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Adama Science and Technology University

Control Scheme Modeling and Analyzing of Three-phase Inverter for Induction Motor Drive Using SVPWM Technique for Three Wheel Electric Vehicles (Bajaj) Applications

By:

Assefa Sefu Gebreegzabher

A Thesis Paper Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

In Partial Fulfillment of the Requirement of the degree of

Master of Science in Electrical Power and Control Engineering

(Specialization in Power Electronics)

Office of Graduate Studies

Adama Science and Technology University

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September, 2019

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Assefa Sefu Gebreegzabher (Candidate)

Advisor: Tefera T. Yetayew (PhD)

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Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by Assefa Sefu Gebreegzabher have read and evaluated his/her thesis entitled **“Control Scheme Modeling and Analyzing of Three-phase Inverter for Induction Motor Drive Using SVPWM Technique for Three Wheel Electric Vehicles (Bajaj) Application”** and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science Electrical Power and Control (Power Electronics).

______________________	________________	______________
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DECLARATION

I hereby declare that this MSc. Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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ADVISOR'S APPROVAL SHEET

To: Electrical Power and Control Engineering department

Subject: Thesis Submission

This is to certify that the thesis entitled **"Control Scheme Modeling and Analyzing of Three-phase Inverter for Induction Motor Drive Using SVPWM Technique for Three Wheel Electric Vehicles (Bajaj) Application"** submitted in partial fulfillment of the requirements for the degree of Masters of Master of Science Electrical Power and Control (Power Electronics), the Graduate program of the department of Electrical Power and Control and has been carried out by Assefa sefu Gebreegzabher Id. No A/PGR15428/11, under our supervision. Therefore, we recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

______________________________ _______________ ______________

Advisor Signature Date

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ABSTRACT

This thesis presents modeling and analyzing of three phase voltage switching inverter control technique by using Space Vector Pulse Width Modulation (SVPWM) for induction motor drive to control speed, direction and torque for three-wheel electric vehicles. Due to the increase in the cost of fuels and pollution there has been a need for an alternative (electric vehicles) to conventional Internal Combustion engine powered vehicle because electric vehicles are environment friendly, they are considered as Green Transportation. In adjustable speed drive system speed control techniques are generally essential. To achieve this it requires variable voltage supply and frequency which is invariably obtained from a three-phase Voltage source inverter. Even though there are numbers of pulse width modulations techniques is used to obtain variable frequency and voltage supply from an inverter but it is less used than the space vector pulse width modulation, because the SVPWM has several merits such as better dc bus utilization, easier digital realization over the other pulse width modulation methods. The space vector pulse modulation method with voltage and frequency control of induction motor drive is widely used in medium performance drive system. It is due to its characteristics like good power factor, extremely rugged and high efficiency. This scheme leads to be able to adjust the speed of the motor by control the frequency and amplitude of the stator voltage, the ratio of stator voltage to frequency should be kept constant. In this thesis the voltage source inverter type space vector pulse width modulation model modeling and analyzing has been done through MATLAB / SIMULINK, Proteus, Easy PC and Arduino software for control scheme of inverter for induction motor. In addition to these parameters like stator current, rotor current, torque and speed are obtained and analyzed graphically. SVPWM gives 15% enhanced fundamental output with better quality and lesser THD compared to SPWM.

***Keywords**: SVPWM, Induction motor, Pulse Width Modulation, Three-wheel electric vehicles, Inverter, MATLAB/SIMULINK, Proteus, Arduino.*

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LIST OF ACRONYM

AC	Alternating Current
BLDCM	Brushless Direct Current Motor
DC	Direct Current
FOC	Sinusoidal Plus Width Modulation
FPGA	Field Programmable Gate Array
HP	Horse Power
IM	Induction Motor
IPMSM	Interior Permanent Magnet Synchronous Motor
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
PF	Power Factor
SPWM	Sinusoidal Plus Width Modulation
SVPWM	Space Vector Plus Width Modulation
THIPWM	Third Harmonic Injection Pulse Width Modulation
THD	Total Harmonic Distortion
UPS	Uninterruptable Power Supplies
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

LIST OF SYMBOLS

V	Vehicle speed
α	Grade angle
P_v	Vehicle driving power
F_R	Rolling resistance force
F_{AR}	Aerodynamic drag force
F_G	Gradient resistance force
F_T	Total tractive force
M	Tire rolling resistance coefficient
M	Vehicle mass
G	Gravitational acceleration constant
C_{rr}	Rolling coefficient
A_f	Vehicle frontal area
V_o	Head wind velocity
G	Gradeability
R_s	Resistance of stator
X_l	Stator leakage reactance
X_m	Magnetizing reactance
R_c	Shunt branch resistance
V_1	Stator voltage
$X_2{}'$	Standstill rotor reactance referred to stator
$R_2{}'$	Rotor resistance referred to stator
S	Slip
E_1	Stator induced emf

CHAPTER ONE

1. INTRODUCTION

1.1. Back ground of study

Three phase induction motor has to be reliable electromechanical energy conversion device for over 100 years. It is a popular choice when compared to other type of motor and can be found easily within our surrounding. Because of its robustness, reliability, low price, lower maintenance cost and no magnetic interference it covers wide range of applications in both industrial and home appliance, fan, compressor, pump, washing machine, freezer and many more. [1]

In 1888, Tesla introduced the alternating current (AC) induction motor for the first time. Tesla believed that his invention is more useful and applicable than DC motor. However, to control the speed of an AC motors you need to vary either the number of poles or magnetic flux. Another way to control the speed of AC motor by changing the frequency but that was also not an easy task at that time. So due to all these steps at that time for the need of output power and accuracy required in speed controlling DC motors were important. Because, technology used was just by simply adding rheostat in low power DC circuit during that time.

For a long decade, that was the most economical and applicable method to fulfill the purpose of changing the speed or varying the torque of the DC motor. By the end of 1980s AC motor drives revolutionized in it and started competing with the traditional DC motor control. Because they were becoming more economical and feasible than DC motor control. These drives are able to control the synchronous and induction motor.

AC drives worked at reduced torque with above rated speed and then also at maximum speed from 0 rpm with full torque [2]. In these AC drives firstly, the incoming AC is being rectified into DC and then by using the technique of pulse width modulation (PWM) to generate output waveform of voltage and current to control the frequency of output [3]. With the development of DSPs, space- vector modulation (SVM) become one of the most important PWM methods for three-phase voltage source inverter. In this technique, space vector concept is used to compute the duty cycle of the switches [4]. Development in the power semi-conductor devices leads to the development in the electrical drives system. In power converters, application of solid-state devices has been initiated in 1957s with the invention of Silicon-Controlled Rectifier (SCR).

The advancement in electrical drives system is further divided in different era. This division is on the basis of development in the field of power semi- conductor devices with the passage of time. These are classified in 3 stages.

- Early 20th century
- In 1950s
- After 1980s

1.1.1. Semi-conductor devices early 20th century

AC drives were used initially used for fixed operation by generate AC voltage with rotary converter of variable frequency, which are bulky and inexpensive. Still with a fixed frequency source it is possible to make variable voltage drive to control AC motor, but in this way the efficiency shown by this drive at low speed will be very poor. On the other side, the variable DC supply could be used in DC motor for controlling armature voltage, and using multi-machine configuration variable DC supply can be produced easily. Hence, because of this DC drives were used for variable speed operation while AC drives were used for only fixed speed applications.

1.1.2. Semi-conductor devices in 1950s

At the time of 1950s, Bipolar Junction Transistors were present**,** but they can’t be used in power circuits as they have very low voltage rating. Since then SCR were introduced in 1957 which made a revolutionary change in AC drive system. As they have higher rating compared to the solid-state transistors which are then be used in variable frequency inverters or converters. The switching frequency of SCR was very low at that time so square wave inverters were used in AC drive system.

In early 1960s, some advancement in the fabrication of BJT and also with the introduction of PWM technique control of AC drive system had significantly contributed a lot. But still the DC drive showed their dominance over AC drives because of the complex magnetic coupling between the rotor and stator of AC machines. But the due to the advancement during that period of time replaced the DC drives with Ac drives, where the applications of medium variable speed were required.

1.1.3. Semi-conductor devices after 1980s

In 1972s, new approach came which is now known as Field Oriented Control (FOC) or vector control also. With the help of this technique AC motor can be used for high performance torque control. In this process, the control of AC motor is transformed into the control of DC motor. But in the decade of 1970s, the concept of FOC is not feasible or even realizable as fast switching microprocessors were not available. After 1980s, the FOC control applications increased in number in industries. AC drives of FOC method replaced the applications which are only run with DC drives. The way this trend is going it seems that AC drives eventually replaces the DC drives in the near future.

1.2. Statement of the problem

Now a day due to a drawback of fossil fuel based vehicle, electric vehicle are fabricated to minimize energy conflict and air pollution. Three-phase AC induction motors are widely used in this electric vehicle and also in industrial and commercial applications. It produces medium to high degrees of starting torque. The power capabilities and efficiency in these motors range from medium to high. For that vast application of induction motor, we need an efficient and effective drive system. In order to avoid the shortage of energy we need design an effective drive system that used DC source. For this purpose, mostly used inverter.

Inverters are also widely used in industrial applications (variable speed AC motors, induction heating, standby power supplies and uninterruptible power supplies……). It is crucial that output voltage of the inverters is maintained so that we realize the requisite of AC loads when such loads are driven by inverters. The voltage can be controlled by External control of ac output voltage and internal control of Inverter. In the case of External Control of AC Output Voltage**,** the control of AC voltage controller through firing angle helps in regulating the voltage input to AC load. However higher harmonic content is seen in the output voltage. In the case of internal control of Inverter By having a control within the inverter itself output voltage can be upheld as well from an inverter. The pulse width modulation control employed in an inverter is the most effective method of doing this. This work is also intended to answer how to analyze the specification of motor for electric vehicle, how to control induction motor speed, torque and direction and how to model induction motor and SVPWM using MATLAB, Arduino and Protous.

1.3. Objective of Study

1.3.1. General objective

The general objective of study is Control Scheme Modelling and Analyzing of Three-phase Inverter for Induction Motor Drive to control Speed, Torque and Direction using SVPWM Technique for three-wheel Electric vehicle Bajaj application.

1.3.2. Specific objective

The specific objective of this research is:

- ❖ To review performance of different types of motor used on Electric Vehicles.
- ❖ To study vehicle dynamics and model mathematically.
- ❖ To model three phase Induction motor for three-wheel Electric Vehicles.
- ❖ To model speed and direction control of Induction motor.
- ❖ To compare THD of SVPWM with SPWM.
- ❖ To simulate the system using MATLAB and proteus software's.

1.4. Significance of study

Now a day the energy source is shifting from non-renewable source that will not available after few decades to renewable energy source that can exist forever. At this time in the world especial in Ethiopia most of energy source is non-renewable energy source due to this shortage of energy is a problem. To minimize this, we need to use renewable energy source especially center of transportation and vehicle engineering member try to develop EV in Ethiopia. And also, we need to use DC source especially for electric vehicle and industrial application in addition to AC source to consume more energy. Since the above-mentioned objectives are full filled, this research can support the trend started by center of transportation and vehicle engineering members in Ethiopia.

1.5. Scope of study

The scope of this thesis is:

- ❖ Modeling and simulation of SVPWM control of PWM inverter for IM using MATLAB and Protuse software.
- ❖ Use squirrel cage induction motor and Arduino @Mega 2560 for our design.
- ❖ Use space vector modulation technique (SVPWM) due to reduction of THD created by the repaid switching inherent algorism and robustness to implement.
- ❖ The study doesn't include about battery source design and other part of EV.

1.6. Limitations of study

Potential problem occurs during the construction of our drives system is related to technical issues and unavailability of materials to work lab research. There are also some other factors that limit the proper working of the drive and on its construction. Current protection circuit is important to build effective drive system. But, due to the shortage of time and capacity current protection circuit is not designed in this work and also hardware implementation is not done. And also, not designed the charge controller of the vehicle, only focus of its dynamics effect.

1.7. Thesis organization

This thesis is organized in to five chapters.

Chapter 1:- The first chapter present introduction, statement of problem, Objectives, significance of study, Scope and Limitation of the research.

Chapter 2: - The second chapter includes literature review on back ground of induction motor drive and different control mechanism.

Chapter 3: - The third chapter describes about methodology that what I have guided to work this thesis and about materials characteristics.

Chapter 4: - The proposed system result discussion and analyzing is presented in this chapter.

Chapter 5: - The last fifth chapter discussed about conclusion and recommendation.

CHAPTER TWO

2. LITRATURE REVIEW

2.1. Introduction

With advances in solid-state power electronic devices and microprocessors, various inverter control techniques employing pulse-width-modulation (PWM) techniques are becoming increasingly popular in AC motor drive applications. These PWM-based drives are used to control both the frequency and the magnitude of the voltages applied to motors [5]. Various PWM strategies, control schemes, and realization techniques have been developed in the past two decades [6]. PWM strategy plays an important role in the minimization of harmonics and switching losses in converters, especially in three-phase applications.

The first modulation techniques were developed in the mid-1960s by Kirnnich, Heinrick, and Bowes as reported in [7]. The research in PWM schemes has intensified in the last few decades. The main aim of any modulation technique is to obtain a variable output with a maximum fundamental component and minimum harmonics [8].

The carrier-based PWM methods were developed first and were widely used in most applications. One of the earliest modulation signals for carrier-based PWM is sinusoidal PWM (SPWM). The SPWM technique is based on the comparison of a carrier signal and a pure sinusoidal modulation signal. It was introduced by Schonung and Stemmler in 1964 as reported in [9]. Utilization rate of the DC voltage for traditional sinusoidal PWM is only 78.5% of the DC bus voltage, which is far less than that of the six-step wave (100%).

Improving the utilization rate of the DC bus voltage has been a research focus in power electronics [6]. This problem of the under-utilization of the DC bus voltage led to the development of the third-harmonic-injection pulse-width modulation (THIPWM). In 1975, Buja developed this improved sinusoidal PWM technique, which added a third-order harmonic content into the sinusoidal reference signal leading to a 15.5% increase in the utilization rate of the DC bus voltage [10]. Another method of increasing the output voltage is the space-vector PWM (SVPWM) technique.

SVPWM was first introduced in the mid-1980s and was greatly advanced by Van Der Broeck in 1988 [13]. Compared to THIPWM, the two techniques have similar results but their methods of implementation are completely different. With the development of microprocessors, SVPWM has become one of the most important PWM methods for three-phase inverters [11]. Many SVPWM schemes have been developed and extensively investigated in the literature. The goal in each modulation strategy is to lower the switching losses, maximize bus utilization, reduce harmonic content, and still achieve precise control [12].

The SVPWM technique utilizes the DC bus voltage more efficiently and generates less harmonic distortion when compared with the SPWM technique [8]. The maximum peak fundamental magnitude of the SVPWM technique is about 90.6% of the inverter capacity. This represents a 15% increase in the maximum voltage compared with conventional sinusoidal modulation. In 1991, Holtz proposed a classical over-modulation technique based on SVPWM, which divided the over-modulation range into two modes of operation and increased the utilization rate of the DC voltage to that of a six-step wave [10, 15, 16,17].

Holtz proposed this technique using switching time calculations in the over-modulation region of SVPWM. In 1998, Lee analyzed Holtz's over-modulation technique graphically, gave some approximate linear expressions between the modulation index and its own auxiliary parameter, and discussed the harmonic problem [18]. He showed that this technique generated less harmonic distortion in the output voltages (or) the currents applied to the phases of an AC motor and provided more efficient use of the DC input voltage. Because of its superior performance characteristics, it has found widespread application in recent years [8]. Accordingly, many other researchers have explored various aspects of this technique in the literature [10, 19].

2.2. Basics of AC drives

Drives are installed in the systems that are needed by motion control. E.g. fans, pumps, robots, machine tools etc. Prime movers that are used in drive systems to provide movement and energy that is used to give motion can be from different types of sources: diesel engine, petrol engine, electric motors, hydraulic motors etc. The electric motors that use drives as a prime mover are called electrical drives. These controls provided by these drives may be simple as an ON/OFF switch. In addition, with ON/OFF control these drives may provide motor overload protection.

In soft start devices the current decreases by decreasing the voltage at startup and relive the motor from stresses. Also, in these devices motor has smooth acceleration up to 100% operating speed and also can control motor smooth deceleration up to zero.

AC drives are also smooth operating soft devices but speed and torque of motor may vary according to the requirements. And motor has not to run at 100% speed and torque but these can vary according to the requirements. These drives are categorized to be variable frequency drives and variable speed drives, but for simplicity we just call them AC drives. These drives have high efficiency, low maintenance requirements, cleaner operation and lower noise. These are available in wide range of speed torque and power. Energy can easily be transported by using AC drives to the motor. These can be expensive at initial cost but saves money at time. Energy saving and reduced tear and wear on machinery repay quickly the initial investment.

The voltage applied to the motor can be changed by using power electronics convertors. These convertors increase and decrease the voltage according to the requirement. AC motor is not limited to the application where alternating current source is available but it can also be used available power source is DC. The available DC is converted to AC by using invertors to run the motor. The inverter also controls the frequency of the output AC [19]. By changing the frequency, we can change the speed and torque of the motor.

AC drives consist of different components which perform different functions according to their requirement. The major components of AC drives are Electrical Motors, Power Processor, Control Unit and Electrical Source.

2.2.1. Electric motor

Selection of the traction motor for an electric vehicle system is a crucial step in designing the overall system. Many criteria such as efficiency, cost, reliability, power density, maturity of technology and controllability must be taken into consideration. In the industrial application point of view, the most common motors used in the hybrid electric vehicles (HEV) and pure electric vehicles (PEV) are classified in the figure2-1 which is, DC motors, induction, permanent magnet synchronous, switched reluctance and brushless DC motors [31].

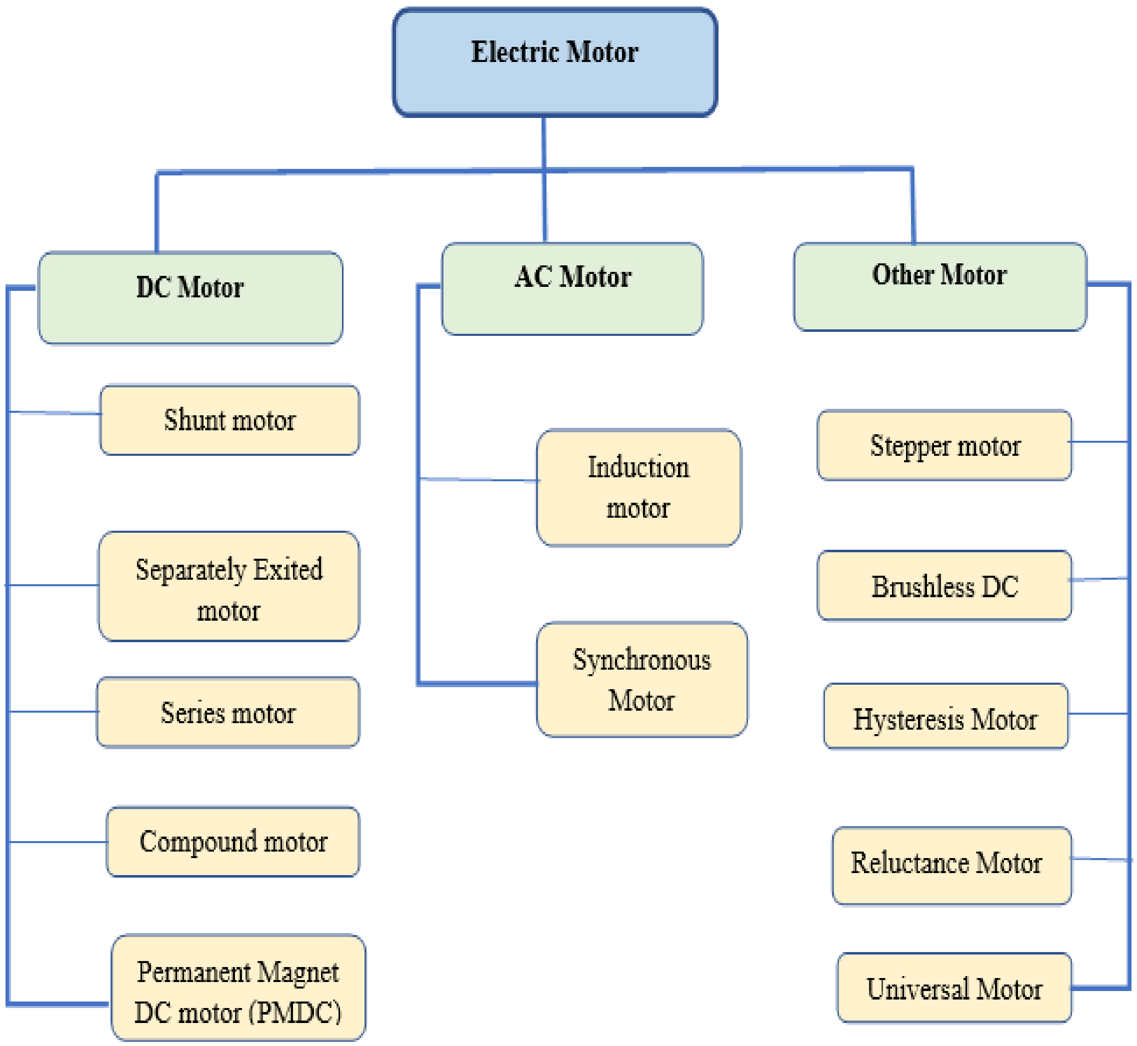


Figure 2-1: Motor classification

The performance of a motor that are usually used in electric vehicle application is discussed below.

