter (VSI) through carrier wave modification. The proposed Inverted Sine Carrier PWM (ISCPWM) method uses a sinusoidal reference signal and an inverted sine carrier which has better spectral quality and higher output limit as compared to the conventional Sinusoidal PWM (SPWM), without any pulse dropping.

In 2006 Solomon. O.R., Famouri. P. [3] proposed A simple approach is presented for obtaining the Switching Loss Factor (SLF) and Quality Factor (QF) used as merit factors for evaluating performances of various Discontinuous Pulse Width Modulating (DPWM) signals derived from a Generalized Discontinuous Pulse Width Modulation Scheme.

In 2006 Iqbal. Atif, Lamine. Adoum, Ashraf. Imtiaz, Mohibullah, [4] demonstrated a VSI model in Matlab Simulink based on space vector modulation technique. They have discussed in detail carrier-based sinusoidal PWM and space vector PWM.

Multi Level Converter System

Multilevel converter based induction motor drives [6]-[10], were proposed to overcome various disadvantages of a 2 level VSI dirve and improve performance of drive system.

In 1981, Nabae. Akira, Takahashi. Isao, Akagi. Hirofumi, [5] first discussed the multilevel power conversion technique. A new neutral-point-clamped pulsewidth modulation (PWM) inverter composed of main switching devices which operate as switches for PWM and auxiliary switching devices to clamp the output terminal potential to the neutral point potential.

In 1991, a novel multilevel structure was proposed for a voltage source inverter for large

capacity drives[9].

In 1994, R.W. Menzies, P.Steimer, and J.K. Steinke described a five-level GTO based voltage-sourced inverter for large induction motor drive [6]. This drive had the advantage that it used only one GTO instead of a series of thyristors for each level.

In 1995, J.S. Lai and F.Z. Peng proposed a multilevel voltage source inverter based drive for large voltage and power applications [7]. The voltage unbalance problem of multilevel converters in the dc capacitors had been solved by the proposed internal connections of the ac/dc and dc/ac converters.

Multilevel power conversion has been receiving increasing attention in the past few years for high power applications [16]. Numerous topologies have been introduced and studied extensively for utility and drive applications in the recent literature. Of particular interest is the topology, which employs series connection of single phase inverters, popularly known as the H-bridge multilevel inverter [17].

In 2000, R.Kieferndorf, G. Venkataramanam, and M.D. Manjrekar presented a novel scheme for nine level H- bridge inverter for large power drive application [14], which could eliminate all the dominant harmonics (5_{th}, 7_{th}, 9_{th}, 11_{th}) over the entire range of operation.

Multilevel converter Modulation techniques

The PWM technique has been widely accepted as a good control strategy, because of its simplicity and ability to control the fundamental voltage and the harmonic content. A literature review of PWM techniques extended to multilevel inverters indicates there are two PWM methods that show good results. One is an extension of the Sinusoidal PWM (SPWM) technique presented in [11], and the other is called the switching frequency opti-mal PWM (SFOPWM) method as applied to three-level NPC) inverters [13].

In 1999, Madhav D. Manjrekar addressed multilevel H-bridge inverter drives rated for high power levels which are normally controlled by extensions of six step waveforms popularly termed as staircase modulation [18].

In 2008 Jingsheng Liao, Corzine Keith, Ferdowsi Mehdi presented [19] with presented a multilevel H bridge inverter using phase-shift modulation, a new control method for cascaded H-bridge multilevel converters with only one independent dc source per phase.

CSI drives and various modulation techniques

In 1992, a combination of two modulation techniques, selected harmonic elimination in the upper frequency range and trapezoidal modulation in the lower frequency range-control of voltage, were proposed [20] for limiting the frequency of current source inverter based drives to less than 180 Hz for large induction motor.

In 1994, two novel switching algorithms were proposed to cover the low-speed and high speed regimes for SCR based naturally commutated drive [21]. With these switching algorithms torque ripple in lower speed range was negligible and commutation in peak device voltage stress limit was guaranteed.

A Number of pulse-width modulated (PWM) current source inverters (CSI) used self extinguishing switches have been reported in the literature [22]-[27].

Usually, a relatively high switching frequency was employed to obtain a near-sinusoidal output voltage and current. With large induction motor drives using GTO switches, it was desirable to limit the switching frequency to a low value, e.g., < 200 Hz, to minimize switching losses. This requirement became increasingly important as the rated voltage of the motor is increased. Reference [28] describes one harmonic elimination approach that could be used to provide acceptable waveform with low switching frequency.

In order to achieve low harmonic content over a wide speed range, two modulation techniques meeting these constraints were used in this drive. Trapezoidal modulation [22] - [25], [29] is used in the low-stator frequency range up to about 20 Hz. At higher frequencies in the 20-60 Hz range, selected harmonic elimination was employed to eliminate one or more of the dominant current harmonics [29], [30]. In both ranges, the number N was adjusted to keep the maximum switching frequency equal to or less than 180 Hz.

In 1994, H. Mok, S. K. Sul, and M. H. Park [31], proposed a load commutated inverter based induction motor drive with a novel dc side commutation circuit.

There were many disadvantages of using output capacitor in CSI drive.

Hybrid Converter System

Hybrid converter system were proposed [32]-[33], to overcome disadvantages of conventional converters.

In 2005, S. Kwak, and H.A. Toliyat proposed [32] a hybrid converter system which overcame almost all the short comings of the conventional converter system. The hybrid converter system consists of both CSI and VSI with dc – dc converter. The VSI compensated for leading power factor for commutation of CSI thyristors, thus compensating for output capacitor.

1.3 Scope of work and Author's Contribution

The dissertation thesis describes different induction motor drives which can be used for high power application. Different induction motor drives which are discussed here are Voltage source inverter (VSI) drive, Multilevel inverter drive Current source inverter (CSI) drive and Hybrid converter system drive, out of these Hybrid converter system is a new strategy of implementing a drive.

All above mentioned drives are simulated in Matlab Simulink and their performance response are noted and at the end of thesis these data is comparatively discussed. At the end conclusion is derived from this comparative discussion.

1.4 Organization of Thesis

Included in this chapter, it gives an overview of thesis with brief discussion of different drives and line of thought for thesis. It also deals with literature review which explains all the material reviewed with this thesis in mind.

Second chapter explains about difference between VSI and CSI. It explains about VSI and different PWM techniques involved. It specially deals with space vector PWM. Finally chapter ends with simulation of VSI drive and it results and disadvantages.

Third chapter deals with Multilevel inverter drive with its advantages over VSI. It goes on to explain different PWM techniques and also briefly discusses different topologies. It ends with simulation of dive and its results.

Fourth chapter deals with CSI drive, which starts with brief discussion of its different firing modes. Then the simulation and results is discussed. The chapter ends with disadvantage of using output capacitors with respect to performance of CSI drive.

Fifth chapter deals with Hybrid converter drive and starts with discussion of advantages over CSI drive. The chapter goes on to discuss the topology of the converter system and also mentions control scheme of the drive. Then it deals with simulation and results of the drive. At the end of chapter, performance of all above drives is displayed in tabular form and then discussion is presented.

Sixth chapter concludes the thesis with conclusion drawn from the discussion done in previous chapter.

Chapter 2

Voltage Source Inverter

Induction motors for high power applications presently in industries uses conventional converter drives. Voltage source inverter (VSI) drive is one of these. This chapter refers to various Pulse width modulation techniques with space vector PWM discussed in length. Simulation VSI drive is discussed in the end with results. Converters that convert d.c. to a.c. are known as inverters. In other words, an inverter is a circuit, which converts a d.c. power to a.c. power at desired output voltage and frequency. The a.c. output voltage could be fixed at fixed or variable frequency. This conversion can be achieved by either controlled turn-on or turn-off devices or by forced commutation thyristors, depending on applications [36].

2.1 Major Inverter Topologies

The two major inverter topologies are Voltage Source Inverter (VSI) and Current Source Inverter (CSI). The VSI had been investigated for optimal operation, but the CSI has not been so well studied. A major limitation for CSI is the availability of modulation strategies with sophistication and performance of their VSI counter parts.

2.1.1 Voltage Source Inverter

A voltage source inverter (VSI), shown in figure 2.1 is one in which D.C. source has small or negligible impedance. In other words, the voltage source inverter has stiff d.c. source at its input terminals. Because of low internal impedance, the terminal voltage of a VSI remains substantially constant with variation in load. It is therefore equally suitable to single motor and multi motor drives. Any short circuits across its terminals cause current to rise very fast, due to low time constant of its internal impedance. The fault cannot be corrected by current control and must be cleared by fast acting fuse.

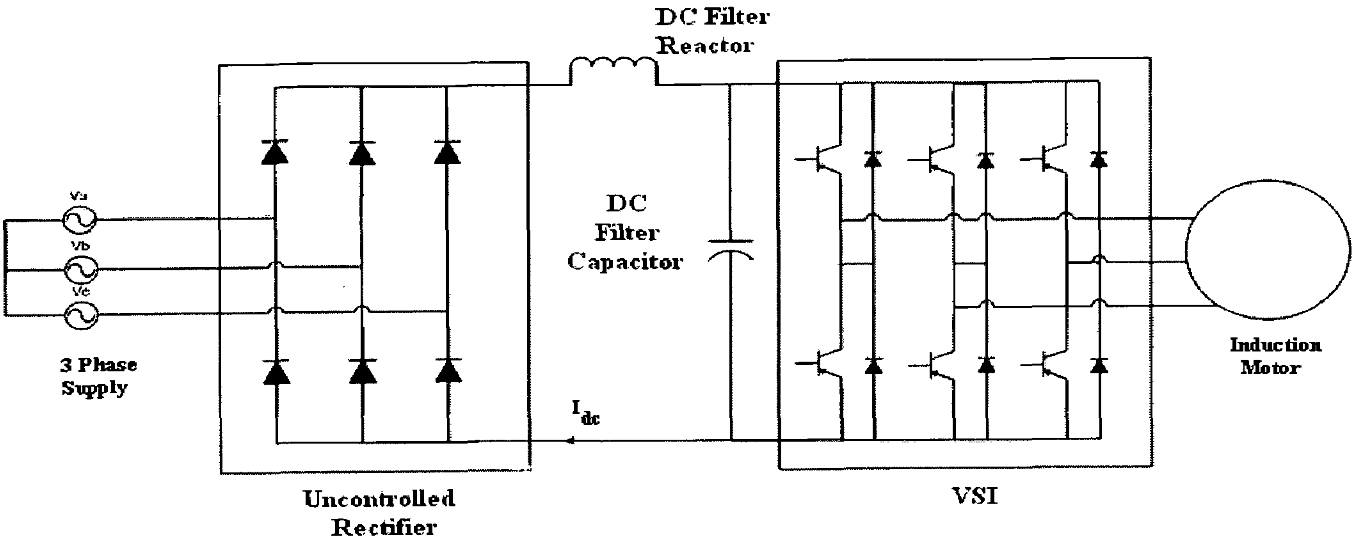


Figure 2.1 Voltage Source Inverter

2.1.2 Current Source Inverter

The Current Source Inverter (CSI) is applied with a control current from D.C. source of high impedance. Typically phase controlled thyristor rectifier feeds the inverter with a large series inductor (figure 2.2). Thus, load current rather than load voltage is controlled, and the inverter output voltage is dependent upon the load impedance. Because of large internal impedance, the terminal voltage of a current source inverter changes substantially with a change in load. Therefore, if used in a motor drive, a change in load on any motor affects other motors. Hence, CSI are not suitable for multi motor applications. Since inverter current is independent of load

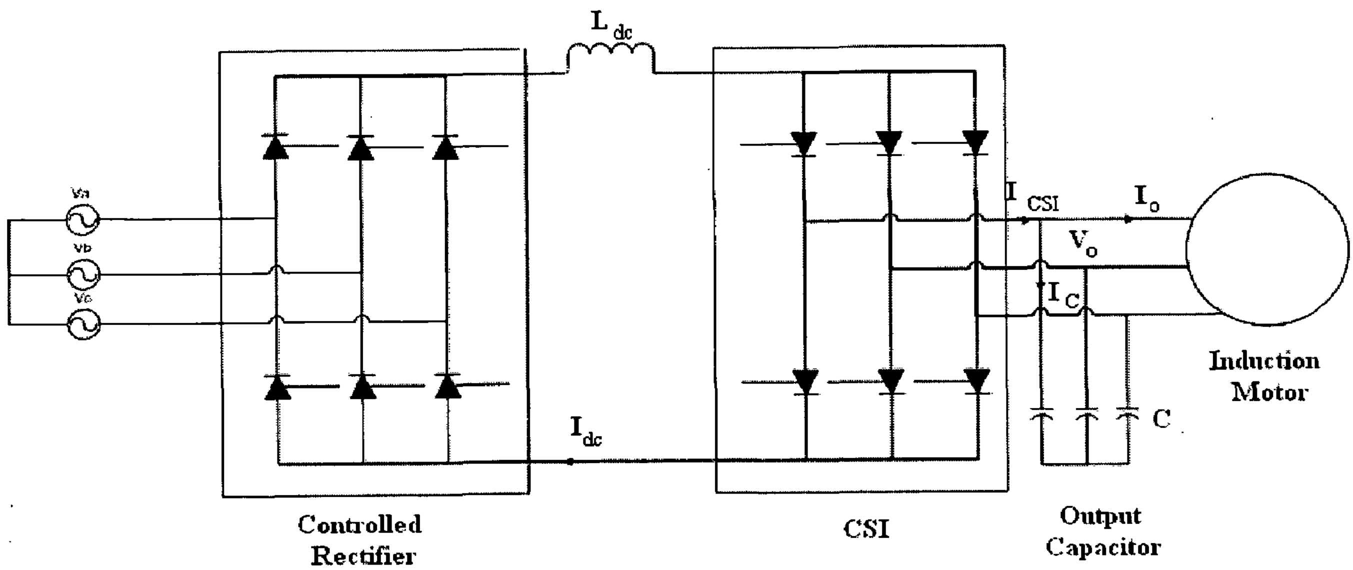


Figure 2.1 Current Source Inverter

impedance, it has inherent protection against short-circuits across its terminals.

Some of the important applications of inverters are [35].

- AC motor drives
- AC uninterruptible power supplies (UPSs)
- Induction heating
- AC power supply from battery, photovoltaic array, or fuel cell
- Static VAR generator (SVG) or compensator (SVC)
- Active harmonic filter (AHF)

2.2 Voltage Source Inverter

Voltage-source inverter (VSI), as the name indicates, receives dc voltage at one side and converts it to ac voltage on the other side. The ac voltage and frequency may be variable or constant depending on the application. In fact, the general name "converter" is given because the same circuit can operate as an inverter as well as a rectifier. A voltage-source inverter should have a stiff voltage source at the input, that is, its Thevenin impedance should ideally be zero. A large capacitor can be connected at the input if the source is not stiff [36]. The dc voltage may be fixed or variable, and may be obtained from a utility line or rotating ac machine through a rectifier and filter. It can also be obtained from a battery, fuel cell, or solar photovoltaic array. The inverter output can be single-phase or polyphase, and can have square wave, sine wave, PWM wave, stepped wave, or quasi-square wave at the output. Voltage-fed converters are used extensively in induction motor drives applications.

In voltage-fed converters, the power semiconductor devices always remain forward-biased due to the dc supply voltage, and therefore, self-controlled forward or asymmetric blocking devices, such as GTOs, BJTs, IGBTs, power MOSFETs, and IGCTs are suitable. A feedback diode is always connected across the device to have free reverse current flow. One important characteristic of a voltage-fed converter is that the ac fabricated voltage wave is not affected by the load parameters [36].

2.2.1 Pulse Width Modulation Techniques

The three-phase inverter discussed before has several advantages and limitations. The inverter control is simple. Unfortunately, the lower order harmonics of the voltage wave will cause large distortions of the current wave unless filtered by bulky and uneconomical low-pass filters. Besides, the voltage control by the line-side rectifier has the usual disadvantages.

An inverter contains electronic switches, so it is possible to control the output voltage as well as optimize the harmonics by performing multiple switching within the inverter with the constant dc input voltage V_d. The PWM principle to control the output voltage is explained in Figure 2.3 [36]. The fundamental voltage V_1 has the maximum amplitude ($4V_d/\pi$) at square wave, but by creating two notches as shown, the magnitude can be reduced. If the notch widths are increased, the fundamental voltage will be reduced.

