CHAPTER 1
INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 General

The railway as a means of transport is a very old idea. Any transportation system needs a source of power to drive its vehicles carrying their passengers or goods from one place to another. From the early invention of steam engines to modern electric locomotives, railway transport systems have had a long history and huge developments to become one of the most popular modes of public transport over the last century [1]. To provide power propulsion and the need of higher-speed, more luxurious and more reliable services, electrification has been the first choice and widely applied to modernize most of the railway transport systems across the world for several decades. The traction system provides the tractive effort to accelerate the train and the electrical braking effort, which assists in the deceleration of the train. The propulsion system is controlled by means of train line commands and a pulse width modulation (PWM) signal. The PWM signal is an input torque demand signal into the Variable Frequency Inverter control unit. The output power to the Traction Motors is controlled to match the PWM signal demand. In this way all the motorcars in the train will produce the same tractive effort.

Earlier DC motor drives were used by Indian railways which were fed by 25kV single phase AC supply rectified by uncontrolled converters [2]. The uncontrolled converters produce harmonics which decrease system efficiency and causes ac mains voltage distortion leading to failure of auxiliary motors. All these effects impair the power quality. Also regeneration could not be obtained from uncontrolled rectifier because they did not work in four quadrants. This further reduces the efficiency of drive. With the advancements in power electronics, it was made possible to replace dc motor with variable frequency induction motor drive. The vector control techniques of induction motor drive combines the features of flexibility of dc motor and ac induction motor which is robust and free from regular maintenance. To improve the distortion of the input line current various converters have been reported which are capable of harmonic control and reactive power compensation for electric traction system [4-7].

Fig 1.1 shows the block diagram of AC motor drive. The traction system comprises of main transformer, converter/ inverter box and traction motor. The traction system is described as a 'three-phase drive' with V/F control. The converter carries out the constant DC output voltage control and AC- side power factor control. The V/F inverter output voltage waveform is PWM type using IGBTs. The converter inverter system converts single-phase AC voltage to the three-phase AC voltage which is necessary to drive the three-phase induction motor. The designing of converter and inverter are very crucial for railway traction as electric locomotive have regeneration capabilities to result in an efficient operation of the drive.

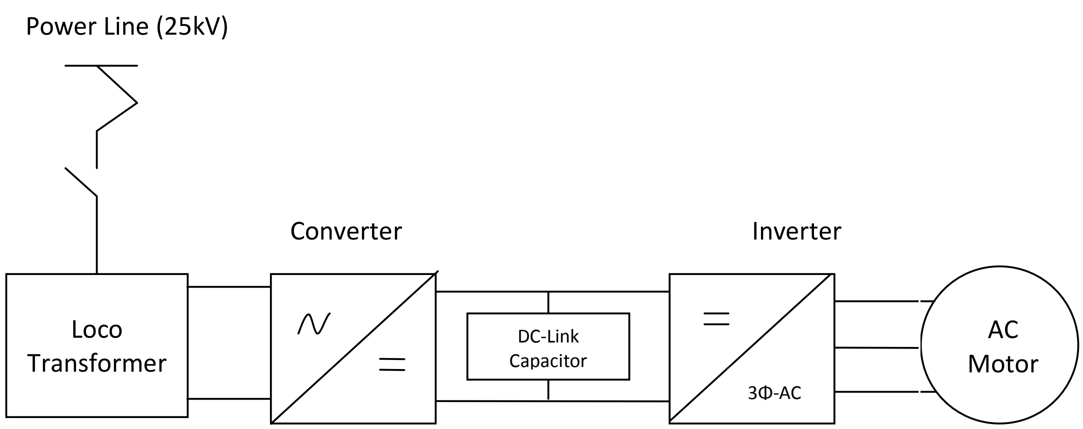


Fig 1.1 Block Diagram of AC-DC-AC traction system for AC motor drive

In the present work, an H-bridge converter configuration and direct torque control technique for speed control of traction motor drive used in Indian railways is simulated. MATLAB/SIMULINK is used for simulation platform. The system is capable of improving the power factor close to unity and the total harmonic distortion of ac mains current is also within IEEE standard 519 limits [9].

1.1.1 Electric Traction System

Like most road running vehicles, a railway traction power system provides mechanical torque that can be converted into kinetic and potential energy and can be used to overcome resistance to motion. DC and AC electric traction systems are commonly deployed in the railway industry. The transmission system requirements for both the systems are very different. The first practical application of electric traction dates back to the second half of the 19th century. At the early stage of development, DC motors, together with low-voltage DC traction lines, were the main traction power supply methods, due to their simple torque control characteristics. Subsequently, low-voltage DC transmission networks and high-voltage, low frequency (25 Hz) AC transmission networks became the two major electric supply methods for traction power. The reason for the emergence of the AC transmission network was due to the inherent tractive characteristics of induction motors and the difficulties of supplying electrical power from a DC transmission line. It was not until the 1950s, with the advancement of power electronics, that high voltage and industry frequency AC transmission became a reality. Since then, 25 kV single-phase at 50 or 60 Hz often replaces the 15 kV DC networks.

1.1.2 Control Techniques for Traction Motor Drive

The induction motor drives play an important role in electric traction, steel, paper and cement factories. This is due to their advantages such as low inrush current, fast dynamic response, robust motor, ease of control etc. Techniques generally used in variable frequency induction motor drives for control of voltage source inverter fed induction motor drive can be broadly classified as scalar control, vector control and direct torque control. Application of scalar control is easy and simple, but it has its disadvantages of sluggish response instability of system because of higher order system effect. This problem can be overcome by vector control and direct torque control, in which induction motor can be controlled like a separately excited dc motor. The revolution in self commutating solid state power devices and the availability of fast computing processors has led to the increased use of control techniques like vector control and direct torque control, resulting in fast dynamic response and simple and linear speed control of induction motor drive. In view of these features of vector control and direct torque control techniques, modelling and simulation of control techniques of induction motor drives is done.

1.1.3 H-Bridge Single Phase AC-DC Converter

With the advancement in power electronics and quality of semi-conductor devices and fast digital processors has led to improvement converter design. Converters provide the rectification of ac voltage and also improve power quality on the ac plus dc side. These converters can be used for both uni-directionals as well as bi-directional power flow load applications. Bi- directional power flow characteristics find wide application in electric traction where drive requires a four quadrant operation. In electric traction application, the energy conservation aspect plays a major role, as the locomotive has to pass a number of up and down gradients on the way and the use of such converters results in regeneration of energy leading to saving in electric consumption.

1.2 Objective of Study

The traction motor drives use a controlled bridge rectifier to connect to the electric supply system. The rectifier and traction drive exhibits non linear features, which deteriorates the power quality at the ac mains.

In this work, power factor corrected converter and voltage source converter based improved power quality ac-dc converters are analysed and implemented for feeding a variable frequency traction motor drive. In view of the increased emphasis on the power quality issues and the restrictions imposed by various standards, the areas were identified for investigation in this work.

The present work aims at:

- Implementing various schemes for speed control of traction drive.
- Design of Converter
- Eliminating harmonics in the ac mains feeding variable frequency traction motor drive.
- Power factor correction of as supply side.

1.3 Organisation of Dissertation

The content of the thesis have been divided into 7 chapters. Chapter 2 deals with the literature review on electric traction system which includes the developments in electric traction system, voltage source converters and traction motor drive. It also includes the developments in control techniques of variable frequency induction motor drives. Chapter 3 gives brief about the electric traction system in India also the system configuration is explained briefly. Chapter 4 describes the modelling and simulation of vector controlled and direct torque controlled induction motor drives. Chapter 5 is based on the modelling and simulation of single phase supply based electric traction drive. Chapter 6 presents the assessment of results obtained from the simulations. Chapter 7 gives the conclusion of the thesis and suggestions for further improvements.

1.4 Conclusion

This chapter briefs the introduction of Indian railways system and some important features of electric traction drive. Objective of study and organisation of the thesis is also discussed.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

2.1 General

This chapter intends to give a brief literature review of electric traction system, without exhaustive subjective area and the work being carried out on different types of control of induction motor drive during last decade. A wide range of research work has been reported in area of converter modelling and also in control techniques for ac-dc converter and vector control methodologies used for induction motor drives. The main focus of literature review is on following points:

- Electric traction system.
- Design of AC-DC converter to impart unity power factor on ac side
- Study of control of induction motor drive for elimination of torque and speed ripples on drive front.

This literature review includes literature survey of different types of DC and AC traction system, control techniques of variable frequency induction motor drive and techniques for converter controlling for electric traction system. In past few years, extensive research has been done in developing different configurations for mitigation of harmonic in variable frequency traction motor drive. A number of developments can be seen control techniques for variable frequency induction motor drive and also unity power factor converters. An extensive literature study was made on electrification of the railways and also the topic Vector control of induction motor in carrying out the proposed work and the area identified for further research.

2.2 Electric Traction System

The knowledge of railway and steam engines has been around since the sixteenth century. Wagon roads for English coalmines using heavy planks were first designed and built in 1633.

Mathew Murray of Leeds in England invented a steam locomotive that could run on timber rails in 1804 and this was probably the first railway engine. Although railway and locomotive technologies were continually developed, the first electrified railway was introduced in the 1880s [1]. As a result of this revolution, the traction motor and the power supply system have become important parts of modern electrified railways. DC power supply system was used earlier in 1900s because of its effortless control. But it does have its share of disadvantages like DC motor commutation, costly power supply equipments and limitations on feeding distance. Long distance feeders became a reality when AC power system was introduced. Earlier DC motors fed from converters were used with AC supply. DC motor has simple torque-speed control. Various countries used different operating frequencies like 15 kV at 16 Hz and 12 kV at 25 Hz to feed AC commutator [8-9]. In 1950s, 50 Hz frequency system was adopted for electrified railways. The Valenciennes-Thionville line in France was the first 50 Hz railway electrification [10]. Then on 25kV at 50 Hz has become standard in single phase feeding system for railway electrification, while 50kV for heavy loaded locomotives. AC railway too uses several configuration [10].

2.3 Voltage Source Converter

K. Thiyagarajah, V. T. Ranganathan [7] has given an inverter/converter system operating from a single- phase supply. IGBT is the power device used. The inverter can operate at switching frequencies up to 20 kHz. Snubber circuits along with energy recovery networks suitable for high frequency operation and experimental results from a laboratory inverter have been presented. The steady-state design considerations of the front-end converter have been discussed. The block diagrams for dynamic control in a rotating as well as a stationary reference frame have been developed. Experimental results from a laboratory converter with stationary reference frame control have been presented in support of the analysis The front end for the system is a regenerative single phase full-bridge IGBT inverter along with an ac reactor. Steady-state design considerations are explained and control techniques, for unity power factor operation and fast current control of the front end converter, in a rotating as well as 'a stationary reference frame, are discussed and compared.
Adrian David Cheok, Shoichi Kawamoto, Takeo Matsumoto, and Hideo Obi [11] described new developments in the design of high-speed electric trains, with particular reference to the induction motor drive system. A new high power three level converter-inverter system applying advanced insulated gate bipolar transistors (IGBTs). Advanced control techniques lead to a unity power factor seen by the ac

supply as well as minimizing the line harmonics, power loss, motor torque ripple, and audible noise. By using advanced ac inverter drive systems the recently developed high speed train offers high level performance, efficiency, and passenger comfort. The described system is implemented in the latest "Bullet" or Shinkansen train sets operating in eastern Japan between Tokyo and Nagano In addition unity power factor is presented to the ac catenary which maximizes the system efficiency and utilization.

P. Enjeti and A. Rahman [12] proposed a new single-phase to three-phase converter topology. The proposed converter is capable of powering a three-phase adjustable-speed ac motor drive from a single phase ac main while maintaining sinusoidal input current at near unity power factor. The proposed topology thus realizes the following features: It employs only six switches. It draws near sinusoidal current from the ac mains at close to unity power factor. It permits bidrectional power flow and, hence, facilitates regenerative braking. Suitable design equations are given for the proposed topology.

J. Itoh and K. Fujita [13] proposed two novel single-phase input to three-phase output converters which use the neutral point of the three-phase load. The feature of those circuits is to drain the power supply current to the motor as a zero-phase sequence current. The proposed circuits have the significant advantages of avoiding the use of additional reactive components and reducing the number of switching devices with respect to conventional circuits. Future efforts will be made for improving the performances of the proposed converters as follows: Optimization of the PWM method; Design of a special motor having accessible neutral point and small stator resistance; Compensation of the motor phase current distortion due to the inverter dead-time.

B. K. Lee, B. Fahimi and M. Ehsani [14] developed various reduced parts converter topologies and control strategies for power factor correction and motor control. From this investigation, the converter topologies could be mainly categorized into cascade type and unified type. The detailed operational principles and the performance comparison is to illustrate merits and limitations of the converters.

C. B. Jacobina, M. B. de R. Correa, A. M. N. Lima, and E. R. C. da Silva [15] have presented two reduced-switch-count ac drive systems for two-phase and three-phase motors. The converters implement both the input rectifier and the inverter by sharing a leg to reduce the switch count as compared to the ten-switch configuration. It has been shown that the overall performance of these topologies is superior to the configurations using the dc-bus midpoint connection (six-switch converter). This happens because the THD is smaller, the voltage capability of the input and output converters can be controlled, and no ac fundamental current flows through the dc-bus capacitor.

R. Q. Machado, S. Buso, and J. A. Pomilio [16] described a line-interactive single-phase to three-phase converter. A typical application is in rural areas supplied by a single-wire with earth return system. The traditional objective of feeding a three-phase induction motor is not anymore the main concern for such conversion. Due to the evolution of the farm technology, some of the local loads (as electronic power converters, computers, communication equipments, etc) require high power quality that is intended as sinusoidal, symmetrical, and balanced three-phase voltage. Additionally, to maximize the power from the feeder, the system provides a unity power factor to the grid. A three-phase voltage source inverter–pulse width modulation converter is used for this purpose. The power converter processes a fraction of the load power and the energy necessary to regulate the dc link voltage. As it does not need to supply active power, it is not necessary to have a source at the dc side. However, if island mode operation is needed, a dc source must be available at the dc link to supply the load.

O. Ojo, W. Zhiqiao, G. Dong, and S. Asuri [17] have presented the methodology for the analysis and control of a high-performance induction motor drive actuated by two controlled rectifier–inverter systems with reduced count of switching devices. The general approach for determining the modulation signals required for the carrier-based PWM pulse generation for this class of minimalist converters has been set forth. The input supply voltage is a single phase and the input current is controlled using a natural reference frame controller to operate close to unity displacement power factor. The nature of the modulation signals, the achievable motor dynamics, and waveforms are clearly laid out in simulation and experimental results. Compared with the conventional high-performance rectifier– converter–motor drive system which has eight controllable switching devices, the converter systems studied in this paper has the same dynamic performance potential.

J. R. Rodrıguez, J. W. Dixon, J. R. Espinoza, J. Pontt, and P. Lezana [18] have reviewed the most important topologies and control schemes used to obtain ac–dc conversion with bidirectional power flow and very high power factor; each topology has advantages and disadvantages. Voltage-source PWM regenerative rectifiers have shown a tremendous development from single-phase low-power supplies up to high-power multilevel units. Current-source PWM regenerative rectifiers are conceptually possible and with few applications in dc motor drive. The main field of application of this topology is the line-side converter of medium voltage CSIs. Especially relevant is mentioning that single-phase PWM regenerative rectifiers are today the standard solution in modern ac locomotives. The control methods developed for this application allow for an effective control of input and output voltage and currents, minimizing the size of energy storage elements.

D.-C. Lee and Y.-S. Kim [19] proposed a novel control scheme of single phase-to-three-phase pulse width-modulation (PWM) converters for low-power three-phase induction motor drives, where a single- phase half-bridge PWM rectifier and a two-leg inverter are used. With this converter topology, the number of switching devices is reduced to six from ten in the case of full-bridge rectifier and three-leg inverter systems. In addition, the source voltage sensor is eliminated with a state observer, which controls the deviation between the model current and the system current to be zero. A simple scalar voltage modulation method is used for a two-leg inverter, and a new technique to eliminate the effect of the dc-link voltage ripple on the inverter output current is proposed. Although the converter topology itself is of lower cost than the conventional one, it retains the same functions such as sinusoidal input current, unity power factor, dc-link voltage control, bidirectional power flow, and variable-voltage and variable-frequency output voltage.

2.4 Control techniques for induction motor drive

Benefits such as high robustness and low maintenance makes squirrel – cage induction motor drives as widely used drive in industrial as well as traction applications. There exits different control schemes of induction motor drives, namely, Scalar control, vector or field orientation control, direct torque and flux control, etc. Here is some brief literature survey on these above mentioned techniques.

2.4.1 Scalar Control

P. Vass et al. [3] describe the scalar control method. It says that it has a broad application field because of simple to easy implement control structure. An encoder or speed tachometer can be used to improve the speed control performance; these added devices are required to feedback the rotor angle or rotor speed signal and compensate the slip frequency. This lead to increase in cost of the drive system and also they destroy the robustness of the induction motor.