2.2.1.1. DC motors

Although DC motors have been the subject of interest since old time because of simple control and decoupling of flux and torque, their construction (having brushes and rings) poses maintenance problems. Therefore, after the growth of vector control for AC motors (synchronous and induction), the DC motors' attraction in traction applications diminished. Of course, DC motors are still good candidates for low power applications. The commutator actually acts as a robust inverter. Therefore, power electronics devices can be mush simple and inexpensive. The Peugeot factory of France has introduced a HEV named "Dynavolt" in which, DC motor has been used as traction motor [33].

2.2.1.2. Induction motors

Induction motor is works based on the principle of electromagnetic principle in which the conductors in the changing magnetic field induces an emf across the conductor [33]. Due to the interaction of stator and rotor flux, the motor rotates. The advantages of induction motor are simple in construction and are cheaper and maintenance less. And they can be operated in dirty environments like dust, presence of water and explosive areas due to the absence of brushes which will produce sparks. They are self-starting motors. The disadvantage is that the speed control is difficult [33].

The induction motors have the most mature technology among all other AC competitors. In Figure 2.2, the main characteristics of an induction motor have been shown. Torque and field control can be decoupled using vector control methods. Speed range may be extended using flux weakening in the constant power region. Existence of break-down torque in the constant power region, reduction of efficiency and increment of losses at high speeds, intrinsically lower efficiency in comparison to permanent magnet motors due to the presence of rotor winding and finally low power factor are among the shortcomings of induction motors. Many efforts have been made by researchers to solve these problems, such as: usage of dual inverters to extend the constant power region, incorporating doubly- fed induction motors to have excellent performance at low speeds and reducing rotor winding losses at the design stage.

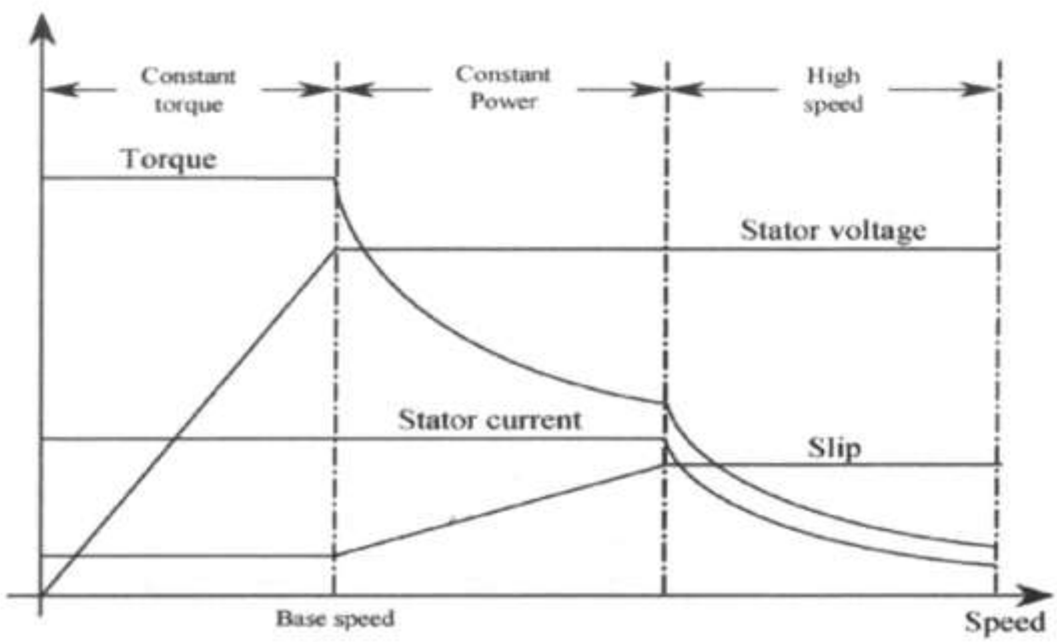


Figure 2-2: Different characteristics of induction motors [33]

2.2.1.3. Permanent magnet synchronous motors (PMSM)

PMSM are the most serious competitor to the induction motors in traction applications. Actually, many car manufacturers (such as Toyota, Honda and Nissan) have already used these motors in their vehicles. These motors have several advantages: higher power density, higher efficiency and the more effective distribution of heat into the environment. However, these motors have intrinsically a narrow constant power region (Figure 2.3-a). Figure 2.3-b shows the torque speed of a PMS motor with conduction angle control. Speed range can be extended to three of four times the base speed. A shortcoming of these motors is that they can be demagnetized due to the heat or armature reaction.

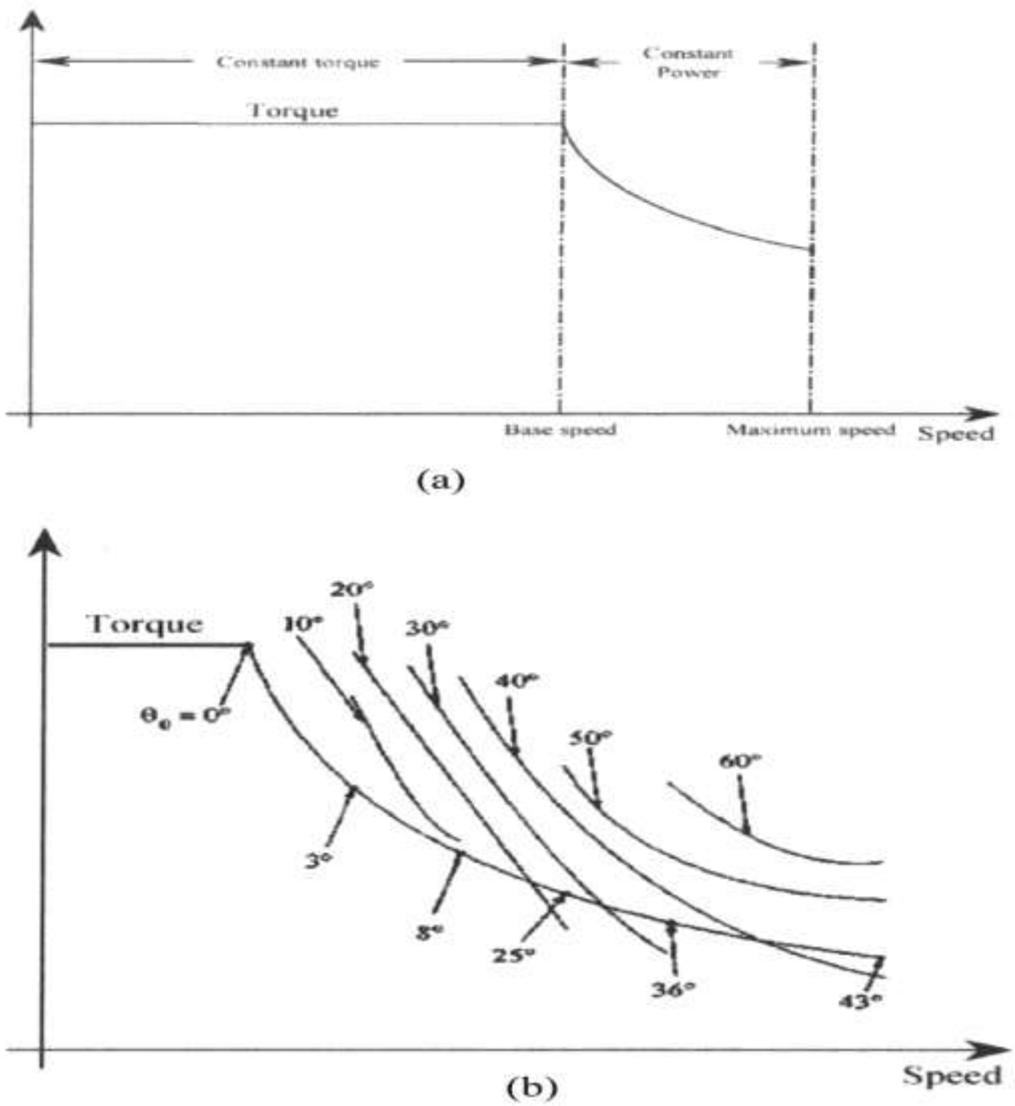


Figure 2-3: Torque- speed characteristic of BLAC motor: (a)- conventional characteristic and (b)- characteristic under conduction angle control. [31]

2.2.1.4. Switched reluctance motors (SRM)

Switched reluctance motors are receiving much attraction in HEV systems every day. Among the advantages of these motors are: simple and rigid construction, fault tolerance, simple control and excellent torque-speed characteristic.

A switched reluctance motor can intrinsically operate under a wide constant power region. Several disadvantages such as high noise, high torque ripple, special convertor topology and electromagnetic interference have been mentioned for this motor [31]. Both the advantages and disadvantages of this motor are important in the EV applications. A conventional torque speed characteristic of an SRM has been depicted in Figure 2.4.

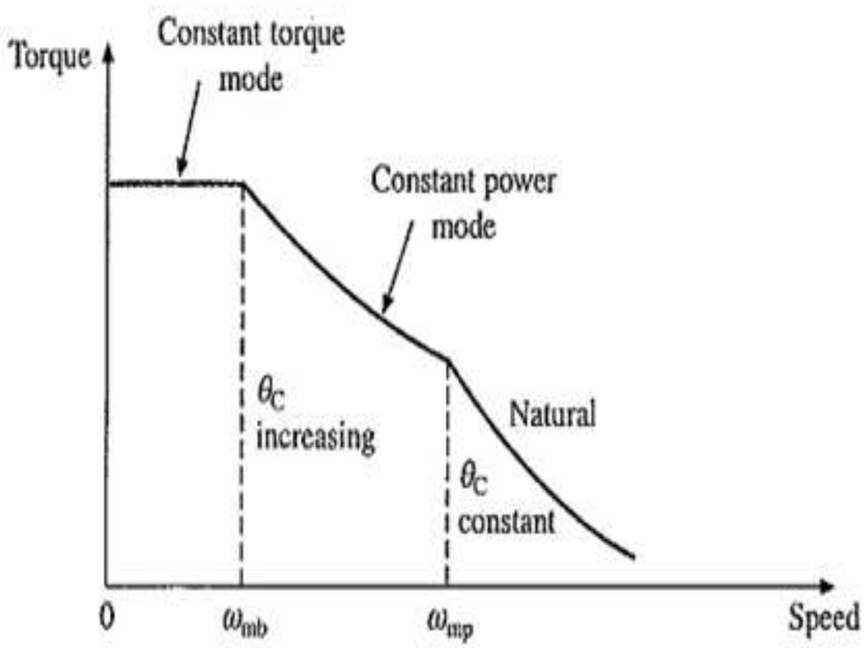


Figure 2-4: Conventional characteristic of an SRM [31]

2.2.1.5. Brushless DC motors (BLDC)

These motors are conceptually the outcome of reversing the stator and rotor of permanent magnet DC motors. They are fed by rectangular waves in contrast to BLAC motors which are fed by sinusoidal waves. Their main advantages are the deletion of the brushes, their compactness, high efficiency and high energy density [32]. In [31], the traction systems commonly used in EVs are evaluated based on six factors. As shown in table. 2-1, a score out of 5 is given for each point to each motor. It is concluded that based on these factors, IM and PM motors are more suitable. However, in the following section the DC and SRM motors are not taken into consideration due to their disadvantages.

The following Table 2.1 is describing the comparison between different motors that used in electric vehicle applications by using different parameters as a measurement.

Table 2.1: Evaluation of different traction systems for electric vehicles [3l]

Population system characteristics	DCM	IM	PM	SRM
Power density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Total	**22**	**27**	**25**	**23**

As can be observed, PM motors have the highest power density due to the presence of high-power density permanent magnets. Moreover, they have the highest efficiency because of the absence of rotor losses. DC and induction motors have the best controllability and their flux and torque control can be easily decoupled. The induction motor has the best reliability due to its robust and rigid construction.

2.2.2. Comparison of IM with BLDCM and IPMSM

Table 2.2: AC Induction Motor Vs BLDC Motor:

BLDC Motor	AC Induction Motor
The speed/torque characteristic is flat in nature. It enables operations at all speeds with rated load.	The speed/torque characteristic is nonlinear in nature. It enables lower torque at lower speeds.
Output power/ Frame size is high. Because it has permanent magnets on the rotor, the smaller size can be achieved for a given output power.	Output power/frame size is moderate. Because both stator and rotor have winding, output power to size is lower than BLDC.
The rotor inertia is low. This enables better dynamic characteristics.	The rotor inertia is high. This enables poorer dynamic characteristics.
The starting current is rated. No special starter circuit is required.	The starting current is approximately up to 7 times of rated. Stator circuit rating should be carefully selected. It normally uses a star delta starter.
A controller always required to keep the motor running. The controller can be used for variable speed control.	No controller is required for fixed speed. A controller is required only if variable speed is desired.
No slip is experienced between stator and rotor frequencies.	The rotor runs at a lower frequency than the stator by slip frequency and slip increases with load on the motor.

IM and IPMSM have been compared in Table 2.3. It is seen that IM provides efficiency optimization and control of regenerative braking by efficiency control. Having high efficiency of IPMSM at low speeds improves battery utilization and driving range. IPSM has better geometrical integration into engine cabinet and reduces total weight of vehicle. Conversely, IPMSM has high cost due to magnets. Current rating is lower than IM.

Table 2.3: Comparison of IM and IPMSM [34].

IM	Advantage in EV
For control the magnetizing current is supplied by stator. IM has flexible efficiency	If state of charge is near maximum limit, efficiency of IM can be reduced by motor drive system in order to limit the return of regenerative energy. Efficiency optimization at light load condition is possible by control of flux reference.
IM field weakening is controlled by reduction of magnetizing current	Efficiency of IM is competitive against IPMSM at high speed region on torque speed curve.
IPMSM	**Advantages in EV**
If IPMSM is compared to IM, it has high efficiency at low speed	Advantages for cars where frequent start stop occurs at low speeds. This also improves battery utilization and driving range.
High torque/volume ratio, smaller size and lighter weight.	It has better geometrical integration in to engine cabinet and reduces total weight of vehicles
Current rating is lower than IM.	Lower current rating for inverter and improved battery utilization.

Generally, the following Table 2.4 describes the Brief comparison of electric motors used for electric vehicle.

Table 2.4: Brief comparison of electric motors used for electric vehicle [5].

Features	Induction motor	Brushless dc motor	Brushed dc motor
Mechanical structure	Both the rotor and stator have windings but the AC lines are connected to the stator	Field magnets on the stator and rotor are made of permanent magnets	Field magnets on the rotor and stator are made of permanent magnets or electromagnets
Maintenance	Low maintenance	Low maintenance	Periodic maintenance because of brushes
Speed vs torque characteristics	Non-linear	Flat – operation at all speeds with rated load	Moderate – loss in torque at higher speeds because of losses in brushes
Efficiency	Low- heat and current losses in both rotor and stator; high efficiency induction motors are also available (higher cost)	High – no losses in the brushes; stator is on the outer periphery and is thus able to dissipate more heat and produce more torque	Moderate – loses in brushes; rotor is on the inner periphery.
Commutation method	Special starting circuit is required	Using solid state switches	Mechanical contacts between brushes and Commutator

Speed range	Low – determined by the AC line frequency; increases in load further reduces speed	High – no losses in brushes	Moderate – losses in brushes
Electrical noise	Low	Low	High – because of the brushes
Direction reversal	By changing the two phases of the motor input	Reversing the switching sequence	Reversing the terminal voltage
Control requirement	No controller is required for a fixed speed; controller required for variable speed	A controller is always required to control the commutation sequence	No controller is required for a fixed speed; controller required for variable speed
System cost	Low	High – because of external controller requirement	Low

2.2.3. Power processor

As the electrical sources are normally uncontrollable, therefore it is necessary to control the flow of power to the motor. By using controllable sources, the motor can be reversed, brake and can be operated with variable speed. Initially relays were used for this purpose to control the voltage but these were inflexible and inefficient. Now a day's convertors are used to shape the voltage or current supplied to the motor. These convertors are flexible. Flexibility means that voltage and current can be shaped by simply controlling the switching action of the power convertor. Also, these are efficient so that power losses in the convertor are negligible. These are compact smaller higher rating solid state electronic devices. Because these are continuously developed, they are getting cheaper.

2.2.4. Input and inverter Section

AC drive is device for controlling speed and torque of a motor. It does this in such a way that first converting three phase AC to DC. Then by using various mechanisms we convert this DC to AC with controllable frequency of the output sine wave. There are generally two types of control: pulse width modulation and six step control. Mostly AC drives use pulse width modulation method for controlling the frequency and that is used in this thesis. There are two main sections of the PWM drives which are described as Rectifier and Inverter that shown in figure 2-5.

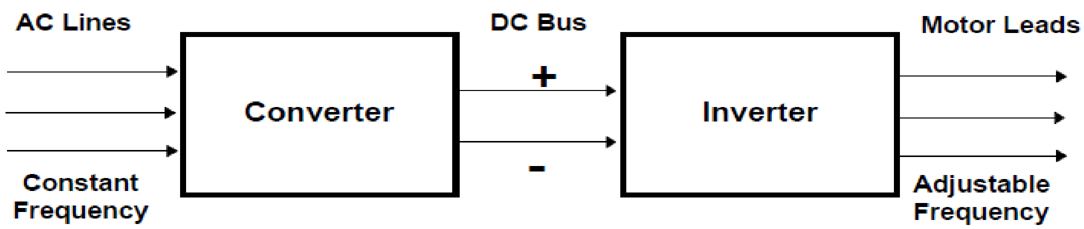


Figure 2-5: Power Processing Unit [8]

2.2.5. Rectifier

Rectifier is used to convert input alternating current to direct current. As shown in the figure 2-6 three phase input supply is fed to the rectifier circuit that yields direct current. It uses six diodes that rectify the input wave.

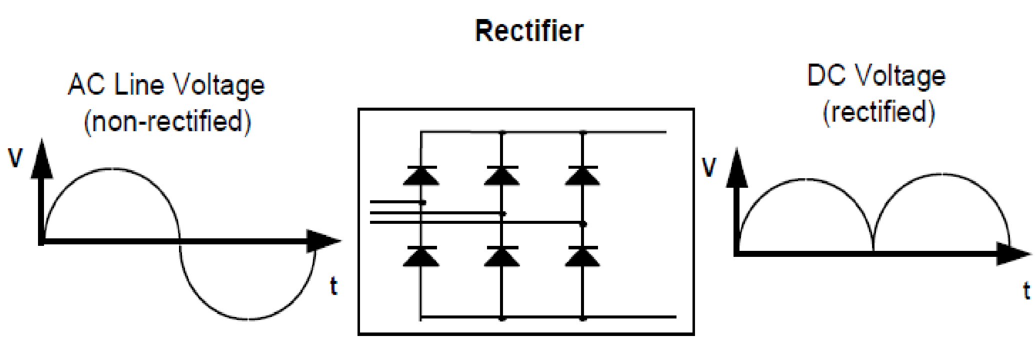


Figure 2-6: Rectifier Circuit Diagram [21]

2.2.6. Control unit

The performance required and type of motor used gives rise to complexity in the control unit of ac drives. A controller can be simple of few op-amps or few digital integrated circuits. It can also be complex as a combination of several ASICs and digital signal processors (DSPs). The types of the main controller may be Analogue**,** Digital and DSP/Microcontroller. Analogue signal is noisy, inflexible. However analog circuit ideally has infinite bandwidth. But, Digital signals resist to noise and are configurable. Their bandwidth is smaller than analogue signals and depends upon their sampling frequency. DSP/Microcontroller is flexible but its bandwidth is lower. DSP performs faster than microcontroller because these perform multiplication in single cycle.

2.3. Three phase inverters

The dc output taken from the rectifier is fed to the inverter that converts it into sine wave. It consists of IGBTs that turn off and on simultaneously so that controls the frequency of the output wave. The gating sequence of the inverter is controlled by the pulse width modulation (PWM) scheme. Basically, as shown in the figure 2-7 inverters inverts the dc input signal to the ac output signal which is used to drive the motor. [21]

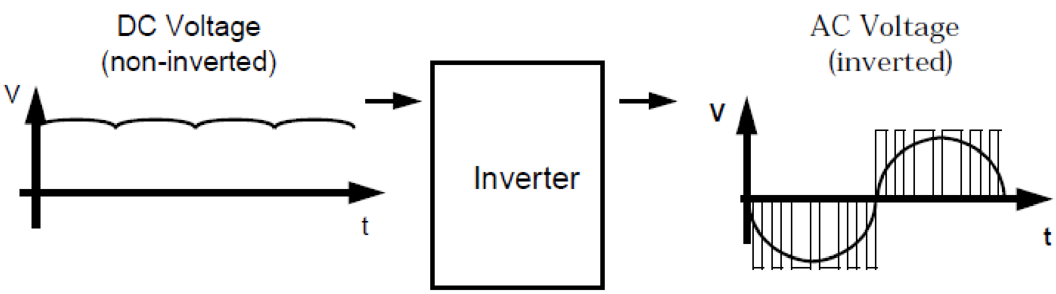


Figure 2-7: Inverter Principle Diagram [21]

Two level inverters associated with pulse width modulation scheme is given as in figure. S1-S6 are the six power switches that shape the output and these are controlled by the terminals a, a', b, b', c, c,'

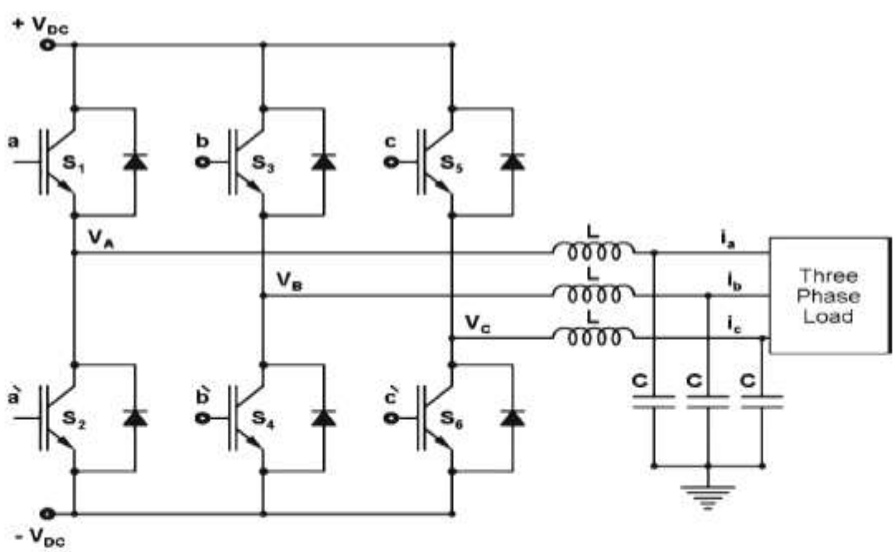


Figure 2-8: Voltage source inverter [L2]

The complete circuit diagram of the drive circuit contains both rectifier and inverter circuit. Initially input is given to the rectifier this gives DC output voltage and this is made smooth with the help of capacitor or another filter circuit. These filter circuit removes the pulses in the output and made it smooth dc voltage. This smooth dc voltage is changed to the ac output voltage by using three phase inverters.