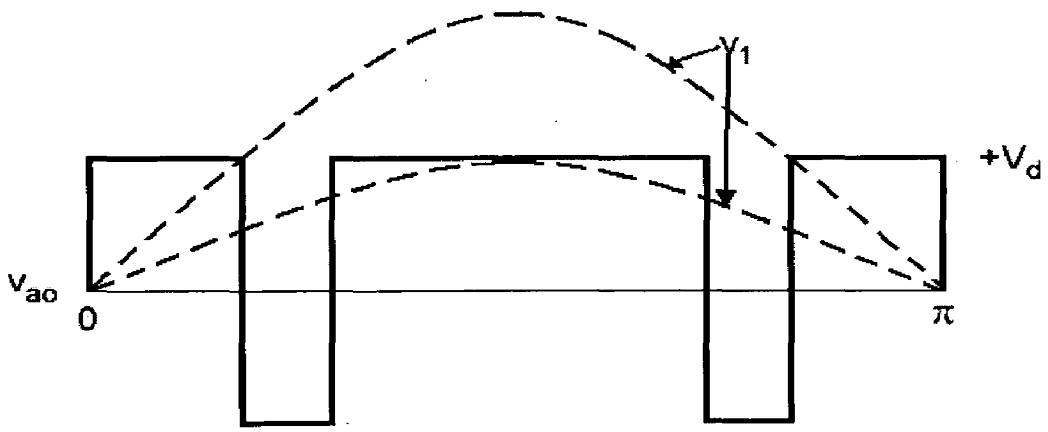


Figure 2.3 PWM principle to control output voltage [36]

2.2.2 Space Vector Pulse Width Modulation

There are many possible PWM techniques proposed in the literature. The classifications of PWM techniques can be given as follows [35]:

- Sinusoidal PWM (SPWM)
- Selected harmonic elimination (SHE) PWM
- Minimum ripple current PWM
- Space-Vector PWM (SVM)
- Hysteresis band current control PWM

The PWM technique used in the simulation presented here is Space Vector PWM. A mathematical model of three-phase is presented here based on space vector representation. The power circuit topology of a three-phase VSI is shown in Fig. 2.4 Each switch in the inverter leg is composed of two back-to-back connected semiconductor devices. One of these two is a controllable device and other one is a diode for protection. Leg voltage waveform is shown in Fig. 2.5 [4] for 180° conduction mode.

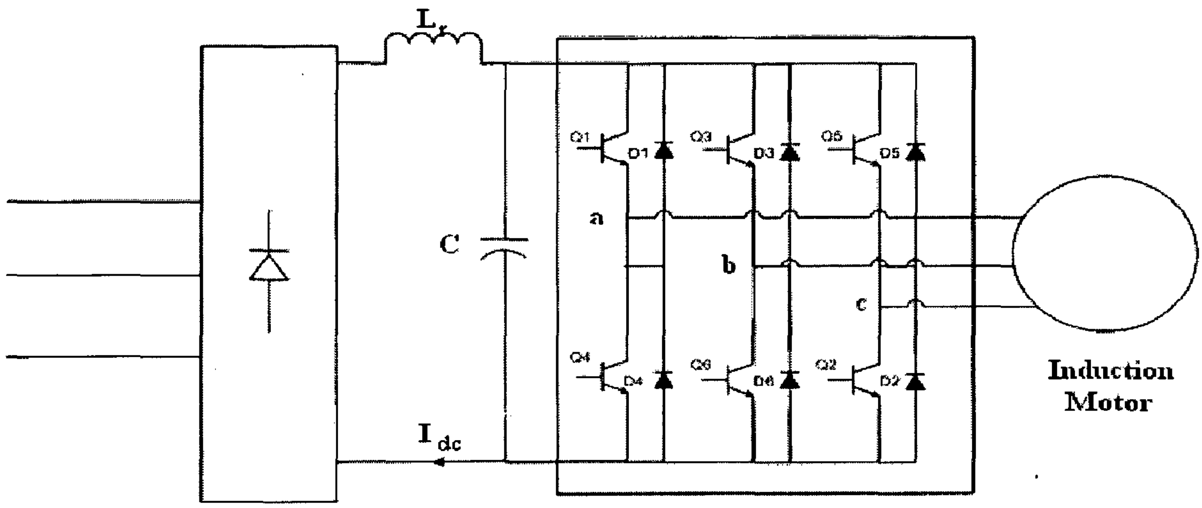


Figure 2.4 Three Phase Bridge Inverter [4]

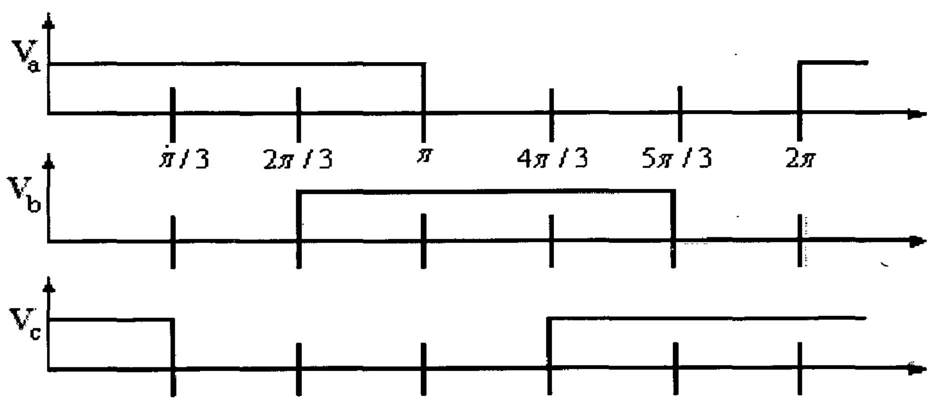


Figure 2.5 Leg Voltage of Three phase VSI

It is observed from Fig. 2.5 that one inverter leg's state changes after an interval of 60° and their state remains constant for 60° interval. Thus it follows that the leg voltages will have six distinct and discrete values in one cycle (360°). Space vector representation of the three-phase inverter output voltages is introduced next. Space vector is defined as;

$$\overline{v_s} = \frac{2}{3}\left(v_a + \bar{a}v_b + \overline{a^2}v_c\right) \qquad (2.1)$$

where $\bar{a} = \exp(j2\pi/3)$ [4]. The space vector is a simultaneous representation of all the three-phase quantities. It is a complex variable and is function of time in contrast to the phasors. Phase-to-neutral voltages of a star-connected load are most easily found by defining a voltage difference between the star point n of the load and the negative rail of the dc bus N. The following correlation then holds true:

$$\begin{aligned} V_A &= v_a + v_{nN} \\ V_B &= v_b + v_{nN} \\ V_C &= v_c + v_{nN} \end{aligned} \qquad (2.2)$$

Since the phase voltages in a start connected load sum to zero, summation of equation (2.2) yields

$$v_{nN} = (1/3)(v_A + v_B + v_C) \qquad (2.3)$$

Substitution of (2.3) into (2.2) yields phase-to-neutral voltages of the load in the following form:

$$\begin{aligned} v_a &= (2/3)v_A - (1/3)(v_B + v_C) \\ v_b &= (2/3)v_B - (1/3)(v_A + v_C) \\ v_c &= (2/3)v_C - (1/3)(v_B + v_A) \end{aligned} \qquad (2.4)$$

Phase voltages are summarized in Table 1 [4] and their 3. Space vector PWM corresponding space vectors are listed in Table 2 [4].

This PWM method is frequently used in vector controlled and direct torque controlled drives. In vector controlled drive this technique is used for reference voltage generation when current control is exercised in rotating reference frame.

State	Switch on	v_a	v_b	v_c
1	1,4,6	$(2/3)V_{dc}$	$-(1/3)V_{dc}$	$-(1/3)V_{dc}$
2	1,3,6	$(1/3)V_{dc}$	$(1/3)V_{dc}$	$-(2/3)V_{dc}$
3	2,3,6	$-(1/3)V_{dc}$	$(2/3)V_{dc}$	$-(1/3)V_{dc}$
4	2,3,5	$-(2/3)V_{dc}$	$(1/3)V_{dc}$	$(1/3)V_{dc}$
5	2,4,5	$-(1/3)V_{dc}$	$-(1/3)V_{dc}$	$(2/3)V_{dc}$
6	1,4,5	$(1/3)V_{dc}$	$-(2/3)V_{dc}$	$(1/3)V_{dc}$
7 8	1,3,5 2,4,6	0	0	0

Table 1 Phase voltage values for different switching states [4].

State	Phase Voltage Space Vector
1	$(2/3)V_{dc}$
2	$(2/3)V_{dc}\exp(j\pi/3)$
3	$(2/3)V_{dc}\exp(j2\pi/3)$
4	$(2/3)V_{dc}\exp(j\pi)$
5	$(2/3)V_{dc}\exp(j4\pi/3)$
6	$(2/3)V_{dc}\exp(j5\pi/3)$
7&8	0

Table 2 Phase voltage space vectors [4]

The discrete phase voltage space vector positions are shown in Fig. 2.6 [4].

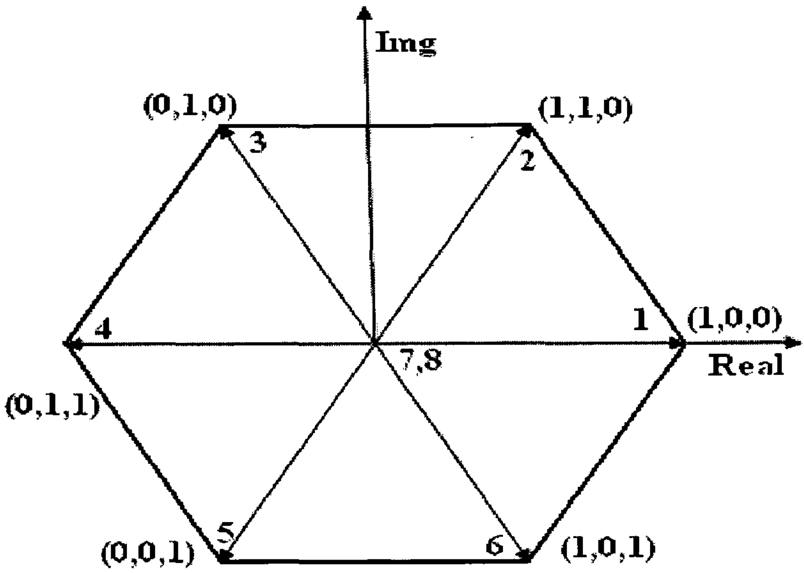


Figure 2.6 Phase voltage space vectors [4].

The binary numbers on the figure indicate the switch state of inverter legs. Here 1 implies upper switch being on and 0 refers to the lower switch of the leg being on. This PWM method is frequently used in vector controlled and direct torque controlled drives. In vector controlled drive this technique is used for reference voltage generation when current control is exercised in rotating reference frame.

It is seen in the previous section that a three-phase VSI generates eight switching states which include six active and two zero states. These vectors form a hexagon (Fig. 2.6) which can be seen as consisting of six sectors spanning 60° each. The reference vector which represents three-phase sinusoidal voltage is generated using SVPWM by switching between two nearest active vectors and zero vector. To calculate the time of application of different vectors, consider Fig. 2.7 [4], depicting the position of different available space vectors and the reference vector in the first sector.

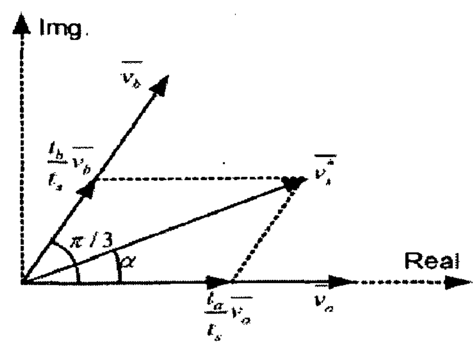


Figure 2.7 Principle of space vector time calculation [4].

$$t_a = \frac{\left|\overline{v_s^*}\right|}{\left|\overline{v_a}\right|} \frac{\sin(\pi/3 - \alpha)}{\sin(2\pi/3)} \quad (2.5)$$

$$t_b = \frac{\left|\overline{v_s^*}\right|}{\left|\overline{v_b}\right|} \frac{\sin(\alpha)}{\sin(2\pi/3)}$$

$$t_0 = t_s - t_a - t_b \quad (2.6)$$

where $\left|\overline{v_a}\right| = \left|\overline{v_b}\right| = (2/3)V_{dc}$ In order to obtain fixed switching frequency and optimum harmonic performance from SVPWM, each leg should change its sate only once in one switching period. This is achieved by applying zero state vector followed by two adjacent active state vector in half switching period. The next half of the switching period is the mirror image of the first half. The total switching period is divided intro 7 parts, the zero vector is applied for $1/4^{th}$ of the total zero vector time first followed by the application of active vectors for half of their application time and then again zero vector is applied for $1/4^{th}$ of the zero vector time. This is then repeated in the next half of the switching period. This is how symmetrical SVPWM is obtained. The leg voltage in one switching period is depicted in Fig. 2.8 [4] for sector I.

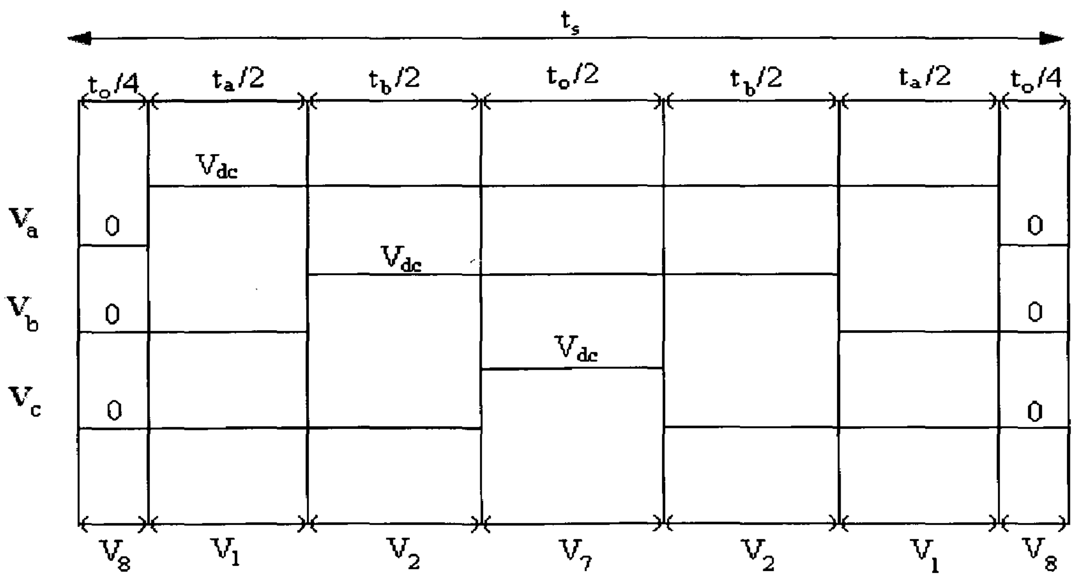


Figure 2.8 Leg voltages and space vector disposition for one switching period in sector I [4].

The sinusoidal reference space vector forms a circular trajectory inside the hexagon. The largest output voltage magnitude that can be achieved using SVPWM is the radius of the largest circle that can be inscribed within the hexagon. This circle is tangential to the mid points of the lines joining the ends of the active space vector. Thus the maximum obtainable fundamental output voltage is given by equation 2.7.

$$\left|\overline{v_s^*}\right| = \frac{2}{3} V_{dc} \cos(\pi / 6) = \frac{1}{\sqrt{3}} V_{dc} \qquad (2.7)$$

2.3 Simulation and Results

In the simulation of a Voltage Source Inverter based drive, the simulation uses an induction motor of 50 h.p. with rated speed at 1440 r.p.m.. For further parameters refer Appendix B. The simulation block diagram is shown in Fig. 2.9. The simulation model consists of a speed control loop with speed Proportional Integral (PI) controller which is followed by slip speed regulator. From slip speed error and speed value required frequency and voltage are found which are then used by space vector modulation block to give required controlling pulses for VSI.

Different testing parameters are given as below

Parameters	0-1200 (rpm)	1200-1300 (rpm)	1300-1100 (rpm)	0 to ½ load	½ to ¼ load
Time	0sec	1sec	1.5sec	2.5sec	3sec

Table 3 Testing parameters for drive

The system performance with graphical representation of speed and torque behavior of the drive is given in figure 2.10. Behavior of different values like motor input current and voltage are shown in figure 2.11.Table 4 gives the tabular representation of system performance.