B.K Bose et al. [4] presented that squirrel-cage induction motor is one of the most robust existing motor and widely thus used. It gives a brief about different speed control techniques of induction motor such as stator voltage control and voltage frequency control, etc. The variable voltage variable frequency control method of the squirrel-cage motor is the best method among all the methods of the speed control for achieving variable speed operation.

Brian Heber et al. [20] described that, Dc drives are generally used for the applications like elevators, mill drives, traction, etc where high initial torque and speed-torque control is important. But due to advancement in power electronics, these applications can now be operated by an induction motor drive with constant volt/hertz (V/f) scheme.

Hassan Baghgar Bostan Abad et al. [21] pointed out that DC motors are easily controllable than AC motors, but they require higher cost and maintenance. In addition to cost factor, DC motors have higher volume and weight for the same amount of power rating.

So, to overcome the coupling effect in the motor and to get a fast torque response, two techniques have been surveyed namely vector control and direct torque control.

2.4.2 Vector Control

J.W finch et al. [22] has showed that the advantage gained from field-orientated control is huge, it controls the production of the transient in the torque and therefore leading to the fast response to load demanded changing the speed. Constant air gap machine due to a single stator winding can be first measured (direct) estimated (indirect) at various points around the air gap. This field strength at any angle around the gap can be represented as a sinusoidal field distribution. One way is to represent it as a Vector. The vector direction is coincident with the field axis and the vector length describes the magnitude of the field. The vector representation is important because it gives a simple method of combining separate field components: if two sinusoidal distributed fields are combined, the vector representation of the resultant field is simply the sum of the component field vectors.

Norman Mariun et al. [23] presented the idea of field oriented control. This control scheme makes to possible to control the induction motor as separately excited dc motor. Like dc motor, field and torque of induction motor can be separately controlled by decoupling corresponding field oriented quantities. Also field oriented control forms the base of advances in the control schemes for induction motors.

F. Biaschke et al [24] represented that field oriented control of induction motor drive uses the d-q coordinates and parks transformation to obtain the closed-loop dynamics of separately controlling the torque and flux of induction motor similar to that of a separately excited dc machine.

Bhim Singh et al. [25] suggested that some particular sensor (speed sensor) is increase the total cost of the drive system and its elimination can be made possible to reduce the total cost effectively. The speed sensor is replaced by a flux model, which needs the use of two additional voltage sensors. The reduction of number of voltage sensors to be used in a VCIMD system is also made.

2.4.3 Direct torque control of an induction motor drive

Takahasi *et. al.* [26] A novel technique for induction motor drive control has been reported by known as direct torque control. This technique made possible obtaining a fast torque control without mechanical speed sensors. Also known as sensorless type control technique. Current regulator and coordinate transformations are not needed in this technique. Drawbacks include difficulty to control torque and flux at very low speed.

Nash et al. [27] has given the evolution of direct torque control. Many have shown use of switching tables to improve performance of direct torque control of an induction motor drive.

Casadei et. al. [28] has given the outcome of flux and toque hysteresis band values in direct torque control of variable frequency induction motor drive. They have also used SVM i.e. space vector modulation technique with constant switching frequency operation.

2.5 Conclusion

This literature review gives an idea about the research work carried out in the desired area is mainly influenced by technical developments in power electronics and control algorithms. The use of power converters can improve the power factor to near unity and can make the line current near sinusoidal. The focus on forthcoming research on these harmonic mitigation techniques is on reduction in number of components and increase in efficiency of the converters.

CHAPTER 3

ELECTRIC TRACTION SYSTEM

CHAPTER 3

ELECTRIC TRACTION SYSTEM

3.1 General

Like most road running vehicles, a railway traction power system provides mechanical torque that can be converted into kinetic and potential energy and can be used to overcome resistance to motion. DC and AC electric traction systems are commonly deployed in the railway industry. The transmission system requirements for both the systems are very different. Diesel electric traction systems are mainly found on routes that are not electrified. The first practical application of electric traction dates back to the second half of the 19th century. At the early stage of development, DC motors, together with low-voltage DC traction lines, were the main traction power supply methods, due to their simple torque control characteristics. Subsequently, low-voltage DC transmission networks and high-voltage, low frequency (25 Hz) AC transmission networks became the two major electric supply methods for traction power. The reason for the emergence of the AC transmission network was due to the inherent tractive characteristics of induction motors and the difficulties of supplying electrical power from a DC transmission line. It was not until the 1950s, with the advancement of power electronics, that high voltage and industry frequency AC transmission became a reality. Since then, 25 kV single-phase at 50 or 60 Hz often replaces the 15 kV DC networks. [29-30].

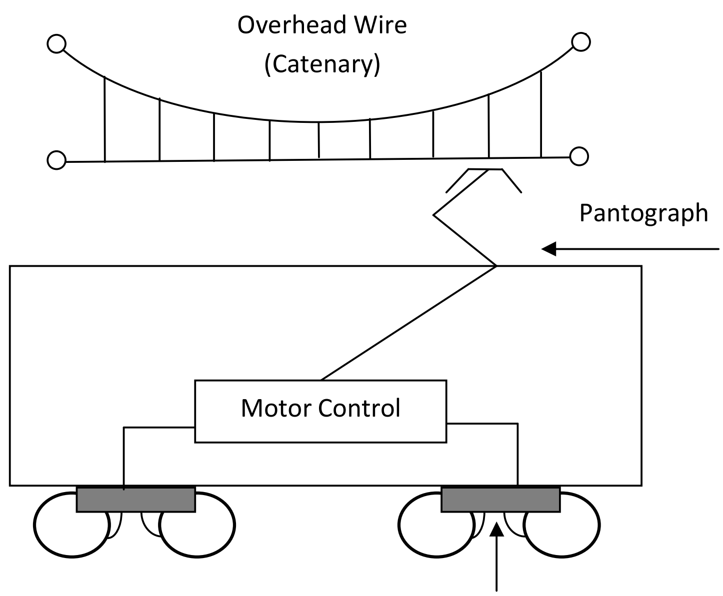
DC and AC electric trains need to be supplied with power through a current collection system. A traction power network is employed to supply the electrical power to the entire electrified rail network. In single phase electrification, the substations are necessarily required to keep the voltage drop within permissible limits. The type of substations required depends on the nature of primary supply and system of electrification. For arrangements of power supply to the various electric traction substations in India, power is purchased from supply authorities who are responsible for the operation and maintenance of 220/132kV transmission lines and grid substations up to 25kV outgoing terminals of Substations.

3.2 Various Traction Power Supplies

There are generally two types of power supply system: DC and AC. The power supply system is usually using an overhead line consists of a contact line carrying live current and catenaries, which is an insulated suspension system supporting the contact line. A certain height depending upon the supply voltage is maintained between overhead line and rails. To reduce electrical losses, high voltage level of power supply system is used.

3.2.1 DC System

In this system electric motors employed are usually dc series motors. The operating voltage is from 1500 to 3000 volts for main line railways. The driving motors receive power from the distribution system consisting of overhead wires with tapings as shown in fig 3.1., which is fed from substations. These substations receive ac power from a 3-phase high voltage transmission lines and convert it to dc by rectifiers. As regards the merits and demerits of dc system the dc motors have better characteristics, low maintenance cost and better speed control. On the other hand because of low operating voltage conductor of large cross-section and more number of substations are required dc is preferred for road transport where stops are frequent and distances of run are small.



(a)

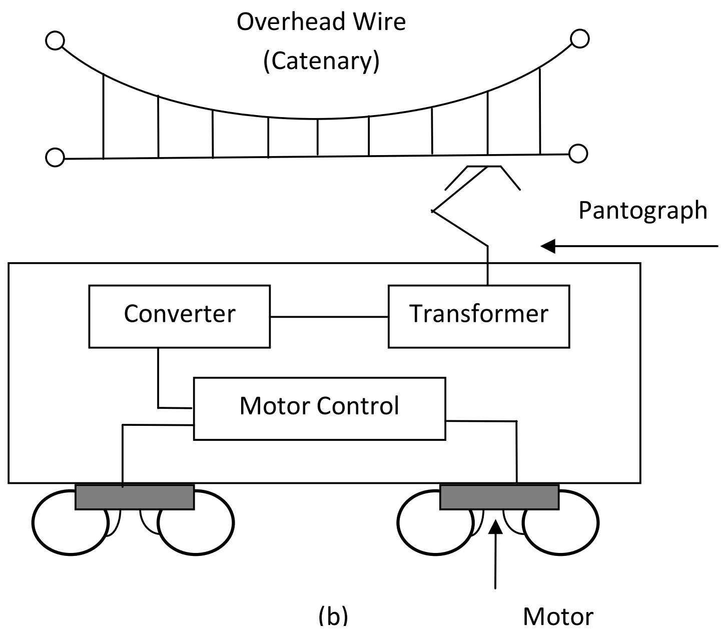


Fig.3.1 Schematic diagram of a) DC electric locomotive, b) AC electric locomotive

3.2.2 AC System

With the development of power electronics technology, AC supply is regarded as advantageous due to its compact size and weight of control devices [37]. Now mostly ac system with induction motors are used. There are two systems 25Hz and %0 Hz. For 25 Hz, the voltage employed for distribution network is 15 kV to 25kV which is stepped down on locomotive to a low voltage of 300 to 400 V. Another is 50 Hz supply which has 25kV distribution network. AC single phase system is adopted for main line service as suburban railways and heavy-haul railways.

Block diagram of an AC electric locomotive is depicted in fig 3.2. It collects current from overhead equipment (OHE) by means of a pantograph collector which usually carries a sliding shoe for contact with the overhead trolley wire. The locomotive essentially consist of circuit breaker, on load tap changer, step down transformer, converting machinery, smoothing chokes and traction motor.

3.3 System Configuration

Fig 3.2 shows the block diagram of the traction motor drive suitable for electric traction. Overhead line is provided with tapings at equal distances. Through pantograph 25kV single-phase supply is tapped. A three winding transformer with two secondary windings is connected to supply. This transformer step down the 25kV supply and provide 975 V supply in secondary side. Further two separate converters are connected to the secondary windings which maintain a constant dc link and mitigate the harmonics created in supply side. H-Bridge configuration of converter is used which consist of IGBT for bidirectional flow of power. Regarding converter feedback control loop, DC-link voltage is sensed and a comparison is done between sensed voltage and reference voltage. The voltage error thus generated is fed to PI controller which generates the reference current. This reference current is then compared with sensed ac mains current. This comparison generates a current error which is then fed to PWM current controller which generates gating signal for the converter. DC-link generated serves as input for inverter which uses Direct torque control scheme for further connected induction motor speed control. Two induction motors are connected to a single inverter.

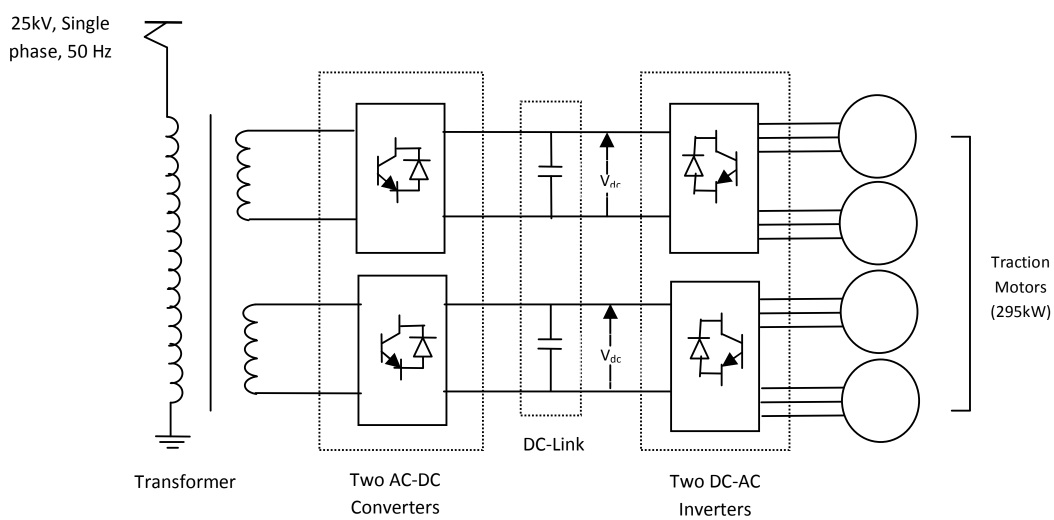


Fig.3.2 Block diagram of electric traction motor drive system configuration

3.4. Induction Motor Drive System

Induction motor tends to work at low power factor particularly under light load conditions. It leads to power drawl from the mains supply to less efficient, which then requires higher current to be drawn for the same amount of power. This leads to increase in the volt-ampere requirement of the power drive components, and the mains supply. So, induction drives along with unity power factor control on supply side are preferred to minimize the line current, power loss and motor torque ripple. Power factor correction provides many additional benefits such as it reduces the line harmonics, boost system capacity, improves the voltage and reduces the heat losses. A block diagram explaining the constituents of an induction motor drive is as shown in Figure 3.3**.**

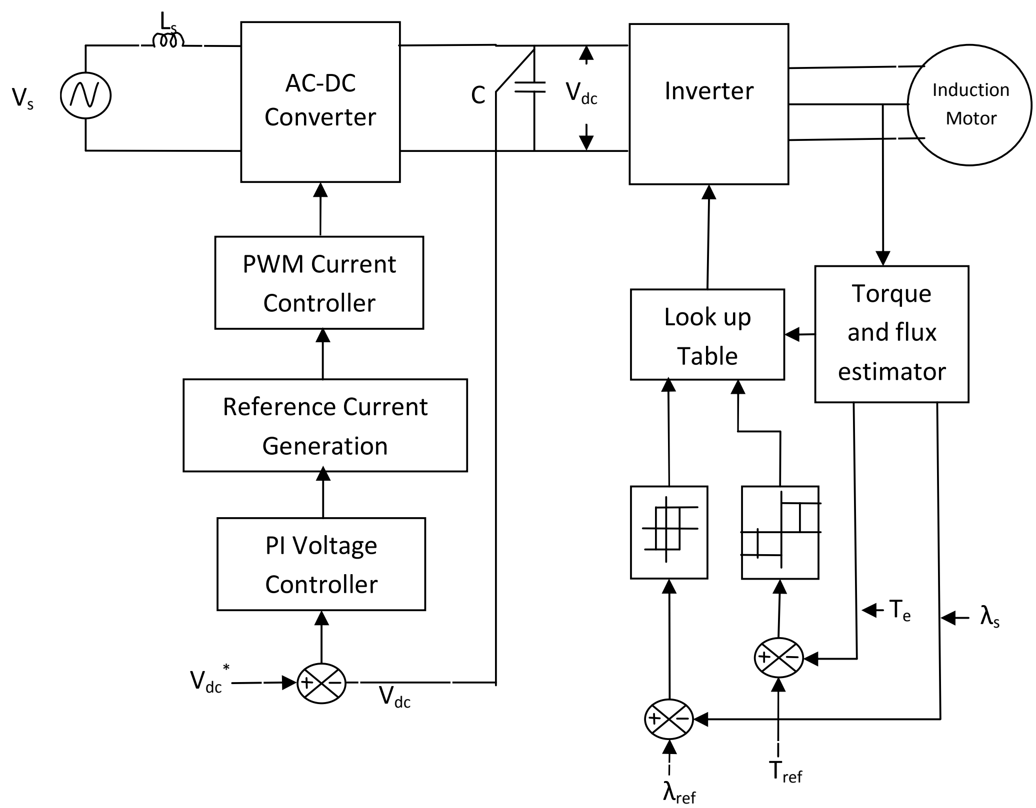


Fig 3.3 Block diagram of induction motor drive

In this system, the 3 phase variable frequency induction motor is supplied with single phase ac power supply. This ac supply is connected to a H-bridge AC-DC converter. The dc link formed by converter supply to an inverter, which provides 3-phase supply to induction motor. Many control techniques are available for controlling the drive of which vector control is mostly used [31-33].

CHAPTER 4

CONTROL TECHNIQUES FOR TRACTION MOTOR DRIVE

CHAPTER 4

CONTROL TECHNIQUES FOR TRACTION MOTOR DRIVE

4.1 General

The induction motor drives play an important role in electric traction, steel, paper and cement factories. This is due to their inherent advantages such as low inrush current, fast dynamic response, robust motor, ease of control etc. Techniques generally used in variable frequency induction motor drives for control of voltage source inverter fed induction motor drive can be broadly classified as scalar control, vector control and direct torque control. Application of scalar control is easy and simple, but it has its disadvantages of sluggish response instability of system because of higher order system effect. This problem can be overcome by vector control and direct torque control, in which induction motor can be controlled like a separately excited dc motor. The revolution in self commutating solid state power devices and the availability of fast computing processors has led to the increased use of control techniques like vector control and direct torque control, resulting in fast dynamic response and simple and linear speed control of induction motor drive. In view of these features of vector control and direct torque control techniques, this chapter presents modelling and simulation of control techniques of induction motor drives. The induction motor drives based on vector control as well as direct torque control techniques are modelled in MATLAB Simulink.