The invertors IGBTs turn off and on in accordance with applied control wave. This wave is supplied by microcontroller which monitors the switching of the IGBTs. The turn ON and OFF pattern of the switches, form ac wave at any desired frequency. In most of the case frequency of the ac output wave is constant but according to the requirement it can be changed [20]. This change of frequency helps us to control the speed and torque of the motor. Also, we are able to control the direction of the motor which means that whether the motor should rotate in clockwise direction or anti-clock wise direction. We can connect any type of load either Y or delta. In Y connected load we measure line to neutral voltage but in delta connected load we measure the line –line voltage. In figure shown below it is shown how rectifier is associated with inverter in order to yield controllable output voltage.

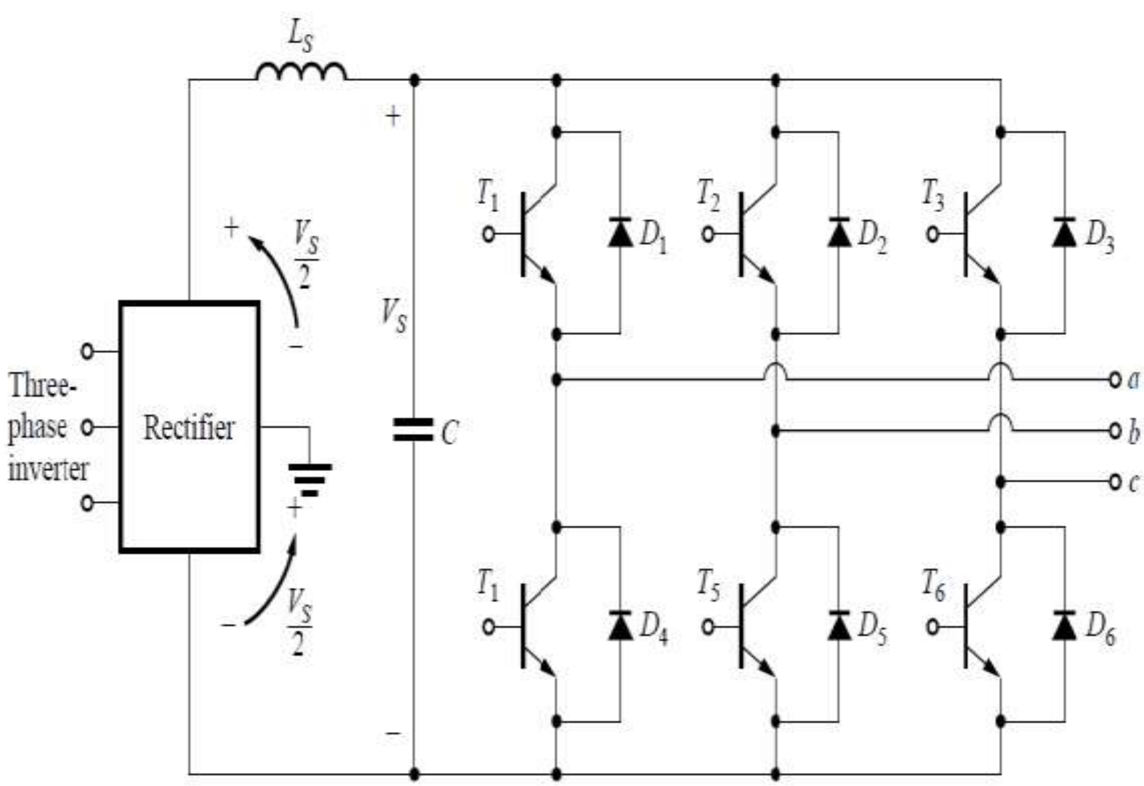


Figure 2-9: Three phase inverter circuit diagram [L2]

2.4. Pulse width modulation

The turn on and turn off the switches is controlled by using pulse width modulation. It is the process that is used to modify the width of pulses that are contained in a pulse train directly proportional to the small control signal. The concept is made in such a way that greater is the control signal, the wider will be the width of pulse. By using sinusoid of the required frequency as a voltage control for pulse width modulation, it is possible to produce high power waveform whose mean voltage varies in sinusoidal manner can be used to drive ac motors.

The basic concept associated with PWM can explained with Figure 2.11. Figure 2.12 shows single phase PWM inverter with using IGBTs. IGBT1 through IGBT4 can be controlled by two comparators as shown in figure 2.12.

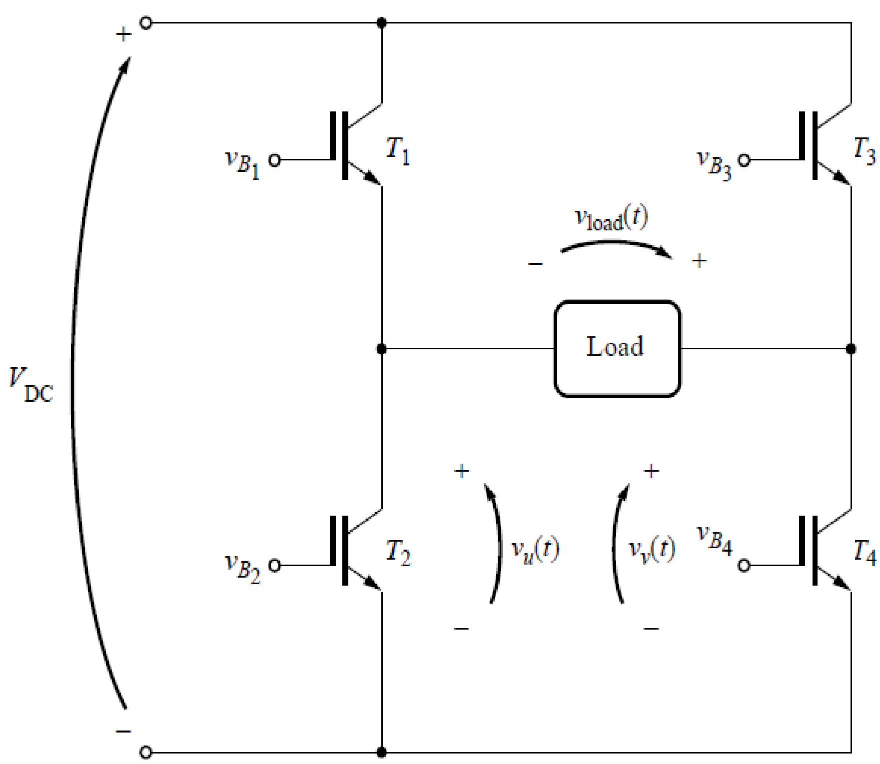


Figure 2-10: Single Phase Inverter Associated with PWM [L2]

A comparator is a device that compares the input signal with the reference signal and turns the transistors on and off as a result of the comparison. Comparator A compares the input signal with the reference signal $V_x(t)$ and controls the IGBTs T1 and T2. Similarly, comparator B compares the input signal with reference signal $V_2(t)$ and controls the IGBT T3 and T4. If the Vin is greater than $V_x(t)$ it will turn on T1 and turn off T2.

Similarly, if V_{in} greater than $V_y(t)$ then comparator B turns IGBT T3 turn on and T4 off. Otherwise the result will be opposite and vice versa.

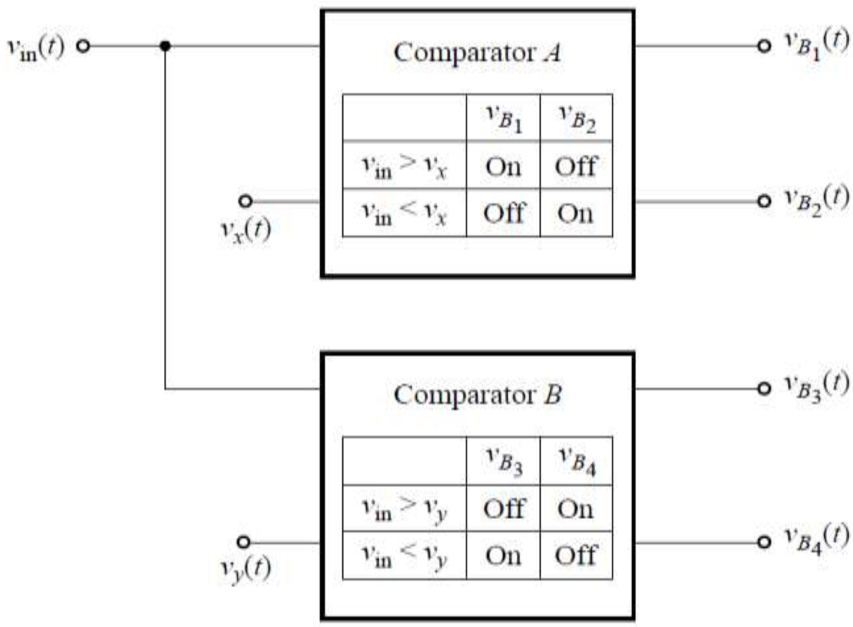


Figure 2-11: Comparators for PWM [L2]

The reference voltage signals are $V_x(t)$ and $V_y(t)$. These signals are that signals which specify the turn on and turn off time for a particular IGBT. These reference signals are the triangular waves which are taken in comparison with the input voltage. There are different PWM techniques that are used in motor drive which are illustrate in the following figure 2-13.

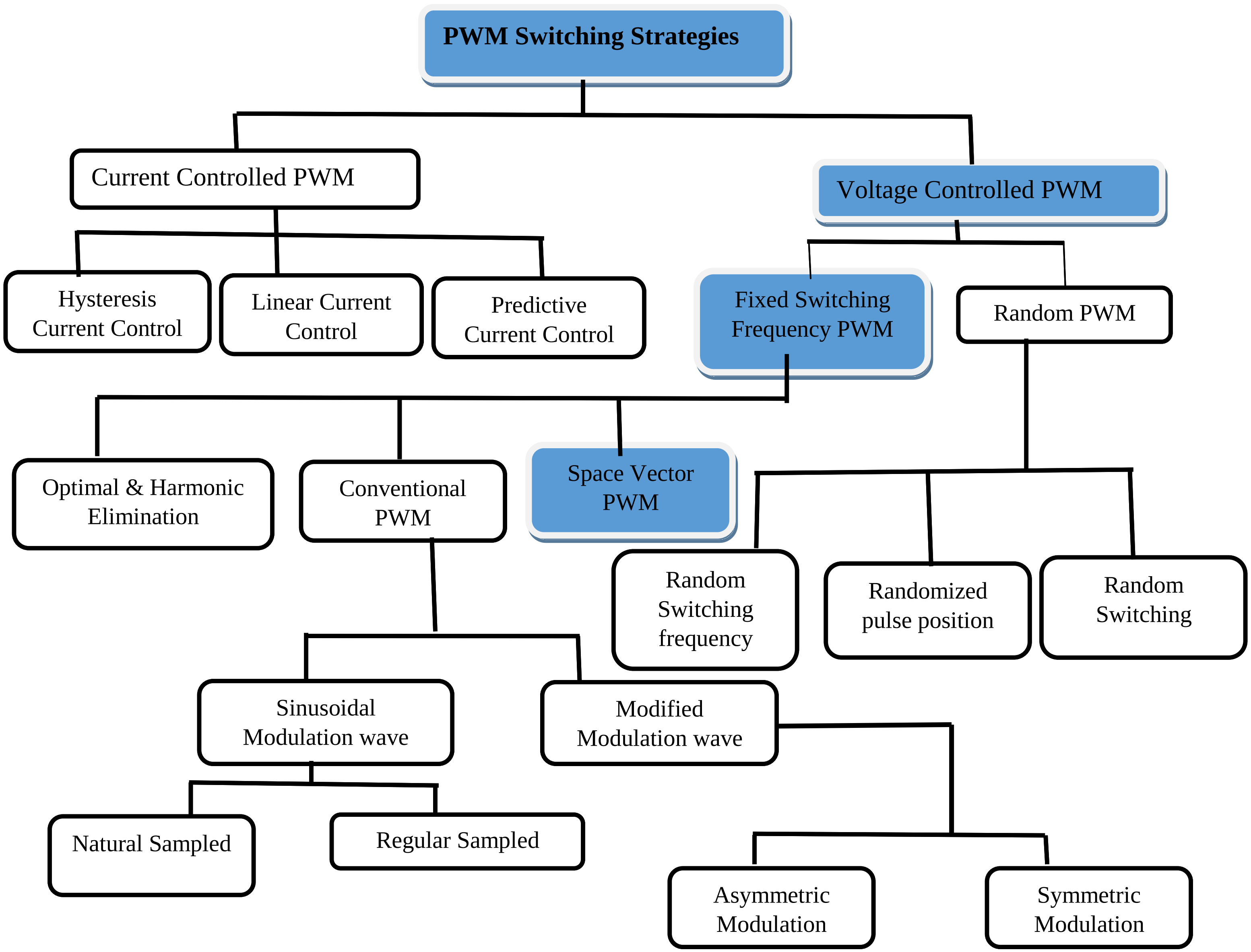


Figure 2-12: Classification of PWM technique [29][30]

2.5. Control methods of IM done by different researcher

No.	Author's Name	Converter	Method/Techniques	Performance
1	***M. H. Nehrir [45]***	3Phase SPWM Inverter	Stator voltage control &Sine wave Variable voltage control	Speed and torque
2	***A. Munoz-garcia [46]***	PWM Inverter	V/F method using Open loop current sensor with stator resistance drop and slip frequency	Stator current
3	***S.Doki et al [47]***	SPWM Inverter	Indirect and direct vector control technology	All Performance Parameter of IM
4	***B.N. Singhetal [48]***	SPWM using CSI	Vector controlled Technology with fuzzy logic	Speed of IM
5	***Bor-renlin [49]***	PWM Three phase ac/dc/ac converter	Space vector modulation with hysteresis current control	Power quality Acoustic noise Resonance vibration Reduction of torque
6	***Jae-Ho Choi et [50]***	PWM using VSI	Indirect & direct current control	Sinusoidal line current unity power factor ripple-free DC output voltage

7	***Ivensky G. Et [51]***	3 phase inverters	ZCS series resonant	Series resonant power converters RMS current
8	***J.S.Lai et al. [52]***	3 phase DC link inverter.	High-frequency resonant	Voltage overshoot Zero crossing failure problems
9	***P.N. Enjeti etal. [53]***	PWM AC-to-DC power converter	Under unbalancing and Balance ng condition	Reduce lower-order abnormal harmonics
10	***José R. Rodríguez, etal. [54]***	PWM AC-DC-AC power converter	Current harmonics injection method	Reduced input harmonics and improved power factor
11	***R. Ghosh et al. [54]***	Single-carrier-based & CSPWM Star connected rectifier system	Split-capacitor topology.	Peak-to-peak neutral current ripple
12	***H. Fujita et al. [55]***	UPQC	Different type filter Two closed loop PI controllers	Voltage imbalance, Reactive power, Negative sequence current & harmonics.
13	***Y. Pal et al. [56]***	UPQC	Series-active filter and shunt active filter	Power factor correction, Voltage regulation, Voltage and current harmonics mitigation, Mitigation of voltage sag, swell and voltage dip.
14	***This thesis***	3 phase inverters	SVPWM Techniques	Speed, Torque and direction

CHAPTER THREE

3. METHODOLOGY

3.1. Introduction

This chapter include data analysis, the methodology what I have follow to done the thesis is described, the characteristic and properties of material and software used are explained, mathematical modelling of induction motor and inverter using Space vector modulation technique finally simulate the system using MATLAB and Proteus software

3.2. Methods

The thesis work consists of the source, the three-phase inverter, the three-phase induction motor as a load and the Arduino controller. Generally, this proposed system is illustrated in the following figure 3-1.

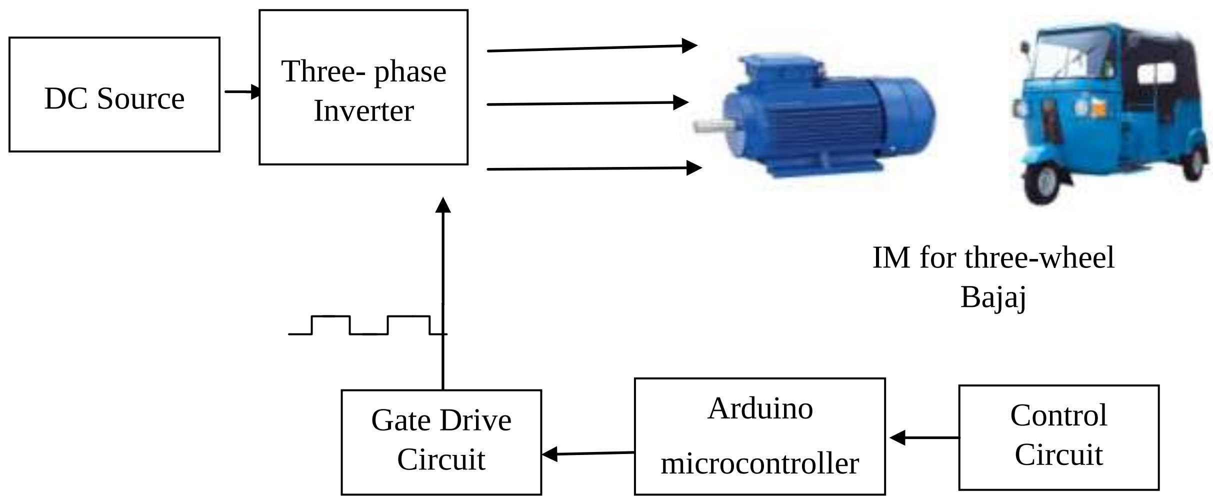


Figure 3-1: Block diagram of the thesis

The first part is the DC source to give the power for the whole system. The second part is the three-phase inverter that convert DC to AC voltage. In this system, the inverter is three phase because the load is the three-phase induction motor. The controller will generate the pulse width modulation (PWM) to feed into the three-phase inverter. The gate driver is used to amplify the PWM signals generated by the Arduino board. This include to produce the appropriate gate signals to drive the IGBT. The whole thesis development including the hardware and software development. The process of designing the controller can be said as the core of the whole thesis and can be resources demanding. In general, the first step designing the three-phase inverter and the gate driver circuit, the process was done using PROTEUS software. After that is the generating the firmware for Arduino. The hardware process starts with the implementation of the generated firmware on the Arduino. The verification stage involves the testing of the designed controller on Arduino prototyping platform. In general, the method followed throughout the research study can be summarized as the following flow chart.

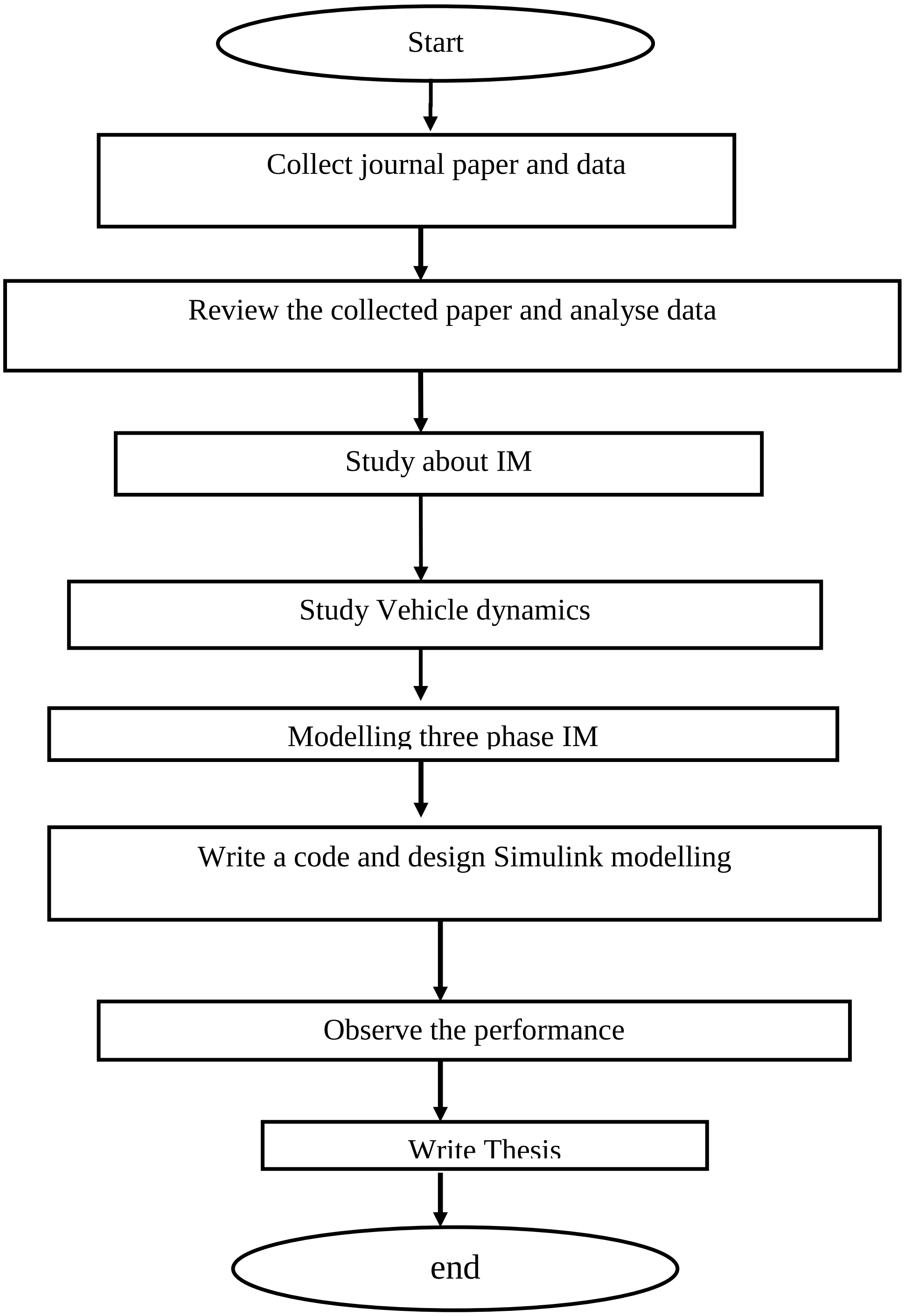


Figure 3-2: Flow chart of the thesis development

3.3. Materials

In this topic, we will discuss the integral parts of complete unit individually. And also discuss the intrinsic properties and characteristics of every component in the operation of this thesis. Each and every entity have specific semi-conductor devices, control devices protective devices and amplifying devices, and also where each component has its own working operation and working principle under certain circumstances to perform clear-cut functions.