2.3.1 Simulation

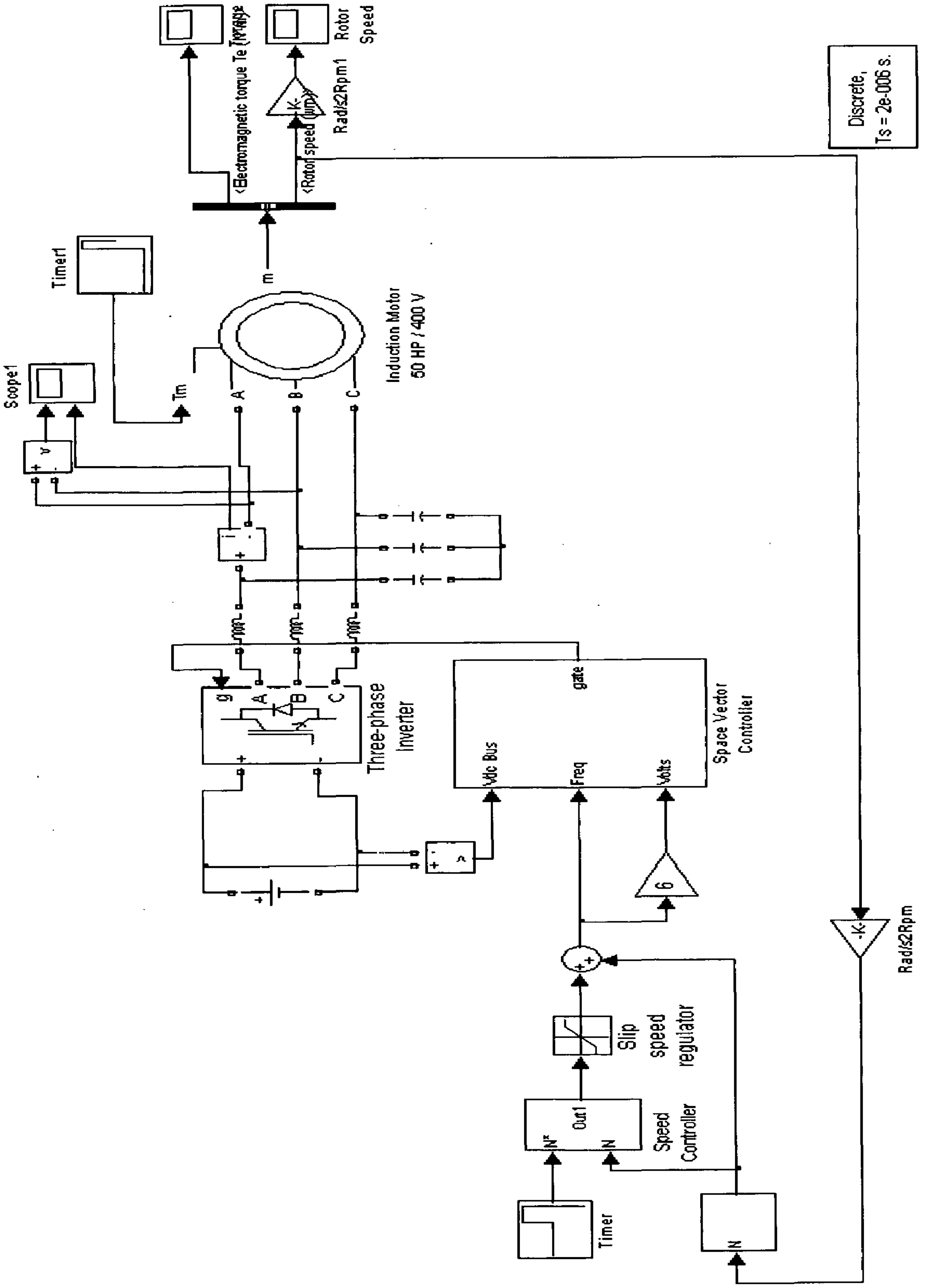


Figure 2.9 Simulation Block diagram for VSI based on space vector modulation

2.3.2 Results

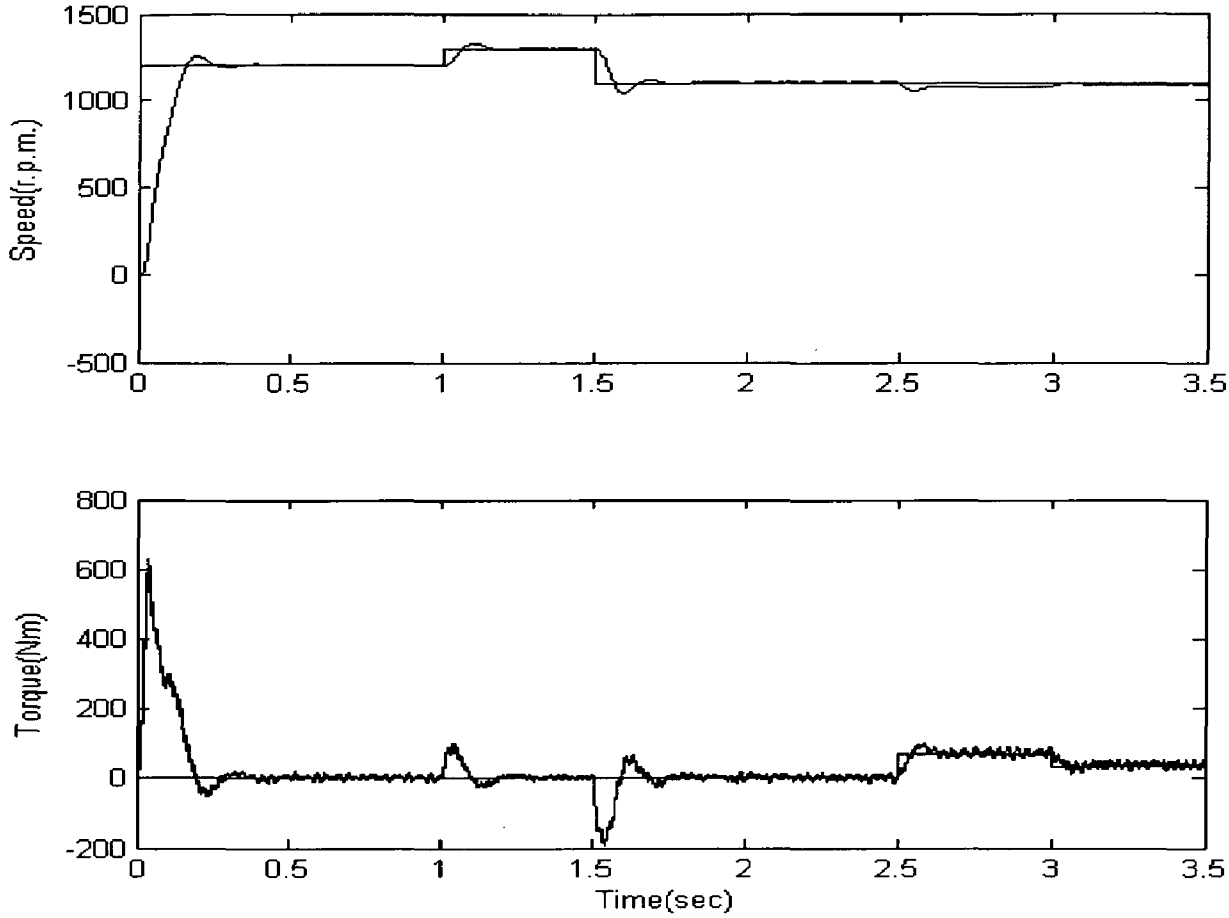


Figure 2.10 Plot of induction motor speed and torque w.r.to time.

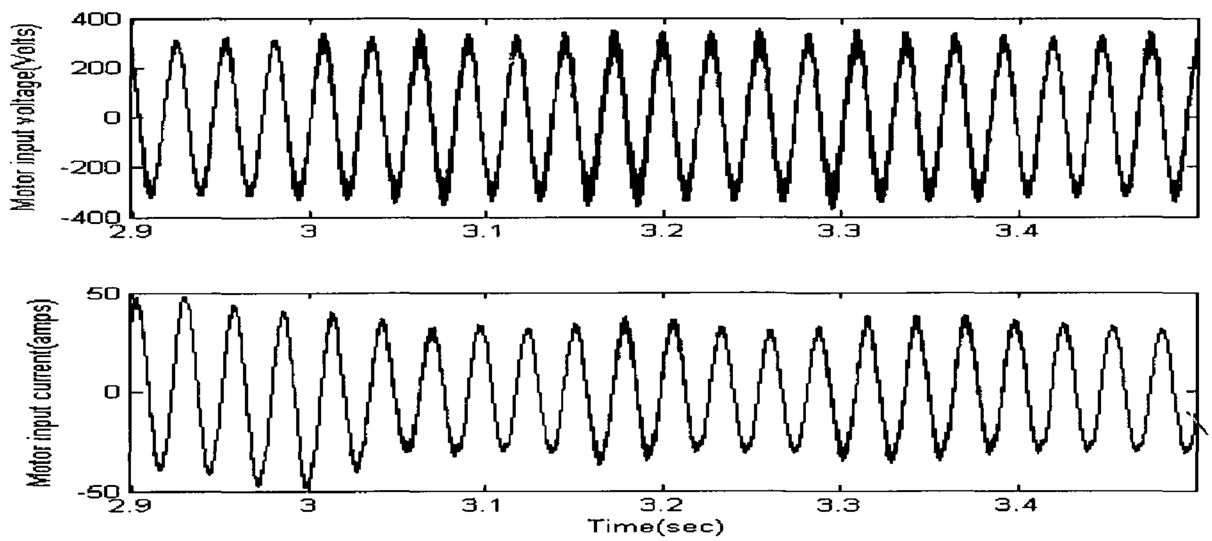


Figure 2.11 Plot of motor input voltage and current w.r.to time

Values of different performance parameters at different instances of time are given in tabular form as shown below in Table 4.

	0-1200 (rpm)	1200-1300 (rpm)	1300-1100 (rpm)	0 to ½ load	½ to ¼ load
Settling time	0.15sec	0.06sec	0.065sec	0.05sec	0.05sec
Maximum overshoot	5.1%	2.5%	4%	10%	10%
Rise time	0.26sec	0.11sec	0.17sec	0.18sec	0.18sec

Table 4 Performance of VSI drive

2.4 Conclusion

Voltage source inverter (VSI) drive is one of the most commonly used drives used in the industry today. It is also used for high power induction motors. There are many Pulse width modulation (PWM) techniques used in VSI control. Space vector PWM being one of the most efficient PWM techniques is used in simulation of VSI drive of 50 hp induction machine.

Speed and torque response of the drive are shown in results with other waveforms of voltage and current. Performance of the drive is displayed in table 4 which can be basis of comparison to other drives.

Chapter 3

Multilevel Inverter

Multilevel power conversion concept involves utilizing a higher number of active semiconductor switches to perform the power conversion in small voltage steps. General concept of multilevel inverter has been discussed also with different topologies and PWM techniques of multilevel inverter. Simulation and performance of multilevel inverter are displayed at the end. There are several advantages to this approach when compared with traditional (two-level) power conversion. The smaller voltage steps lead to the production of higher power quality waveforms and also reduce the *dv/dt* stresses on the load and reduce the electromagnetic compatibility (EMC) concerns. Another important feature of multilevel converters is that the semiconductors are wired in a series-type connection, which allows operation at higher voltages [37]. However, the series connection is typically made with clamping diodes, which eliminates over voltage concerns. Furthermore, since the switches are not truly series connected, their switching can be staggered, which reduces the switching frequency and thus the switching losses.

In recent years, there has been a substantial increase in interest in multilevel power conversion. Recent research has involved the introduction of novel converter topologies and unique modulation strategies.

Some applications for these new converters include [37]:

- industrial drives,
- flexible AC transmission systems (FACTS),
- vehicle propulsion.

One area where multilevel converters are particularly suitable is that of medium & high voltage drives. It may be easier to produce high power, high voltage inverter with the multilevel structure because of the way in which device voltage stresses are controlled in the structure. Increasing the number of voltage levels in the inverter without requiring higher ratings on individual devices can increase the power rating. The unique structure of multilevel inverter allows them to reach high voltages with low harmonics without the use of transformers or series connected synchronized switching devices. As the number of voltage levels increase, the harmonic content of output voltage wave form decreases.

3.1 Multilevel Concept

Consider a 3 phase inverter system, as shown in figure 3.1 [35], with a d.c. voltage V_{dc}. Series connected capacitor constitute the energy tank for the inverter, providing some nodes to which the multilevel inverter can be connected. Each capacitor has the same voltage E_m, given by

$$E_m = \frac{V_{dc}}{m-1} \tag{3.1}$$

where m denotes the number of levels. The term level is referred to as number of nodes to which the inverter can be accessible. An m-level needs (m-1) capacitors.

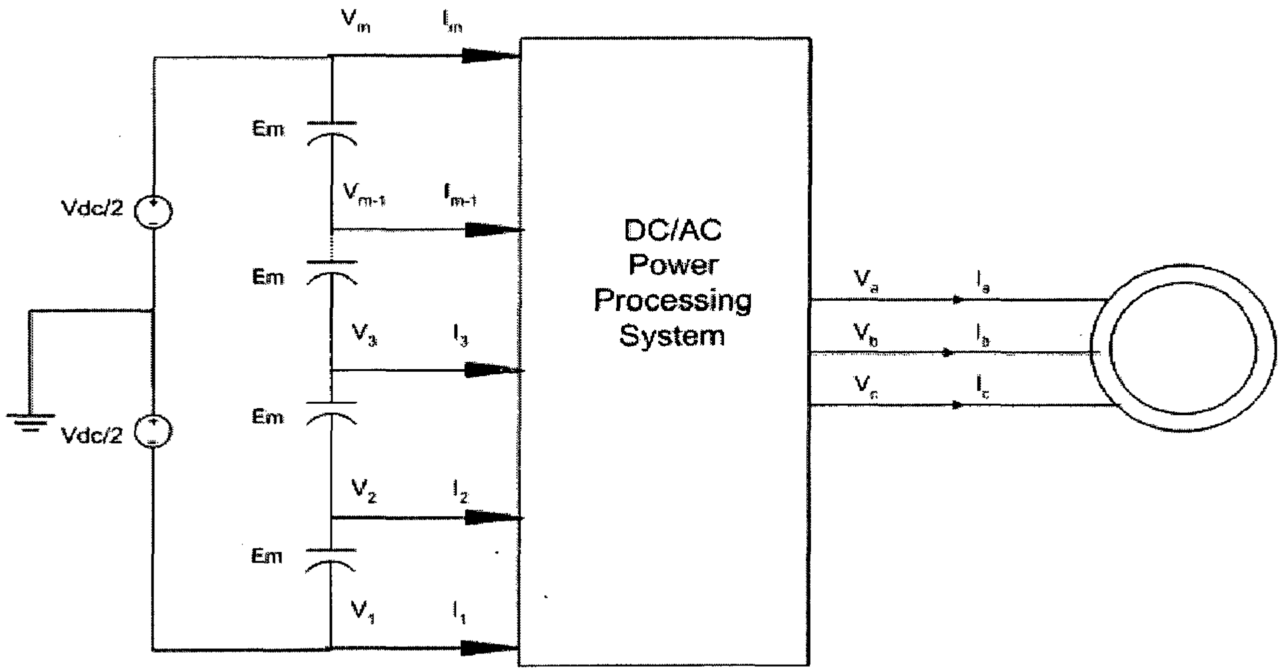


Figure 3.1 Three phase multilevel system [35]

Output phase voltage can be defined as voltage across output terminals of the inverter and the ground point shown in figure 3.1. Multilevel inverter consists of pole which can be represented as a single pole multi throw switch. By connecting the switch to one node at a time, one can obtain the desired output. Figure 3.2 [35] shows the typical output voltage of a three level inverter.

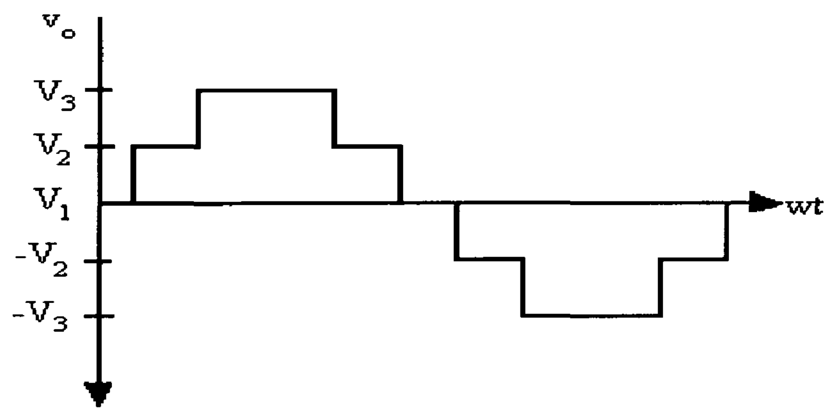


Figure 3.2 Typical output voltage of three level inverter [35]

3.2 Types of Multilevel Inverters

The general structure of multilevel inverter is to synthesize a near sinusoidal voltage from several levels of d.c. voltages, typically obtained from capacitor voltage sources. As the number of levels increases, the synthesized output waveform has more steps, which produces staircase waveform that approaches the desired waveform. Also, harmonic distortion is decreased.

The multilevel inverter can be classified into basic three types [35].