4.2 Control Techniques for Traction motor drive

The control techniques for traction motor drive constitute a vast subject, and the technology has further advance in recent years. We have scalar vector and direct torque control schemes for induction motor drives. Scalar control is due to magnitude variation of the control variable only, and does not take into consideration the coupling effect in machine. Scalar control is not in much use these days due to poor transient response and non linear control behaviour. The better-quality performance of vector control and direct torque control induction motor drives have superseded the scalar control technique based drives. The operating principle of these two most commonly used control techniques namely vector controlled and direct torque controlled induction motor drives are explained here [37-39].

4.2.1 Scalar Control

Scalar control as the name indicates, is due to magnitude variation of the control variable only, and disregards the coupling effect in machine. For example, the voltage of machine can be controlled to control the flux, and frequency or slip can be controlled to control the torque. However flux and torque are also function of voltage and frequency respectively. A scalar controlled drive gives somewhat inferior performance. Scalar control is easy to implement. Scalar controlled drives have been widely used in industry, but the inherent coupling effect (both torque and flux are function of voltage or current and frequency) gives sluggish response and system is easily prone to instability because of higher order (fifth order) system effect. To make it clearer, if torque is increased by incrementing the slip (the frequency), the flux tends to decrease. It has been noted that the flux variation is also sluggish. Decreases in flux then compensated by the sluggish flux control loop feeding an additional voltage. This temporary dipping of flux reduces the torque sensitivity with slip and lengthens the response time. However, their importance has diminished recently because of the superior performance of vector control drives.

To improve speed control performance of the scalar control method, an encoder or speed tachometer is required to feedback the rotor angle or rotor speed signal and compensate the slip frequency. However, it is expensive and destroys the mechanical robustness of the induction motor. So these are the limitation of scalar control which is overcome by vector control and direct toque controlfor induction motor drive.

4.2.2 Vector Control

A DC machine has traditionally been a superior choice for torque control. The commutator of the DC machine holds a fixed, orthogonal spatial angle between the field flux and the armature MMF, allowing for the torque and flux to be controlled in a decoupled manner. Induction machines, via FOC, can emulate this control method. FOC control utilizes the position of the rotor combined with two-phase currents to generate a means of instantaneously controlling the torque and flux. Field-orientated controllers require control of both magnitude and phase of the AC quantities and are, therefore, also referred to as vector controllers [6]. FOC produces controlled results that have a better dynamic response to torque variations in a wider speed range compared to other scalar methods. Also, FOC control can induce a high torque at zero speed.

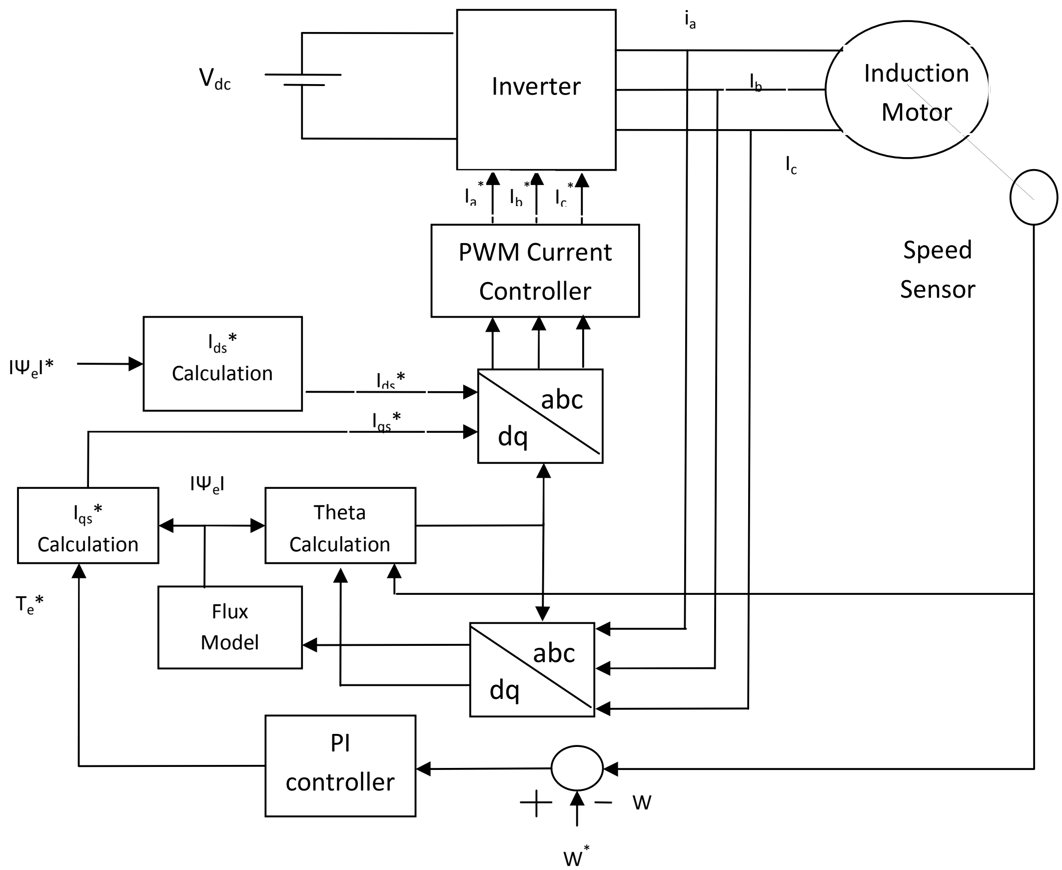


Fig.4.1 Block diagram of Vector control scheme of traction motor drive.

A block diagram of vector controlled induction motor drive is shown in fig.4.1. The induction motor is fed by a current- regulator. The motor drives a mechanical load characterized by inertia J, friction coefficient B, and load torque T_L. The speed control loop uses a proportional-integral controller to produce the quadrature axis current reference i_q* which controls the motor torque. The motor flux is controlled by the direct-axis current reference i_d*. Block d-q to abc is used to convert i_d* and i_q* into current references i_a*, i_b*, and i_c* for the current regulator [3].

4.2.2.1 d-q to abc Transformation

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axes at 2π/3 angle apart. To transform the three-phase stationary reference frame (as-bs-cs) variable into two-phase stationary reference frame (d^s-q^s) variables and then transform these to synchronously rotating reference frame(d^e-q^e).and following transformation equations are used given by (4.1).

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta & 1 \\ \cos(\theta - 120°) & \sin(\theta - 120°) & 1 \\ \cos(\theta + 120°) & \sin(\theta + 120°) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} \tag{4.1}$$

The corresponding inverse relation is given by equation (4.2)

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\theta & \cos(\theta - 120°) & \cos(\theta + 120°) \\ sin\theta & \sin(\theta - 120°) & \sin(\theta + 120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{4.2}$$

where v_{os}^s is added as the zero sequence component, which may or may not be present. We have considered voltage as the variable. The current and flux linkage can be transformed by similar equations. Here θ is the angle of the orthogonal set α-β-0 with respect to any arbitrary reference. If the α-β-0 axes are stationary and the α axis is aligned with the stator a-axis, then θ = 0 at all times,thus(4.3)

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{4.3}$$

If the orthogonal set of reference rotates at the synchronous speed ω_1, its angular position at any instant is given by equation (4.4)

$$\theta = \int_0^t \omega_1\, t + \theta_0 \tag{4.4}$$

The orthogonal set is then referred to as d- q- 0 axes. The three-phase rotor variables, transformed to the synchronously rotating frame, are (4.5)

$$\begin{bmatrix} v_{qr}^s \\ v_{dr}^s \\ v_{or}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega_e - \omega_r)t & \cos((\omega_e - \omega_r)t - 120°) & \cos((\omega_e - \omega_r)t + 120°) \\ sin(\omega_e - \omega_r)t & \sin((\omega_e - \omega_r)t - 120°) & \sin((\omega_e - \omega_r)t + 120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{4.5}$$

It should be noted that the difference $\omega_e - \omega_r$ is the relative speed between the synchronously rotating reference frame and the frame attached to the rotor. This difference is also the slip frequency, ω_{sl}, which is the frequency of rotor.

4.2.2.2 θ_e Calculation Block

The rotor flux position θ_e required for coordinates transformation is generated from the rotor speed ω_m and slip frequency ω_{sl} as (4.6)

$$\theta_e = \int(\omega_m + \omega_{sl})dt \tag{4.6}$$

The slip frequency is calculated from the stator reference current i_{qs}* and the motor parameters given by (4.7)

$$\omega_{sl} = \frac{L_m}{|\psi_r|_{est}} \frac{R_r}{L_r} i_{qs}^* \tag{4.7}$$

4.2.2.3 I_{ds} Calculation Block

The stator direct-axis current reference i_{ds}* is obtained from rotor flux reference input $|\psi_r|$* (4.8)

$$i_{ds}^* = \frac{|\psi_r|^*}{L_m} \tag{4.8}$$

4.2.2.4 I_{qs} Calculation Block

The stator quadrature-axis current reference i_{qs}* is calculated from torque reference T_e* as (4.9)

$$i_{qs}^* = \frac{2}{3} \cdot \frac{2}{p} \cdot \frac{L_r}{L_m} \frac{T_e^*}{|\psi_r|_{est}} \tag{4.9}$$

Where L_r is the rotor inductance, L_m is the mutual inductance, and $|\psi_r|_{est}$ is the estimated rotor flux linkage.

4.2.3 Direct Torque Control

An advanced scalar control technique based on direct torque and flux control (known as DTC) was introduced in 1985[3]. Basically, it uses torque and stator flux control loops, where the feedback signals are estimated from the machine terminal voltages and currents [4]. The torque command can be generated by the speed loop as shown.

The loop errors are processed through hysteresis bands and fed to a voltage vector look up table. The flux loop has outputs +1 and -1, whereas the torque loop has three outputs, +1, 0, and -1 as shown in table. The inverter voltage vector table also gets the information about the location of the stator vector to control the PWM inverter switches. The control strategy is based on the torque equation expressed by (4.10):

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{L_m}{L_r(L_s L_r - L_m^2)}\psi_r \psi_s \sin\gamma \tag{4.10}$$

Where ψ_r and ψ_s are the rotor and stator fluxes, respectively, and γ is the angle between them. The voltage vector lookup table for DTC control is shown in Tables I and II

Table I. Vector look up table

H_ψ	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
-1	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_3	v_4

Table II. Flux and Torque variations due to applied voltage vector

Voltage Vector	v_1	v_2	v_3	v_4	v_5	v_6	v_0 or v_7
Ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

4.2.3.1 DTC Controller Design

The required stator flux can be obtained by means of choosing the most suitable Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the following equations (4.11).

$$\Delta\psi_s = V_s . \Delta t \tag{4.11}$$

Decoupled control of the stator flux modulus and torque is achieved by acting on the radial and tangential components respectively of the stator flux-linkage space vector in its locus. These two components are directly proportional to the components of the same voltage space vector in the same directions. So imposing of proper voltage vector is important in direct torque control of induction motor. This we will obtain by using voltage source inverter.

4.2.3.2 Space Vectors

There are many topologies for the voltage source inverter used in DTC control of induction motors that give high number of possible output voltage vectors [16], [17] but the most common one is the six step inverter. A six step voltage inverter provides the variable frequency AC voltage input to the induction motor in DTC method. The DC supply to the inverter is provided either by a DC source like a battery, or a rectifier supplied from a three phases (or single phase) AC source. The inductor L is inserted to limit shot through fault current. A large electrolytic capacitor C is inserted to stiffen the DC link voltage.

The switching devices in the voltage source inverter bridge must be capable of being turned off and on. Insulated gate bipolar transistors (IGBT) are used because they have this ability in addition; they offer high switching speed with enough power rating. Each IGBT has an inverse parallel-connected diode. This diode provide alternate path for the motor current after the IGBT, is turned off. Each leg of the inverter has two switches one connected to the high side (+) of the DC link and the other to the low side (-); only one of the two can be on at any instant. When the high side gate signal is on the phase is assigned the binary number 1, and assigned the binary number 0 when the low side gate signal is on. Considering the combinations of status of phases a, b and c the inverter has eight switching modes ($V_aV_bV_c$=000-111) two are zero voltage vectors V0 (000) and V7 (111) where the motor terminals is short circuited and the others are nonzero voltage vectors V1 to V6.

The dq model for the voltage source inverter in the stationary reference frame is obtained by applying the dq transformation Equation to the inverter switching modes. The six nonzero voltages space vectors will have the orientation shown in Figure 4.3, and also shows the possible dynamic locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors signaled by the discontinuous line. Each vector lies in the center of a sector of 60^o width named V1 to V6 according to the voltage vector it contains.

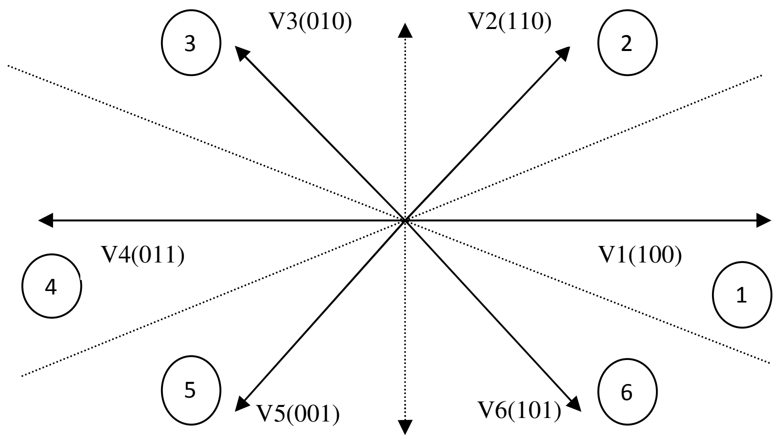


Fig 4.2 Stator flux vector locus and Voltage vectors for possible switching.

The inverter voltage directly force the stator flux, the required stator flux locus will be obtained by choosing the appropriate inverter switching state. Thus the stator flux linkage move in space in the direction of the stator voltage space vector at a speed that is proportional to the magnitude of the stator voltage space vector. By selecting step by step the appropriate stator voltage vector, it is then possible to change the stator flux in the required way. If an increase of the torque is required then the torque is controlled by applying voltage vectors that advance the flux linkage space vector in the direction of rotation. If a decrease in torque is required then zero switching vector is applied, the zero vector that minimize inverter switching is selected. In summary if the stator flux vector lies in the k-th (k" being the sector number)sector and the motor is running anticlockwise then torque can be increased by applying stator voltage vectors Vk+1 or Vk+2, and decreased by applying a zero voltage vector V0 or V7. Decoupled control of the torque and stator flux is achieved by acting on the radial and tangential components of the stator voltage space vector in the same directions, and thus can be controlled by the appropriate 111inverter switching. In Accordance with figure 4.2, the general table III can be written. It can be seen from table III, that the states Vk and Vk+3 , are not considered in the torque because they can both increase (first 30 degrees) or decrease (second 30 degrees) the torque at the same sector depending on the stator flux position.

Table III. General Selection Table for Direct Torque Control

Voltage Vector	**Increse**	**Decrease**
Stator Flux	V_k, V_{k+1}, V_{k-1}	V_{k+2}, V_{k-2}, V_{k+3}
Torque	V_{k+1}, V_{k+2}	V_{k-1}, V_{k-2}

Block diagram for the direct torque control scheme of induction motor is shown in figure 4.4.

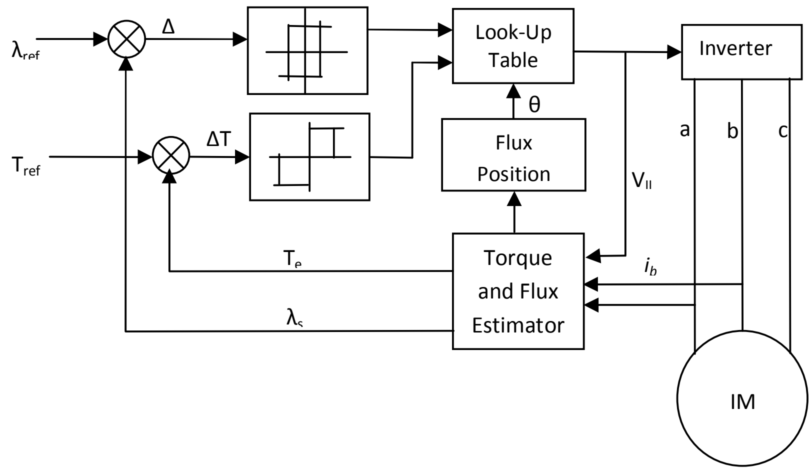


Fig 4.3 Block diagram of direct torque control of traction motor

As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two level and three-level hysteresis blocks respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table. The inputs to the look up table are given in terms of +1, 0,-1 depend on whether the torque and flux errors within or beyond hysteresis bands and the sector number in which the flux sector presents at that particular instant.