3.3.1. Elaboration of entities

As discussed in previous chapters, the units of Ac drives are rectifier, inverter, gate driver or control unit for inverter, processing unit or controller unit to regulate the speed of the motor, direction control unit to move the load or induction motor in clock-wise and anti-clockwise by using push buttons, and the control of torque using voltage or current technique. All of these are the basic characteristics and requirements of drives. Initially, the AC voltage is transformed into DC voltage through single phase rectification which is further smoothens by DC link which includes the capacitor and inductor coil collectively forms the LC filter. This smooth voltage is then applied to IGBTs. They receive their gate signal through gate driver unit.

Gate drivers include the set of ARDUINOS MEGA 2560 to generate the power gate signal for IGBTs gate terminal. In this process, rectification, amplification and signal generating actions are performing through programming. At this stage, first task of project is achieved i.e. control the speed of motor. And then the next one is the direction of rotation of motor i.e. in which direction it will have to move. This may be done by programming or through push buttons to change the supply of the motor windings. In this way, the second objective also achieved profitably which is of direction of motor. And now the last and final objective, which is a gain of about control idiosyncratic of our drive i.e. torque control.

As we know that, when the speed of the motor increases the torque starts decreases respectively. In the same way, current also starts decreasing. So, at this phase, if we want to increase the torque too with the increase in the speed then we have to gradually increase the current supply to the motor. Hence, the torque starts increasing and consequently this objective also achieved successfully. Now as we have gone through each and every process by taking its overview so then this is lap for detailed description of the components utilize in these steps. Every task is performed and achieved by different components. So, it is important to discuss them briefly one by one.

3.3.2. Filter system

LC filter is one of the most basic filters in electronics, which comprises of just one inductor (coils) and a capacitor. It is a circuit used to suppress the noise in the power source created by motors. An inductor resists changes to the current flowing through it. While a capacitor resists changes to the voltage across it. Filters are used for smoothening of DC by which includes the capacitor and inductor coil collectively forms the LC filter. This smooth voltage is then applied to IGBTs.

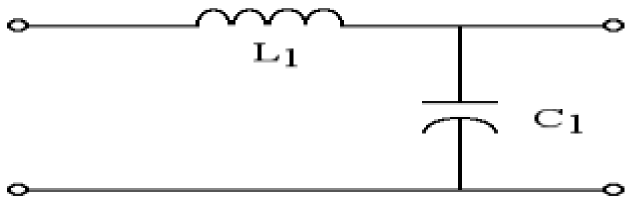


Figure 3-3: LC filter

The value of capacitor and inductor affects the ability of noise suppression at certain frequency bands. When choosing capacitor, ensure the capacitor voltage rating is above the max line voltage. Typical range 100uF to 2000uF is a good one. Where for the inductor we can make it with ferrite ring can be obtained from radio power supply and pc mother board.

3.3.3. Fuse system

The fuse is an electronic device, which is used to protect circuits from over current, overload and make sure the protection of the circuit. Fuse consists of a low resistance metallic wire enclosed in a non-combustible material. Whenever a short circuit, over current or mismatched load connection occurs, then the thin wire inside the fuse melts because of the heat generated by the heavy current flowing through it. Therefore, it disconnects the power supply from the connected system. In normal operation of the circuit, fuse wire is just a very low resistance component and does not affect the normal operation of the system connected to the power supply.

Figure 3-4: Fuse [L1]

Such types of fuses can be categories on the basis of Current carrying Capacity of Fuse, Breaking capacity, Response Characteristic, Rated voltage of Fuse and I^2t value of Fuse.

The exact fusing current is not as well controlled as an enclosed fuse, and it is extremely important to use the correct diameter and material when replacing the fuse wire, and for these reasons these fuses are slowly falling from favor.

3.3.4. Components used in inverter and gate driver system

3.3.4.1. 4PC40UD (IGBT)

4PC40UD IGBT is used in 3-phase inverter circuit for which is further connected to 3 phase winding of motor. Their electrical characteristics, benefits, features and other important details will be discussed. Their most useful features are as follow:

- ❖ Optimized for high operating frequency ranging from 8-40 KHz.
- ❖ 4^{th} generation these IGBTs provide higher efficiency than 3^{rd} generation IGBTs.
- ❖ IGBT's optimized for specific application conditions.
- ❖ Minimized recovery characteristics require.
- ❖ The gate to emitter voltage ratings is V_{GE}=15V.
- ❖ The forward current from collector is I_C=20A.
- ❖ While collector to emitter voltage is of about V_{CE}=600V.

3.3.4.2. IR2110 (driver)

The IR2110 is high voltage, high speed power MOSFET and IGBT drivers with independent high and low side reference output channels. CMOS technologies enable ruggedized construction. Logic inputs are compatible with standard CMOS output. The driver output features a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications. The floating channel can be used to drive an N-channel power IGBT in the high side configuration which operates up to 500 or 600 volts.

The technical and some side features of IR2110 have many aspects. The driver output features a high pulse current buffer stage designed for minimum driver cross-conduction. Propagation delays are matched to simplify use in high frequency applications, which are described one by one in the following points:

- ❖ Gate drives supply range from 10 to 20V.
- ❖ Separate logic supply ranges from 3.3V to 20V.
- ❖ Logic and power ground ±5V offset.
- ❖ Outputs in phase with inputs.

- Matched propagation delay for both channels.
- Under-voltage lockout for both channels.
- Offset voltage ranges from 500-600V
- Maximum output current ranges from I_O =2A
- Output voltage 10-20V
- Typical $T_{on/off =}$ 120-94ns

3.3.5. Arduino @mega 2560 controller

ARDUINO MEGA 2560 micro controller is peripheral and other benefit features with the developing of C language. C has become the predominant development language are discussed below.

- C compiler optimized architecture/instruction set Source code compatible.
- High current sink/source 25 mA/25 mA
- Three external interrupt pins
- Timer0 module: 8-bit/16-bit timer/counter with 8-bit programmable pre-scalar
- Timer1 module: 16-bit timer/counter
- Timer2 module: 8-bit timer/counter with 8-bit period register (time-base for PWM)
- Timer3 module: 16-bit timer/counter
- Programmable code protection, Low power, high speed FLASH, Fully static design
- Wide operating voltage range (2.0V to 5.5V)
- The Arduino Mega 2560 can be operated in eight different Oscillator modes.
- Oscillator modes require an external clock source to be connected to the OSC1 pin.

3.4. Electric vehicle dynamics

The drive train consists of six components: the electrical motor, power electronics, battery, motor controller, battery controller and vehicle interface. In the figure 3-5 the vehicle interface provides the interface for the sensors and controls which communicate with the motor controller and battery controller. The motor controller normally controls the power supplied to the motor, while the battery controller controls the power from the battery. The battery is for energy storage, usually lithium-ion cells which provide more than 200 V and high current to the power electronics. The power electronics manipulate the voltage, current and frequency provided to suit the motor requirements.

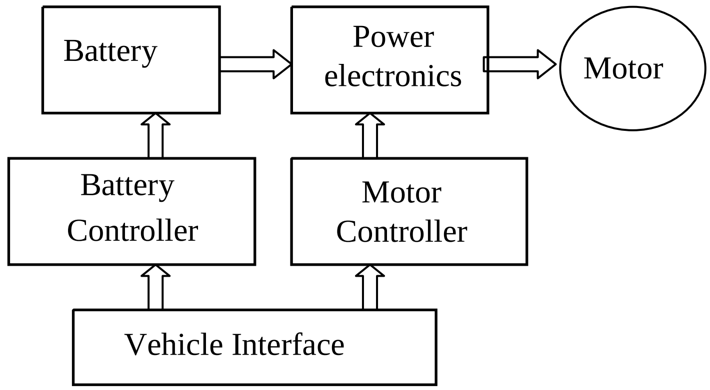


Figure 3-5: EV drive vehicles [36].

In designing the EV various variables are to be considered. The design variables include:

- Electric motor rated speed.
- Electric motor power rating.
- Maximum speed of the electric motor.
- Constant power region beyond the rated speed.

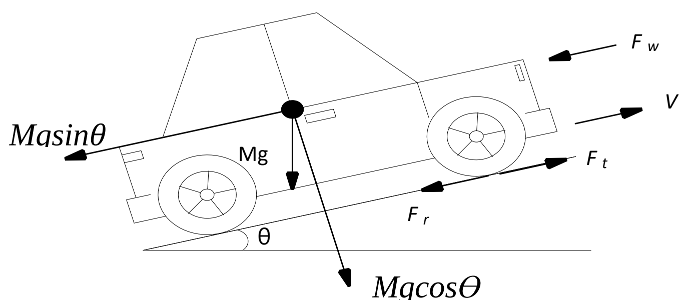


Figure 3-6: Forces acting on electric vehicle

The vehicle has to overcome several forces acting on it while travelling is known as road load [37] - [39] as shown in Figure. This road load F_l consist of four components aerodynamic drag force F_d, rolling resistance force F_r, Clamping (gradient) force F_c.

$$F_l = F_r + F_d + F_c + F_a \quad (3.1)$$

3.4.1. Rolling resistance

Rolling resistance is the resistive force of vehicle which opposes the rolling of the wheels, which is caused due to non-elastic effects at the tire-road surface [40], it is calculated by the formula:

$$F_r = C_{rr} * M * g * \cos(\theta) \quad (3.2)$$

$$F_r = 700 * 9.81 * 0.01 * \cos(7.67) = 68.05N$$

Where, C_{rr}: Coefficient of rolling resistance, $(M * g)$: Vehicle weight in N and θ: Inclination angle. The power required to overcome the rolling resistance of the N is:

$$P_r = F_r * v\left(\frac{m}{sec}\right) \tag{3.3}$$

$$P_r = 68.05 * \frac{50}{3600} = 0.94KW$$

Table 3.1 show that the value of rolling resistance coefficient for different types of road.

Table 3.1: Values of Co-efficient of Rolling Resistance

Contact Surface	C_{rr}
Concrete(good/fair/poor)	0.010/0.015/0.020
Asphalt(good/fair/poor)	0.012/0.017/0.022
Macadam(good/fair/poor)	0.015/0.022/0.037
Snow (2 inch/4 inch)	0.025/0.037
Dirt(smooth/sandy)	0.025/0.037
Mud(firm/medium/soft)	0.037/0.090/0.150
Grass(firm/soft)	0.055/0.075
Sand(firm/soft/dune)	0.060/0.150/0.300

3.4.2. Gradient (climping) resistance

Gradient resistance is the form of gravitational force. It is the force that tends to pull the vehicle back when it is climbing an inclined surface. The grade resistance acting on the vehicle can be calculated as:

$$F_c = M * g * si\,n(\theta) \tag{3.4}$$

$$F_c = 700 * 9.81 * si\,n(7.67) = 916.5N$$

And the climbing power of the Bajaj is given by $P_C = F_C * V_C$. Where, v_c is the climbing velocity we take $V_c = {}^{V_{max}}/_{2}$,

$$P_C = 916.5 * \frac{25\,{}^{km}/_{hr}}{3600} = 6.36KW$$

3.4.3. Aerodynamic drag force

The aerodynamic drag force is the force acting on the vehicle body when it is travelling through air. It consists of three components: the skin friction drags (due to air flow in the boundary layer), normal pressure drags (depends on the vehicle frontal area and speed), induced drag (due to trailing vortices). The expression for aerodynamic drag is given by

$$F_d = \frac{1}{2} * V^2 * C_d * A * \rho \quad (3.5)$$

where, C_d is the aerodynamic drag coefficient, ρ is the air density in $^{kg}/_{m^3}$, V is the sum of speed of vehicle and speed of air in m/s. In general, ρ is taken as 1.23 $^{kg}/_{m^3}$, C_d lies between 0.2 and 1.5, A is frontal area of the plat form A = 0.58 ∗ 0.92 = 0.5336m^2. and can be calculated using the following expression: $C_d = {}^{F_a}/_{0.5\rho AV^2}$ and the air density ρ calculated as; $\rho = \frac{M\rho_0(1-\frac{lh}{T_0})^{\frac{gm}{RL}}}{RT}$ Where, $\rho_0 = 101325$ Pa, sea level standard atmospheric pressure, T_0 = 288.15 K (sea level standard temperature), G = 9.81 m/s2 is the earth-surface gravitational acceleration, 0.0065 K/m, L = is the temperature lapse rate, R =8.31447 J/ (mole K) · universal gas constant, 0.0289644 kg/mole M = molar mass of dry air. $T_L = (0.5\rho C_L BV^2)\, r$.

3.4.4. Aerodynamics lift force

FL aerodynamics lift force and it is caused by pressure difference between the vehicle platform's roof and underside, and is expressed as $F_L = 0.5\rho C_L BV^2$. Where B is the vehicle platform's reference area, C_L is the coefficient of lift, (C_L is 0.10 or 0.16), and can be calculated using the following expression $C_L = {}^{L}/_{0.5\rho BV^2}$, where L is lift and ρ is the air density at STP, ρ is 1.2041. And the aerodynamics lift torque can be expressed as; $T_L = (0.5\rho C_L BV^2)r$.

There are three main force which act on the Bajaj when it travels at constant speed. but while the vehicle is accelerating or decelerating the effect of the force due to the inertia also act up on the vehicles. Gradient force increases when the approaching angle is increase. Aerodynamics force is constant if the speed of the vehicle is assumed to be constant. The total motive force with each component of the force acting on the vehicle is shown on the figure 3.7. We assumed the vehicle speed when move up is 25$^{km}/_{hr}$ and velocity of the air also assumed equals to zero.

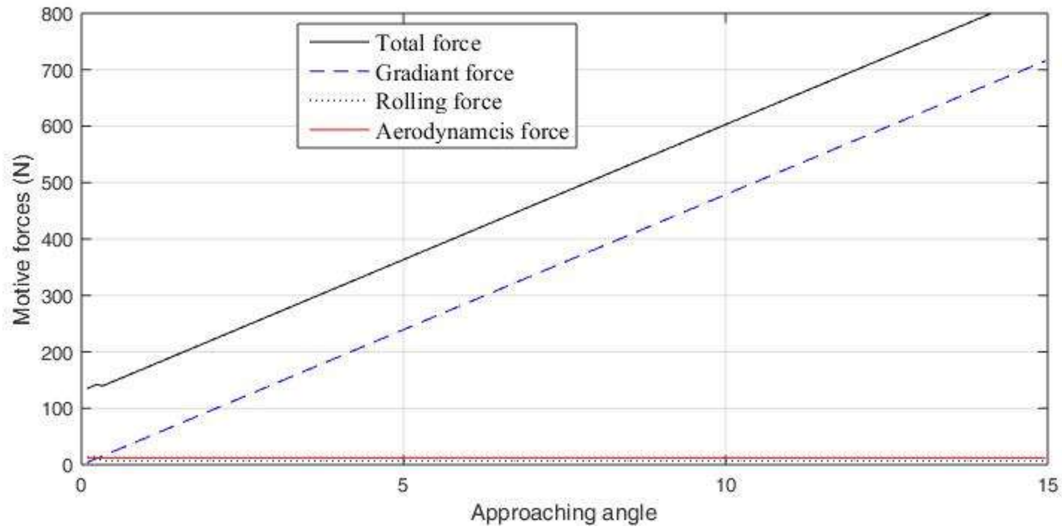


Figure 3-7: Motive force verses Approaching angle

The road load F_l is overcome by the motive force F available at the wheels so the vehicle is driven with the acceleration 'a' which is given by

$$a = \frac{F - F_l}{K_r M} \tag{3.6}$$

where, K_r is correction factor because there is an increase in vehicle mass due to inertia of rotational masses. The tractive power is expressed as given below.

$$P_t = \frac{K_r M}{2t_a}({V_f}^2 + {V_b}^2) \tag{3.7}$$

where, $P_t$is the tractive power, t_a is the acceleration time, V_f is the vehicle final speed and V_b is the vehicle base speed. The power rating obtained by (3.7) is only used for accelerating the vehicle. The power consumed to overcome rolling resistance and dynamic drag should also be considered. During acceleration, the average drag power is given by (3.8)

$$P_{drag} = \frac{1}{t_a}\int_0^{t_a}(Mg\,F_r V + \frac{1}{2}\rho C_d A V^3)dt \tag{3.8}$$

Where, V is the vehicle speed. The acceleration time for an EV is given by (3.9)

$$t_a = \int_0^{V_b} \frac{K_r M}{{P_t}/{V_b} - MgF_r - \frac{1}{2}\rho C_d A V^2} dV + \int_{V_b}^{V_f} \frac{K_r M}{{P_t}/{V_b} - MgF_r - \frac{1}{2}\rho C_d A V^2} dV \tag{3.9}$$

The vehicle speed is expressed in terms of time t, as

$$V = V_f\sqrt{\frac{1}{t_a}} \tag{3.10}$$

Substituting (3.10) in (3.8) and integrating we get

$$P_{drag} = \frac{2}{3}MgC_rV_f + \frac{1}{5}\rho C_d A{V_f}^3 \quad (3.11)$$

The total power required to drive the Bajaj is given by: $P_t = P_r + P_a + P_c$

$$P_T = 0.94KW + 0.5KW + 6.36KW = 7.8KW$$

But the electric motor with output power rating of 7.8KW should not be selected. The losses due to transmission of power to the wheel must be included. Therefore, the mechanical power output (motor tractive) required to drive the wheel is given by the equation:

$$M_{peak} = \frac{P_{max}}{efficiencyof\ gear} \quad (3.12)$$

$M_{peak} = \frac{7.8}{0.98} = 7.95KW$ Approximately we use 8KW maximum power IM motor.

The total motive force with each component of force acting on the Bajaj is shown in the Figure 3.8. (Assumed to be the Bajaj moving average speed from 0 to 50 $^{km}/_{hr}$).

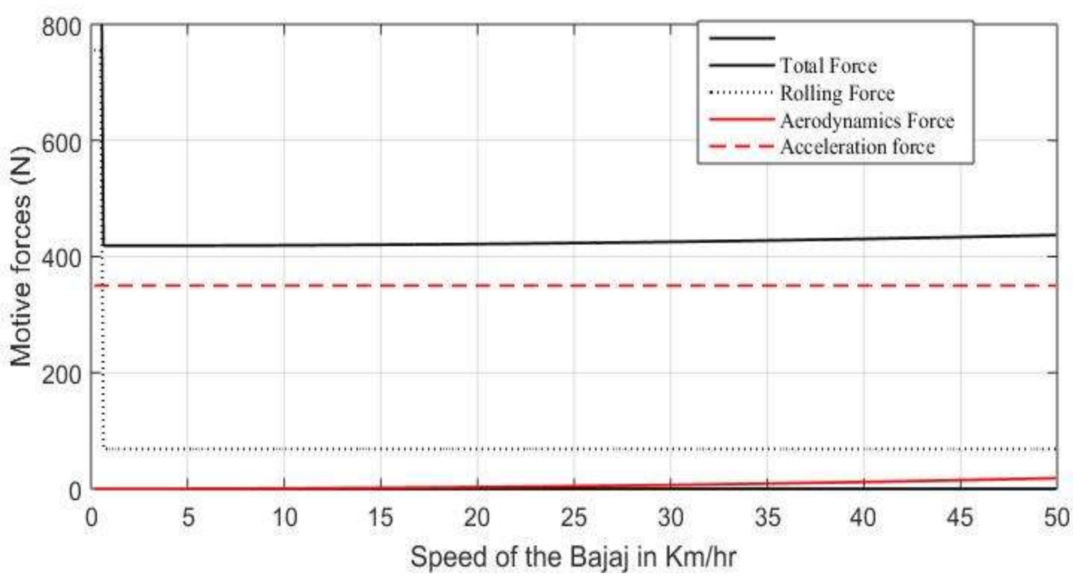


Figure 3-8: Motive force verses speed of the vehicle in km⁄hr

The maximum reactive power is supplied when the Bajaj is clamping the hill of maximum approaching angle which is 7.67 degree with its full load at the speed of 25 $^{km}/_{hr}$. The reason why the speed of the Bajaj is reduced while clamping the hill is to increase torque with limited power supply of the battery and limited power output of the motor. Figure 3.9 show the power needed to be supplied by the motor to drive the Bajaj at constant speed of 25 $^{km}/_{hr}$ with verses approaching angle.