1) **Diode clamped multilevel inverter:** This inverter typically consists of (m-1) capacitors on the d.c. bus and produces m-level on the phase voltage. An m-level inverter leg requires (m-1) capacitors, 2(m-1) switching devices and (m-1)(m-2) clamping diodes.
2) **Flying Capacitor multilevel inverter:** The voltage level for flying capacitor converter is similar to that of the previously discussed. That is the phase voltage of an m-level converter has m-levels and the line voltage has 2(m-1) levels. For m-levels dc bus needs (m-1) capacitors.
3) **Cascade multilevel inverter:** A cascade inverter consists of a series of H-bridge (single phase, full-bridge) inverter units. The general function of this multilevel inverter is to generate a desired voltage fro several separate dc sources, which may be obtained from batteries, fuel cells or solar cells. Each dc source is connected to an H-bridge inverter. The ac terminals of different level inverters are connected in series. Unlike the previous inverters discussed, the cascade inverter does not require any voltage clamping diodes or voltage balancing capacitors.

3.3 Control Strategies for Multilevel Inverters

Various strategies for the control of the output voltage and frequency are studied on the basis of number of thyristor switching per fundamental cycle and the distortion factor defined as the rms value of the harmonic voltages normalized to the maximum fundamental voltage and divided by the harmonic number. A low distortion factor implies low losses due to harmonic voltages and currents and a low torque ripple.

Different control strategies are described as following:

1) **Sinusoidal Pulse Width Modulation (SPWM):** The control principle of the SPWM is to use several triangular carrier signals keeping only one modulating sinusoidal signal.
2) **Optimized Harmonic Stepped-Waveform Technique(OHPWM):** The objective of the optimized harmonic stepped waveform technique is to reduce, as much as possible, the harmonic distortion in the load voltage, working with a reduced switching frequency. The concept of this technique is to combine the idea of the selective harmonic elimination PWM with the quarter-wave symmetric idea concept.
3) **Selective Harmonic Eliminated Pulse Width Modulation (SHEPWM):** Selective Harmonic Elimination (SHE) is an off-line (precalculated) non carrier based PWM technique. In this method the basic square-wave output is "chopped" a number of times, which are obtained by proper off-line calculations.

In the Matlab Simulink simulation worked out here, out of the above three PWM strategies discussed here, sinusoidal pulse width modulation strategy is used. For the five level inverter, four triangular carriers are needed (Generally speaking, if a m-level inverter is employed, (m-1) carriers will be needed). The carriers have the same frequency fc and the same peak-to-peak amplitude AC. The zero reference is placed in the middle of the carrier set. The modulating signal is a sinusoid of frequency fm and amplitude Am. At every instant, each carrier is compared with the modulating signal. Each comparison switches the switch "on" if the modulating signal is greater than the triangular carrier assigned to that switch. Obviously, the actual driving signals for the power devices can be derived from the results of the modulating-carrier comparison by means of a logic circuit.

3.4 Simulation and Results

3.4.1 Simulation

The simulation of a three level multilevel inverter is done in Matlab Simulink by using pulse width modulation technique of sinusoidal PWM. The simulation block diagram shown in Figure 3.3 uses mathematical model of induction motor which is described in Appendix A. Different parameter values used in this induction motor model is given in Appendix B. The simulation block set uses a feedback loop which feedbacks updates values of voltage and current to torque and flux estimator which calculates torque and flux values.

The updated value of rotor speed is used in speed PI controller with reference speed to get the reference torque value which is the used by torque PI controller to get reference quadrature axis voltage value. For flux PI controller using reference flux value as 0.4Wb we get direct axis reference voltage value. Torque flux estimator also calculates the angle of system theta. Sinusoidal PWM block uses value of direct and quadrature axis reference voltage value and theta to give the required 3 phase voltage to induction motor model as shown in Figure 3.5. Values of various system parameters are given in Appendix C.

Using the control parameters given in Table 3, this system is simulated to get desired results. The speed and torque response plot for the simulation is given in Figure 3.4. The plot of phase voltages and line voltage with phase current is given in Figure 3.5. Table 4 gives the tabular representation of system performance.

Simulation Block Diagram

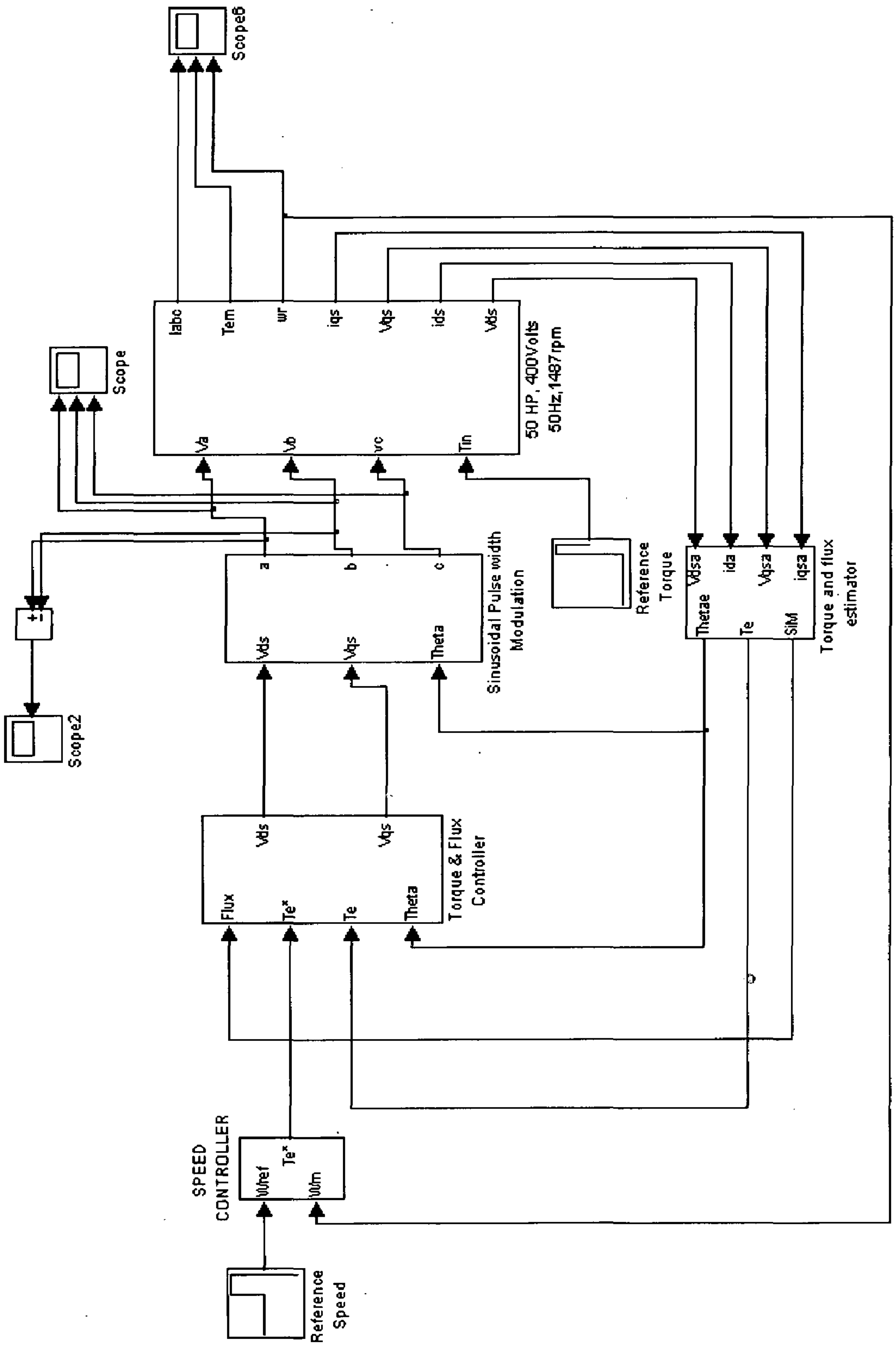


Figure 3.3 Simulation Block diagram for Three Level Inverter

3.4.2 Results

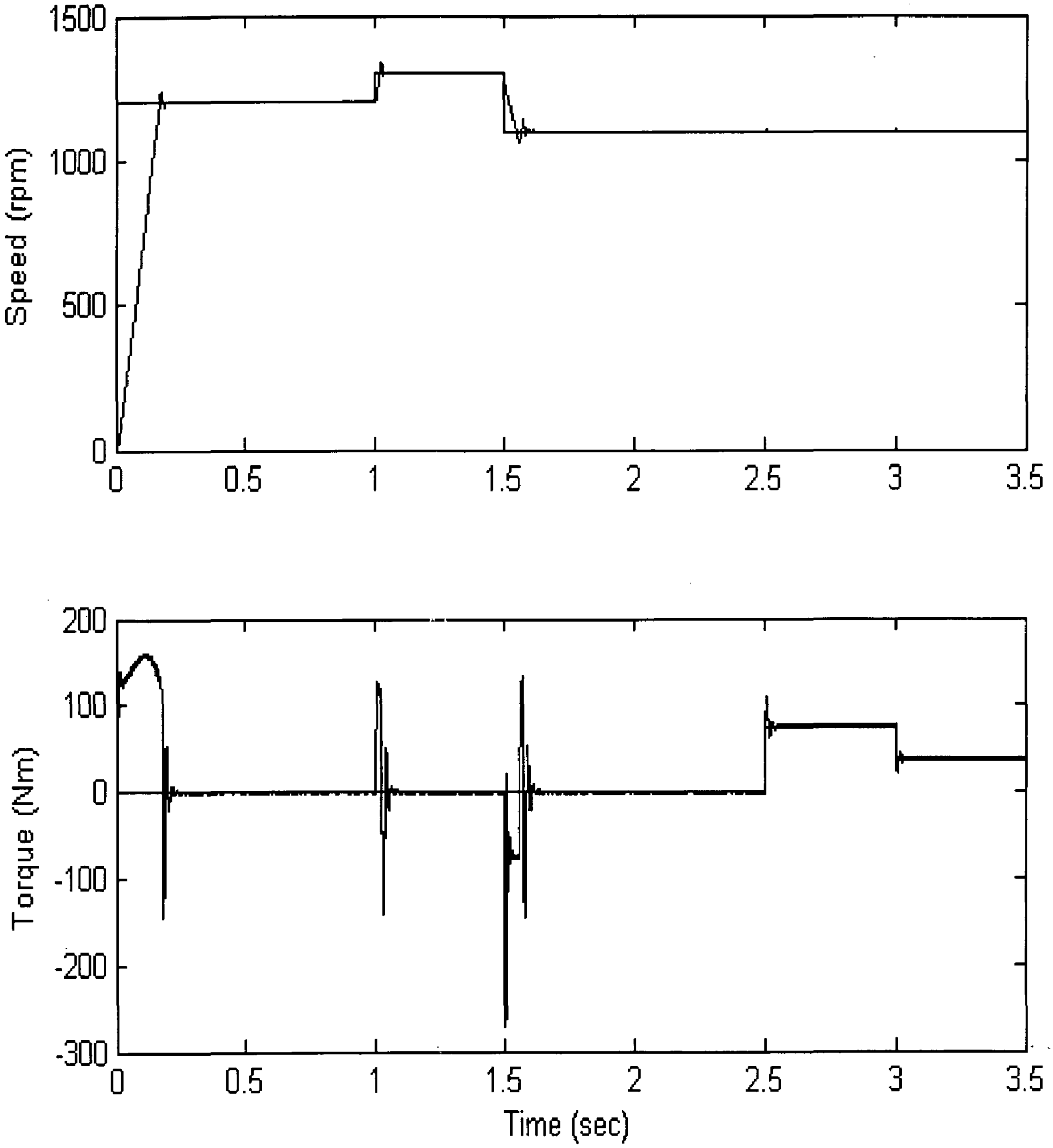


Figure 3.4 Speed and Torque plot

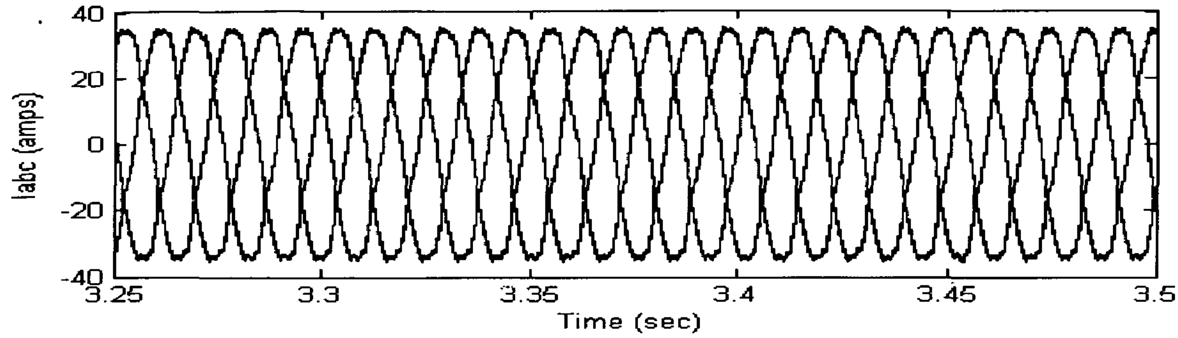


Figure 3.5 Phase current plot

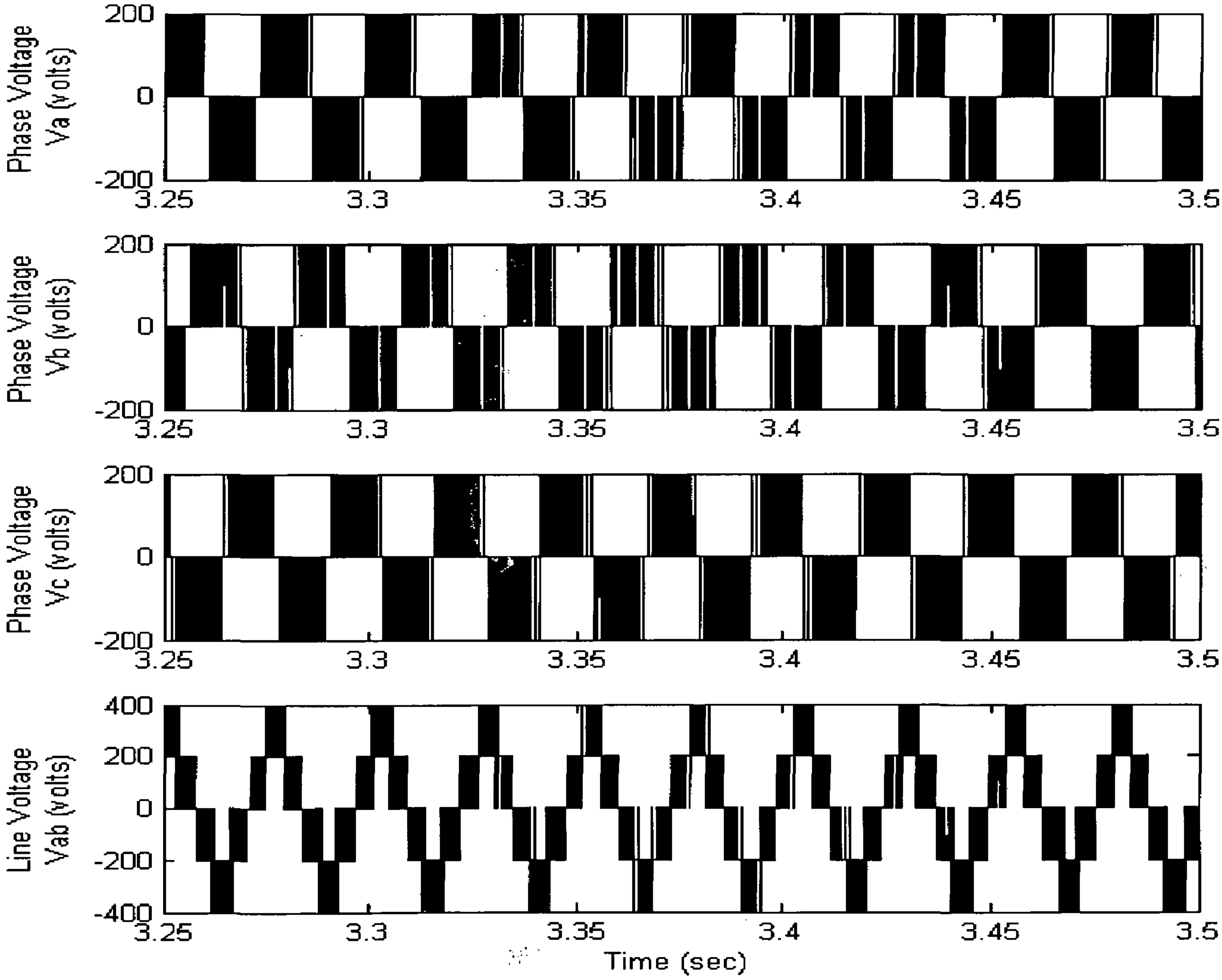


Figure 3.6 Phase and Line Voltage Plots

Values of different performance parameters at different instances of time are given in tabular form as shown below in Table 5.