4.3 MATLAB based Modelling of Variable Frequency Induction Motor Drives

The variable frequency induction motor drives are simulated in MATLAB Simulation using two techniques namely vector control and direct torque control. For study of the output characteristics of above mentioned control schemes for the induction motor drives, the performance of a 200 HP induction motor drive fed from dc supply is simulated. Later 295kW motor rating vector control and direct torque control schemes were implemented for traction motor drive. Details of the parameters of the simulated model are given in Appendix-A.

4.3.1 Vector Control

Fig 4.5. Shows the MATLAB model an indirect vector control technique used to control induction motor drive. Different blocks such as a PI speed controller, two phase rotating to three phase stationary converter block, hysteresis current controller, voltage source inverter (VSI), an induction motor etc. Are realized using Simulink.

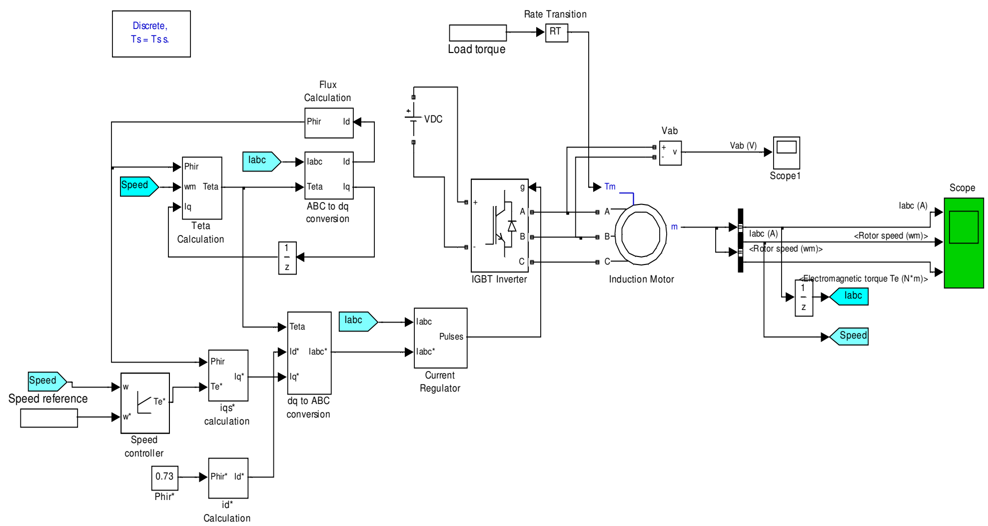


Fig 4.4 Simulink model of field oriented control of induction motor

4.3.2 Direct Torque Control

Fig 4.6. Shows the MATLAB Simulink model of an induction motor drive controlled using direct torque control technique.

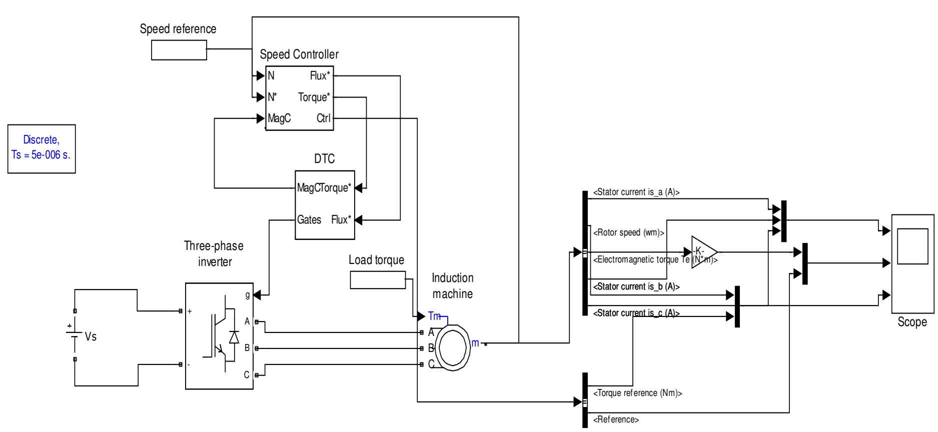


Fig 4.5 Simulink model of direct torque control of induction motor

The different blocks realized using Simulink are PI speed controllers, voltage source inverter, hysteresis comparators, estimators, induction motor, etc. The selection of switching state is made.

4.3.3 Performance of control schemes

The simulation results for both methods are shown in figure 4.6 to figure 4.11. The load is applied at 0.5 second. The results for electromagnetic torque (Nm), rotor speed (rad/s) and stator currents (A) at no load condition for the reference speed at 150 rad/sec shown in figure 4.6 and 4.7. Similarly the results for electromagnetic torque, rotor speed and stator currents at 50% load condition and full load for the reference speed at 150 rad/sec are also shown in figure 4.8- 4.11.

It is observed that the torque oscillations in FOC control scheme are negligible whereas in DTC scheme oscillations in torque are observed. These oscillations are relatively less at no load and then become nearly constant with the increase in percentage loading. Also, it is found that the distortion of motor current is higher in case of DTC.

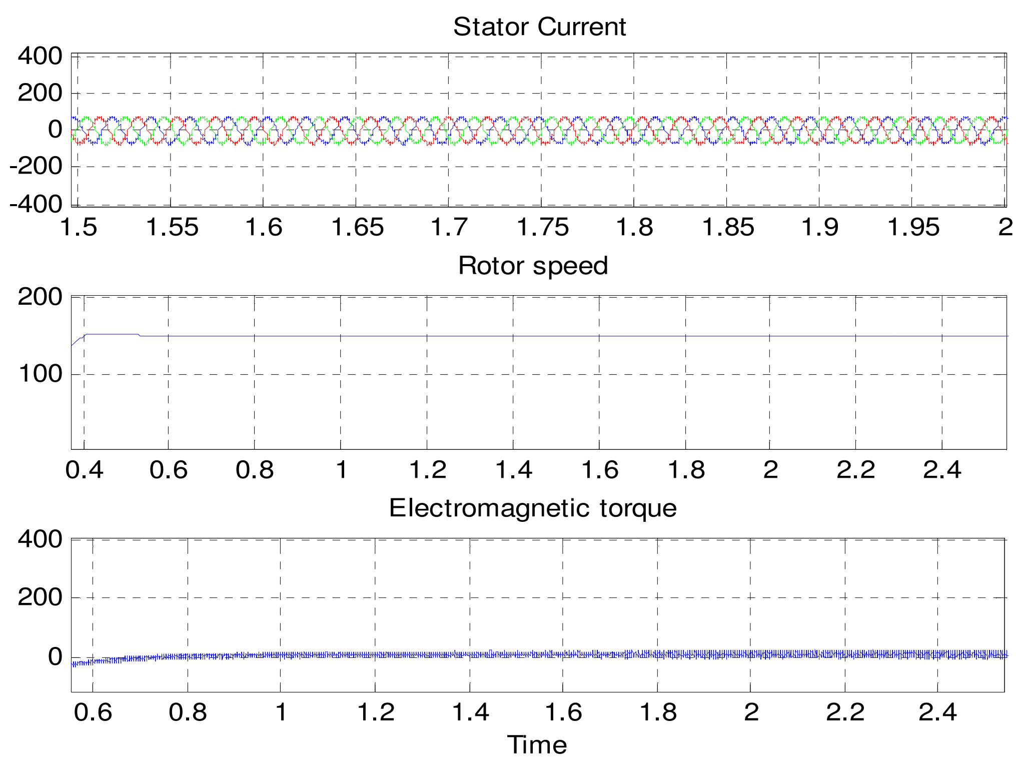


Fig 4.6 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for no load at 150rad/sec speed.

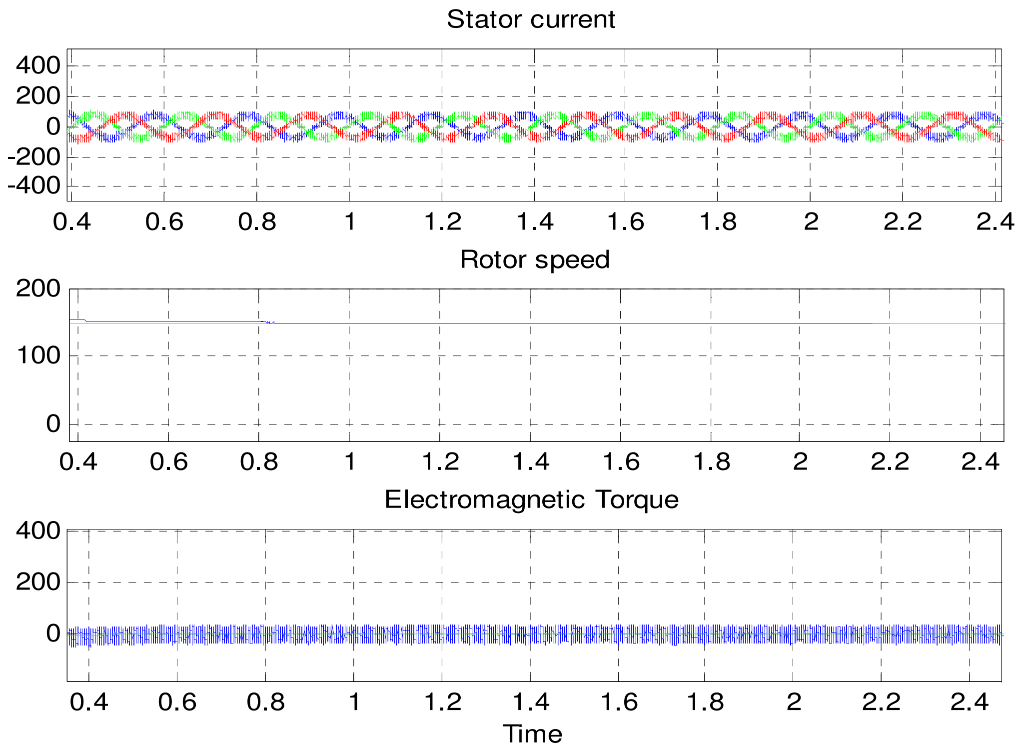


Fig 4.7 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for no load at 150rad/sec speed.

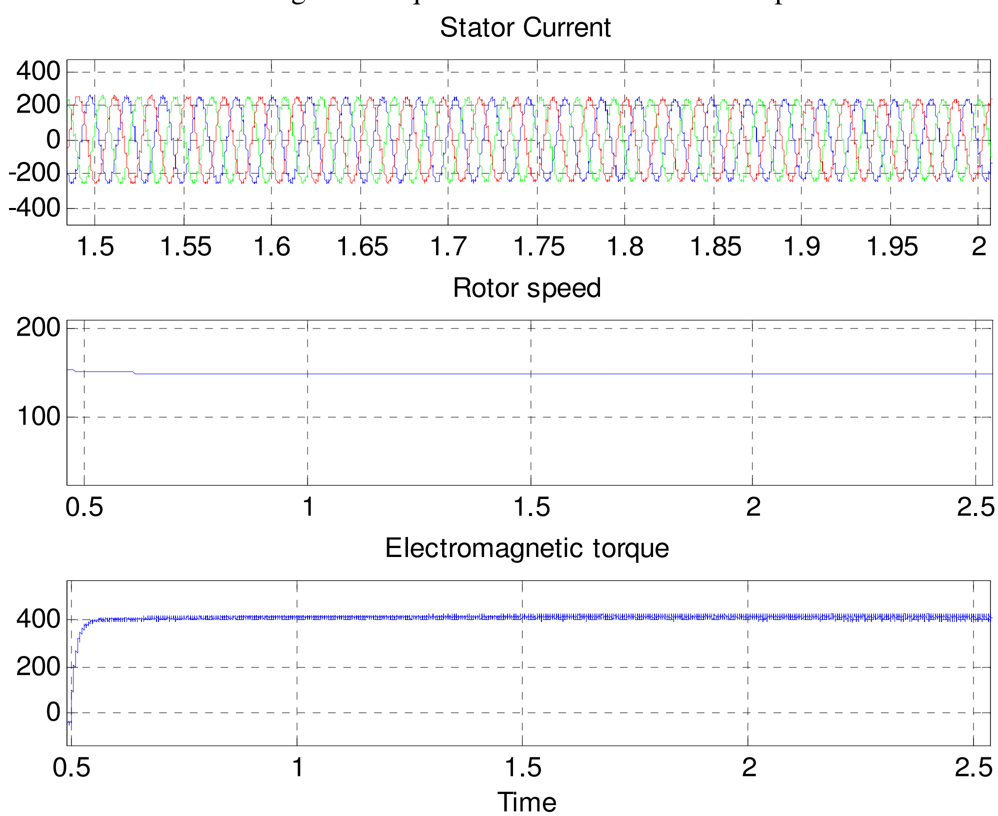


Fig 4.8 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for half load (400Nm) at 150rad/sec speed.

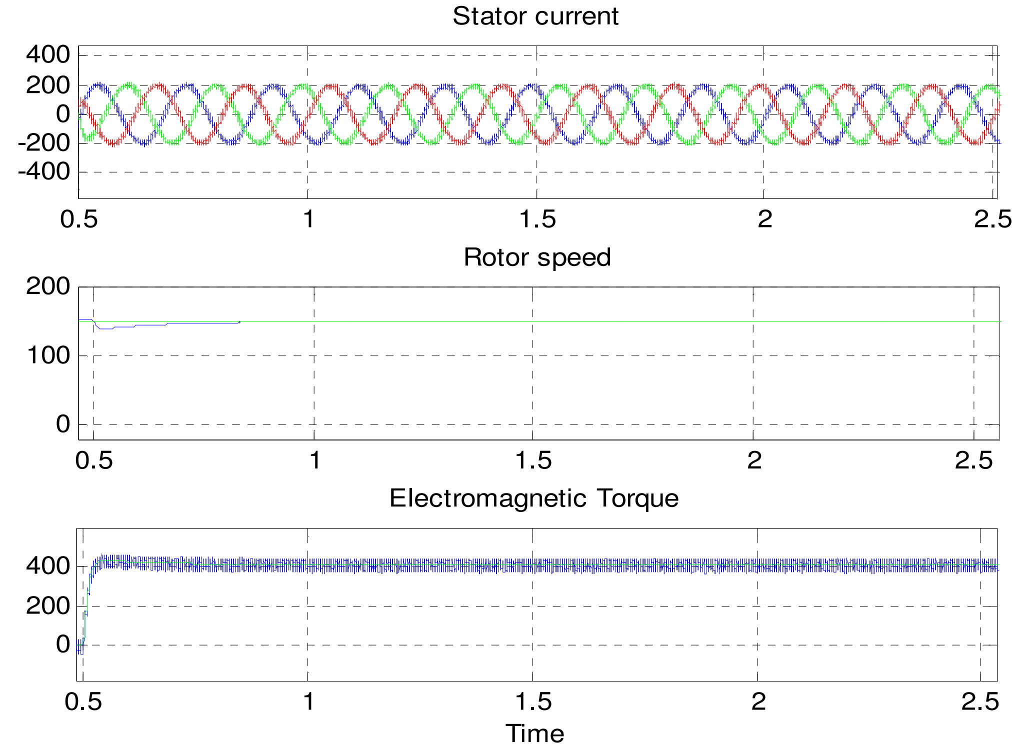


Fig 4.9 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for half load (400Nm) at 150rad/sec speed.

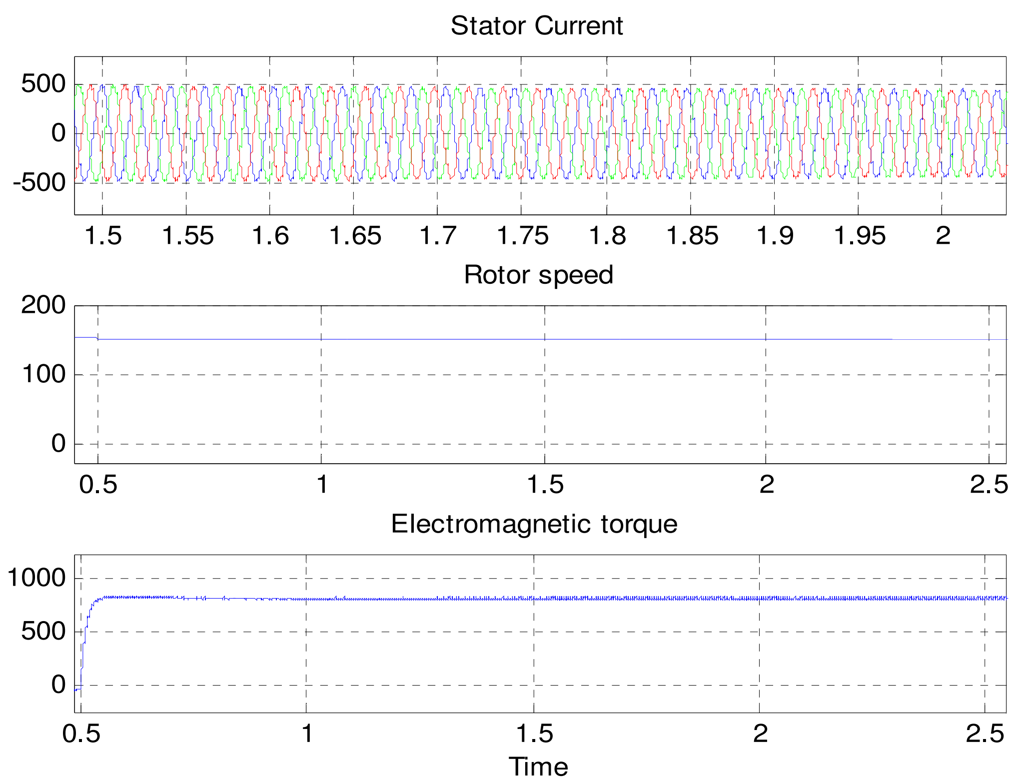


Fig 4.10 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 150rad/sec speed.