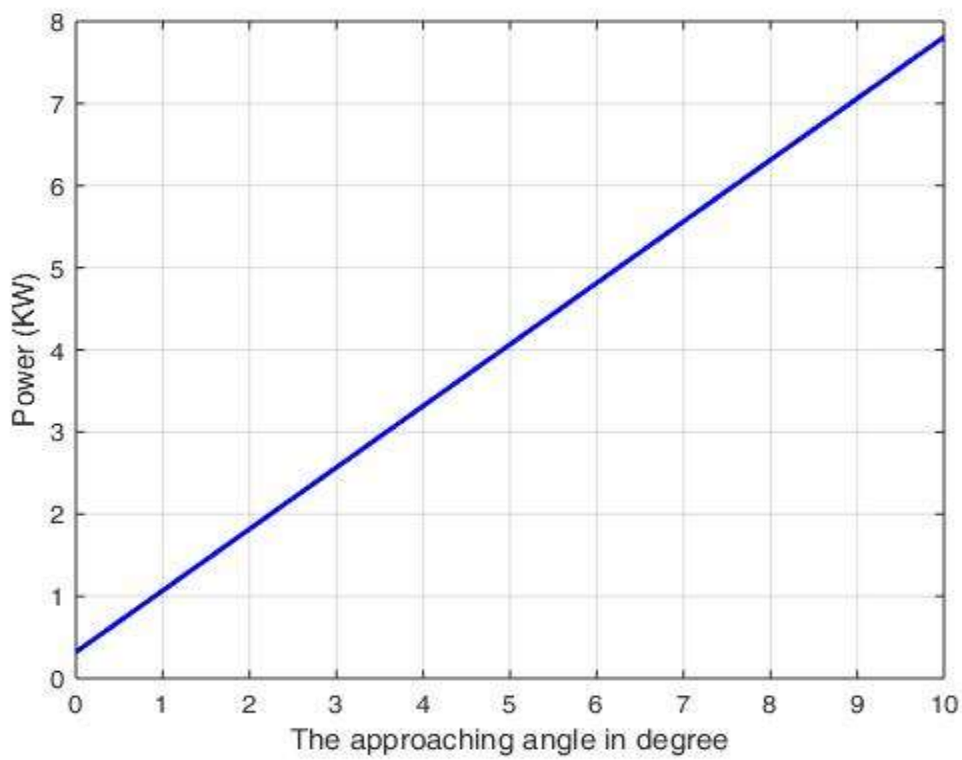


Figure 3-9: T he motor power consumption with respect to approaching angle

In this figure it is assumed that the Bajaj is moving with constant speed of 25 $km/_{hr}$ and suddenly come to face an inclined road of a defined approaching angle.

To obtain the road load characteristics, the following assumptions are made:

1) Velocity is independent of rolling resistance.
2) Head wind velocity is zero.

3.4.5. Torque required on the drive wheel

The torque that is required on the drive wheel will be the one that the drive motor requires to produce so as to obtain the desired drive characteristics. The torque is:

$$T = F_t \times \frac{r}{G} \tag{3.15}$$

$$T = 7900 * \frac{0.1}{15} = 52.6Nm$$

Where, T is torque, r is radius of drive wheel and G is gear ratio. This torque can be obtained by directly mounting a motor with the torque value on the differential of the vehicle or by using a gearbox or chain drive to magnify a lesser torque to this value before it drives the wheel.

3.4.6. Vehicle specification and traction motor selection

We have taken Hora trading Bajaj as a source vehicle whose vehicle parameters and specification are shown below:

Table 3.2: Electric Bajaj specification

Parameter	Symbol	Value
Maximum power	P	7.52kw
Wheel base	B	1980mm
Overall length	L	3030mm
Overall width	W	1500mm
Overall height	H	1780mm
Coefficient of rolling friction	C_{rr}	0.01
Vehicle mass	m	700 Kg
Air density	ρ	1.23 Kg/m^3
Frontal area	A	$0.35m^2$
Aerodynamic drag coefficient	C_d	0.2
Tyre radius	R	0.1m
Gravitational acceleration	g	$9.81m/s^2$

Based on the above calculation and three-wheel electric Vehicle data the Induction motor specification used in this thesis is given as in the following table 3.3.

Table 3.3: Induction motor specification

Parameter	**Value**
Pole	4
Power	8KW
Efficiency	89.5%
Speed	1500-2000RPM
Frequency	50Hz
Slip	2.5%
Voltage	440V
Power factor	0.89
Moment of inertia	0.02
Full load Torque	52.6

3.5. Induction motor modeling

3.5.1. Generalized concept in an arbitrary reference frame

Reference frame are very much like observer platforms, in that each of the platforms gives a unique view of the system at hand as well as a dramatic simplification of the system equation. For example, for the purpose of control, it is desirable to have the system variables as dc quantities, although the actual variables are sinusoidal. This could be accomplished by having a reference frame revolving at the same angular speed as that of the sinusoidal variable. As the reference frames are moving at an angular speed equal to the angular speed equal to angular frequency of sinusoidal supply, so that differential speed between them is reduced to zero, resulting in the sinusoid signal behaving as DC signal from the reference frames. So, by moving that lane, it becomes easier to develop a small-signal equation out of a nonlinear equation, as the operating point is described only by DC values; this then leads to linearized system around operating point. Such advantages are many from using reference frame s. instead of deriving the transformation for each and every particular reference frame; it is advantageous to derive general transformation for an arbitrary rotating reference frame. Then any particular reference frame model can be derived by substituting the appropriate frame speed and position.

3.5.2. Three phases to two phase transformation

The dynamic model of induction motor can be derived if the equivalence between three-phase and two-phase machine is studied. The equivalence is based on the quantity of MMF produced in two-phase and three-phase windings along with equal current magnitudes. Assuming that each of the three-phase winding has N_s turns per phase and equal currents magnitudes, the two-phase winding will have $3N_s/2$ turns per phase for MMF equality. The d and q axes MMF are found by resolving MMF of the three-phase along d and q axes. The common term, the number of turns is cancelled on both sides of equations leaving behind the current equalities. The three-phase stator voltages of an induction machine under balanced conditions can be expressed as,

$$V_a = \sqrt{2}V_{rms}\sin(\omega t) \tag{3.16}$$

$$V_b = \sqrt{2}V_{rms}\sin(\omega t - \tfrac{2\pi}{3}) \tag{3.17}$$

$$V_c = \sqrt{2}V_{rms}\sin(\omega t + \tfrac{2\pi}{3}) \tag{3.18}$$

Here $V_a, V_b\ and\ V_c$ are the three line voltage.

The relationship between α_β and ABC is as follows

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.19}$$

Then, the direct and quadrature axes voltages are: -

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{3.20}$$

The instantaneous values of the stator and rotor currents in three-phase system are ultimately calculated using the following transformation;

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{3.21}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.22}$$

3.5.3. Block diagram and transfer function of induction motor

Mathematical modeling of induction motor can be obtained by taking all the basic equation of machine. The per phase equivalent circuit that refers to stator side is shown in figure 3-10 below.

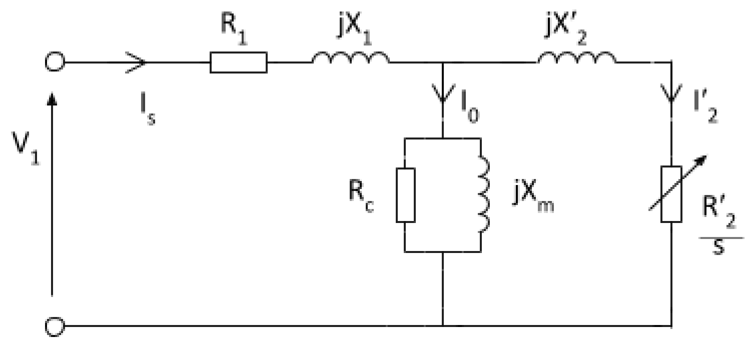


Figure 3-10: Per-phase equivalent circuit referred to stator side[L2]

$$V_a = I_a R_a + JX_s I_a + E_b \quad (3.23)$$

$$E_b \infty \frac{d\theta}{dt}$$

Applying Laplace transforms,

$$V_a = V_1, I_a = I_s$$

$$V_a = I_a(s)(R_a + jX_s) + E_b(S) \quad (3.24)$$

We know that

$$E_b = k_t s\Theta(s) \quad (3.25)$$

Substituting, we get,

$$V_a(s) = I_a(S)Z(s) + k_t s\Theta(s) \quad (3.26)$$

$$\frac{V_a(s) - k_t s\Theta(s)}{Z(s)} = I_a(s) \quad (3.27)$$

Electrical torque is given by

$$T_e = \frac{KE^2R}{R^2 + X^2} \quad (3.28)$$

Taking Laplace transforms,

$$T_e = E^2 sin(\Theta) \quad (3.29)$$

Mechanical torque is given by

$$T_m = J\ddot{\Theta} + B\Theta \quad (3.30)$$

Taking Laplace transforms,

$$T_m(S) = (Js^2 + Bs)\Theta(s) \tag{3.31}$$

$$T_m = T_e \Rightarrow E^2\Theta(s) = Js^2 + Bs(\Theta(s))$$

$$(Js^2 + Bs - E^2)\Theta(s) = T_m$$

$$Js^2 + Bs - E^2 = \frac{T_m}{\Theta(s)}$$

$$\frac{\Theta(s)}{T_m(s)} = \frac{1}{Js^2 + Bs - E^2} \tag{3.32}$$

We know that T ∝ $\Phi I_a \cos(\theta)$ (take θ =0)

$$T = K\Phi I_a$$

$$T = K\Phi(s) I_a(s) \tag{3.33}$$

From above we know

$$\frac{K_a[V_a(s) - K_t s\theta(s)]}{Z(S)} = (Js^2 + Bs - E^2)\theta(s) \tag{3.34}$$

$$K_a V_a(s) = (Js^2 + Bs - E^2)\theta(s)Z(s) + K_t s\theta(s)$$

$$\frac{V_a(s)}{\theta(s)} = \frac{(Js^2 + Bs - E^2)Z(s) + K_a K_t s}{K_a}$$

$$\frac{\theta(s)}{V_a(s)} = \frac{K_a}{(Js^2 + Bs - E^2)Z(s) + K_a K_t s} = \frac{K_a}{(Js^2 + Bs - E^2)(R_a + L_a S) + K_a K_t s} \tag{3.35}$$

$$\frac{\theta(s)}{V_a(s)} = \frac{K_a}{JL_a s^3 + (R_a J + BL_a)s^2 + (BR_a + K_a K_t)s}$$

Parameters taken:

$K_a =$ 0.004, Where $K_a = \frac{3}{2\pi n_s}$

K_t = 0.5

J (Inertia constant) = 0.449 kgm^2

R = 1.2Ω

B (Friction coefficient) = 8

L = 0.0059H

Transfer function gives $\frac{\theta(s)}{V_a(s)} = \frac{0.004}{0.003s^3 + 0.587s^2 + 9.6s}$

Transfer function G(s) = $\frac{0.004}{0.003s^3 + 0.587s^2 + 9.6s}$ block diagram of the motor is shown in the following figure. Based on the transfer function block diagram of motor is design in the figure 3-11 below.

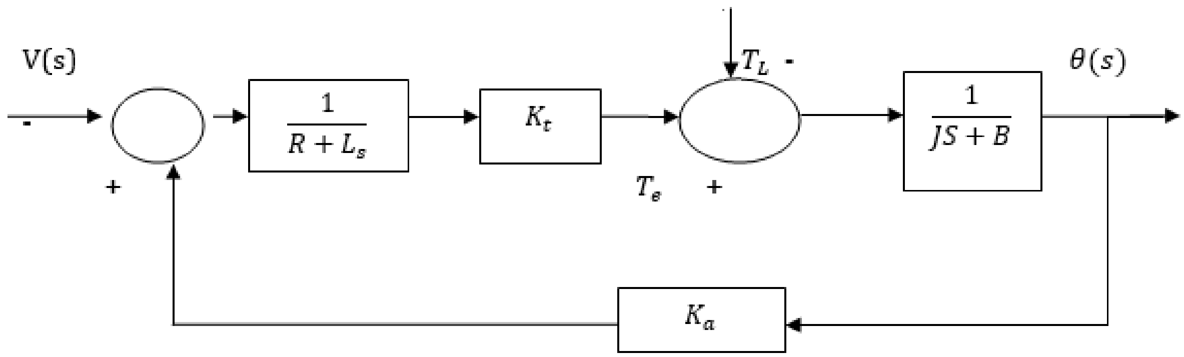


Figure 3-11: Block diagram of motor

3.6. Space vector pulse width modulation

The circuit in Figure 3-12 demonstrates the foundation of a two-level voltage source converter. It has six switches (1- 6) and each of these are represented with an IGBT switching device. A, B and C represents the output for the phase shifted sinusoidal signals. Depending on the switching combination the inverter will produce different outputs, creating the two-level signal. The biggest difference from other PWM methods is that the SVPWM uses a vector as a reference. This gives the advantage of a better overview of the system.

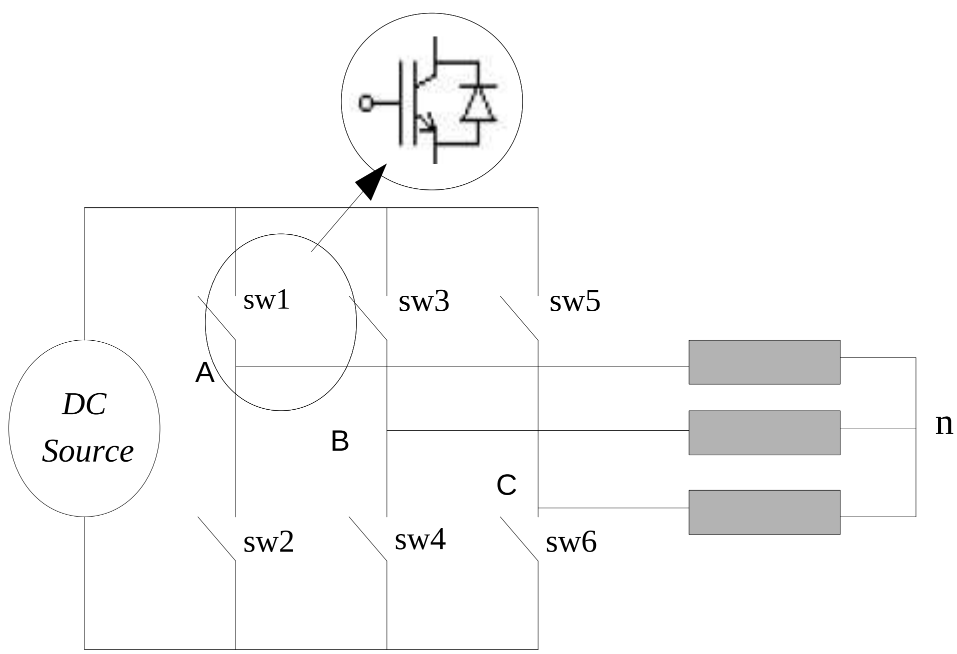


Figure 3-12: Three-phase inverter, with a load and neutral point [L2]

3.6.1. Reference vector

The reference vector is represented in a αβ-plane. This is a two-dimensional plane transformed from a three-dimensional plane containing the vectors of the three phases. The switches being ON or OFF is determined by the location of the reference vector on this αβ-plane.

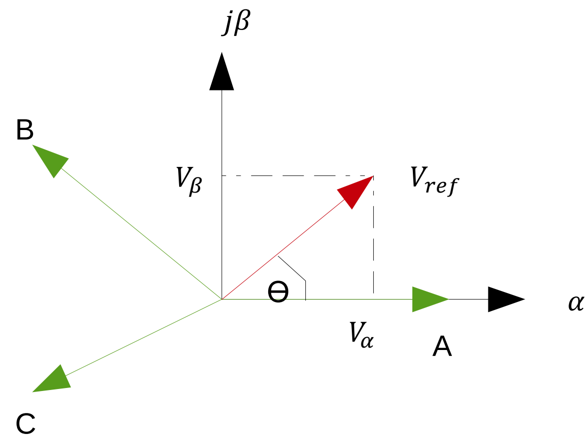


Figure 3-13: The reference vector in the two- and three-dimensional plane

Table 3.4 shows that the switches can be ON or OFF, meaning 1 or 0. The switches 1, 3, 5 are the upper switches and if these are 1 (separately or together) it turns the upper inverter leg ON and the terminal voltage (V_a, V_b, V_c) is positive ($+V_{DC}$). If the upper switches are zero, then the terminal voltage is zero).

Table 3.4: Switching states for each phase leg

Switching states	***A***			***B***			***C***		
	S_1	S_2	V_{an}	S_3	S_4	V_{bn}	S_5	S_6	V_{cn}
1	ON	OFF	V_{DC}	ON	OFF	V_{DC}	ON	OFF	V_{DC}
0	OFF	ON	0	OFF	ON	0	OFF	ON	0

The lower switches are complementary to the upper switches, so the only possible combinations are the switching states: 000, 001, 010, 011, 100, 110, 110, 111. This means that there are 8 possible switching states, for which two of them are zero switching states and six of them are active switching states. These are represented by active ($V_1 - V_6$) and zero (V_0) vectors. The zero vectors are placed in the axis origin (Figure 3-14).

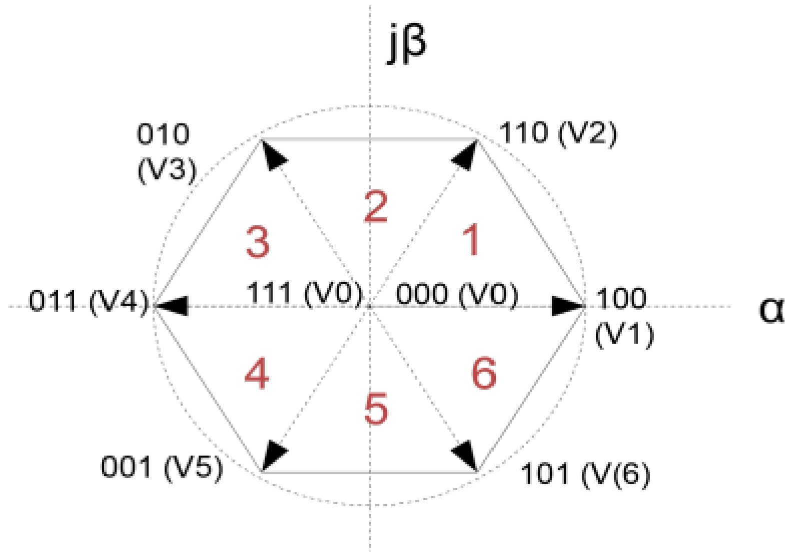


Figure 3-14: Space voltage vectors in different sectors

It is assumed that the three-phase system is balanced

$$V_{AO} + V_{BO} + V_{CO} = 0 \tag{3.36}$$

These are the instantaneous phase voltages:

$$V_A = V \sin(\theta t) \tag{3.37}$$

$$V_B = V \sin(\theta t + \tfrac{2\pi}{3}) \tag{3.38}$$

$$V_c = V \sin(\theta t + \tfrac{4\pi}{3}) \tag{3.39}$$

When the three phase voltages are applied to an AC machine a rotating flux is created. This flux is represented as one rotating voltage vector. The magnitude and angle of this vector can be calculated with Clark's Transformation:

$$V_{ref} = V_\alpha + jV_\beta = \tfrac{2}{3}(V_a + aV_b + a^2 V_c) \tag{3.40}$$

$$a = e^{j\frac{2\pi}{3}}$$

The magnitude and angle (determining in which sector the reference vector is in) of the reference vector is:

$$|V_{ref}| = \sqrt{{V_\alpha}^2 + {V_\beta}^2} \tag{3.41}$$

The reference voltage can then be expresses as:

$$V_\alpha + jV_\beta = \frac{2}{3}(V_a + e^{j\frac{2\pi}{3}}V_b + e^{-j\frac{2\pi}{3}}V_c) \qquad (3.42)$$

Inserting the phase shifted values for V_a, V_b and V_C, give

$$V_\alpha + jV_\beta = \frac{2}{3}(V_a + \cos(\frac{2\pi}{3})V_b + \cos(\frac{2\pi}{3})V_c) + j\frac{2}{3}(V_a + \sin(\frac{2\pi}{3})V_b - \sin(\frac{2\pi}{3})V_c) \qquad (3.43)$$

The voltage vectors on the alpha and beta axis can then be described as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & \cos(\frac{2\pi}{3}) & \cos(\frac{2\pi}{3}) \\ 0 & \sin(\frac{2\pi}{3}) & -\sin(\frac{2\pi}{3}) \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (3.44)$$

$$V_\alpha = \frac{2}{3}(V_a - \frac{1}{2}V_b - \frac{1}{2}V_c) \qquad (3.45)$$

$$V_\beta = \frac{2}{3}(\frac{\sqrt{3}}{2}V_b - \frac{\sqrt{3}}{2}V_c \qquad (3.46)$$

In this step V_α, V_β, V_{ref} and the reference angle is calculated. The next step is to calculate the duration time for each vector $V_1 - V_6$.