	0-1200 (rpm)	1200-1300 (rpm)	1300-1100 (rpm)	0 to ½ load	½ to ¼ load
Settling time	0.17sec	0.02sec	0.05sec	0.02sec	0.01sec
Maximum overshoot	3.8%	3.5%	3.5%	15%	15%
Rise time	0.185sec	0.035sec	0.08sec	0.04sec	0.03sec

Table 5 Performance of Three level Inverter drive

3.5 Conclusion

Multilevel inverter drive is the field in which latest development have been going on with respect to high power induction motor drives. There are many topologies for multilevel inverter which have been discussed in the chapter. There are also many pulse width modulation (PWM) techniques which are used to control multilevel inverter out of which sinusoidal PWM is used here as it is very simple.

Simulation of multilevel inverter displayed in chapter uses sinusoidal PWM as control technique. Speed and torque response is shown with other voltage and current waveforms. Performance response of drive is presented in table 5.

Chapter 4

Current Source Inverter Drive

A current-fed or current-source inverter (CFI or CSI), as the name indicates, likes to see a stiff dc current source (ideally with infinite Thevenin impedance) at the input, which is in contrast to a stiff voltage source (zero Thevenin impedance), which is desirable in a voltage-fed inverter [36]. This chapter deals with a general control strategy of CSI drive. The simulation and performance response are displayed at the end of chapter.A current-fed inverter should not be confused with the current-controlled, voltage-fed inverter.

A variable voltage source can be converted to a variable current source by connecting a large inductance in series and controlling the voltage within a feedback current control loop. The variable dc voltage can be obtained from a utility supply through a phase-controlled rectifier, or from a rotating excitation-controlled ac generator through a diode rectifier, or from a battery-type power supply through a dc-dc converter. With a stiff dc current source, the output ac current waves are not affected by the load condition (just as voltage waves in a voltage-fed inverter are not affected by the load).

The power semiconductor devices in a current-fed inverter must withstand reverse voltage, and therefore, standard asymmetric voltage blocking devices, such as power MOSFETs, BJTs, IGBTs, MCTs, IGCTs, and GTOs cannot be used. Symmetric voltage blocking GTOs and thyristor devices should be used. Of course, forward-blocking devices can be used with series diodes. It can be shown that in many respects, current-fed inverters are somewhat dual to voltage-fed inverters.

The application of current-fed converters may include the following [36]:

- Speed control of large power induction and synchronous motors
- Variable-frequency starting of 60 Hz wound-field synchronous motors
- High-frequency induction heating
- Superconducting magnet energy storage (SMES)
- DC motor drives

4.1 Operation of Six step Inverter

Six-step inverters are extremely important circuit configurations for high-power motor drives. The general operation principles of this type of inverter with induction machine loads [36]. Figure 4.1 shows the power circuit for a current-fed inverter, which is being supplied by a phase-controlled rectifier on the line side. A variable dc link voltage V is generated by the phase control of the rectifier, and it is converted to a current source I_d by connecting a series inductance L_{dc} and providing a feedback current control loop as shown. The current magnitude, as desired, can be established by the command current I_d^*. Although an infinite value of L_{dc} is desirable for an ideal ripple-free current source, size and cost constraints limit the practical L_{dc} within a reasonable value, thus permitting some amount of ripple.

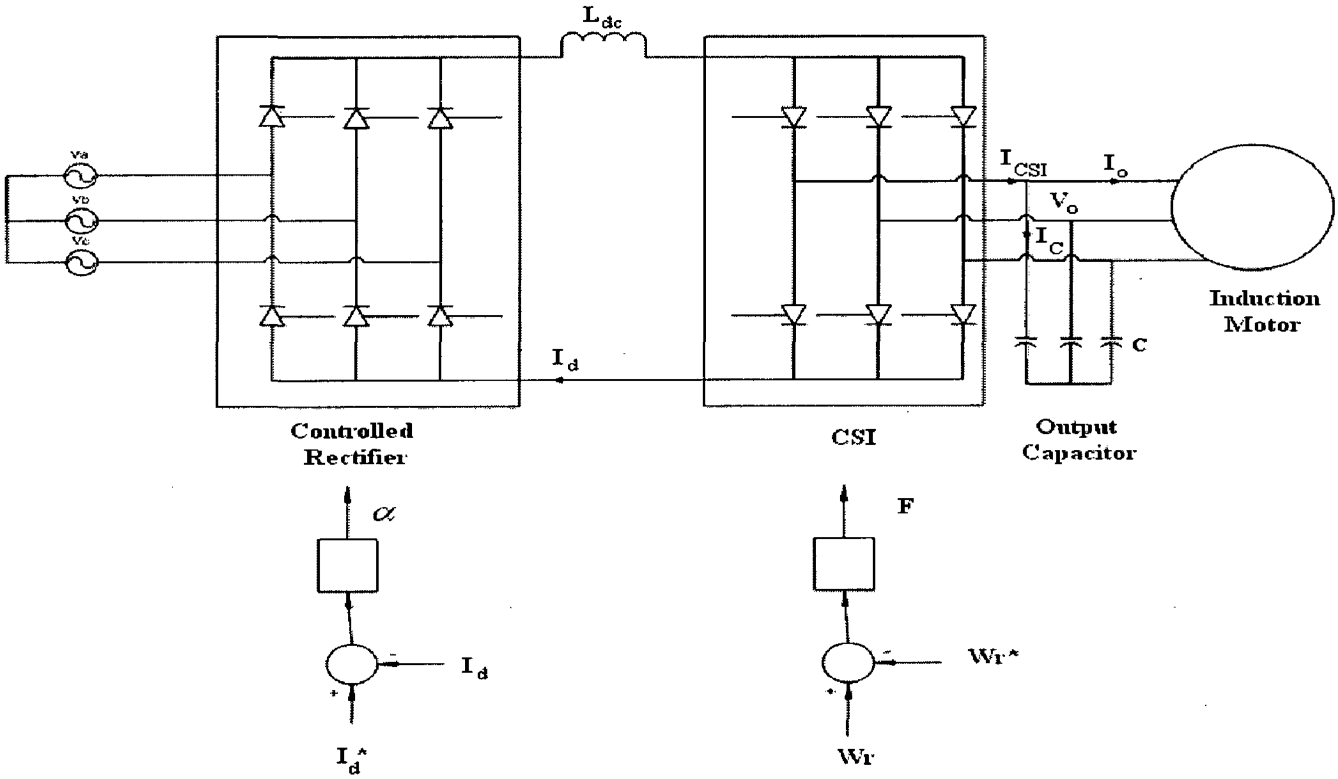


Figure 4.1 Current Source Inverter

The control of the pulses which are to control the inverters switching device is done by a pulse generator. The frequency at which the pulse generator generates pulses is controlled by a feedback speed control loop as shown. The required speed or demanded speed can be controlled by Wr* which in comparison with the present drives speed Wr can give the error function and thus generate required frequency signal for the pulse generator to control the Inverter.

The sequence of triggering of switching devices is depicted in pulse pattern in Figure 4.2. The triggering sequence used here is such that switching device has time for safe commutation of devices for a single leg to avoid simultaneous triggering of switching device in a single leg. Figure also shows the waveform of phase current Ia.

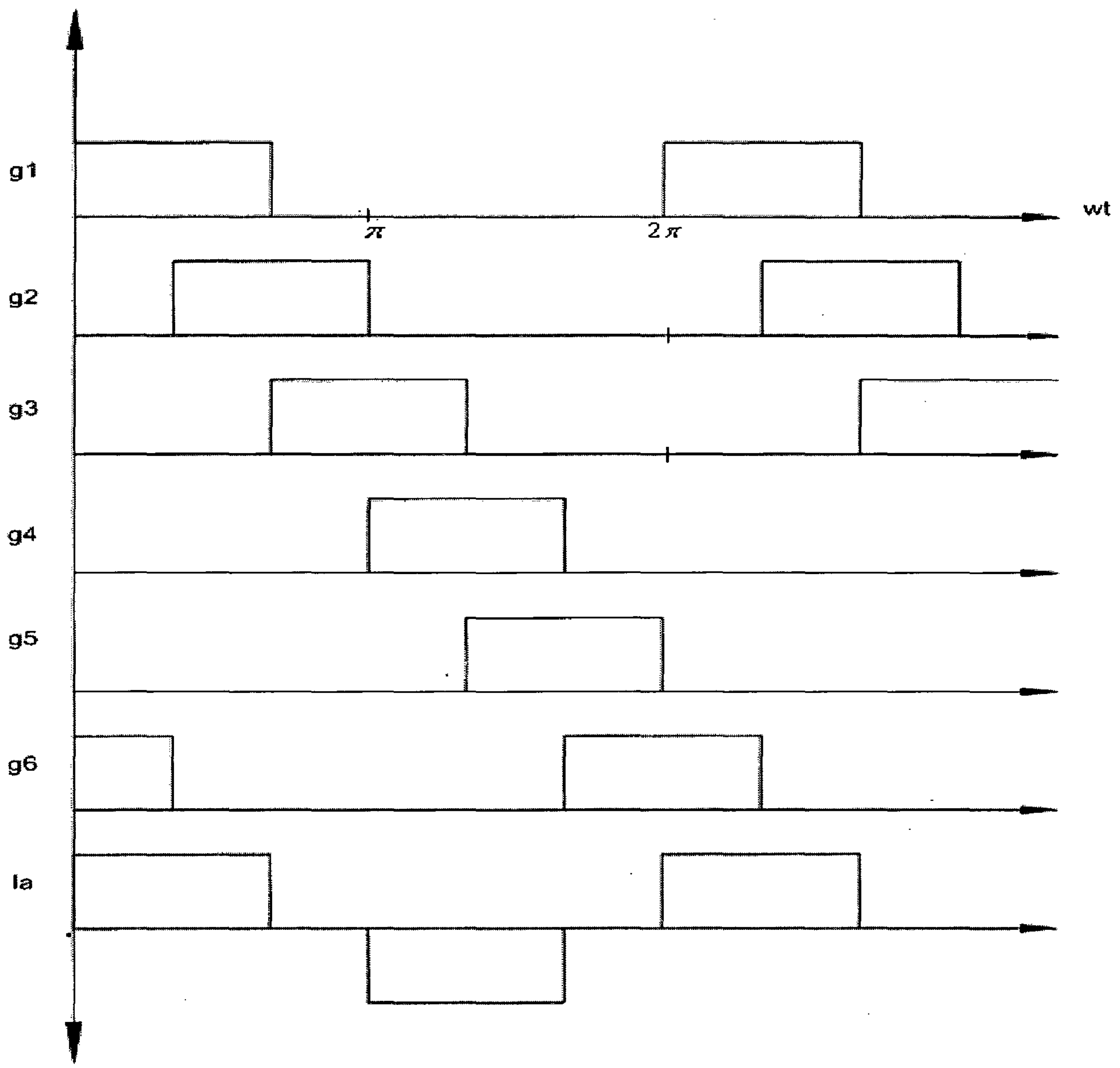


Figure 4.2 Gate triggering pulses and phase current

The CSI can control only the fundamental frequency of the motor currents by selecting the gating instances of thyristors. For successful commutation of thyristors in the CSI, the output current of the CSI, I_{CSI} must lead the corresponding motor phase voltage Vo. Since the motor currents in induction motors always lag the corresponding motor phase voltages, the leading power factor for the commutation is obtained by the output capacitor. The output capacitors in parallel with the induction motor provide a phase shift of the motor current to produce a leading power factor, as shown in Fig.4.3 [32].

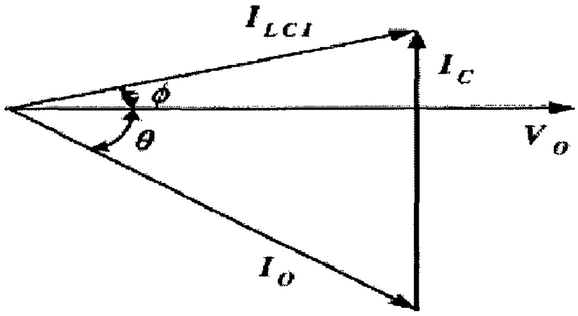


Figure 4.3 Vector diagram For CSI drive [32]

the leading angle of the LCI and the lagging angle of the induction motor are depicted by Ø and θ , respectively.

4.2 Simulation and Results

4.2.1 Simulation

The simulation of Current Source Inverter Drive is done in Matlab Simulink using 120˚ mode of operation. The Simulation block diagram is shown in Figure 4.4 and is tested for the same rating induction motor as before (Appendix B). In the simulation there are basically two control loops as explained previously. On the dc link side there is dc link current control loop which controls the rectifier. And for inverter side there is speed control loop which controls the frequency of CSI. The controlling and circuit parameters used in the simulation are mentioned in Appendix C.

The simulation of this system is done by using the same controlling parameters as given in Table 3. The results for the simulation are given in figures following the block diagram.