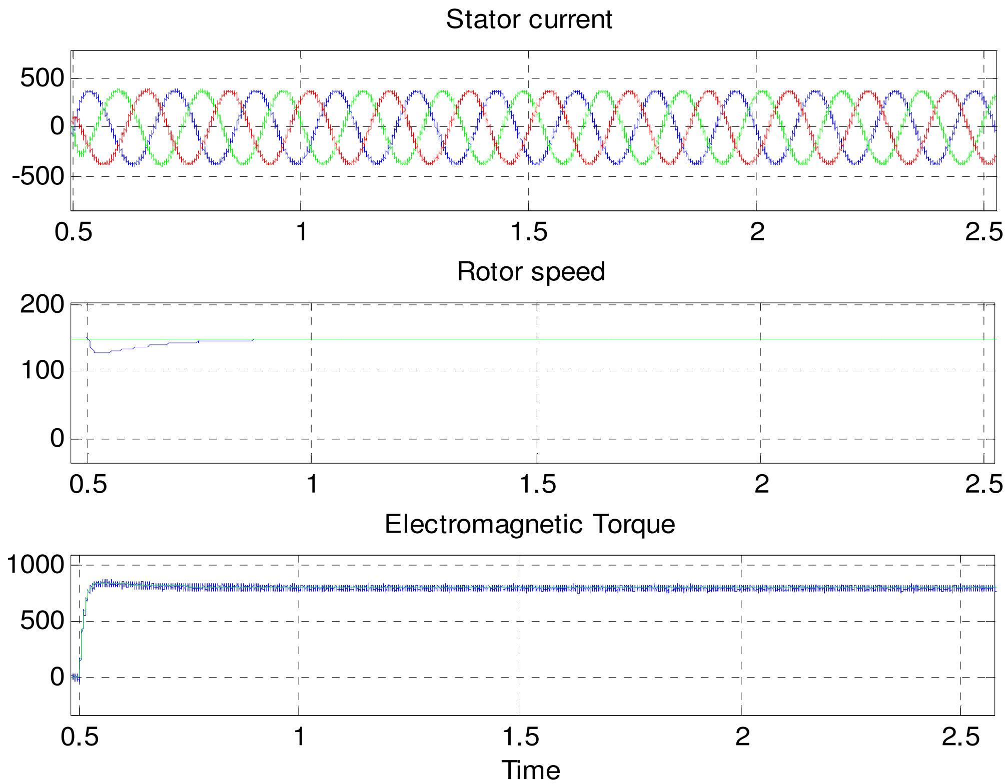


Fig 4.11 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 150rad/sec speed.

CHAPTER 5

H-BRIDGE SINGLE PHASE AC-DC CONVERTER

CHAPTER 5

H-BRIDGE SINGLE PHASE AC-DC CONVERTER

5.1 General

With the advancement in power electronics and quality of semi-conductor devices and fast digital processors has led to improvement converter design. Converters provide the rectification of ac voltage and also improve power quality on ac and dc side. These converters can be used for both uni-directionals as well as bi-directional power flow load applications. Bi- directional power flow characteristics find wide application in electric traction where drive requires a four quadrant operation. In electric traction application, the energy conservation aspect plays a major role, as the locomotive has to pass a number of up and down gradients on the way and the use of such converters results in regeneration of energy leading to saving in electric consumption. Configuration of bi-directional power flow based converter is presented in this chapter to feed traction motor drive.

5.2 Power Factor Control using PWM Converter

The rectifiers used in earlier times comprises of thyristors, natural commutation from the ac supply, and phase angle firing delay control. This resulted in ac currents that are both distorted and lag the voltage. The non-sinusoidal nature of the currents and the poor power factor cause numerous problems to the ac supply power system of the electricity generating and distribution companies.

Ideally there should be converters which take current at near unity power factor. Such a converter is now possible by using fast switching devices available easily in the market and a control strategy known as pulse width modulation (PWM). The insulated gate bipolar transistor (IGBT) is the switching device which can be possibly used as it can be turned off from the base or gate and it works in all four quadrants. The basic circuit configuration for the converter is shown in fig.5.1 where the essential components of the voltage-sourced PWM converter are shown. The converter has four arms and each arm consists of a diode with an inverse parallel connected switching device and the IGBT. An inductor of reactance X_s is included in series with the ac supply.

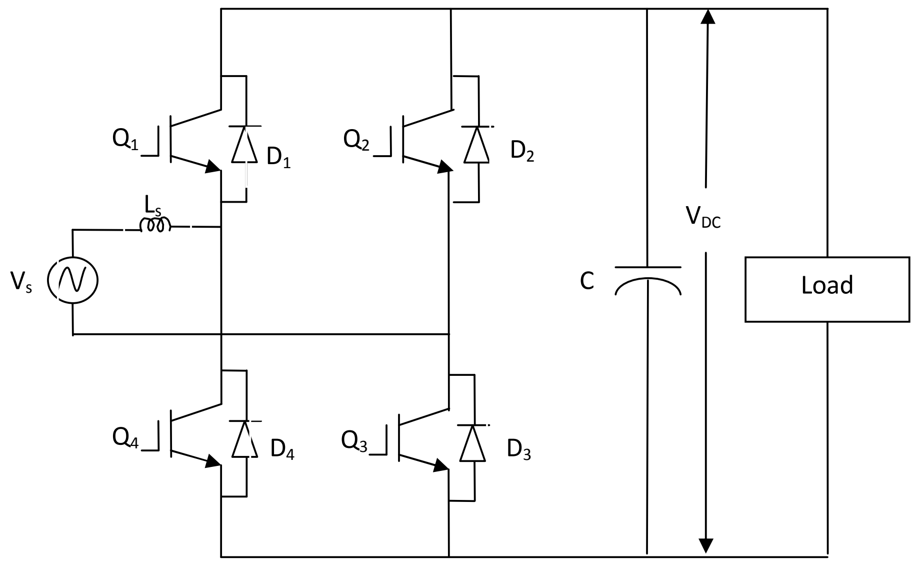


Fig 5.1 Single Phase Bridge Voltage Source Converter

The control scheme implemented here for the converter for traction motor drive provides constant dc link and also helps to improve ac supply side distortions. To achieve this functioning real time feedback of voltage and current is used. It controls the difference between current and the voltage on as supply side. The converter voltage amplitude is given by (5.1):

$$V_L = \sqrt{V_s^2 + (I_s X_s)^2} \tag{5.1}$$

where, V_S is the supply voltage and V_R, terminal voltage

In order to maintain the unity power factor, converter voltage has to be controlled to this value. A feedback control system is used to maintain unity power factor in this real time controller. This real time controller also helps to maintain a constant dc output voltage, in order that a steady dc link voltage is fed to the inverter.

5.2.1 Design Considerations for steady state operation

The single-phase converter described in Fig. 5.1 consisting of a four legged converter using IGBTs, with a reactor at the ac input side. The operation of converter is based on PWM technique which uses sine-triangle modulation. The fundamental component of V_R and the supply voltage V_S at the ac terminals of the converter are two voltages separated by a reactor. Therefore, the power flow depends on the phase angle displacement between the two voltage phasors. The Phasor diagrams on the ac side assuming unity power factor that is the current in phase with the supply voltage. The voltage drop across the reactance adds in quadrature to the supply voltage to give the input ac voltage to the bridge. The rectified ac input voltage is greater in magnitude than that of the supply voltage.

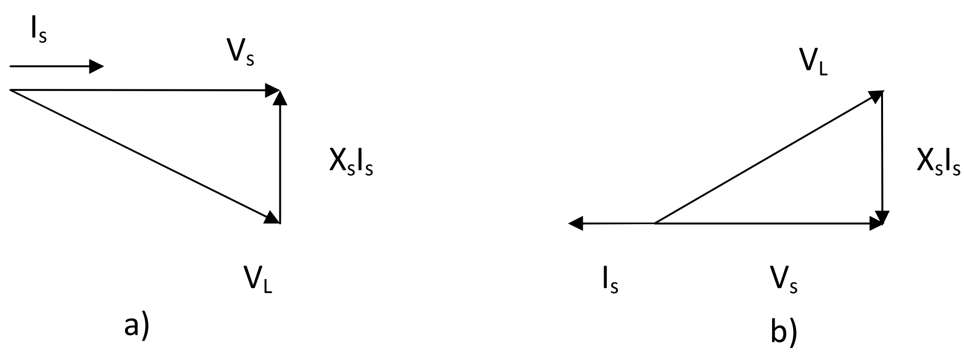


Fig 5.2 Phasor Diagram of Converter a.) Forward power flow, b.) Reverse power flow

The power flow in the inductor shown fig. 5.1 can be easily derived from the above phasors diagram of fig. 5.2(a) or 5.2(b) as

Power = VsIs, and substituting for I_S from (5.2)

$$V_L Sin\delta = X_S I_s \tag{5.2}$$

we get (5.3)

$$Power = \frac{VsV_L}{X_S} Sin\delta \tag{5.3}$$

where δ is known as the displacement or load angle.

If V_L lags V_S then the power flow is from the ac supply towards the converter, but if V_L leads V_S then the power is reversed. The phasor diagrams of fig. 5.2(a) or 5.3(b) show unity power factor, but conditions involving reactive power flow, that is lagging or leading power factor are possible by changing the magnitude of one voltage while retaining the same displacement angle δ.

5.3 Voltage Source Converter

Fig 5.3 shows the schematic diagram of a multilevel converter based electric drive used for electric traction applications. In electric traction, the traction motors in different bogies cannot be controlled from the same converter. Electric multiple unit has been considered as the typical application of the electric traction. Here, the traction transformer is having two secondary windings, feeding each individual converter. The transformer is rated for 1170 kVA, with primary winding designed for 25kV and the two secondary windings rated for 952V each. Each bogie of the motor coach is having two induction motors of 295-hp, 1040 V [4]. The details of the parameters considered for the modelling of the induction motor are given in Appendix A. One transformer winding is connected to one voltage source converter, which generates constant dc link and supply inverter fed three- phase induction motors. Two motors are connected to a single inverter. Similarly, the other secondary winding of the transformer is connected to the other voltage source converter, which feeds power to two traction motors. Fig 5.3 shows the schematic diagram of the converter and corresponding MATLAB model is developed. The complete circuit of the PFC fed drive can be divided into the following sections:

5.3.1 Voltage Controller

The real time feedback value of voltage is sensed (V_{ref}) and is then compared with a corresponding reference value (V_{ref}^*) [4]. An error voltage value (V_{err}) is generated which is given by (5.4):

$$V_{err} = V_{ref}^* - V_{ref} \tag{5.4}$$

The generated voltage error is then passed through PI controller, having K_p as the proportional gain and K_i as the integral gain of the voltage controller. The amplitude of the AC mains current is then taken as the PI controller output, after limiting it to an acceptable value. This is further passed through current control module.

5.3.2 Current Controller

A unit model is developed from the ac mains voltage and the PI voltage controller output and its amplitude is given as (5.5):

$$x(t) = \frac{V_i^*}{V_i} = \sin wt \qquad (5.5)$$

This unit model developed is then used to generate a reference current expressed as (5.6):

$$I_{ref}^* = I_i\,|u(t)| \qquad (5.6)$$

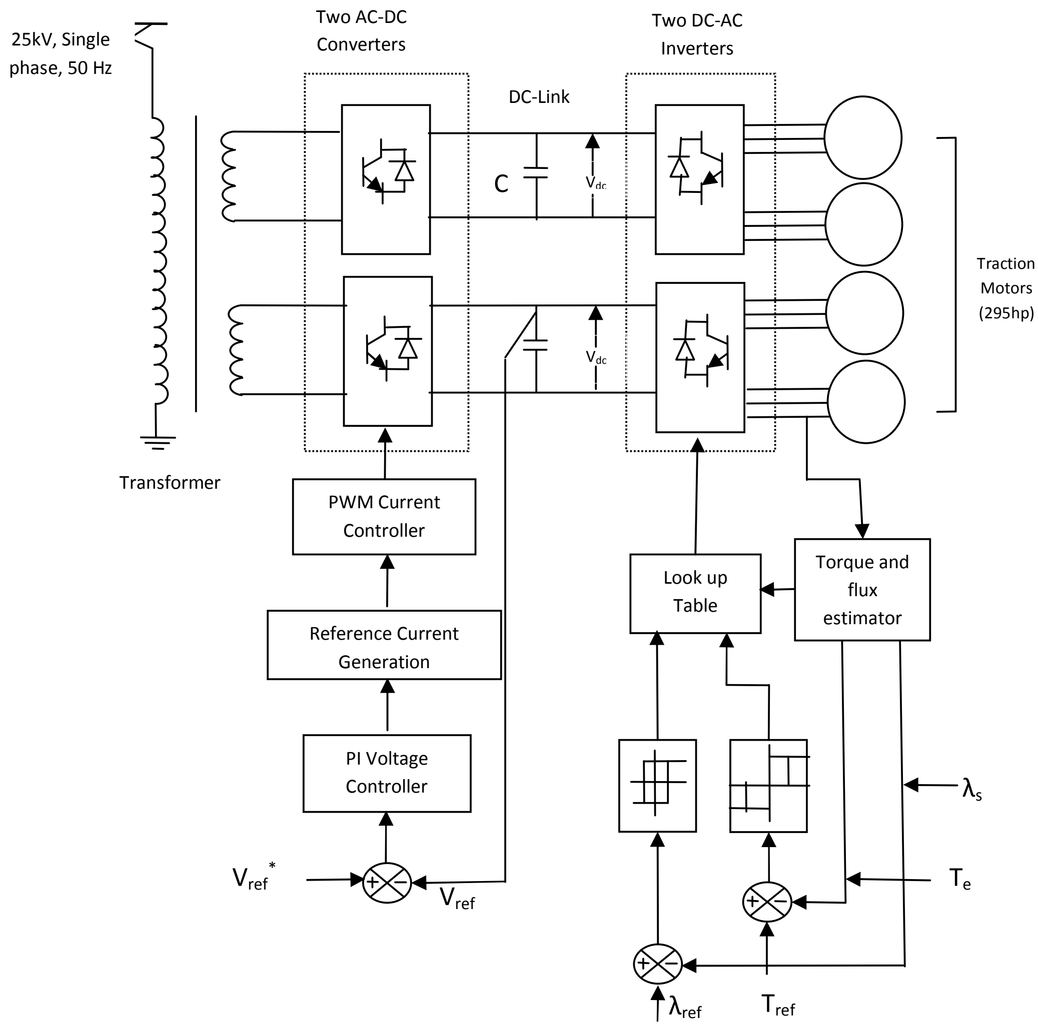


Fig 5.3 Schematic control diagram of the converter fed electric traction motor drive

Then another comparison is made between the reference current value generated (i_{ref}^*) and real time sensed value of the input ac mains current (I_i). This generates an error signal (i_e) which after amplification is inputted to PWM signal generator. This sinusoidal current error signal is compared with a triangular carrier wave in PWM signal generator generates the gating signals for the converter. The PWM signal generator turns on the IGBT of corresponding leg whenever the sinusoidal current error signal is more than the triangular carrier wave otherwise it is turned off.

5.3.3 H-Bridge VSC

The fig 5.4 shows the feedback controlling scheme of the converter is modelled for the applications of the electric traction drive. As electric traction application uses regeneration so IGBTs are used to design the H-bridge configuration of this converter.