3.6.2. Time duration

V_{ref} can be found with two active and one zero vector. For sector 1 (0 to $\frac{\pi}{3}$): V_{ref} can be located with V_0 , V_1 and V_2 . V_{ref} in terms of the duration time can be considered as:

$$V_{ref} * T_c = V_1 * \frac{T_1}{T_c} + V_2 * \frac{T_2}{T_c} + V_0 * \frac{T_0}{T_c}$$

$$V_{ref} = V_1T_1 + V_2T_2 + V_0T_0 \qquad (3.47)$$

The total cycle is given by:

$$T_C = T_1 + T_2 + T_0 \qquad (3.48)$$

The position of V_{ref}, V_1, V_2 and V_0 can be described with its magnitude and angle:

$$V_{ref} = V_{ref} * r^{j0}$$

$$V_1 = \frac{2}{3} * V_{DC} * e^{j\frac{\pi}{3}}$$

$$V_0 = 0 \qquad (3.49)$$

$$T_C * V_{ref} * \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} = T_1 * \frac{2}{3} * V_{DC} * \begin{pmatrix} 1 \\ 0 \end{pmatrix} + T_2 * \frac{2}{3} * V_{DC} * \begin{pmatrix} \cos(\frac{\pi}{3}) \\ \sin(\frac{\pi}{3}) \end{pmatrix} \qquad (3.50)$$

Dividing these in real and imaginary parts simplifies the calculation for each duration time:

Real part: $T_C * V_{ref} * \cos(\theta) = T_1 * \frac{2}{3} * V_{DC} + T_2 * \frac{1}{3} * V_{DC}$

Imaginary part: $T_C * V_{ref} * \sin(\theta) = T_2 * \frac{1}{\sqrt{3}} * V_{DC}$

T_1 and T_2 is then given by:

$$T_1 = T_c * \frac{\sqrt{3}*V_{ref}}{V_{DC}} * \sin\left(\frac{\pi}{3} - \theta\right) = T_c * a * \sin\left(\frac{\pi}{3} - \theta\right) \quad (3.51)$$

$$T_2 = T_c * \frac{\sqrt{3}*V_{ref}}{V_{DC}} * \sin(\theta) = T_c * a * \sin(\theta) \quad (3.52)$$

Where $a = \frac{\sqrt{3}*V_{ref}}{V_{DC}}$ is modulation index.

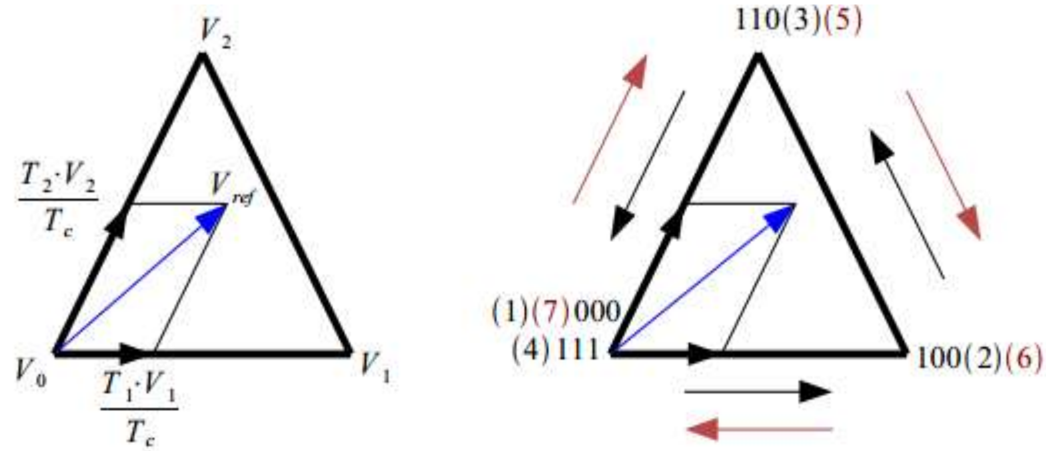


Figure 3-15: Space vector diagram for Sector 1 (a) described with the duty cycle for each vector (b) described with it switching states

The general calculation to receive the duty times in the rest of the sectors is given by:

$$T_1 = T_c * a * \sin\left(\frac{\pi}{3} - \theta + \frac{n-1}{3} * \pi\right) = T_C * a * \left[\sin(\tfrac{n}{3}\pi)\cos(\theta) - \cos(\tfrac{n}{3}\pi)\sin(\theta)\right] \quad (3.53)$$

$$T_2 = T_c * a * \sin\left(\theta - \frac{n-1}{3} * \pi\right) = T_C * a * \left[-\cos(\theta)\sin\left(\frac{n-1}{3}\pi\right) + \sin(\theta)\cos(\tfrac{n-1}{3}\pi)\right] \quad (3.54)$$

$$T_0 = T_c - T_1 - T_2 \quad (3.55)$$

Choosing n as the number of the sector (n = 1, 2, 3, 4, 5, 6) the calculations for the time duration in each sector is mentioned in tables 3.5 below.

Table 3.5: Switching states and its corresponding voltage vectors

Switches states			***corresponding Voltage Vectors***		
A	***B***	**c**	***Vector***	***Magnitude***	***Angle***
0	0	0	V_0	0	0
1	1	1			
1	0	0	V_1	$\frac{2}{3}V_{DC}$	0
1	1	0	V_2	$\frac{2}{3}V_{DC}$	$\frac{\pi}{3}$
0	1	0	V_3	$\frac{2}{3}V_{DC}$	$\frac{2\pi}{3}$
0	1	1	V_4	$\frac{2}{3}V_{DC}$	π
0	0	1	V_5	$\frac{2}{3}V_{DC}$	$\frac{4\pi}{3}$
1	0	1	V_6	$\frac{2}{3}V_{DC}$	$\frac{5\pi}{3}$

For each sector there are 7 switching states for each cycle. It always starts and ends with a zero vector. This also means that there is no extra switching state needed when changing the sector. The uneven numbers travel counter clockwise in each sector and the even sectors travel clockwise. The time duration taken for each sector is illustrated in table 3.6 below.

Table 3.6: Duration time for each sector

Sector	***Duration times***		
	T_1	T_2	T_0
1	$T_c * a * \sin\left(\frac{\pi}{3} - \theta\right)$	$T_c * a * \sin(\theta)$	$T_c - T_1 - T_2$
2	$T_c * a * \sin\left(\frac{2\pi}{3} - \theta\right)$	$T_c * a * \sin\left(\theta - \frac{\pi}{3}\right)$	$T_c - T_1 - T_2$
3	$T_c * a * \sin(\pi - \theta)$	$T_c * a * \sin\left(\theta - \frac{2\pi}{3}\right)$	$T_c - T_1 - T_2$
4	$T_c * a * \sin\left(\frac{4\pi}{3} - \theta\right)$	$T_c * a * \sin(\theta - \pi)$	$T_c - T_1 - T_2$
5	$T_c * a * \sin\left(\frac{5\pi}{3} - \theta\right)$	$T_c * a * \sin\left(\theta - \frac{4\pi}{3}\right)$	$T_c - T_1 - T_2$
6	$T_c * a * \sin(2\pi - \theta)$	$T_c * a * \sin\left(\theta - \frac{5\pi}{3}\right)$	$T_c - T_1 - T_2$

3.6.3. Switching time

Duty cycle for each sector there are 7 switching states for each cycle. It always starts and ends with a zero vector. This also means that there is no extra switching state needed when changing the sector. The uneven numbers travel counter clockwise in each sector and the even sectors travel clockwise. For sector 1 it goes through these switching states: 000 – 100 – 110 – 111 – 110 – 100 - 000, one round and then back again. This is during the time T_c and it has to be divided amongst the 7 switching states, three of them being zero vectors.

$$T_c = \frac{T_0}{4} + \frac{T_1}{2} + \frac{T_0}{2} + \frac{T_2}{2} + \frac{T_1}{2} + \frac{T_0}{4} \tag{3.56}$$

This can be calculated for all the sectors (Figure 3-17). There are different kinds of waveforms: center aligned and edge aligned. Edge aligns waveforms makes it easier when comparing with the carrier wave, but the center aligned has the advantage of reducing the harmonics and also reducing noise.

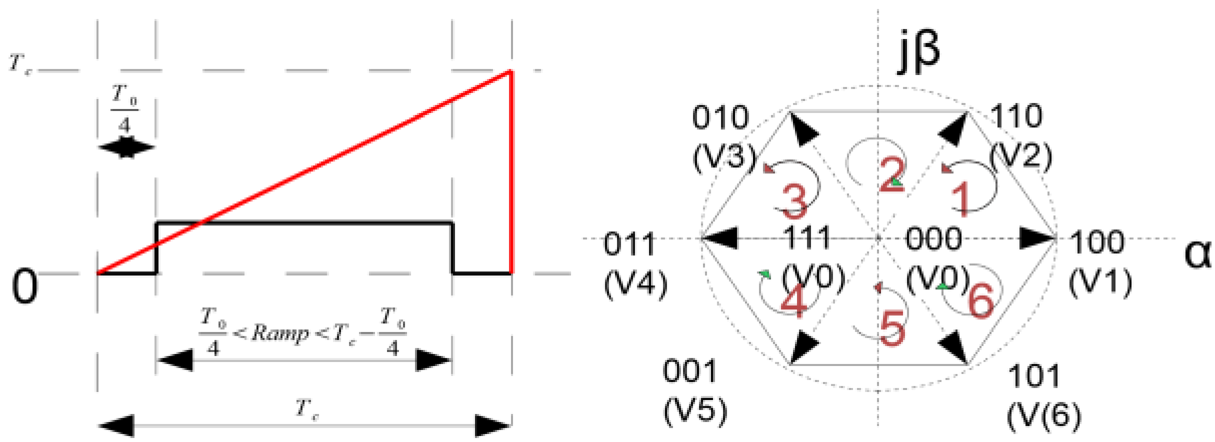


Figure 3-16: (a) Illustration ramp (b) Space vector diagram with every switching state and sequence

Following the pattern for each sector results in a ON/OFF waveform for each sector and phase. Each switch has it switching information depending on where the reference vector is located. For Sector 1, the switch is ON between ${T_0}/_4$ and $T_C - {T_0}/_4$ in the first phase, between ${T_0}/_4 + {T_1}/_2$ and $T_C - ({T_0}/_4 + {T_1}/_2)$ for the second phase and so on. For the switch to know that it should be switched ON at these specific times requires a timer that can give this information. Something like a ramp or a repeated sequence can be used as a reference (Figure 3-16a), so the ramp indicates that the switches should be ON/OFF at specific times. Table 3.10 describe duty time for each sectors

Table 3.7: Duty time for each sector

Sector	***Duty Time Upper Switches***		***Duty Time Lower Switches***	
1	S_1	$T_1 + T_2 + \frac{T_0}{2}$	S_2	$\frac{T_0}{2}$
	S_3	$T_2 + \frac{T_0}{2}$	S_4	$T_1 + \frac{T_0}{2}$
	S_5	$\frac{T_0}{2}$	S_6	$T_1 + T_2 + \frac{T_0}{2}$
2	S_1	$T_2 + \frac{T_0}{2}$	S_2	$T_1 + \frac{T_0}{2}$
	S_3	$T_1 + T_2 + \frac{T_0}{2}$	S_4	$\frac{T_0}{2}$
	S_5	$\frac{T_0}{2}$	S_6	$T_1 + T_2 + \frac{T_0}{2}$
3	S_1	$\frac{T_0}{2}$	S_2	$T_1 + T_2 + \frac{T_0}{2}$
	S_3	$T_1 + T_2 + \frac{T_0}{2}$	S_4	$\frac{T_0}{2}$
	S_5	$T_2 + \frac{T_0}{2}$	S_6	$T_1 + \frac{T_0}{2}$
4	S_1	$\frac{T_0}{2}$	S_2	$T_1 + T_2 + \frac{T_0}{2}$
	S_3	$T_2 + \frac{T_0}{2}$	S_4	$T_1 + \frac{T_0}{2}$
	S_5	$T_1 + T_2 + \frac{T_0}{2}$	S_6	$\frac{T_0}{2}$
5	S_1	$T_2 + \frac{T_0}{2}$	S_2	$T_1 + \frac{T_0}{2}$
	S_3	$\frac{T_0}{2}$	S_4	$T_1 + T_2 + \frac{T_0}{2}$
	S_5	$T_1 + T_2 + \frac{T_0}{2}$	S_6	$\frac{T_0}{2}$

6	S_1	$T_1 + T_2 + \frac{T_0}{2}$	S_2	$\frac{T_0}{2}$
	S_3	$\frac{T_0}{2}$	S_4	$T_1 + T_2 + \frac{T_0}{2}$
	S_5	$T_2 + \frac{T_0}{2}$	S_6	$T_1 + \frac{T_0}{2}$

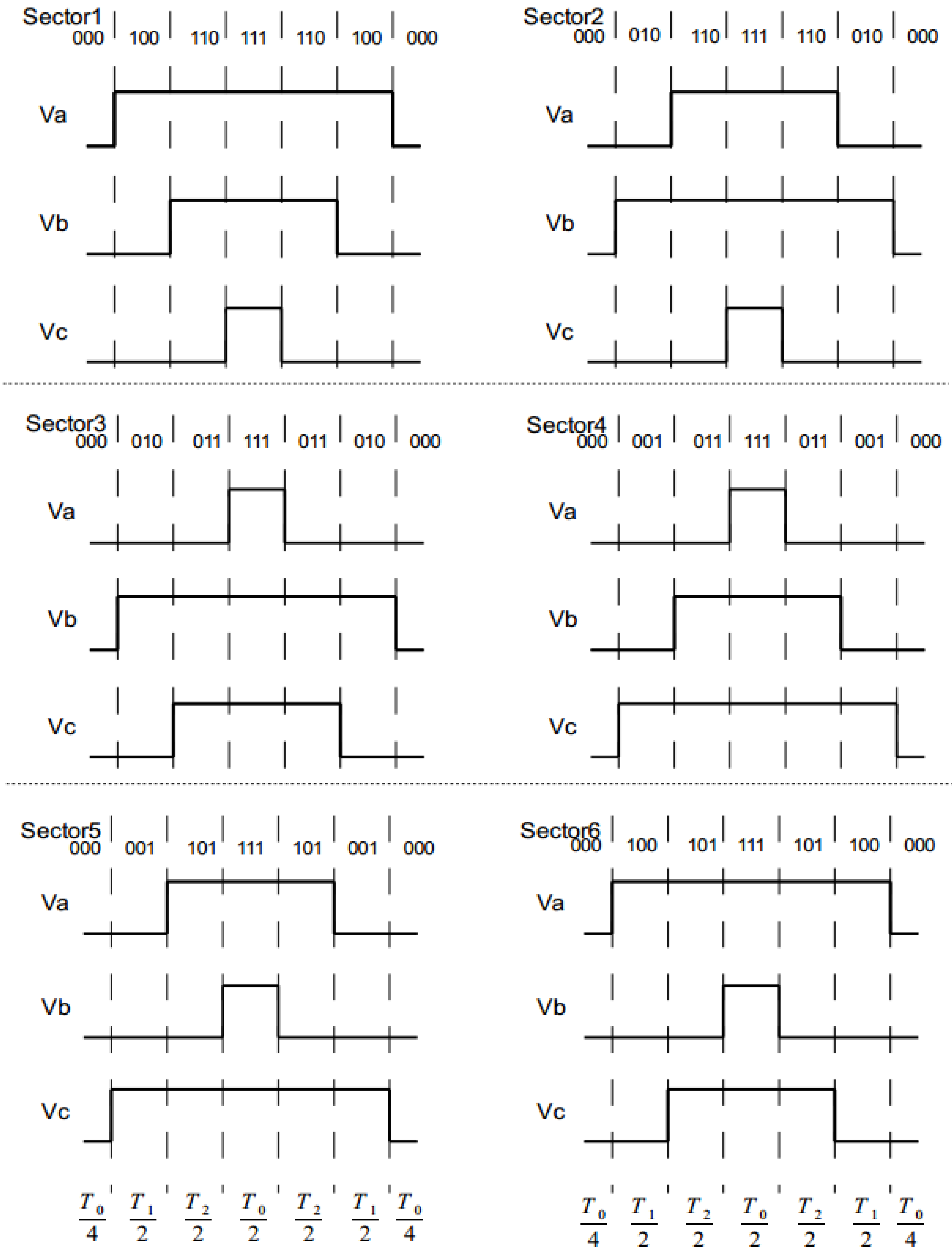


Figure 3-17: Waveform showing sequencing of switching states for all the regions

3.7. Proportional integral controller

Because of easy design, low cost and simple structure the proportional integral controllers are most widely used in industries. As an on-off controller the proportional integral controller eliminates forced oscillation and steady state error. The overall stability and response of the speed will have negative impact due to integral mode. Therefore, the proportional integral controller will not increase the speed of the response. Because, proportional controller does not have means to predict what will happen with the error in near future. So, by introducing derivative mode this problem will be solved. So now the proportional controller now gets the ability to predict error in future and then decreases reaction time.

In industries speed of the response is not an issue then proportional integral controller is most widely used. Actually, proportional integral controller is an integral error compensation scheme. The integral of the actuating signal is the reason for the response of the output.

The output produced by this type of controller consists of two terms. In those two terms one is the proportional to the actuating signal and other is proportional to its integral. Therefore, in general this type of controller is known as PI controller or proportional plus controller.

Based on Ziegler Nichols tuned technique the value of K_p and K_t are calculated from the wave form that are simulated using the transfer function its calculated value is $K_p = 0.6$ and $K_t = 80$.

$$output(t) = K_p\, e(t) + K_t \int_0^t e(\tau)d\tau \tag{3.57}$$

$$e(t) = Set\ Referance\ Value - Actual\ Calculated\ Value$$

$$e(t) = \omega_{ref} - \omega_m(t) \tag{3.58}$$

$$T_{ref}(t) = T_{ref}(t-1) + K_p[e(t) - e(t-1)] + K_1 e(t) \tag{3.59}$$

Where K_p and K_I is Speed Controller gain of proportional and integral controller respectively.

3.8. Software simulation modeling and design

3.8.1. MATLAB/SIMULINK model

The simulation results are given for the induction motor for the following specification: Number of poles [P] = 4, Frequency [F] = 50 Hz, Number of phases = 3, Stator resistance [Rs] = 1.115 ohms, Rotor resistance [Rr] = 1.083 ohms, Stator inductance [Ls] = 0.00597H, Mutual inductance [Lm] = 0.2037 H, Moment of inertia [J] = 0. 02 Kg-m/sec. Figure 3-18 describe the overall Matlab Simulink model of thesis work.