Simulation Block Diagram

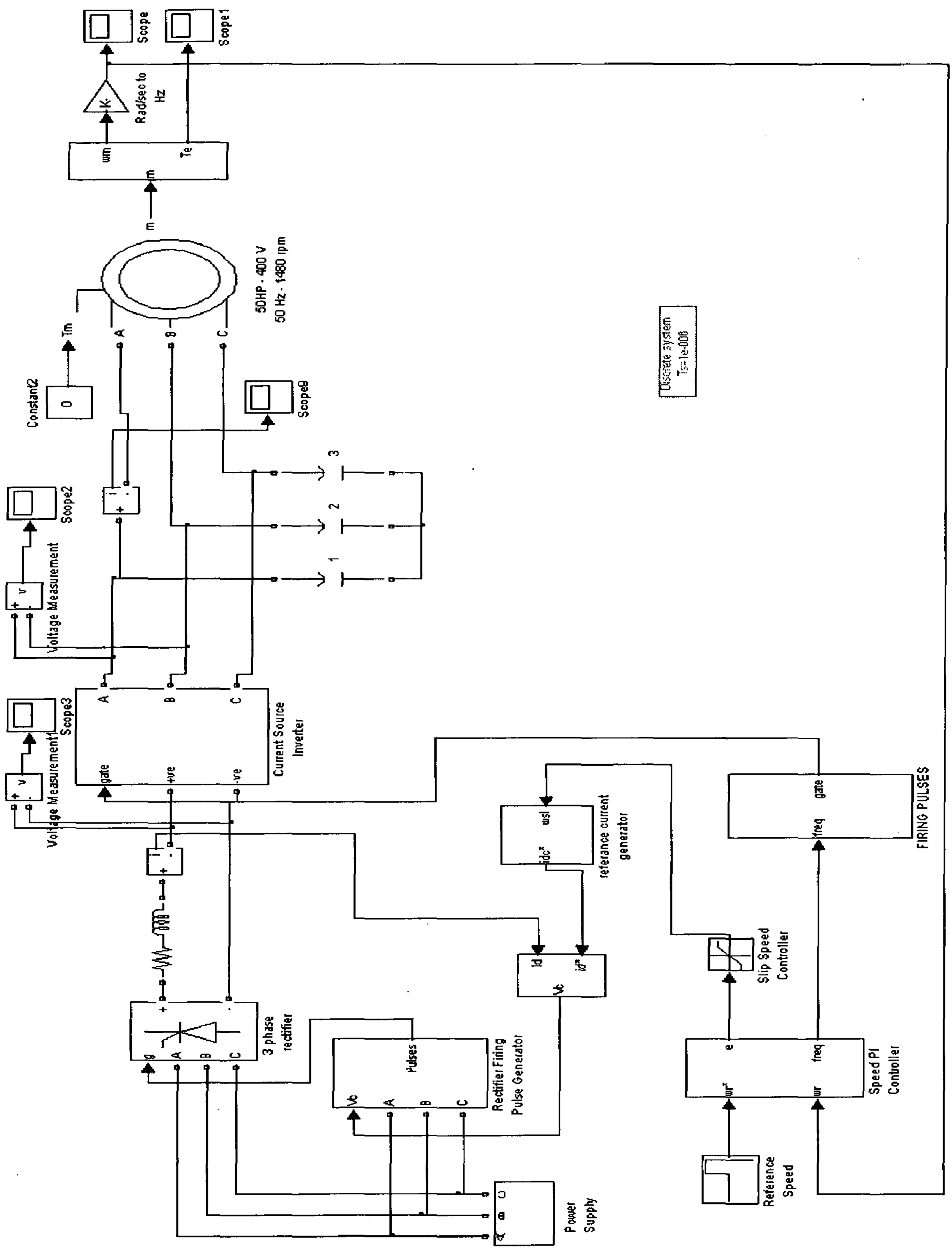


Figure 4.4 Simulation Diagram for Current Source Inverter

4.2.2 Results

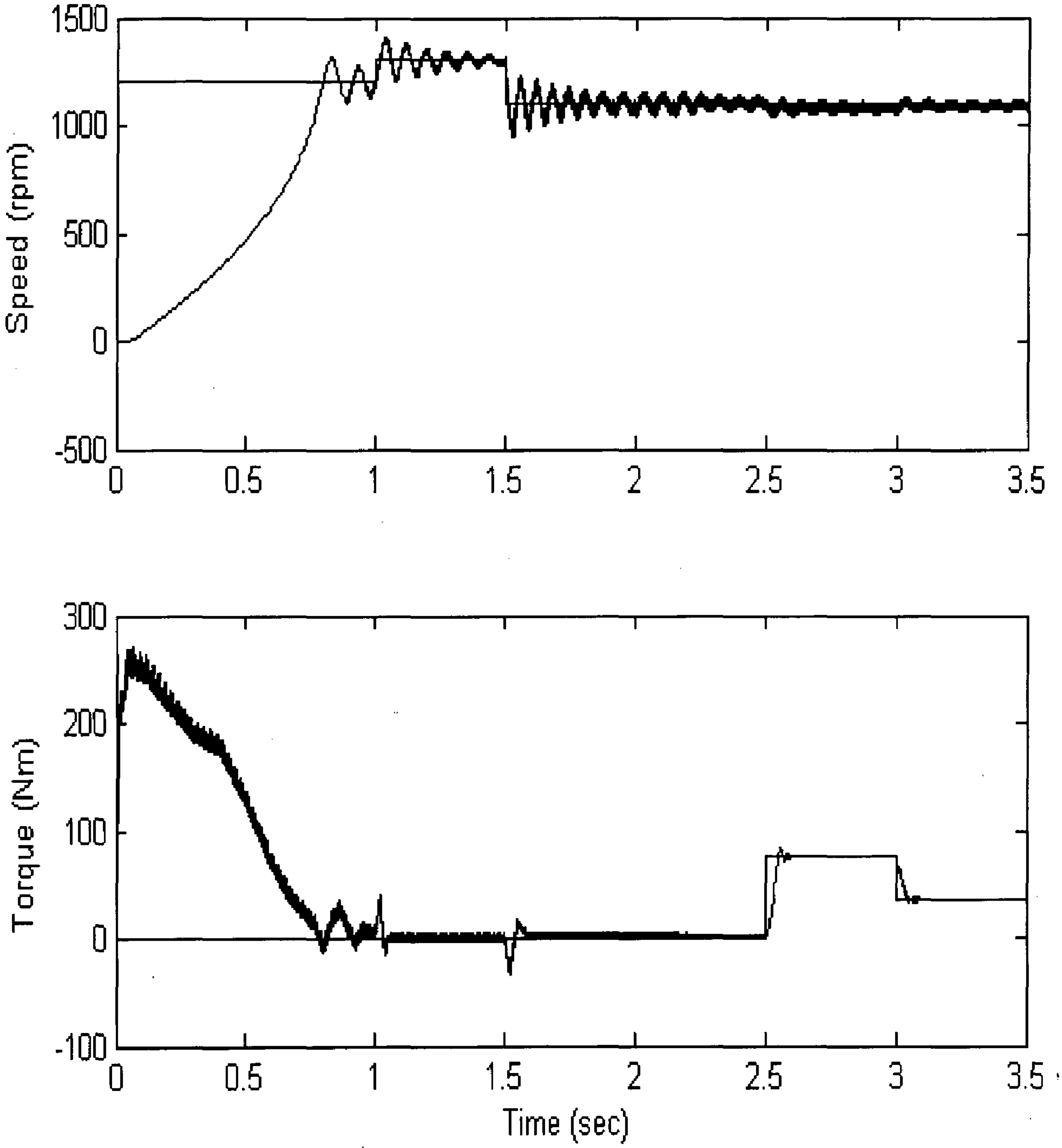


Figure 4.5 Plot of speed and torque

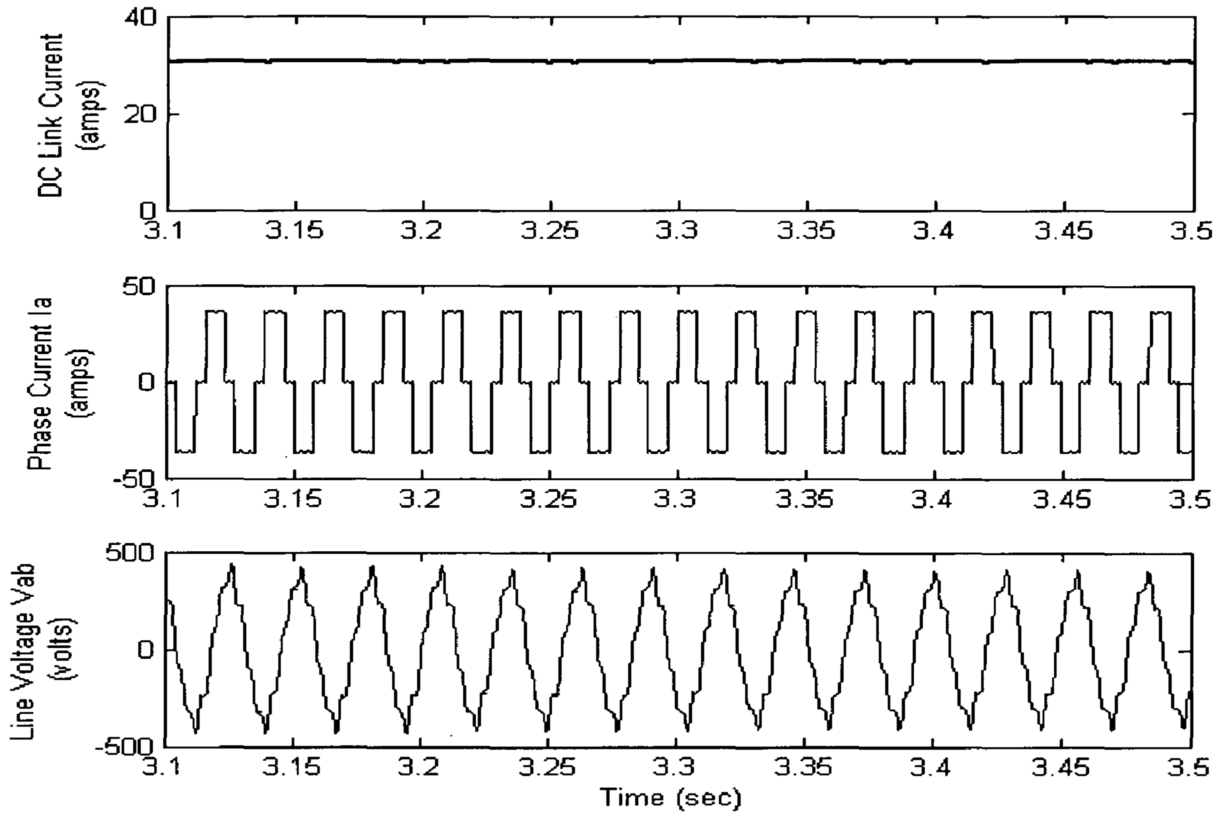


Figure 4.6 Plot of voltage and current for CSI

Figure 4.5 show the plot of speed and torque vs time respectively with specified changes in parameters. Figure 4.6 shows the plot of dc link current Id, line voltage Vab and phase current Ia. The performance parameters for this drive are given in Table 6 as shown below.

	0-1200 (rpm)	1200-1300 (rpm)	1300-1100 (rpm)	0 to ½ load	½ to ¼ load
Settling time	0.77sec	0.02sec	0.03sec	0.05sec	0.04sec
Maximum overshoot	7.5%	7.14%	8%	9%	8.5%
Rise time	1.1sec	0.31sec	0.25sec	0.011sec	0.09sec

Table 6 Performance of Current Source Inverter Drive

4.3 Conclusion

Current source inverter (CSI) drive is one of the simplest drives which are used to control induction motor drive. It has a very simple control technique to control the triggering pulses to switching devices.

The simulation of CSI drive is shown in the chapter with speed and torque response of drive displayed. Waveforms of current and different voltages are also shown with simulation. Table 6 shows performance response of the drive.

Chapter 5

Hybrid Converter System Drive

Induction motor drives discussed till now have many disadvantages in application of high power induction motor drives. Voltage source inverter (VSI) drive has many disadvantages that are:

- Constraints of device ratings which are used in inverter.
- The semiconductor devices must be used in such a manner so as to avoid problems associated with their series parallel combinations that are necessary to obtain capability of handling high voltages and currents.

Multilevel inverter drive has many disadvantages for high power application, such as:

- Larger number of semiconductor switches required which increases the overall cost of drive.
- Each active semiconductor added requires associated gate drive circuitry and adds further complexity to the converter.
- Multilevel inverter use isolated voltage sources, which are not readily available. Series capacitors are also used but voltage balancing is a problem.

The Current source inverter (CSI) drive using capacitor commutation has shown some drawbacks in high power applications.

- Since output capacitors should fully compensate the effect of inductance in the induction motor, the required capacitor size must be increased proportional to the power rating of an induction motor. Output ac capacitors are not reliable, especially in high-power applications.
- Resonance phenomena can be caused by the interaction between the output capacitor and the inductance of the motor. These fundamental and harmonics resonance problems have seriously restricted the system performance.
- Inherent instability in the high-frequency region can be caused by the output capacitor.

Thus as described above a conventional CSI based induction motor drives have many drawbacks, which holds back this drive from high performance.

To overcome problems described in previous topic, a hybrid converter system drives is proposed. Hybrid converter topology is explained in detail in the chapter with control strategy of the drive. The simulation and results are discussed at the end of chapter. A hybrid converter system uses an assembly of a Current Source Inverter (CSI), a voltage commutated inverter (VSI), and a dc to dc converter [32]. The VSI generates the leading power factor for the CSI commutation and compensates the harmonic and reactive power to the motor. In all operating regions, the safe commutation of the CSI is ensured from active angle control by the VSI, rather than the passive capacitor commutation in the conventional drives. Therefore, all drawbacks caused by the output capacitor in the conventional CSI-based induction motor drives can be eliminated.

The buck converter enables the proposed system to be supplied by simple-diode rectifier. As a result, both the CSI and the VSI are fed from the uncontrolled rectifier, and the dc-link inductor size can be greatly reduced by the buck converter operation. This system shows much faster dynamic response by the VSI and the buck converter. Finally, minimum VSI rating and cost are achieved by this strategy in all motor operating regions.

This hybrid converter has the following features and advantages.

- The leading power factor required for load commutation of the LCI is fully provided by the VSI in all operating regions. This safe commutation for the LCI is produced by active control of the leading angle through the VSI, rather than the passive capacitor commutation.
- All problems caused by the output capacitors in the conventional LCIs, such as fundamental and harmonic resonance, and inherent instability in the high frequency region, can be solved since the VSI emulates the output capacitors.
- Both load currents and voltages are nearly sinusoidal, containing low harmonic components.
- The proposed converter shows fast dynamic response by the VSI operation.
- Minimum VSI rating and cost are achieved by the proposed strategy.

5.1 Topology and properties

The structure for hybrid converter system, consisting of a diode rectifier, a buck converter, an CSI, and a VSI is illustrated in figure 5.1 [32]. The VSI is connected with the CSI in parallel through a small *LC* filter. The buck converter is employed between the diode rectifier and the CSI, in order to convert uncontrolled dc voltage to controlled dc current. The dc-link current regulated by the buck converter is supplied to the CSI. As a result, both the VSI and the CSI can be fed from the single-diode rectifier. In addition, the dc-link inductance L_{dc} can be greatly reduced due to the buck converter switching operation.

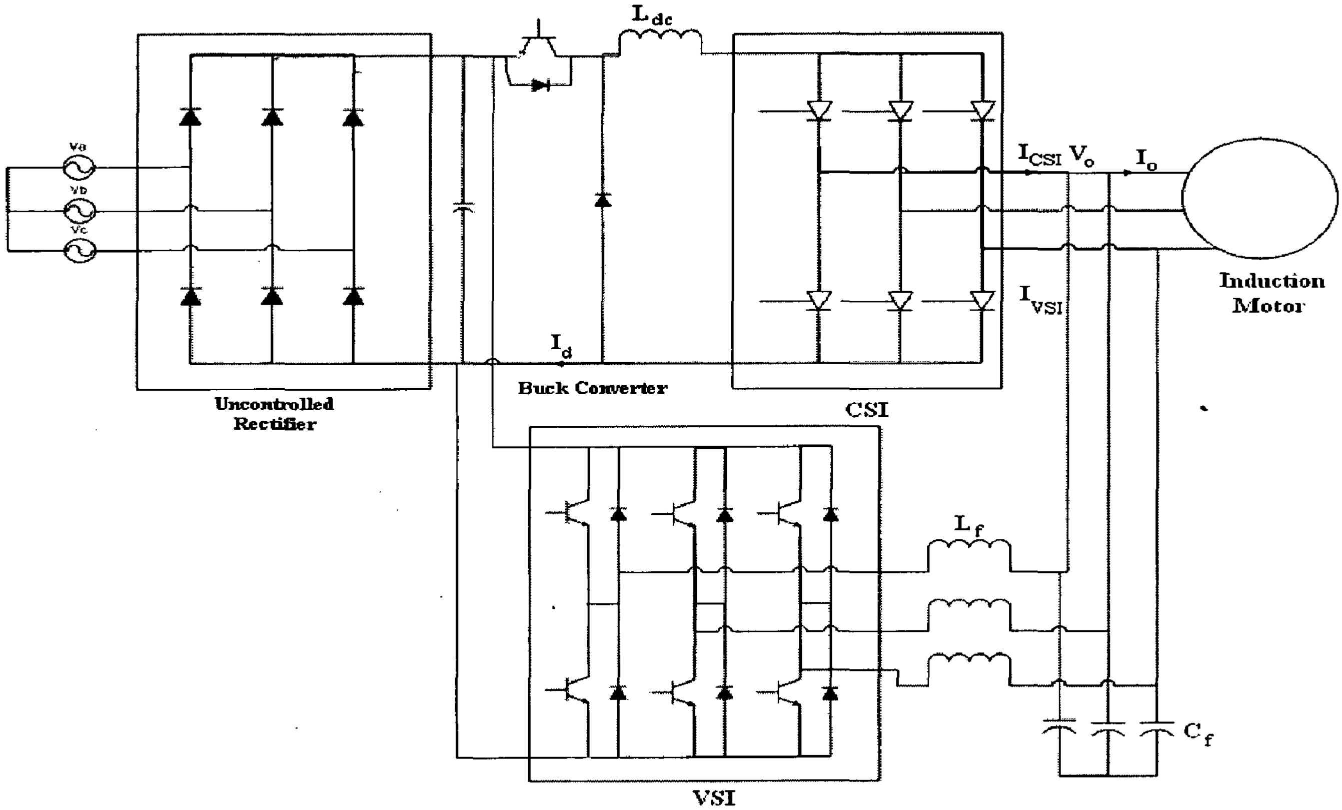


Figure 5.1 Hybrid Converter System Drive [32]

The VSI generates sinusoidal phase voltage to the induction motor. The amplitude and frequency of the VSI output voltage is continuously regulated by the motor speed control. In addition, the phase angle of the VSI output voltage is set from adjusting the firing angle of the CSI to provide a safe CSI commutation angle. Therefore, the leading powerfactor for the CSI operation is entirely obtained by the VSI over the whole speed range of the induction motor. Based on the leading power factor by the VSI, this system can operate the CSI without the dc-commutation circuit as well as output capacitors. Therefore, the proposed system can successfully solve all problems caused by the output capacitors of the conventional CSI-based induction motor. Another advantage by bringing the VSI is to generate sinusoidal motor currents for all speed regions, leading to large induction motor drives with high performance. At the expense of the increased device count and the associated costs, the parallel assembly of the CSI and the relatively small-size VSI is expected to fulfill the niche in high-power applications, where a stand-alone PWM VSI cannot be utilized to generate sinusoidal motor currents. In addition, the sinusoidal motor voltages are also achieved through the *LC* filters. A small *LC* filter is required to smooth out the pulse width-modulated voltages from the VSI.

Per-phase equivalent circuit of the system is shown in Figure 5.2 [32]. In the figure, the CSI and the VSI are represented by the current source I_{CSI} and the voltage source V_{VSI}, respectively. A motor phase current Io is determined by the sinusoidal motor phase voltage Vo controlled by the VSI. Concurrently, the CSI supplies a current I_{CSI} to the motor. Therefore, the motor current Io is the sum of the CSI output current I_{CSI} and the VSI output current I_{VSI}. From the operating point of view, the fast VSI operates as a master inverter and the slow CSI as a slave.