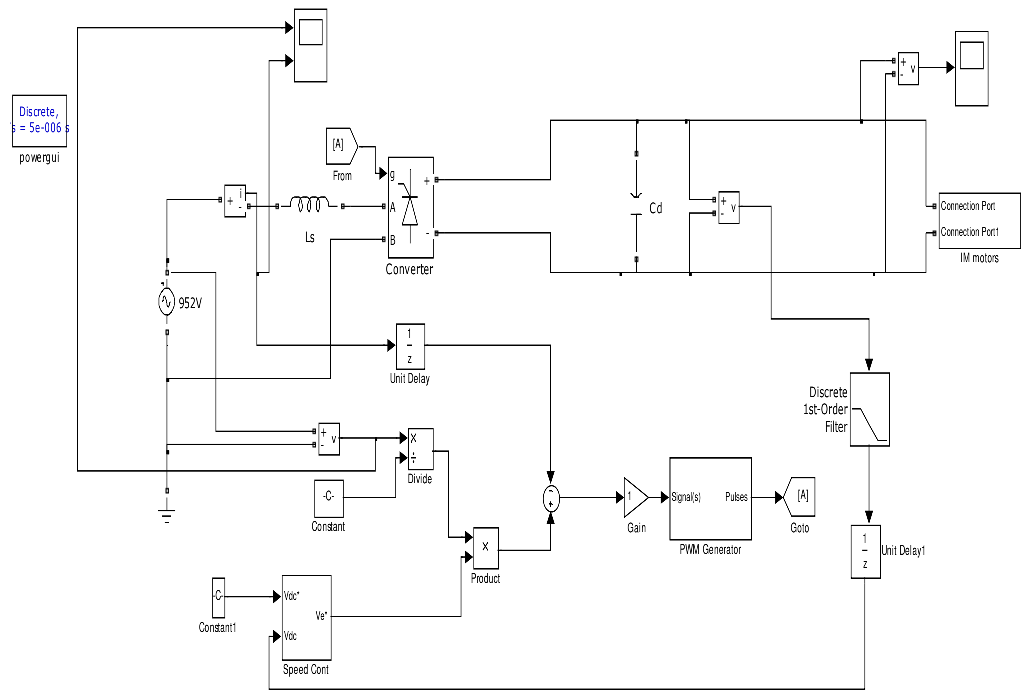


Fig 5.4 MATLAB model of Converter fed electric traction motor drive.

The converter uses H-bridge configuration, in which the load is connected between the two bridges giving it a H-shape. It is modelled using two first order differential equationsgiven as follows (5.7-5.8):

$$d/dt(I_i) = \{ V_s - V_{ref}(S_a - S_b) - R_s i_s \} / L \quad (5.7)$$

$$d/dt(V_{ref}) = \{ I_i (S_a - S_b) - I_{dc} \} / C \quad (5.8)$$

where, L is the inductance reactor in the starting of VSC, R_s is the resistance of the input inductor, C is the DC-link capacitor, I_{dc} is the inverter DC-link current and V_{ref} is the DC-link voltage.

Also, load current can be expressed as (5.9):

$$I_{dc} = V_{ref} / R \tag{5.9}$$

where, R is the equivalent load resistance at the DC bus. These equations are used to model the multi-motor induction drive system for eletric traction applications.

CHAPTER 6

SIMULATION AND RESULTS

CHAPTER 6

SIMULATION AND RESULTS

6.1 Simulations

The converter and the control techniques i.e. vector control and direct torque control for induction motor drive used in electric traction have been simulated in MATLAB Simulink R2007a on Intel Core 2 Duo Processor 2.4 GHz Window Vista Home basic (32-bit) Laptop.

Initially both the control techniques i.e. vector control and direct torque controls were implemented on 295hp motor with dc supply. The simulation results for both methods are shown in figure 6.1 to figure 6.6. The results for electromagnetic torque (Nm), rotor speed (rad/s) and stator currents (A) at no load, half the load and full load conditions for the reference speed at 215 rad/sec are shown. Details of the parameters of the simulated model are given in Appendix-A.

Fig 6.1 and 6.2 shows the steady state waveform of the three phase stator current, speed and electromagnetic torque for no load at rated speed. Then further fig6.3 to 6.6 shows the steady state waveform for both the schemes for half of the rated load and full load

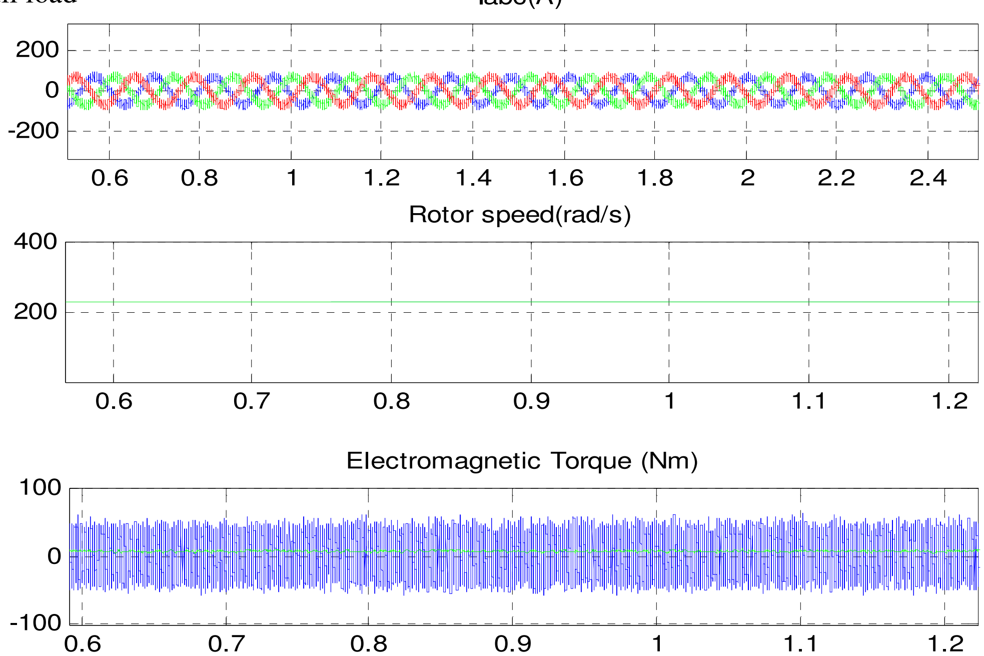


Fig 6.1 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for no load at 215rad/sec speed.

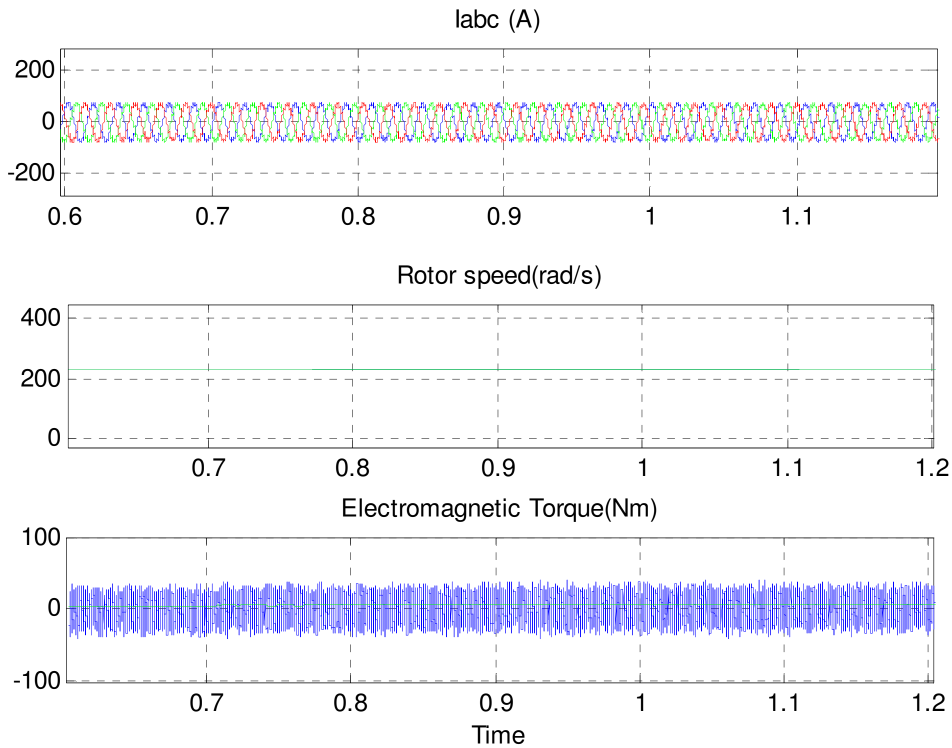


Fig 6.2 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for no load at 215rad/sec speed.

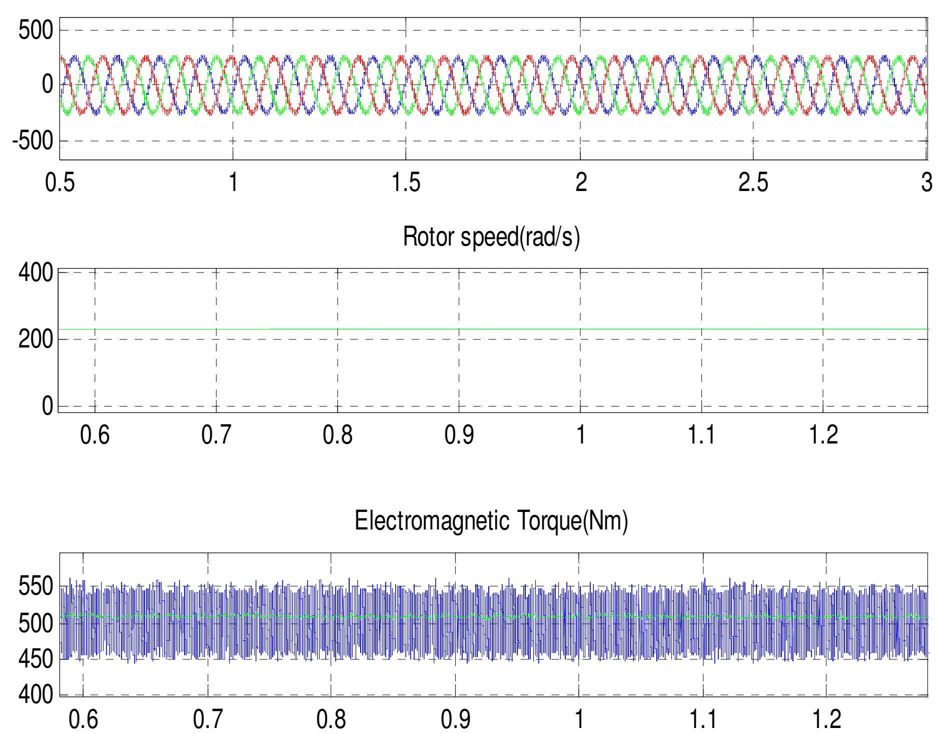


Fig 6.3 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for half load at 215rad/sec speed.

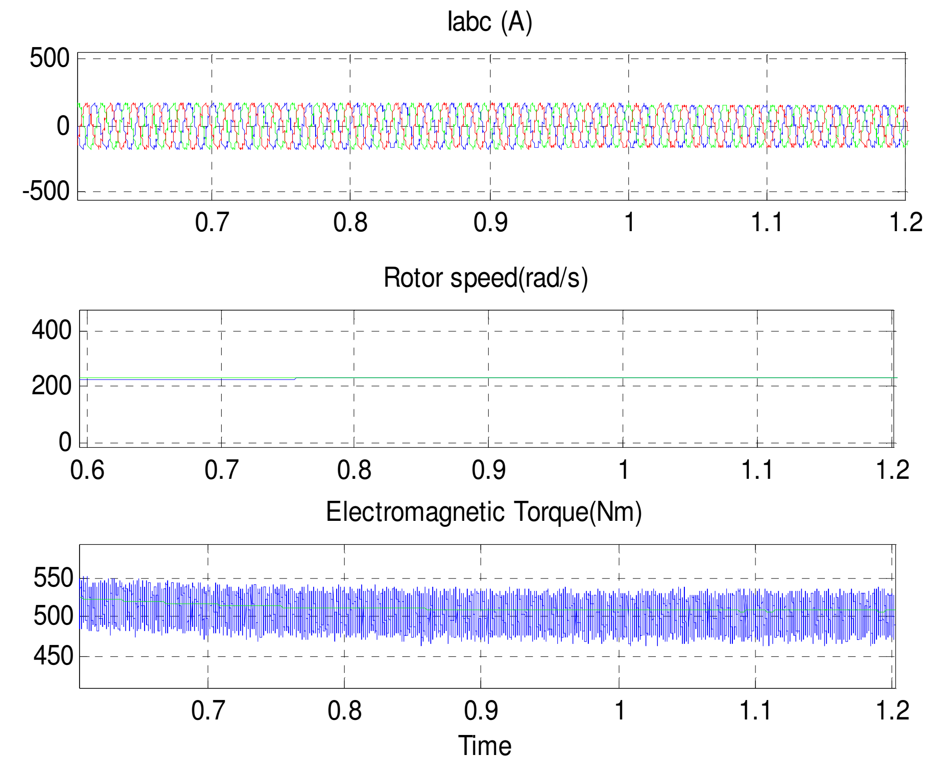


Fig 6.4 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for half load at 215rad/sec speed.

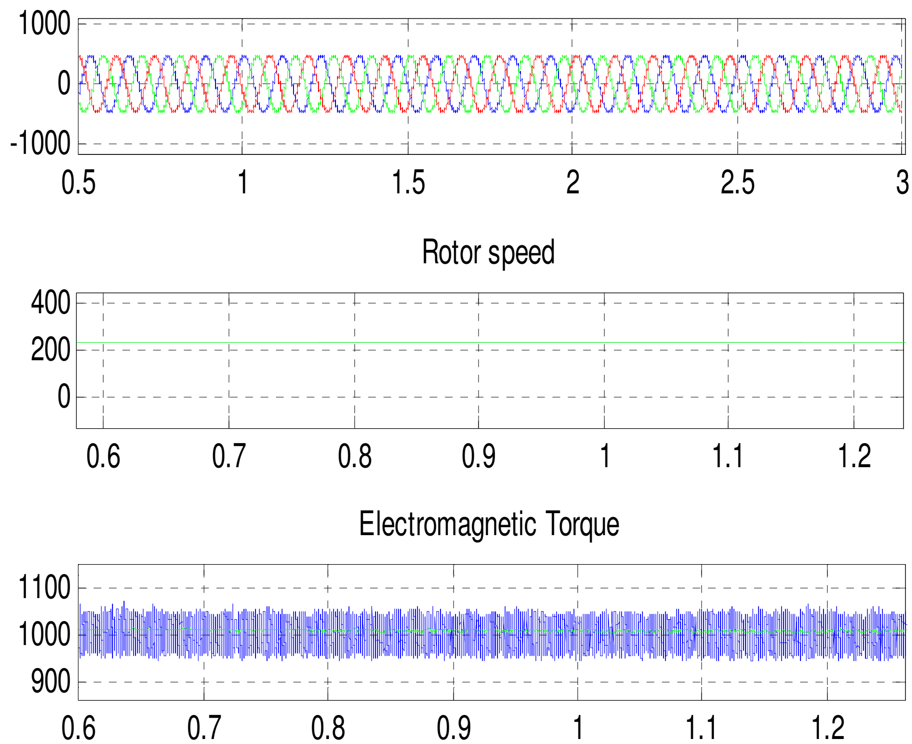


Fig 6.5 Simulink plot for FOC showing three phase stator current, speed and electromagnetic torque for full load at 215rad/sec speed.

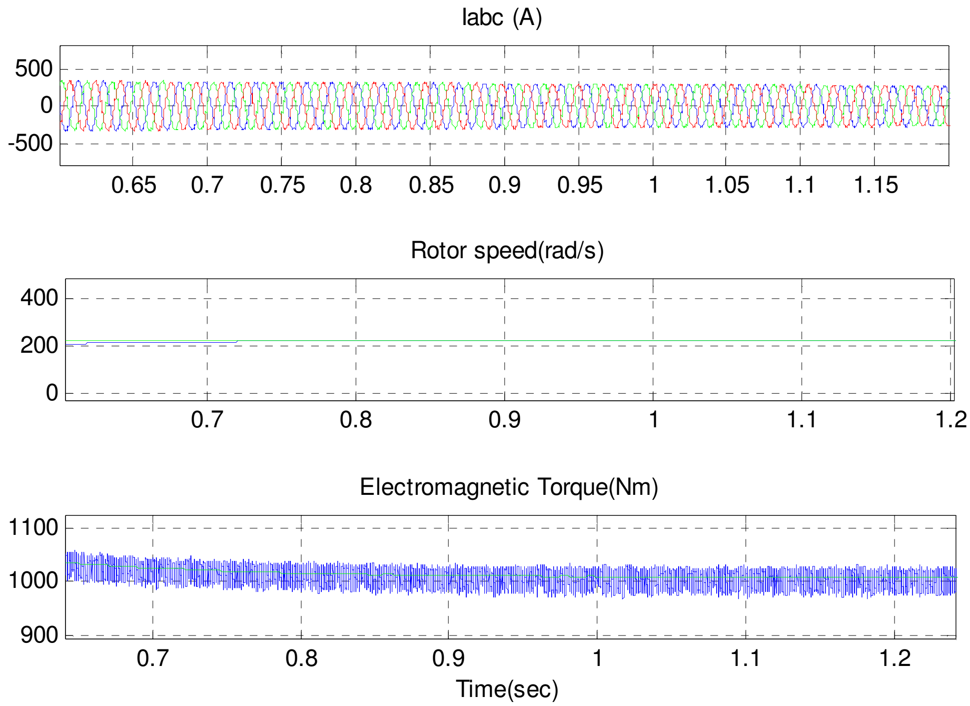


Fig 6.6 Simulink plot for DTC showing three phase stator current, speed and electromagnetic torque for full load at 215rad/sec speed.