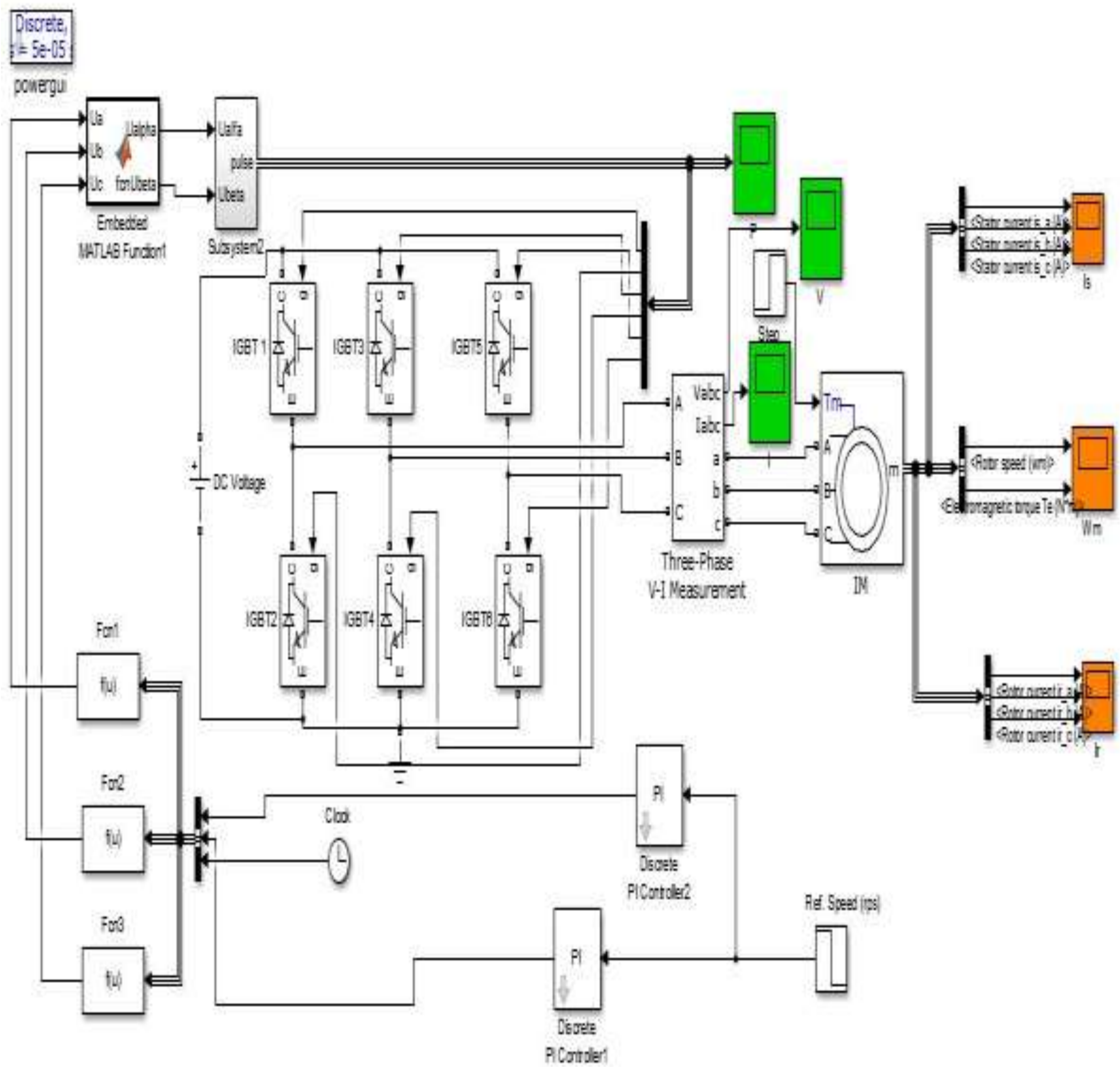


Figure 3-18: MATLAB open loop Simulink model of SVPWM based induction motor

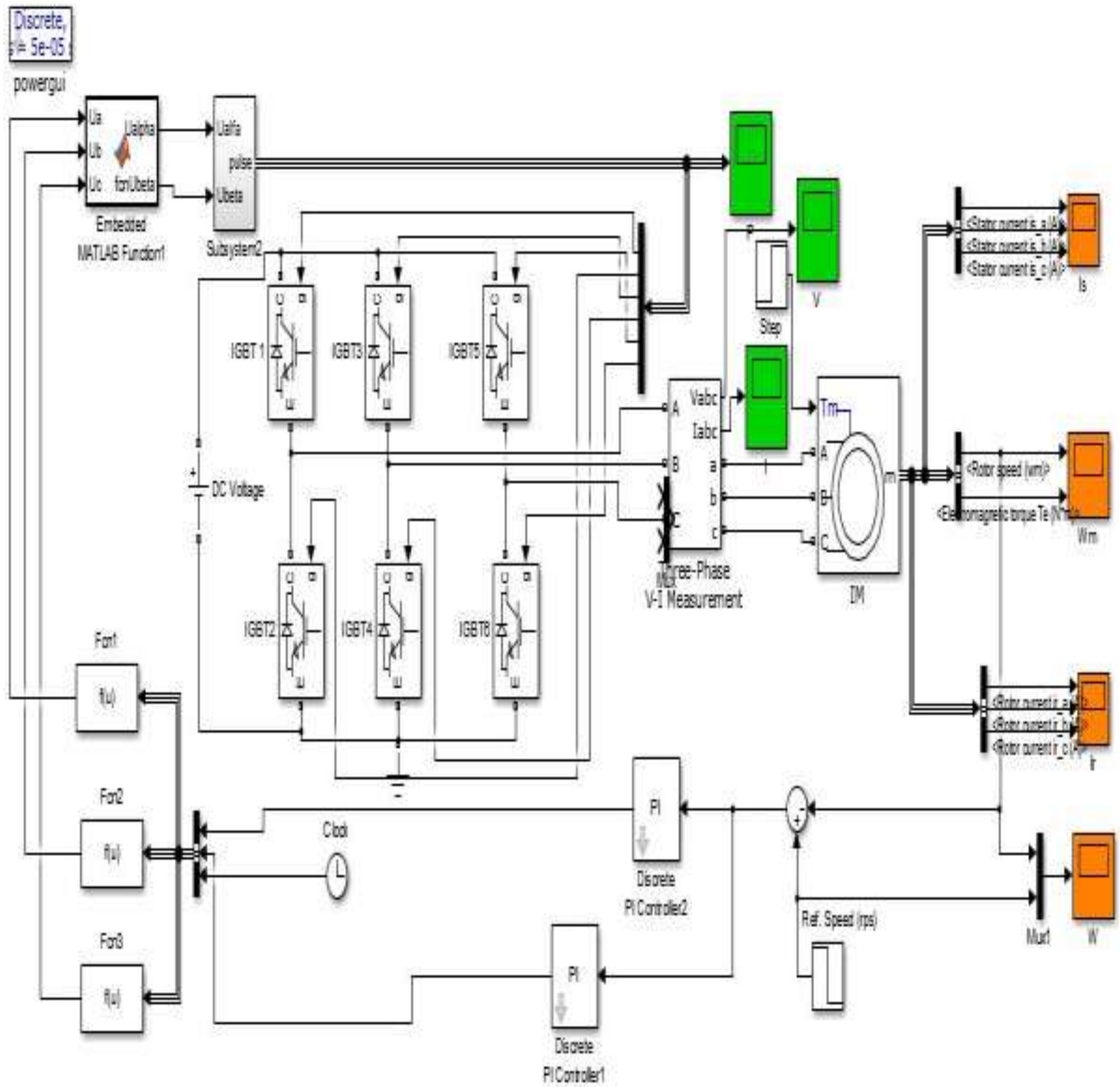


Figure 3-19: Closed loop MATLAB Simulink model of SVPWM based induction motor

The above Figure 3-19 shows the complete MATLAB / SIMULINK model of the space vector pulse width modulation-based induction motor with PI control. The step by step subsystem model of the SVPWM method is shown Figure.A1, Figure.A2, Figure.A3, Figure.A4, Figure.A5 and Figure.A6. These subsystem models are designed on the basis of the mathematical equation of SVPWM methods as it is discussed at the beginning of this chapter.

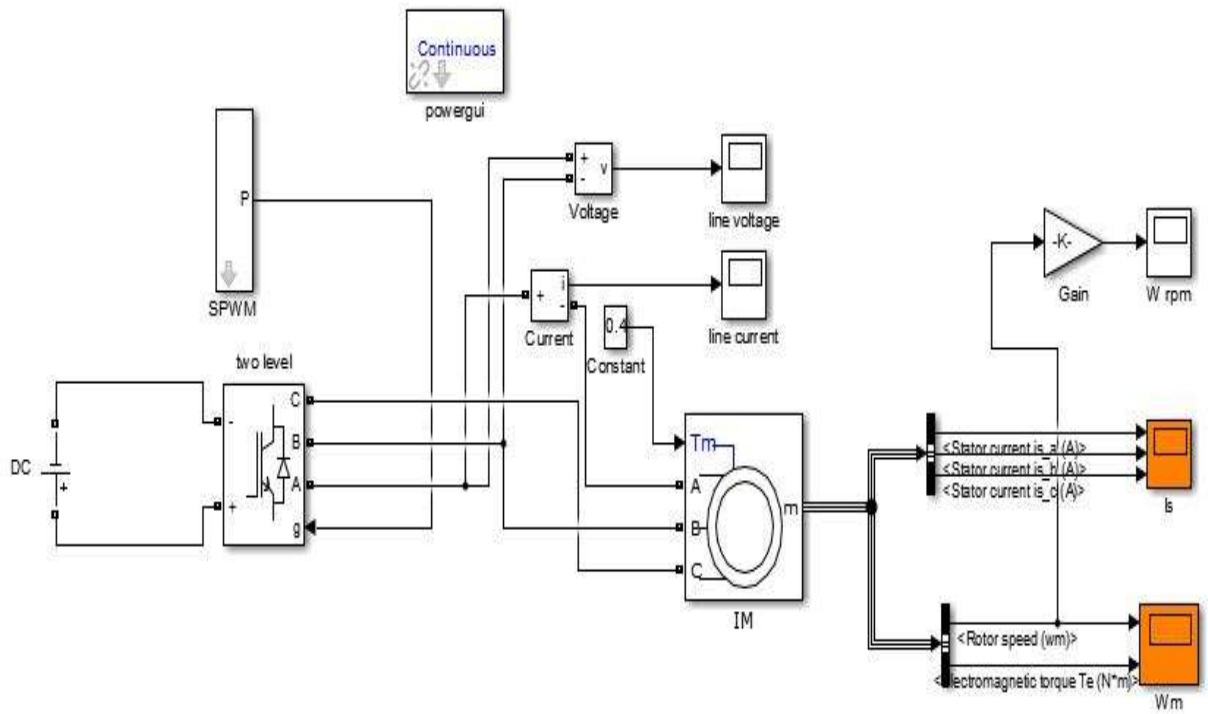


Figure 3-20: SIMULNK model of SPWM inverter fed induction motor

3.8.2. Proteus simulation

Proteus 8 is best simulation software for various designs with microcontroller. It is mainly popular because of availability of almost all microcontrollers and CONTROLLER in it. So, it is a handy tool to test programs and embedded designs. We can simulate your programming of microcontroller in Proteus 8 Simulation Software. Proteus is used for the schematic and simulation of our thesis. It uses ISIS of the proteus for drawing circuit diagram of AC drive system. By using this software, we can check the complete working of our thesis.

In Proteus phase inverter is made by using CONTROLLER ARDUINO MEGA 2560. This uses six IGBT switches that are turned on and off by using pulse width modulation. The turn on and off of the IGBTs give rise to three phase output from single phase input. The IGBT used is 4PC40UD. These are high speed switching devices that turn on and turn off by sequence to produce three phase output. The inverter is simulated and switching of inverter is indicated with LEDs. The switching with LED positions is shown as in figure below. The LEDs turn on and turn off as directed with pulses resulting from pulse width modulation. The oscilloscope is used to observe the three-phase output. Figure 3-21 describe the overall protous simulation design of the systems.

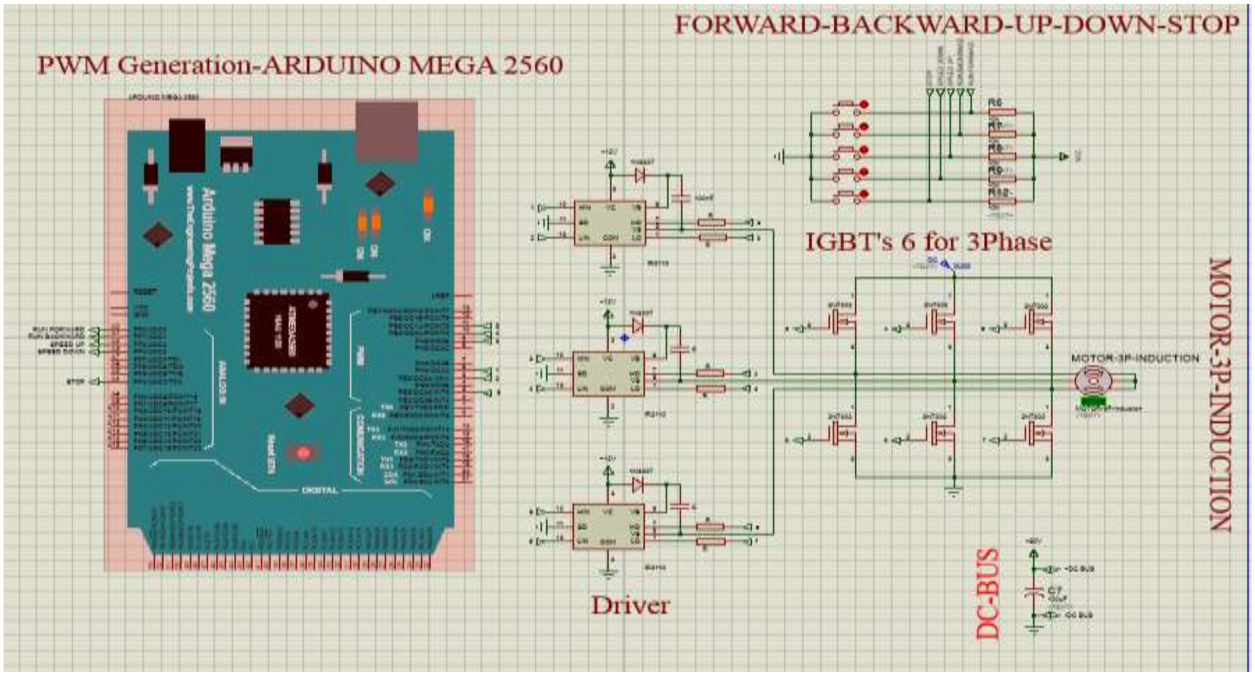


Figure 3-21: Inverter with Switching Sequence

3.8.3. Easy PC design

Easy PC software is easy to use for drawing layouts. This software is used to draw layout of the inverter, base driver and control circuit. This is mostly used by Engineers because of its simplicity.

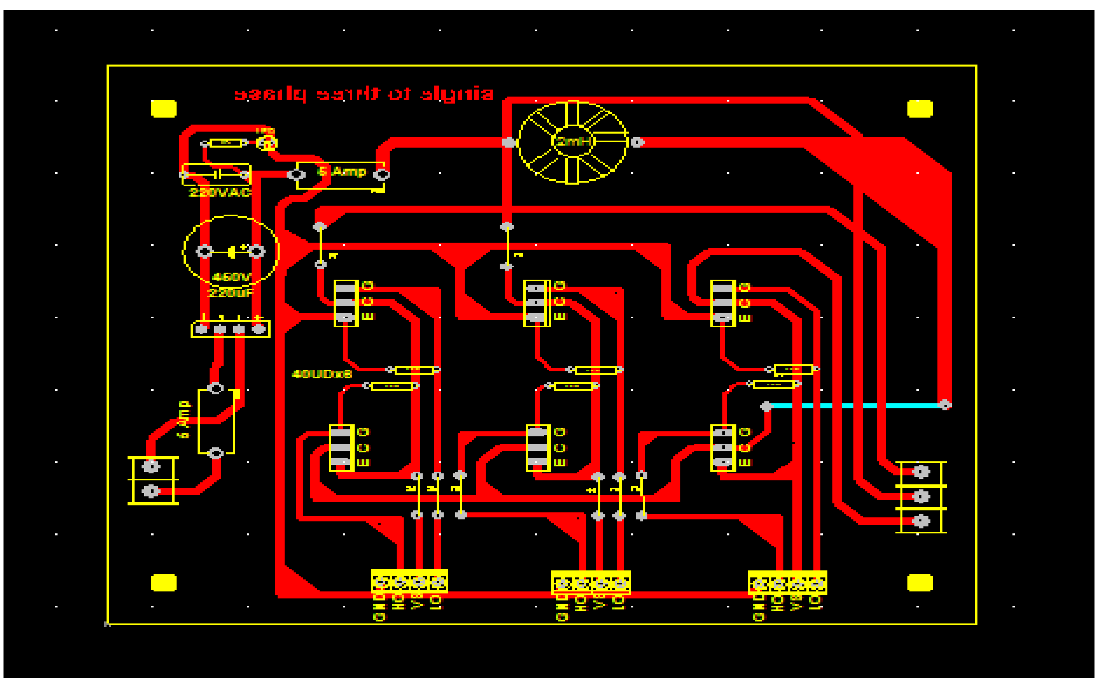


Figure 3-22: Three Phase Inverter Layout

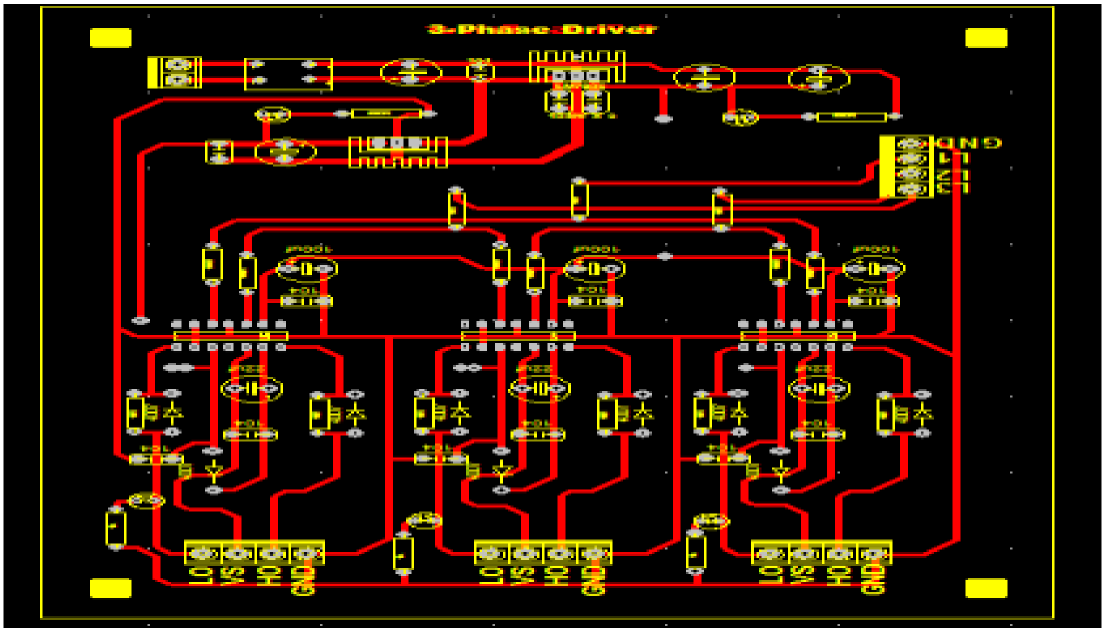


Figure 3-23: IR2110 Base Driver Layout

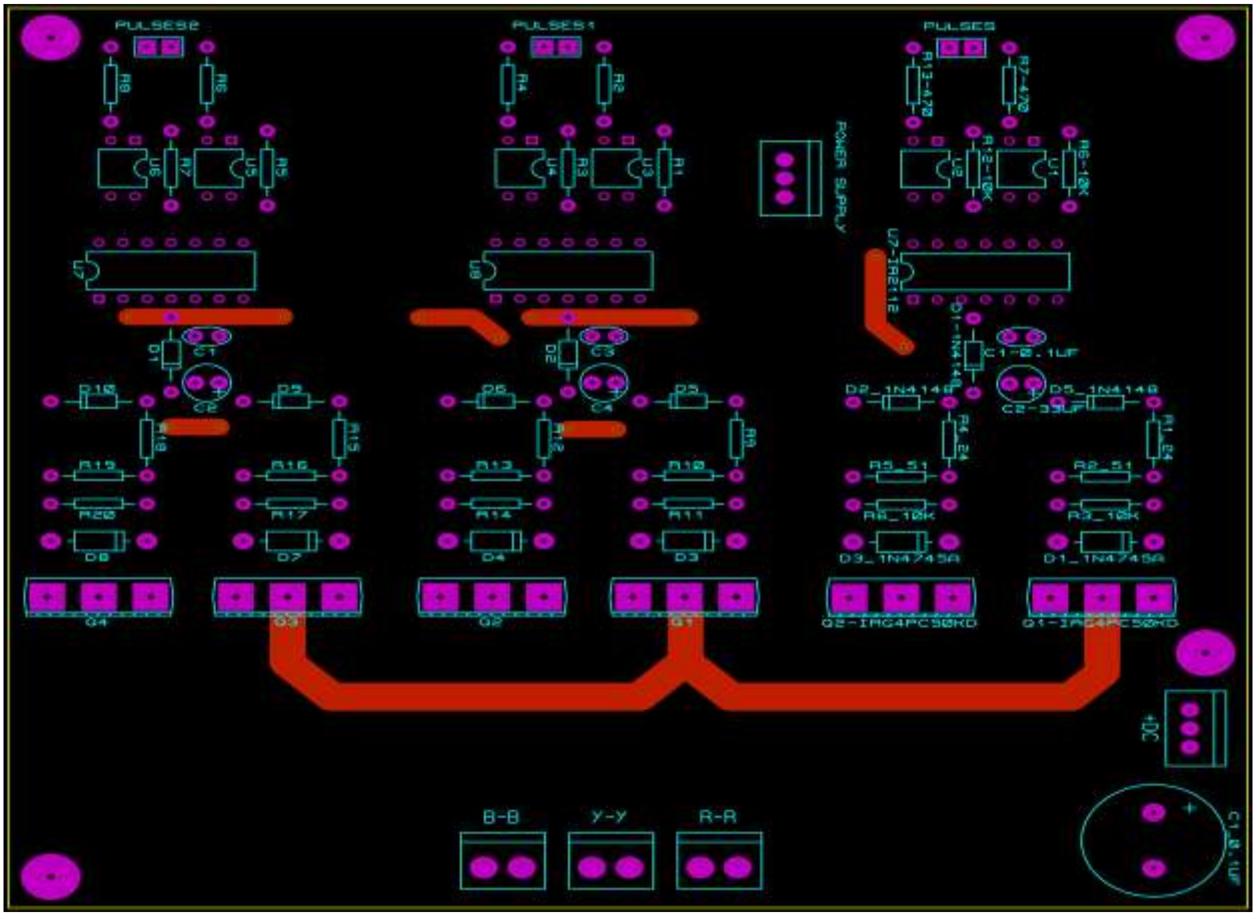


Figure 3-24: Top & Bottom layer pictures of PCB for control 3 Phase IM

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1. MATLAB Simulation results

4.1.1. $\alpha\beta$ Transformation out put

The voltage vectors: V_a, V_b, V_C is replaced with V_α and V_β based on $\alpha\beta$ transformation. V_a and V_α have the same direction, but different magnitude. As seen in Figure 4.1. The αβ-transformation the signals are demonstrated in a two-dimensional plane, making it easier to use in the calculations done in chapter three.

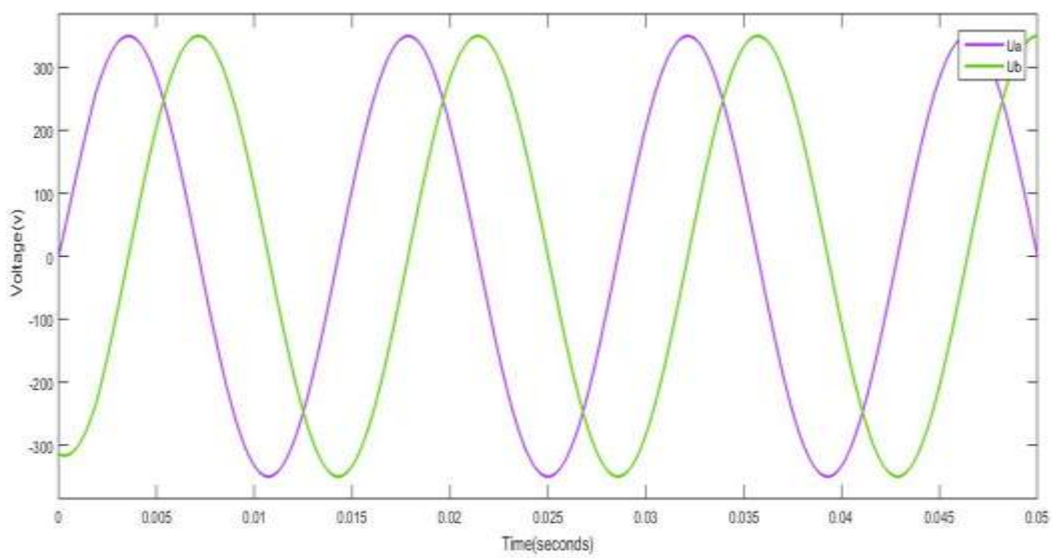


Figure 4-1: αβ-transformation output voltage

4.1.2. Switching pattern of SVPWM inverter

The SVPWM based on a carrier with reduced switching ratio, is the batter implementation of SVPWM because, the switching ratio can be reduced that leads to reduce the heat of switches, as shown in Figure 4-2.