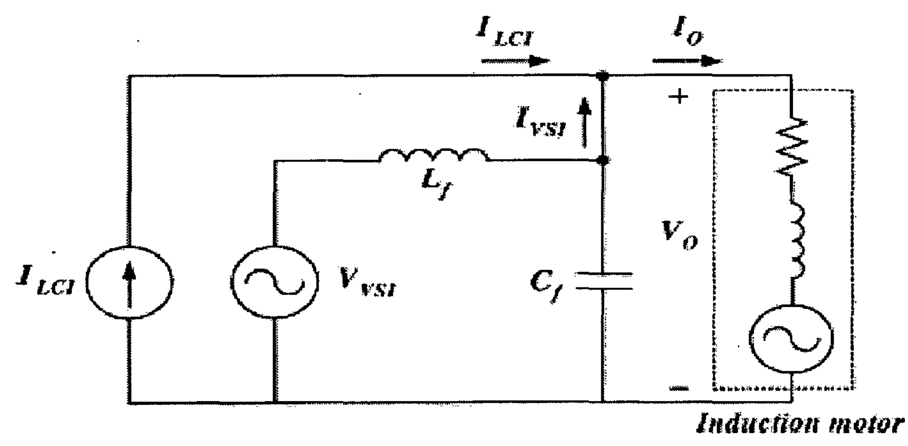


Figure 5.2 Equivalent Circuit Diagram of system [32]

Vector diagram of the described system is shown in Figure 5.3 [32]. The leading angle Ø is actively controlled from adjusting the phase angle between the VSI output voltage and

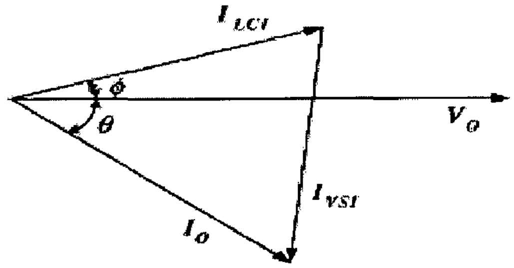


Figure 5.3 Vector Diagram for Hybrid Converter [32]

the gating instant of the CSI. In terms of power supplied to the motor, the CSI supplies the real power to the motor load, while the VSI provides the real power corresponding to phase shift between the CSI output current and the motor phase voltage, as well as the real harmonic power of the CSI. The VSI power rating should be kept to a minimum to make this system a cost-effective solution. Because the VSI should supply its output current equal to the difference between the motor phase current I_o and the CSI output current I_{LCI}, the VSI output current I_{VSI}, is proportional to the phase angle between I_o and I_{CSI}, corresponding to Ø+θ. Thus, it is desirable that the phase angle should be maintained to be minimum for a small VSI rating. This condition can be obtained by adjusting the leading angle Ø to the minimum value satisfying the safe commutation, and controlling the induction motor with good power factor. Since a high-power induction motor shows better power factor characteristics than a small rating motor, it is expected that the power factor angle θ is small in high-power motor applications. It makes the proposed system more competitive and useful for high-power applications.

5.2 Control System Structure Block

The general control system block diagram of hybrid converter system based drive is given in figure 5.4 [32]. The overall control strategy is composed of two main control loops. The first control loop is the motor speed control based on VSI operation. The motor speed can be regulated using a closed-loop speed controller based on the slip speed regulator, which determines the slip speed reference. The synchronous speed, obtained by adding the actual speed and the slip speed, sets the inverter operating frequency. The voltage amplitude command then is settled from the VSI frequency using a function generator, which ensures a nearly constant flux operation. Finally, the phase angle of the motor voltage is decided in order to provide a leading power factor (Ø) for the safe CSI commutation. The space-vector modulator produces the switching signals based on the amplitude, frequency, and phase command signal for the sinusoidal output voltage of the VSI. This speed loop control implemented by the VSI ensures a fast dynamic response with a much faster sampling period than the conventional CSI. The gating command of the CSI is controlled based on the frequency and the phase command signal, yielding the safe commutation for the thyristors.

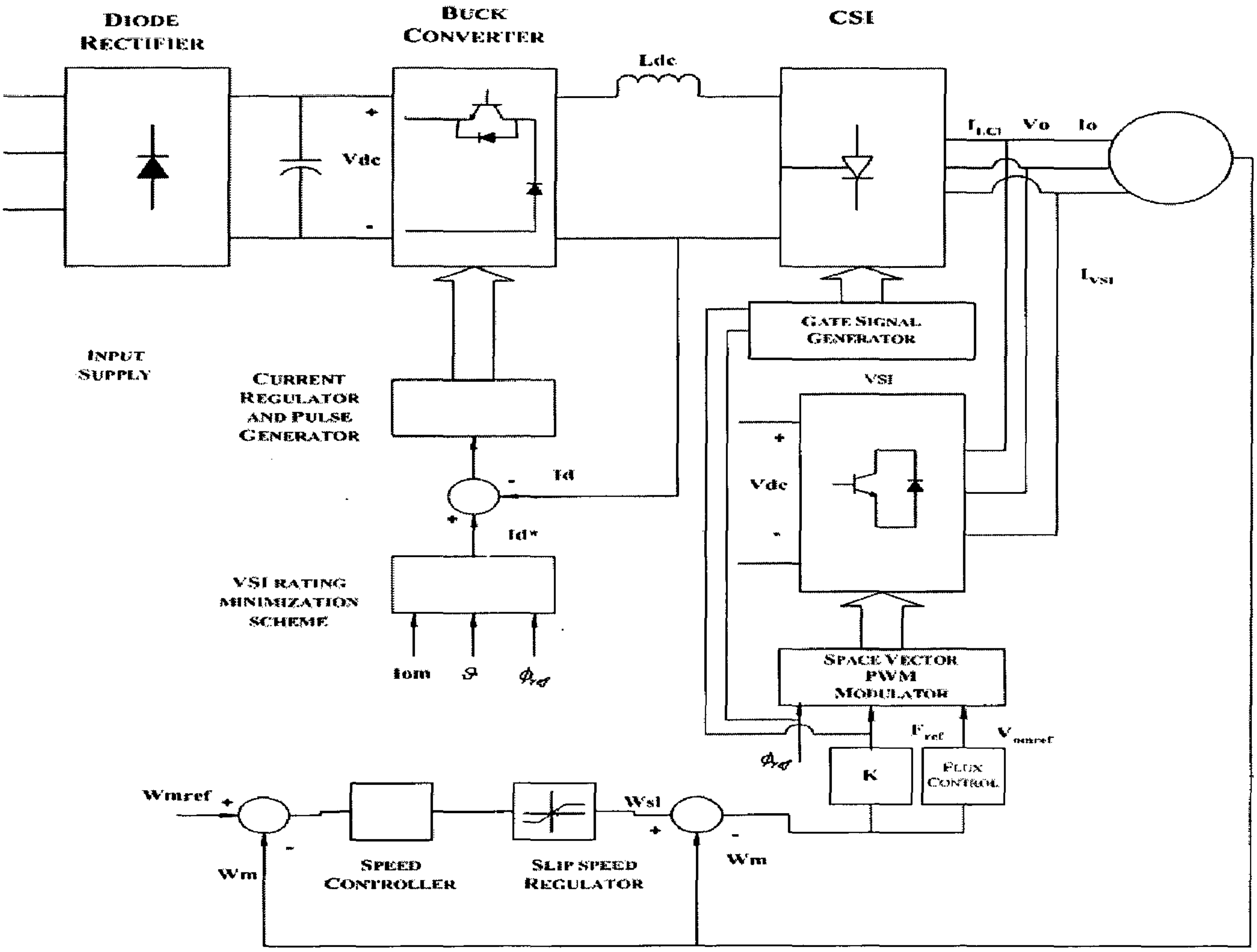


Figure 5.4 Overall Control Scheme of Hybrid system [32].

The second control loop is for the dc-link current control using the buck converter. The switching operation of the buck converter ensures that the input to the CSI appears as a current source with a much smaller inductor, compared to that of the conventional controlled rectifier. The function of this loop is to control the dc-link current in such away that the VSI rating is minimized, based on the motor current, the power factor angle of the induction motor θ, and the leading power factor Ø.

5.3 Buck Converter Control Principle

Since the hybrid converter system is comprised of two inverters, the output power distribution between the inverters, given a certain motor power requirement, is important. A rating factor η is defined as the ratio of the CSI rating and the VSI rating. From a cost point of view, the CSI is not comparable to the VSI. As a result, it is desirable to minimize the rating factor under operating power required for the induction motor. The dc link current control to minimize the rating factor is derived with the dc-link stage of the CSI modeled by a pure current source with no switching components [32].

The motor phase current amplitude depends on the motor shaft speed, and the leading power factor angle is a control factor for the CSI safe commutation. In addition, is the lagging power factor angle of the induction motor, which is detectable. The dc-link current control purpose is to achieve the minimum VSI rating and the maximum CSI rating, based on the motor current and phase shift between the motor current and the CSI output current. This dc-link current control algorithm is implemented by the buck converter.

5.4 Simulation and Results

5.4.1 Simulation

The simulation of Hybrid Converter System Drive is shown as a block diagram in Figure 5.5. The simulation of the system is done on induction machine is same as before (refer Appendix B). The simulation details are identical to the control scheme discussed in section discussed previously. There are two control loops. One controls CSI and VSI simultaneously. The second loop controls the dc link current to CSI. Different control parameters are mentioned in Appendix C.

The simulation of this system is done by using the same controlling parameters as given in Table 3. The results for the simulation are given in figures and tables following the block diagram.