Two schemes namely vector control and direct toque control were simulated and compared and the simulation results of electromagnetic torque, rotor speed and stator currents for both methods are shown in figure 6.1 to figure 6.6. The results for at full load, half load and no load condition for the reference speed at 215 rad/sec are shown. It has been found that in DTC scheme, time to attain steady state remain relatively constant at 0.55 seconds. Whereas in case of FOC time to attain steady state increases with the increase in percentage loading. It is observed that the torque oscillations in DTC control scheme are negligible whereas in FOC scheme oscillations in torque are observed. These oscillations are relatively less at no load and then become nearly constant with the increase in percentage loading. Also, it is found that the distortion of motor current is higher in case of FOC. Hence DTC scheme is implemented for traction motor scheme with 25kV supply.

Fig 6.7 shows the block diagram of the traction motor drive suitable for electric traction. Two induction motors are connected to a single inverter. The simulated performance of the converter inverter drive system is shown in figures 6.8 to 6.11. Fig 6.8 shows the steady state waveform of three phase stator current (A), source current

(A), source voltage (V), speed (rad/sec) and electromagnetic torque for full load (1000Nm) at 215rad/sec speed. Similarly fig 6.9 and fig 6.10 shows waveform at half load and no load conditions. Fig6.11 shows the waveform of three phase stator current, source current, source voltage, speed and electromagnetic torque for full load (1000Nm) at 50% of the rated speed and full load.

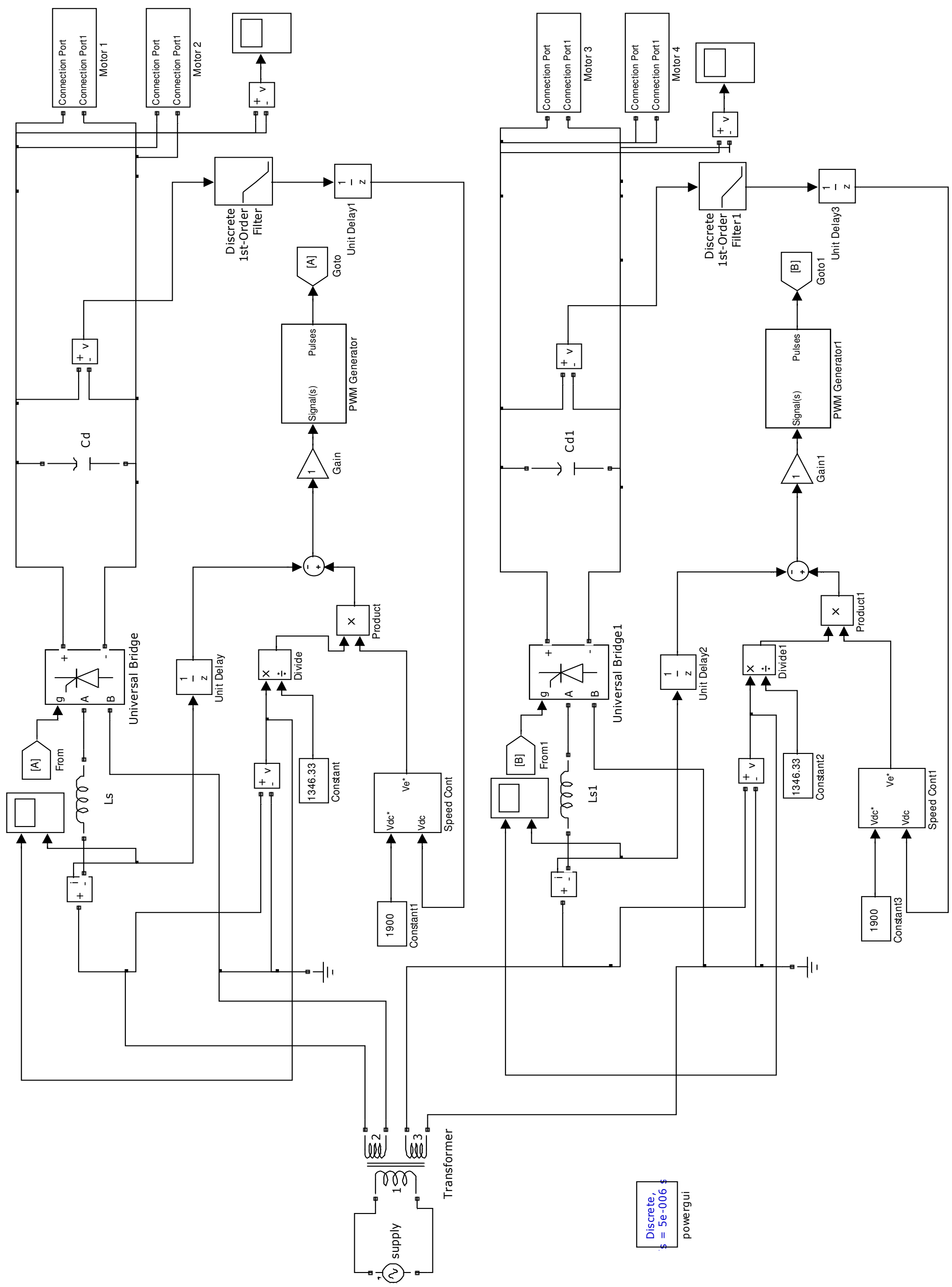


Fig 6.7 MATLAB model of single phase supply fed electric traction motor drive.

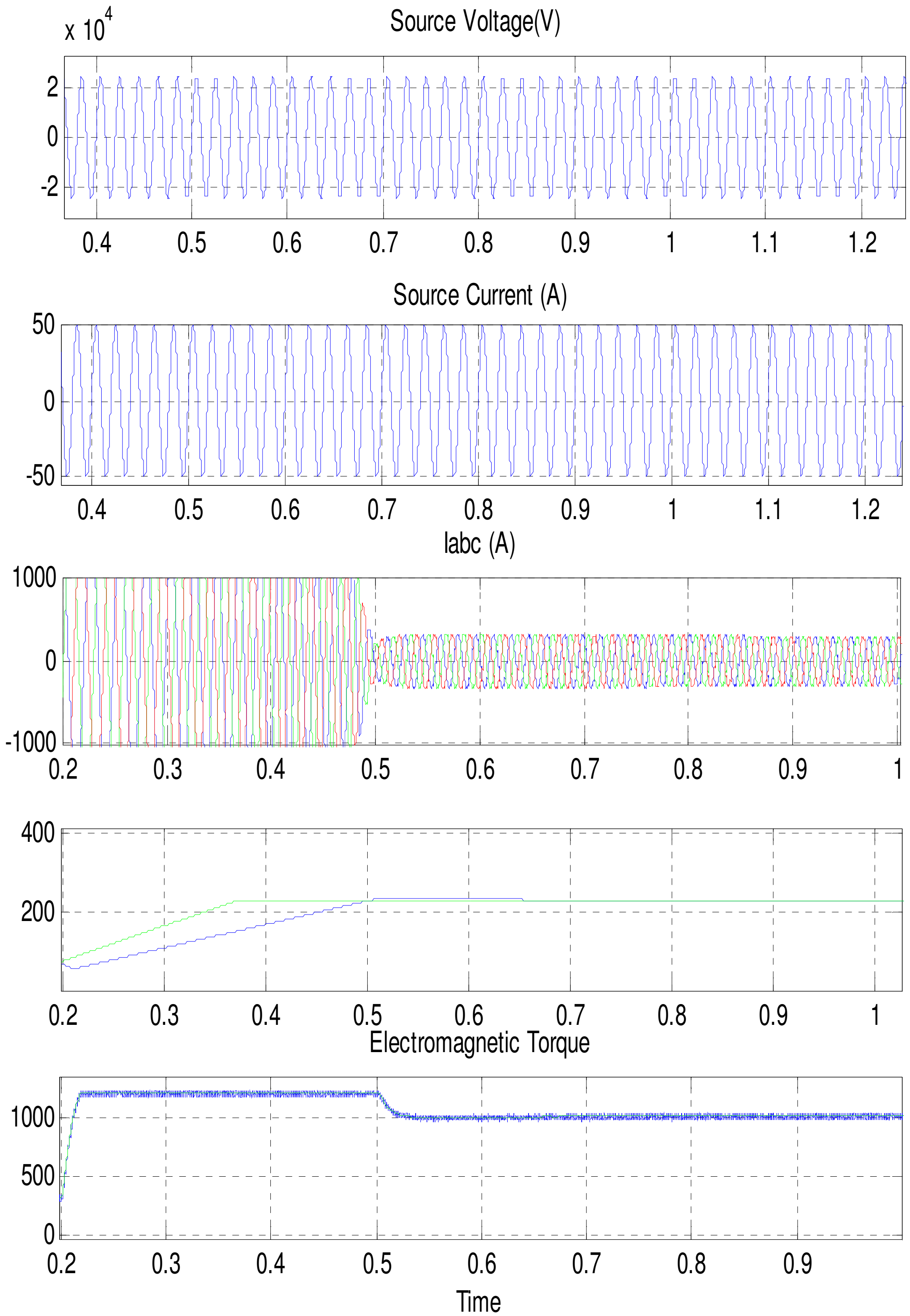


Fig 6.8 Simulink plot showing source voltage, source current, three phase stator current, speed and electromagnetic torque for full load (1000Nm) at 215rad/sec speed.

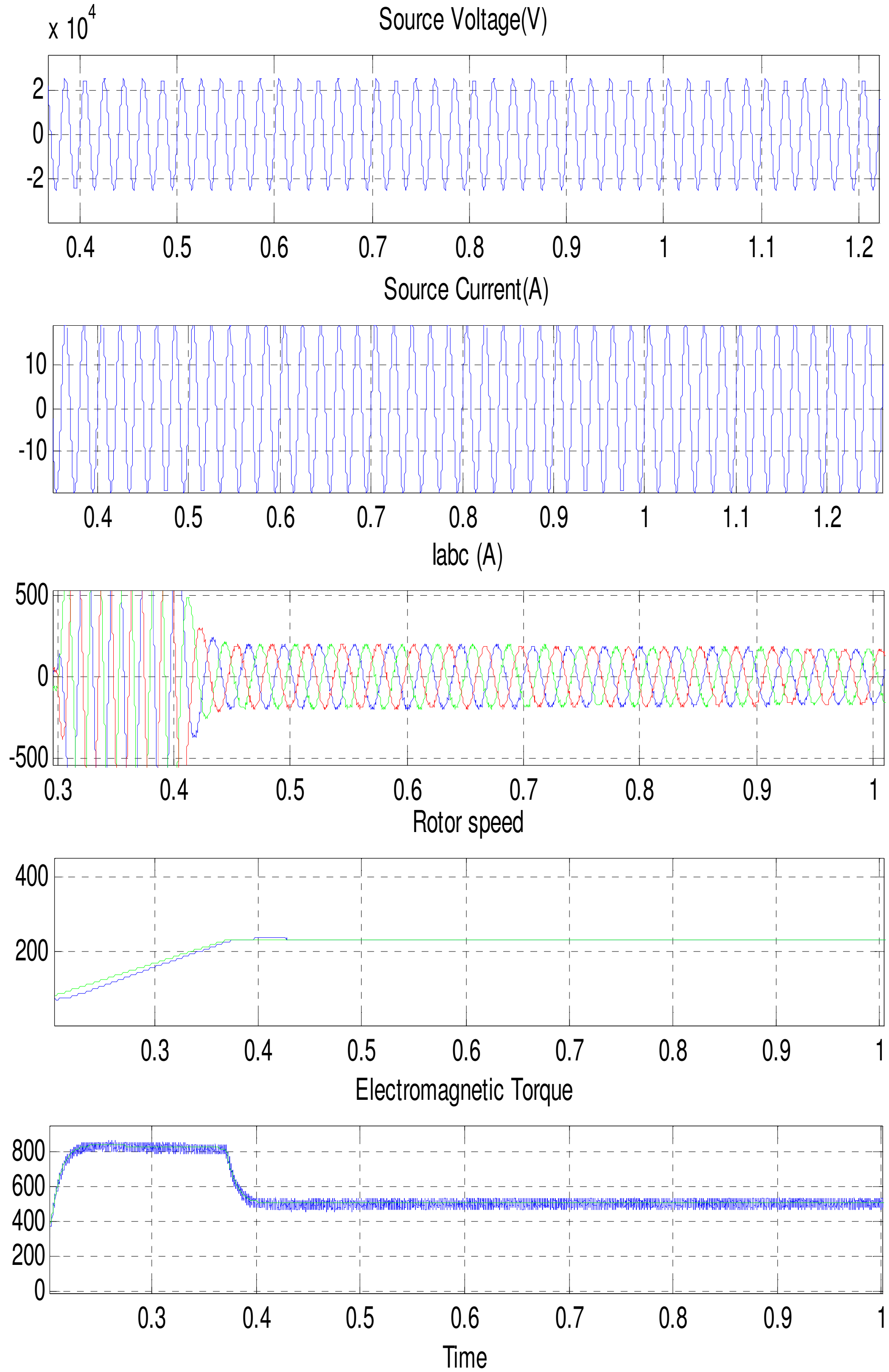


Fig 6.9 Simulink plot showing source voltage, source current, three phase stator current, speed and electromagnetic torque for half load (500Nm) at 215rad/sec speed.

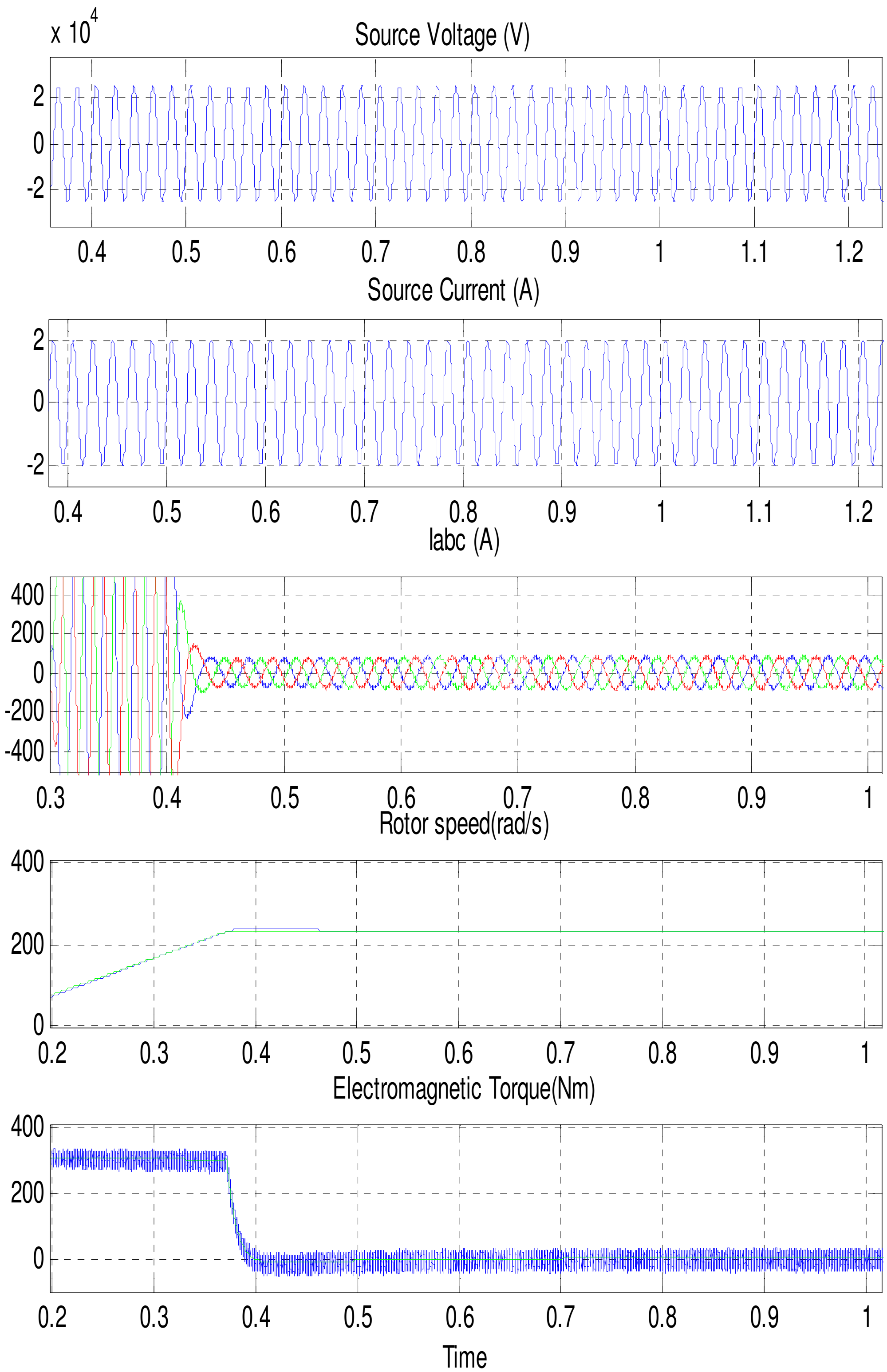


Fig 6.10 Simulink plot showing source voltage, source current, three phase stator current, speed and electromagnetic torque for no load (0Nm) at 215rad/sec speed.