Simulation Block Diagram

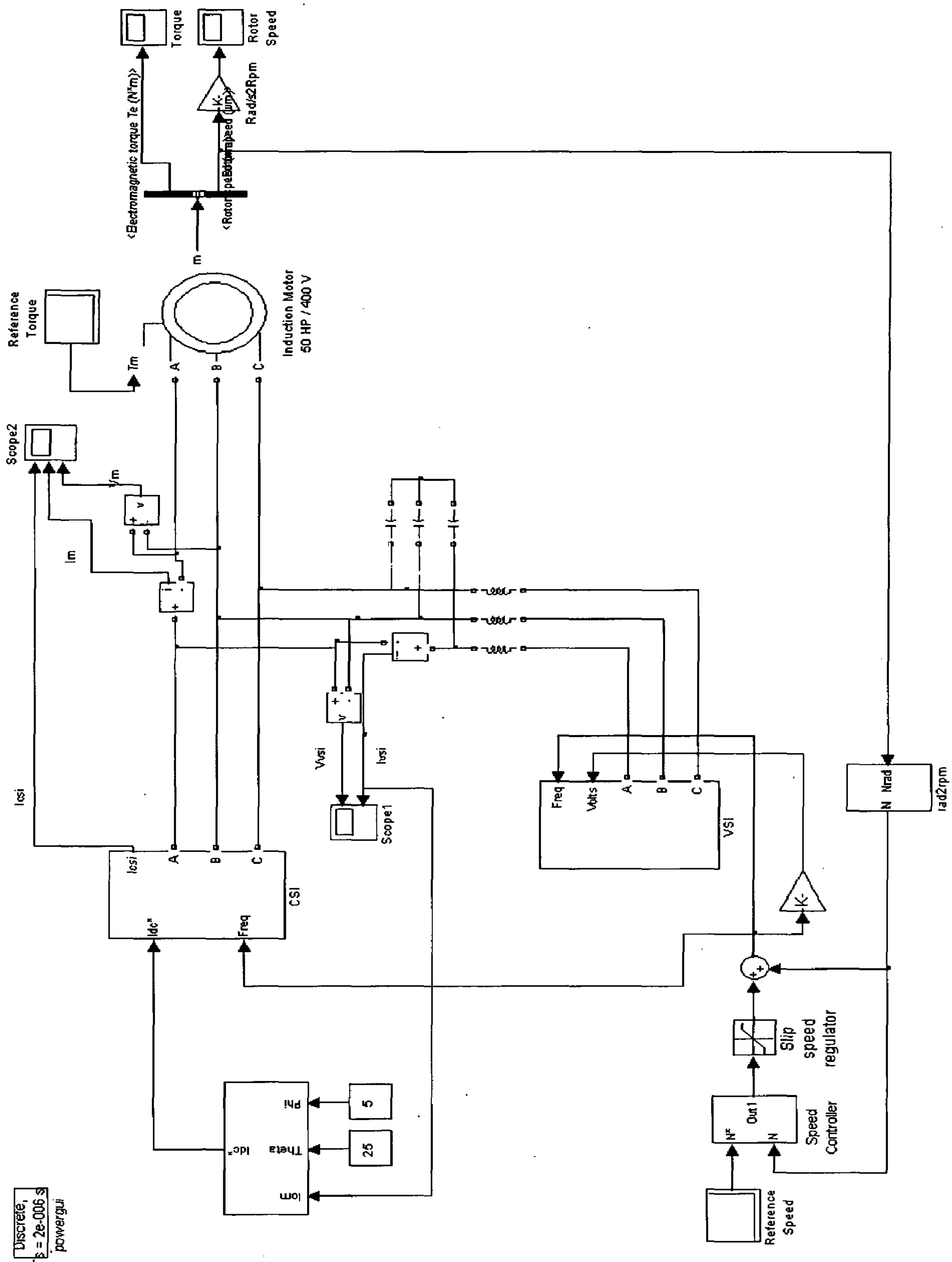


Figure 5.5 Simulation block diagram of Hybrid Converter System Drive

5.4.2 Results

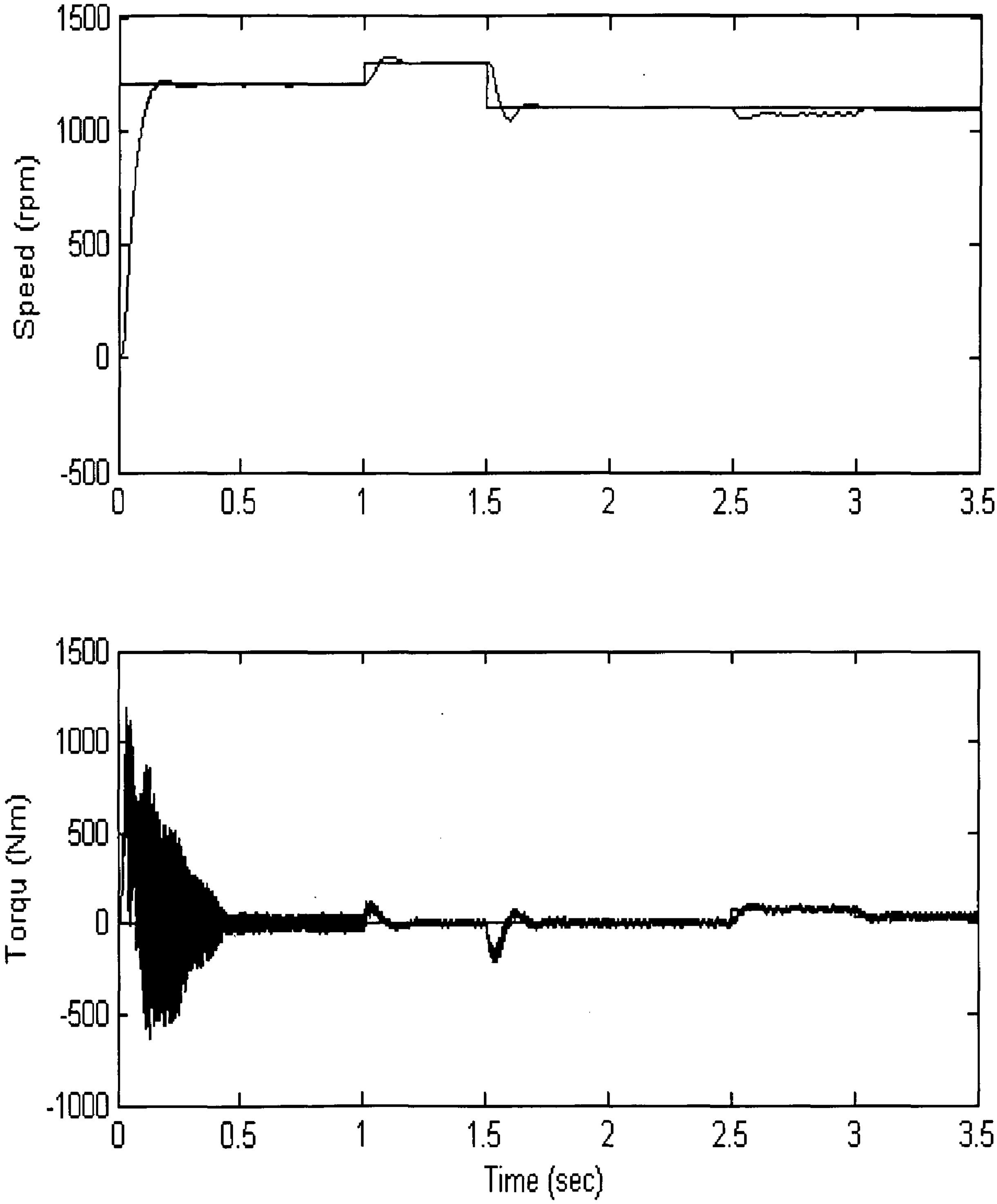


Figure 5.6 Plot of speed and torque response of drive

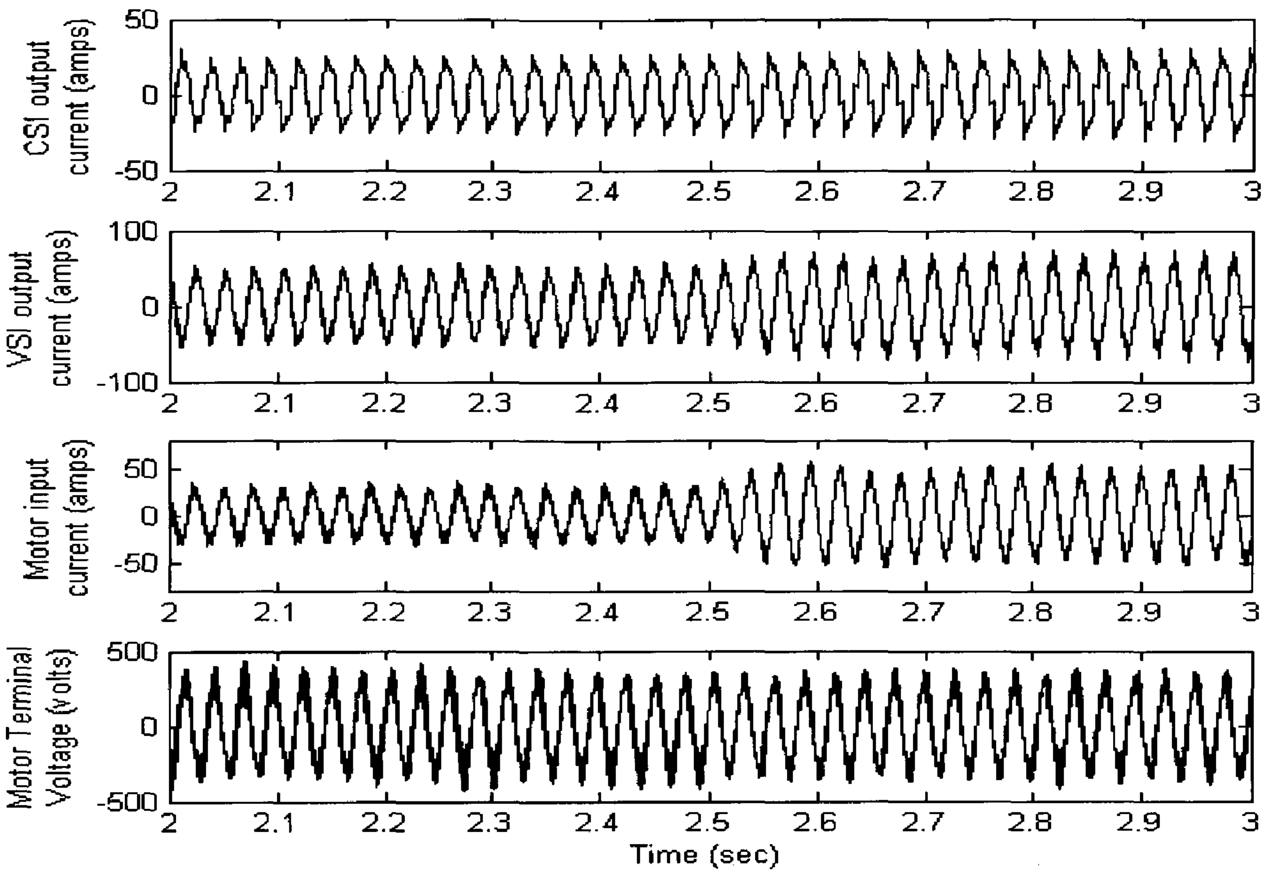


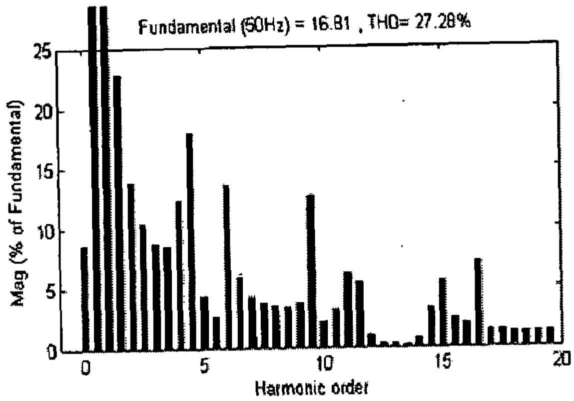
Figure 5.7 Plot of various circuit parameters for drive

Plot of speed and torque response of hybrid converter system drives are given in Figure 5.6 for full simulation time. The Figure 5.7 gives the response of various circuit parameters with their waveform. This figure gives waveforms of CSI output phase current, VSI output phase current, motor input phase current and motor terminal voltage respectively.

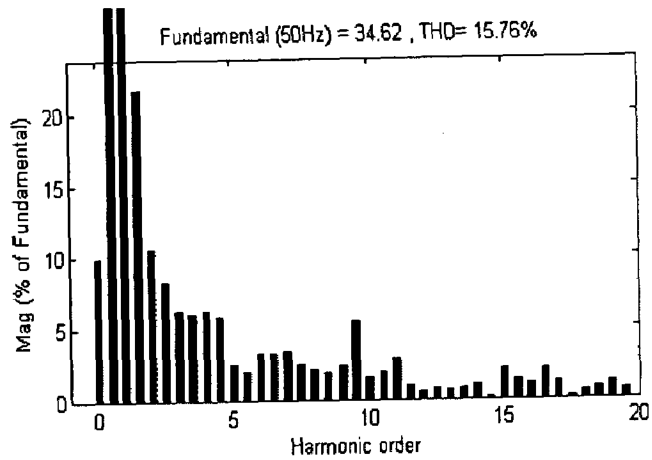
In further study of the system, Fast Fourier Transform for different signal are studied. These signals are CSI output current, VSI output current and induction motor input current. For above signals total harmonic distortion percentage are given in Table 7.

	CSI output current Icsi	VSI output current Ivsi	Motor input current Im
THD%	27.28%	15.76%	12.28%

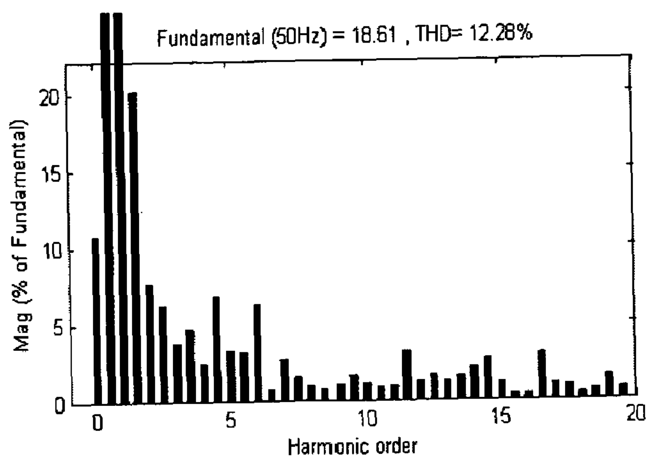
Table 7 Total Harmonic Distortion for different signals



FFT Analysis for CSI output current



FFT Analysis for VSI output current



FFT Analysis for motor input current

Figure 5.8 FFT Analysis Chart for signals

As Table 7 shows the output current of VSI helps in making the motor input current from CSI more sinusoidal, which otherwise would have been quite distorted. This is also true for motor input voltage. This is one of the major advantage of using Hybrid converter drive system as induction motor performance improves because of sinusoidal input supply.

In next section, performance of hybrid converter system is discussed and is compared with drives already discussed.

5.4.3 Discussion of Results

Performance criteria		V.S.I. Drive	Multilevel Inverter Drive	C.S.I. Drive	Hybrid Converter Drive
0 to 1200 rpm	Settling time	0.15sec	0.17sec	0.77sec	0.14 sec
	Maximum overshoot	5.1%	3.8%	7.5%	2 %
	Rise time (+/- 2 %)	0.26sec	0.185sec	1.1sec	0.18 sec
1200 to 1300 rpm	Settling time	0.06sec	0.02sec	0.02sec	0.06 sec
	Maximum overshoot	2.5%	3.5%	7.14%	2.1 %
	Rise time (+/- 2 %)	0.11sec	0.035sec	0.31sec	0.1 sec
1300 to 1100 rpm	Settling time	0.065sec	0.05sec	0.03sec	0.055 sec
	Maximum overshoot	4%	3.5%	8%	4 %
	Rise time (+/- 2 %)	0.17sec	0.08sec	0.25sec	0.16 sec
0 to ½ load	Settling time	0.05sec	0.02sec	0.05sec	0.05 sec
	Maximum overshoot	10%	15%	9%	10 %
	Rise time (+/- 2 %)	0.18sec	0.04sec	0.011sec	0.15 sec
½ to ¼ load	Settling time	0.05sec	0.01sec	0.04sec	0.05 sec
	Maximum overshoot	10%	15%	8.5%	10 %
	Rise time	0.18sec	0.03sec	0.09sec	0.13 sec

Table 8 Comparison of performance of different drives

Comparative chart of performance of four different induction motor drives have been shown in Table 8. This table includes performance data of previously discussed drive and also of hybrid.

As it can be observed from the table performance of Hybrid converter system drive and Multilevel inverter drive are quite comparable. But as discussed previously multilevel inverter drives have some disadvantages like complexity of operation and difficulty of voltage balance. Because of this Hybrid converter system is more suitable than multilevel inverter drive.

Current source inverter drive is the most simple drive of all the above discussed drive with least device count also in its favor. But still as can be seen in the table it has the worst performance of all four drives. It also has other disadvantages related to output capacitor which makes it unsuitable for large induction motor applications.

Also as can be observed from the table the performance of Voltage source inverter drive is at par with hybrid converter system drive. But it also has disadvantages of complexity and cost.

Hybrid converter system drive, by looking at it performance in table, is most suitable drive of above discussed drive for large induction motor drive. But this drive also has some disadvantages:

- Device count is more than CSI drive, making it more tedious.
- Complexity of control increases.

5.4 Conclusion

Hybrid converter system drive has been found to be a better drive than other drives discussed above either by way of performance or because of some inherent disadvantages of other drives. Hybrid converter system has minor disadvantages like marginal increase in device count and increase in complexity of control with respect to CSI drive.

Chapter 6

Conclusion and Future Scope

In the industry, Voltage source inverter (VSI) drives and Current source inverter (CSI) drives have been very popular for induction motor drive applications. They have their own sets of advantages and disadvantages to make them suitable for respective applications.

But as industrialization expanded, induction motor power capacity too expanded and this development lead to demand for large induction motor drives. As discussed before VSI drive which is most preferred drive for small to medium induction motor applications. But for high power applications disadvantages, like constraints of device ratings and problems related to series – parallel combination of devices, are present.

To solve VSI drive problems, Multilevel inverter drive are used for high power applications. Multilevel inverter drive has a good performance response as observed in results. But this inverter drive has its own set of disadvantages like problem of voltage unbalance and increase in complexity.

For medium power application CSI based drive is a very good option, but the output capacitor required for commutation of inverter devices keeps it from its optimal performance in high power applications. There are various difficulties raised by capacitors like resonance with inductor in induction machine leading to instability in high frequency region and higher rating for high power applications.

Hybrid converter system drive uses a VSI instead of capacitor thus negating most of its problems. It has many advantages.

- VSI fully compensates for capacitors for all operating regions and makes overall response of Hybrid drive faster than CSI drive.
- Input voltage and current to motor is sinusoidal for hybrid converter drive system.

Above advantages for Hybrid converter system drive makes it a very good option for large induction motor application even with some minor disadvantages like marginal increase in device count and increase in complexity of control with respect to CSI drive.

Future Scope

This dissertation presents simulation of three level inverter with sinusoidal PWM. Recent researches have been going on for multilevel inverter for level of 5 or above, which can be simulated to get better performance. New PWM techniques have been researched for multilevel inverter which can be used in simulation for better results.

Hybrid converter system simulated here using two level voltage source inverter in place of which multilevel inverter can be used for better performance and control of overall drive.

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Appendix A

Mathematical model of induction motor drive is given by equations given below. Equations a.1 to a.4 when substituted into equations a.5 to a.8 gives instantaneous values of direct and quadrature axis values of stator and rotor currents.

$$si_{qs} = \frac{1}{s}\left[V_{qs} - \frac{R_s}{L_{ls}}\left[\left(1 - \frac{L_{ml}}{L_{ls}}\right)si_{qs} - \left(\frac{L_{ml}}{L_{lr}}\right)si_{qr}\right]\right] \quad \text{(a.1)}$$

$$si_{ds} = \frac{1}{s}\left[V_{ds} - \frac{R_s}{L_{ls}}\left[\left(1 - \frac{L_{ml}}{L_{ls}}\right)si_{ds} - \left(\frac{L_{ml}}{L_{lr}}\right)si_{dr}\right]\right] \quad \text{(a.2)}$$

$$si_{qr} = \frac{1}{s}\left[w_r si_{dr} - \frac{R_r}{L_{lr}}\left[\left(1 - \frac{L_{ml}}{L_{lr}}\right)si_{qr} - \left(\frac{L_{ml}}{L_{ls}}\right)si_{qs}\right]\right] \quad \text{(a.3)}$$

$$si_{dr} = \frac{1}{s}\left[w_r si_{qr} - \frac{R_r}{L_{lr}}\left[\left(1 - \frac{L_{ml}}{L_{lr}}\right)si_{dr} - \left(\frac{L_{ml}}{L_{ls}}\right)si_{ds}\right]\right] \quad \text{(a.4)}$$

$$i_{qs} = \frac{1}{L_{ls}}\left[\left(1 - \frac{L_{ml}}{L_{ls}}\right)si_{qs} - \left(\frac{L_{ml}}{L_{lr}}\right)si_{qr}\right] \quad \text{(a.5)}$$

$$i_{ds} = \frac{1}{L_{ls}}\left[\left(1 - \frac{L_{ml}}{L_{ls}}\right)si_{ds} - \left(\frac{L_{ml}}{L_{lr}}\right)si_{dr}\right] \quad \text{(a.6)}$$

$$i_{qr} = \frac{1}{L_{lr}}\left[\left(1 - \frac{L_{ml}}{L_{lr}}\right)si_{qr} - \left(\frac{L_{ml}}{L_{ls}}\right)si_{qs}\right] \quad \text{(a.7)}$$

$$i_{dr} = \frac{1}{L_{lr}}\left[\left(1 - \frac{L_{ml}}{L_{lr}}\right)si_{dr} - \left(\frac{L_{ml}}{L_{ls}}\right)si_{ds}\right] \quad \text{(a.8)}$$

Substitute equations a.1, a.2, a.5 and a.6 in equation a.9 we get values of torque developed and eventually rotor revolutions per unit time.

$$T_{em} = \frac{3}{2}p\frac{L_m}{L_r}\left[\mathrm{i}_{ds}\mathrm{si}_{qs} - \mathrm{i}_{qs}\mathrm{si}_{ds}\right]$$
$$w_r = \frac{p}{J}\frac{1}{s}T_{em} \quad \text{(a.9)}$$

For above mathematical model of induction motor updated value of torque and speed can be attained at the end of every calculation cycles.

Given below is the list of symbols used in above equations.

i_{ds} , i_{qs} are direct and quadrature axis stator currents.

i_{dr}, i_{qr} are direct and quadrature axis rotor currents.

R_s is stator resistance.

R_r is rotor resistance with respect to stator.

L_{ls} is self inductance of stator.

L_{lr} is self inductance of rotor with respect to stator.

L_{ml} is mutual inductance of motor.

T_{em} is torque developed

w_r is rotor revolutions per unit time.

p is number of pole pairs.

J is moment of inertia.

Appendix B

Induction motor used all simulation discussed in previous chapters have following ratings.

Power rating – 50 h.p.

Voltage rating – 400 Volts.

Frequency – 50 Hertz.

Stator resistance R_s - 0.08233 ohms.

Rotor resistance R_r - 0.0503 ohms.

Stator inductance L_{ls} - 0.000724H.

Rotor inductance L_{lr} - 0.000724H.

Mutual inductance L_{ml} - 0.02711H.

Number of pole pairs p - 2.

Moment of inertia J - 0.37 kgm^2

Appendix C

Following are the circuit and control parameters used in different simulations presented in previous chapters.

Voltage source inverter drive simulation

Speed controller: Proportional gain – 0.37

Integral gain – 0.035

Filter: Capacitor – 50 micro farad.

Inductor – 0.5 milli henry.

Multilevel inverter drive simulation

Speed controller: Proportional gain – 1

Integral gain – 124

Torque controller: Proportional gain – 6

Integral gain – 180

Flux controller: Proportional gain – 4.8

Integral gain – 238

Current source inverter drive simulation

Speed controller: Proportional gain – 1

Integral gain – 0.05

Current Controller: Proportional gain – 1.05

Integral gain – 5

Hybrid converter system drive simulation

Speed controller: Proportional gain – 0.365

Integral gain – 0.034

Filter: Capacitor – 50 micro farad.

Inductor – 0.5 milli henry.