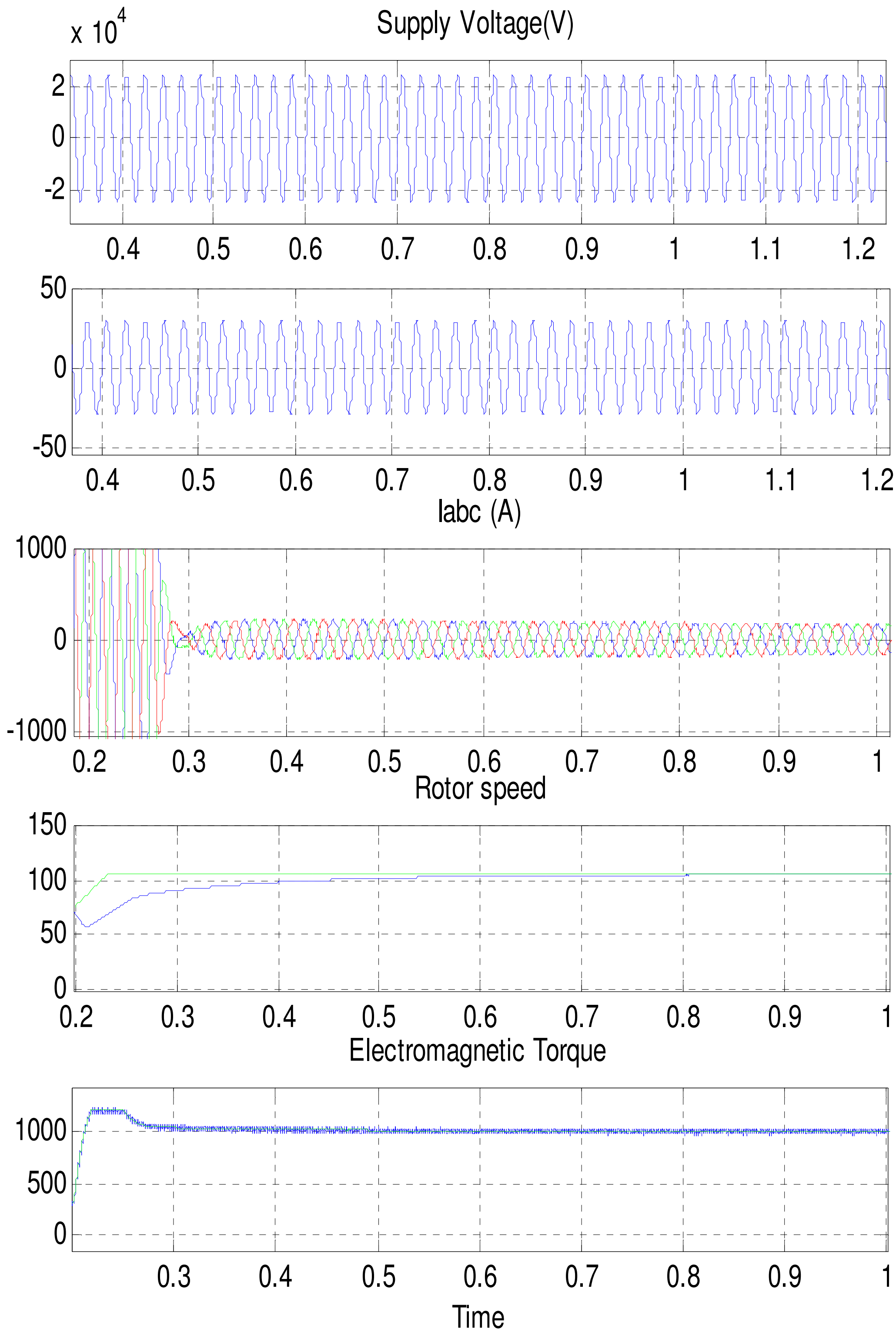


Fig 6.10 Simulink plot showing source voltage, source current, three phase stator current, speed and electromagnetic torque for at half the rated speed and full load.

6.2 Results

The results of complete H-bridge fed traction drive have been shown for different loading and speed conditions. In scheme, time to attain steady state remain relatively constant at 0.52 seconds.The AC mains current at full load condition has the THD of 6.74% and for half the load is, and it goes to 7.56% at half the load condition. Also in the entire operating range, power factor remained close unity. It has been observed from figure 6.8 to figure 6.9 that time to attain steady state in no load condition is less as compare to full load and half the load. Also load perturbations remain more or less same in all loading conditions. Table IV shows the time required to attain steady state and steady state torque oscillations for traction motor scheme with reference to results shown in figure 6.8 to figure 6.9 for different percentage loading at a given speed of 215 rad/sec.

Table IV. Analysis of traction motor drive scheme implemented

% Loading	**Time to attain steady state(s)**	**Steady state torque oscillations (%)**
No Load	0.4	±4.375
50% load	0.41	±4.375
Full Load	0.52	±4.375

Similarly, from figure 6.10 for half the rated speed and full load it can be shown that the torque oscillations at low speed are comparatively very high and then decreases with increase in speed for DTC control scheme.

CHAPTER 7

CONCLUSIONS AND FURTHER SCOPE OF WORK

CHAPTER 7

CONCLUSIONS AND FURTHER SCOPE OF WORK

7.1 Main Conclusions

In this work two schemes for control of drives, namely vector control and direct torque control, are compared and it has been found that time to attain steady state and the torque perturbations are less in DTC scheme. So, direct toque control scheme is implemented for speed control of traction motor drive.

Also the complete H-bridge converter fed AC traction motor drive has been designed and simulted. Results show that, the AC mains power factor remains close to unity during the operation which leads to efficient operation of the system. Also, even with the disturbance in the input voltage, dc link voltage is maintained at its reference value.

7.2 Further Scope of Work

The main objective for this work has been successfully achieved; the areas in which the presented work can be further extended are listed as follows:

- Hardware implementation can be done to validate the model and control schemes.
- Desired power quality improvement can be made using current source inverters and matrix converters for such a large rating traction motor drive.
- PI controller was used as speed controller for drive. A number of control techniques such as fuzzy, neuro fuzzy are available today that can be implemented for speed control of induction motor drive to further increase their performance and improve response time.
- Multilevel converter could be studied and it can be implemented for traction motor drive.
- Harmonics in the supply current can be reduced further by using the active power filter.

REFERENCES

REFERENCES

[1] L. Wolfgang, Railroad history, San Diego Railroad Museum, March 2002.
[2] W.S. Chan, "Whole system simulator for AC traction", PhD Thesis, University of Birmingham, UK, July 1988.
[3] P. Vas, Vector control of AC machines, New York: Clarendon, 1990
[4] B.K. Bose, Power electronics and AC Drive. Englewood Cliffs,NJ. Prentic hall, 1986
[5] Ramesh Oruganti, Kannan Nagaswamy and Lock Kai Sang, "A constant frequency variable power factor PWM scheme for single phase boost type AC-DC converter," Proc. Int. Conf. EMPD'95, 1995, Vol.1 pp, 215- 221.
[6] Singh,B. Bhuvaneswari,G. Garg,V. "Improved power quality AC-DC converter for electric multiple units in electric traction" *Power India Conference, 2006 IEEE*.
[7] K.Thiyagarajah, V.T.Ranganathan and B.S. Ramakrishna, "A high switching frequency IGBT PWM rectifier/ inverter system for AC motor drives operating from single phase supply," IEEE Trans. on Power Electronics, Vol.6, No.4, October1991, pp. 576-584.
[8] R.J. Hill, "Electric railway traction – Part 2 traction drives with three-phase induction
motors", Power Engineering Journal, pp. 143-152, June 1994.
[9] IEEE Guide for Harmonics Control and Reactive Compensation of Static Power Converters, IEEE Standard 519, 1992.
[10] Z. Shao, "Auto-transformer power supply system for electric railways", PhD Thesis, University of Birmingham, UK, November 1988.
[11] Adrian David Cheok, Shoichi Kawamoto, Takeo Matsumoto, and Hideo Obi , "High Power AC/DC Converter and DC/AC Inverter for High Speed Train Applications," 0-7803-6355-8/00/$10.00@ 2000 IEEE
[12] P. Enjeti and A. Rahman, "A new single phase to three phase converter with active input current shaping for low cost AC motor drives," IEEE Trans. Ind. Appl., vol. 29, no. 2, pp. 806–813, Jul./Aug. 1993.
[13] J. Itoh and K. Fujita, "Novel unity power factor circuits using zero-vector control for single-phase input systems," IEEE Trans. Power Electron., vol. 15, no. 1, pp. 36–43, Jan. 2000.
[14] B. K. Lee, B. Fahimi, and M. Ehsani, "Overview of reduced parts converter topologies for AC motor drives," in Proc. IEEE PESC, 2001, pp. 2019–2024.
[15] C. B. Jacobina, M. B. de R. Correa, A. M. N. Lima, and E. R. C. da Silva, "AC motor drive systems with a reduced switch count converter," IEEE Trans. Ind. Appl., vol. 39, no. 5, pp. 1333–1342, Sep./Oct. 2003.
[16] R. Q. Machado, S. Buso, and J. A. Pomilio, "A line-interactive single- phase to three-phase converter system," IEEE Trans. Power Electron., vol. 21, no. 6, pp. 1628–1636, May 2006.
[17] O. Ojo, W. Zhiqiao, G. Dong, and S. Asuri, "High-performance speed-sensorless control of an induction motor drive using a minimalist single- phase PWM converter," IEEE Trans. Ind. Appl., vol. 41, no. 4, pp. 996– 1004, Jul./Aug. 2005.
[18] J. R. Rodrıguez, J. W. Dixon, J. R. Espinoza, J. Pontt, and P. Lezana, "PWM regenerative rectifiers: State of the art," IEEE Trans. Ind. Electron., vol. 52, no. 1, pp. 5–22, Feb. 2005.

[19] D.C. Lee and Y.S. Kim, "Control of single-phase-to-three-phase AC/DC/AC PWM converters for induction motor drives," IEEE Trans. Ind. Electron., vol. 54, no. 2, pp. 797–804, Apr. 2007.
[20] Brian Heber, Longya Xu, and Yifan Tang, "Fuzzy Logic Enhanced Speed Control of an Indirect Field-Oriented Induction Machine Drive". IEEE Transactions on Power Electronics, Vol. 12, No. 5, pp. 772-778, September 1997.
[21] Hassan Baghgar Bostan Abad, Ali Yazdian Varjani, Taheri Asghar, "Using Fuzzy Controller in Induction Motor Speed Control with Constant Flux", Proceedings of World Academy of Science, Engineering And Technology, Vol. 5, pp. 307-310, 2005.
[22] J.W Finch, DJ Atkinson and PP Acarnleg University of Newcastle up on Tyne, UK, "General Principles of Modern Induction motor control"
[23] F. Biaschke, " The principle of field oriention as applied to new transvector closed loop control system for rotating field machine," Siemens Rev, vol. 34,,pp 217-220'may 1972
[24] N. Mariun, S. B Mohd Noor, J. Jasni, and O. S. Bennanes, "A Fuzzy Logic Based Controller For An Indirect Vector Controlled Three-Phase Induction Motor" IEEE IECON Conf. Rec., Vol. 4, pp. 1-4, Nov. 2004.
[25] Bhim Singh, B. N. Singh, and B. P. Singh, "Performance Analysis of a Low Cost Vector Controlled Induction Motor Drive: A Philosophy for Sensor Reduction", IEEE IAS Annu. Meet. Conf. Rec., pp. 789-794, 1997.
[26] T.Noguchi and Takahashi, "Quick torque reponse of an induction motor based on a new concept ," *IEEE Tech. Meeting Rotating Mach.*, Vol.RM 84-72, Sept. 1984, pp. 61-70
[27] James N. Nash, "Direct torque control, induction motor vector control without an encoder," *IEEE Trans. On Industry Applications*, vol.33, no.2, pp. 333-341, March/April 1997
[28] D. Casadei, G. Grandi, G.Serra, " Effects of flux and torque hysteresis band amplitude in the direct torque control of induction motors," in *Porc. IEEE IECON'94*, vol.1, pp.299-304
[29] Ramin Zaeim and Asyieh Khoshkholgh," Gain-Scheduling Adaptive Control of the STATCOM for Electrified Railway systems using PSO", 2010 International Congress on Ultra Modern Telecommunications and Control Systems and Workshops, Publication Year: 2010
[30] P. C. Tan, R. E. Morrison, and D. G. Holmes, "Voltage Form Factor Control and Reactive Power Compensation in a 25-kV Electrified Railway System Using a Shunt Active Filter Based on Voltage Detection," IEEE trans. on industrial applications, vol. 39, no.2, pp. 575-581, 2003.
[31] Adrian David Cheok, Shoichi Kawamoto, Takeo Matsumoto, and Hideo Obi , "High Power AC/DC Converter and DC/AC Inverter for High Speed Train Applications," 0-7803-6355-8/00/$10.00@ 2000 IEEE
[32] Ashutosh Mishra, Prashant Choudhary,"Speed Control Of An Induction Motor By Using Indirect Vector Control Method ", International Journal of Emerging Technology and Advanced Engineering Volume 2, Issue 12, Dec 2012.
[33] B. K. Lee, B. Fahimi, and M. Ehsani, "Overview of reduced parts converter topologies for AC motor drives," in *Proc. IEEE PESC*, 2001, pp. 2019–2024.
[34] Divya Asija, "Speed Control of Induction Motor using Fuzzy-PI Controller ", IEEE 2010,2nd International Conference on Mechanical and Electronics Engineering(ICMEE2010),vol.2,pp.460-463.

[35] Modeling & Simulation using Matlab® -Simulink® by Dr. Shailendra Jain,First Edition :2011.

[36] Bimal K. Bose, Nitin R. Patel, And Kaushik Rajashekara, "A Start-Up Method For A Speed Sensorless Stator-Flux- Oriented Vector-Controlled Induction Motor Drive", IEEE Transactions on Industrial Electronics, vol. 44, no. 4, august 1997

[37] Gopal K Dubey, "Fundamentals of Electrical Drives", second edition, narosa publishing house: 2001.

[38] M. S. Zaky, "Stability analysis of speed and stator resistance estimators for sensorless induction motor drives," IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 858–870, Feb. 2012.

[39] Z. Gao, Y. Huang, and J. Han, "An alternative paradigm for control systemdesign," in Proc. 40th IEEE Conf. Decision Control, Orlando, FL, 2001, vol. 5, pp. 4578–4585.

APPENDIX I

- The 295-hp induction machine used in the MATLAB /simulation is 3phase, 4 pole, 72.5Hz induction machine having the following parameters.

Power output	295HP(220kW)
Rated Voltage	1040V
R_s (stator resistance)	0.0749Ω
R_r (rotor resistance)	0.0801Ω
L_s (stator inductance)	0.000971H
L_r (rotor inductance)	0.000891H
L_m (magnetizing inductance)	0.03041H
J (moment of inertia)	10 Kg m^2

- The 200-hp induction machine used in the MATLAB /simulation is 3phase, 4 pole, 50Hz induction machine having the following parameters.

Power output	200HP
Rated Voltage	480V
R_s (stator resistance)	0.01485Ω
R_r (rotor resistance)	0.009295Ω
L_s (stator inductance)	0.0003027H
L_r (rotor inductance)	0.0003027H
L_m (magnetizing inductance)	0.01046H
J (moment of inertia)	3.1Kg m^2

LIST OF PUBLICATIONS

- Garg Rachana, Mahajan Priya, Gupta Nikita and Saroa Harsha *Comparative Study between Field Oriented Control and Direct Torque Control of AC Traction Motor* IEEE International Conference on recent advances and innovation in engineering(icraie-2014) May 09-11, 2014, Jaipur India
- Dogra Rahul and Gupta Nikita *Glowworm swarm optimization technique for optimal power flow.* Advances in Electronic and Electrical Engineering, ISSN 2231-1297, Volume 4, Number 2, pp.155-160
- Dogra Rahul, Gupta Nikita and Saroa Harsha *Economic Load Dispatch Problem and MATLAB Programming Of Different Methods.* International Conference of Advance Research and Innovation.
- Saroa Harsha and Gupta Nikita *Hardware Implementation of Prototype Model Of Two Port Network* International Conference of Advance Research and Innovation
- Garg Rachana, Gupta Nikita and Saroa Harsha *Symmetrical and Non-Symmetrical Fault Simulation by DIgSILENT Power Factory Software* National conference on IPRoMM-2014
- Garg Rachana, Saroa Harsha and Gupta Nikita *Design and Development of Prototype Distribution System* National conference on IPRoMM-2014.