This pattern when compared to high frequency triangular carrier wave produces gating signal to drive the inverter. It is clear from the waveform that there is an extra boost in voltage compared with sinusoidal PWM as there is an addition of common mode component in SVPWM compared to SPWM.

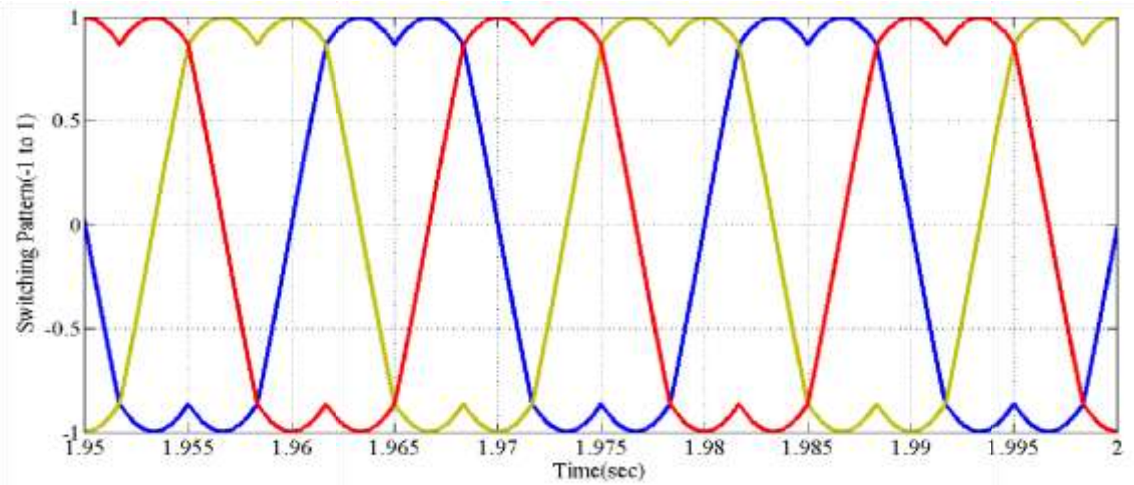


Figure 4-2: Switching Pattern of SVPWM Invertes

4.1.3. Gate pulse

The output get signal that is generated based on SVPWM techniques in order to switching the IGBT sequentially to generate three phase AC voltage to drive the induction motor is shown in the figure 4-3, figure 4-4 and figure 4-5 below. The signal that generated from the driver circuit is out phase in one leg. Because in one leg the two switches are on simultaneously a short circuit is happen and cause damage on the inverter. Therefore the switches are on and off sequentially based on the pattern of sector vectors to generate three phase sinusoidal waves.

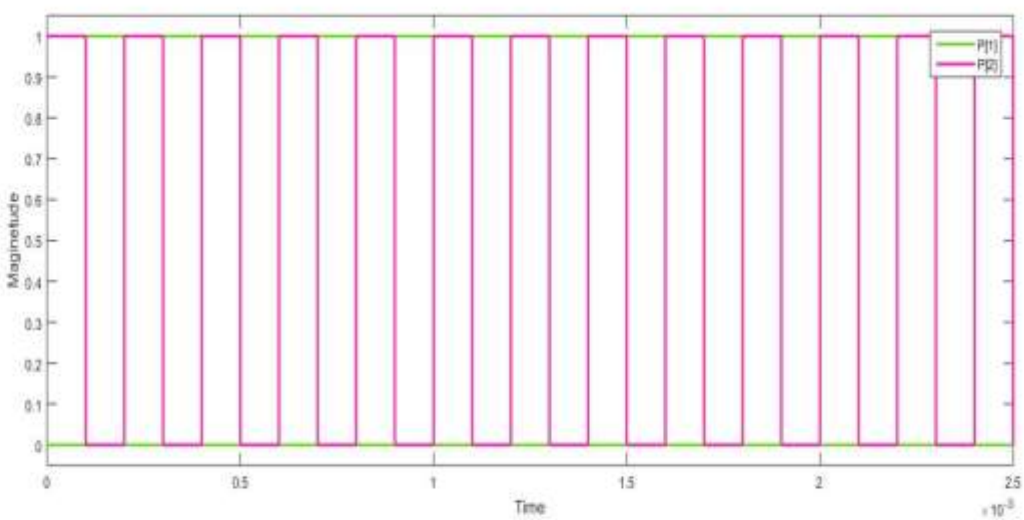


Figure 4-3: Gate pulse for IGBT 1 and IGBT 2

Figure 4-4 show that agate pulse generated from the driver circuit to on and off IGBT 3 and IGBT4 switches.

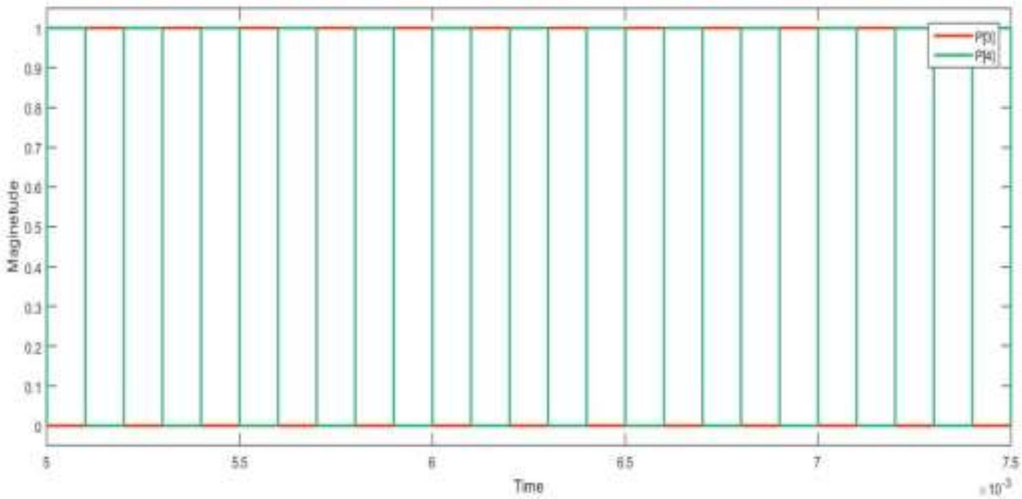


Figure 4-4: Gate pulse for IGBT 3 and IGBT 4

Figure 4-5 show that agate pulse generated from the driver circuit to on and off IGBT 5 and IGBT 6 switches.

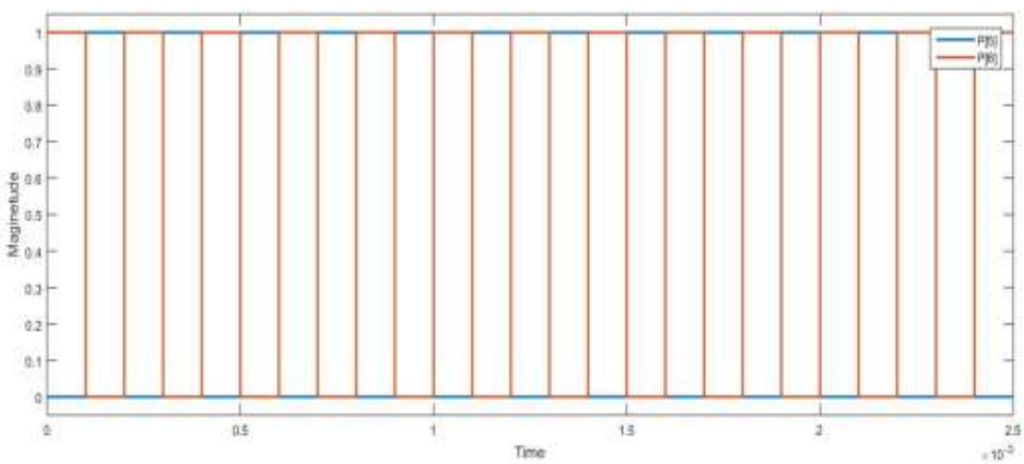


Figure 4-5: Gate pulse for IGBT 5 and IGBT 6

4.1.4. Phase voltage

Phase voltage that are generate from the inverter is shown in the figure 4-6 below, which have three steps 0, $\pm\frac{V_{DC}}{2}$, and $\pm\frac{3V_{DC}}{2}$ that are generate from the gate pulse on and off sequentially based on SVPWM techniques. Line neutral voltage is determined from the switching state and the neutral point voltage of the load which can be found by assuming that the load consists of three-phase resistor bank.

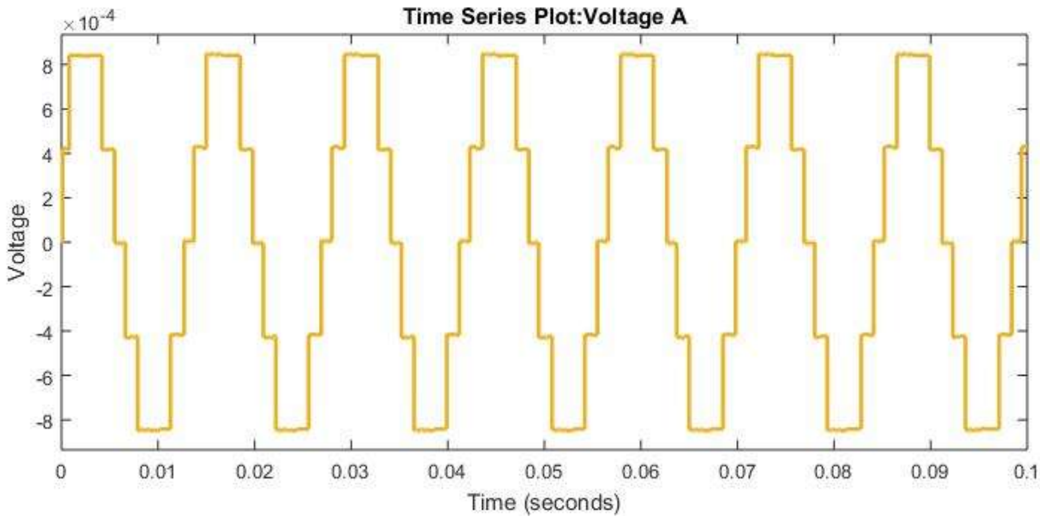


Figure 4-6: Phase voltage

4.1.5. Line voltage

The line voltage generate from the three phase inverter is shown below in the figure 3-7, figure 3-8 and figure 3-8, which is a voltage between phase A, phase B and phase C.

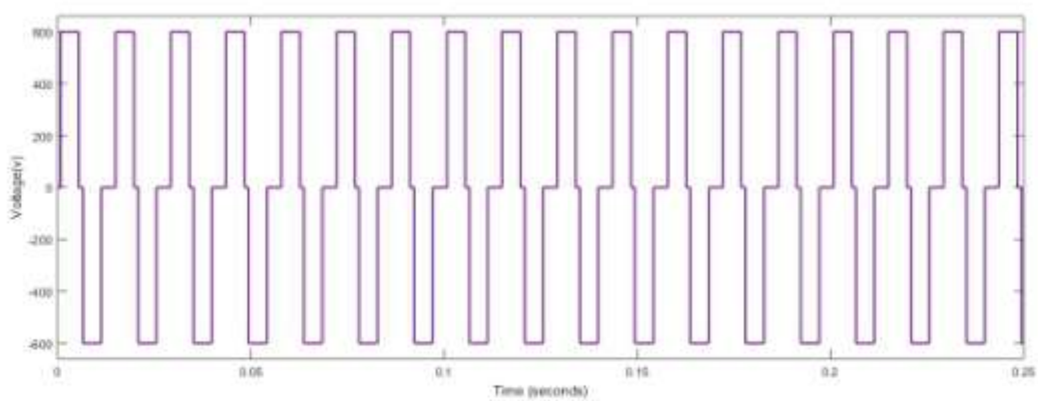


Figure 4-7: Line voltage V_ab

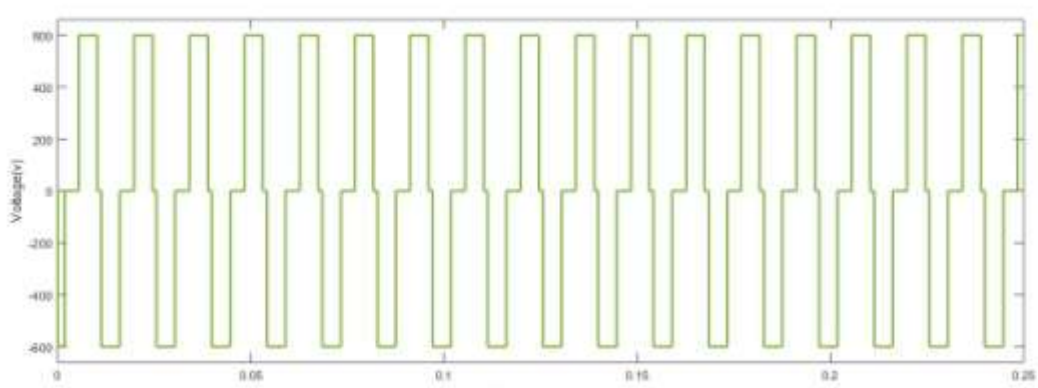


Figure 4-8: Line voltage V_bc

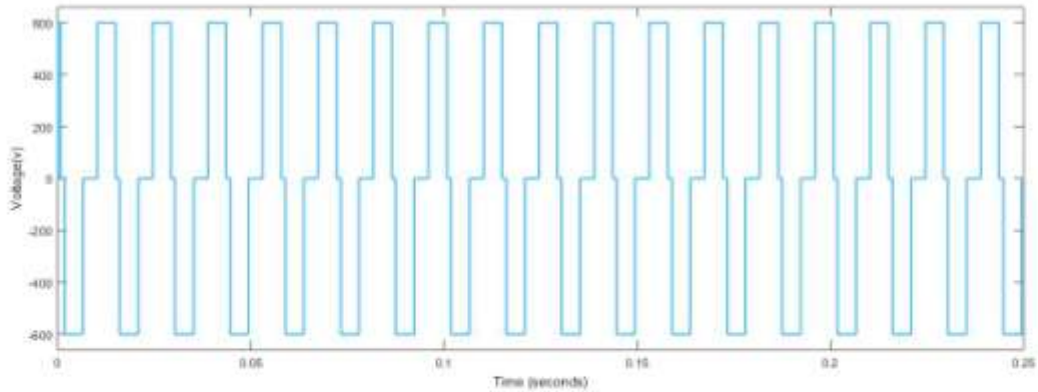


Figure 4-9: Line voltage V_ac

4.1.6. Stator current

The current in that flows through the stator winding of induction motor is shown in figure 4-10 Depending on the motor shaft mechanical load torque the stator current should decrease the controller will supply stator of motor with proper voltage and frequency using appropriate control algorithm for motor.

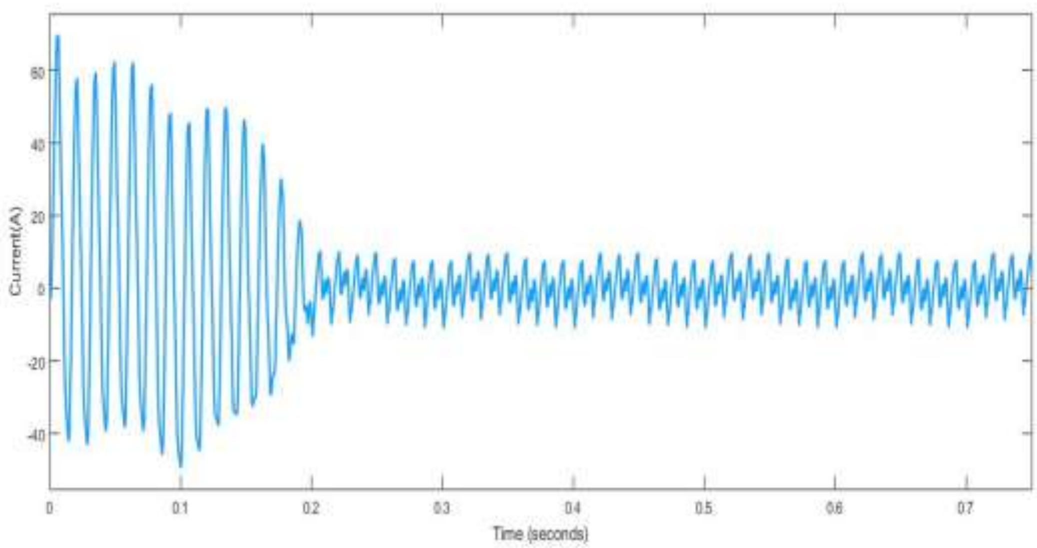


Figure 4-10: Stator current

4.1.7. Rotor current

The current in the rotor winding of the induction motor is high in the starting. But as shown in figure 4-11 when the motor accelerates it decreases. The drive automatically decreases the voltage after the motor is smoothly driven.

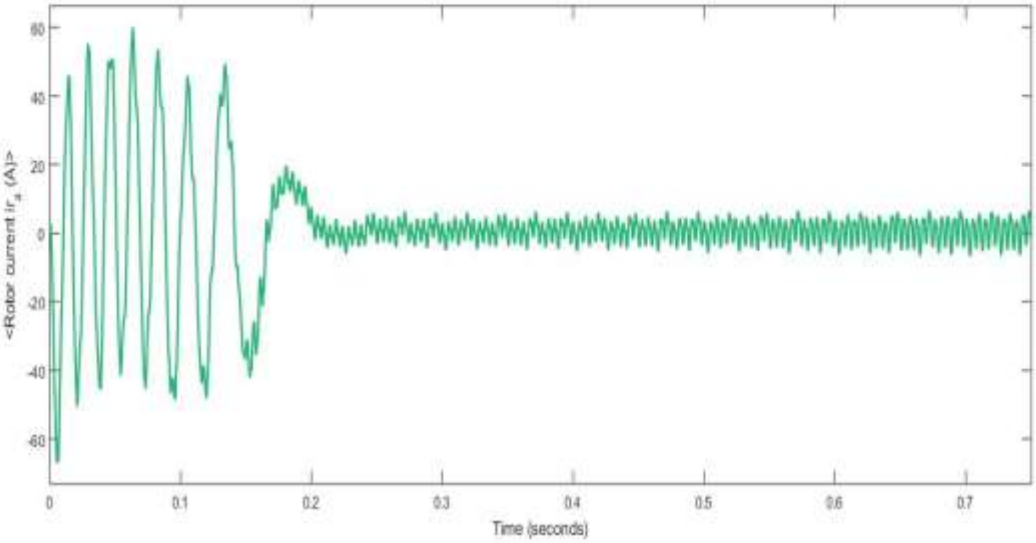


Figure 4-11: Rotor current

4.1.8. Open loop speed

The rotor speed through which it rotates is shown in figure 4-12 below. At the start of the induction motor speed is slow and gradually increases as the motor rotates. The speed is controlled by controlling the switching frequency and times of the gate pulse signals.

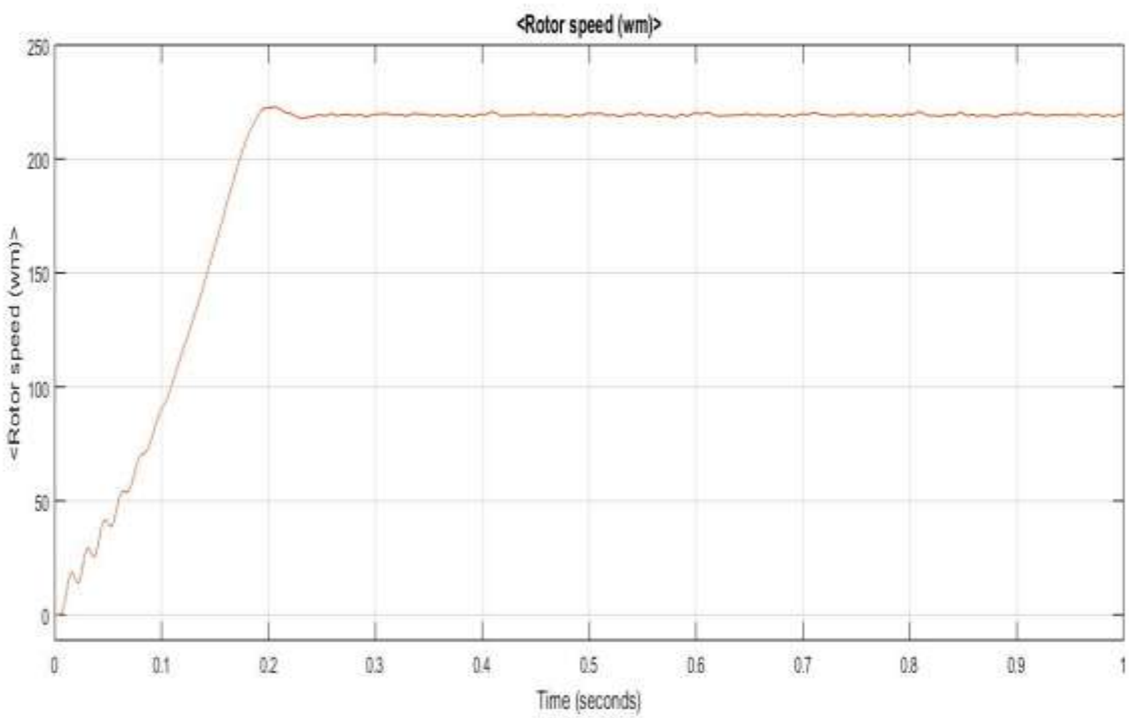


Figure 4-12: open loop speed

4.1.9. Rotor speed Vs reference speed

The rotor speed when compared to the reference speed by is shown below in the figure 4-13. At the start of the induction motor speed is slow and gradually increases as the motor rotates. The rotor speed is controlled according to the required speed of the Bajaj to drive effectively.

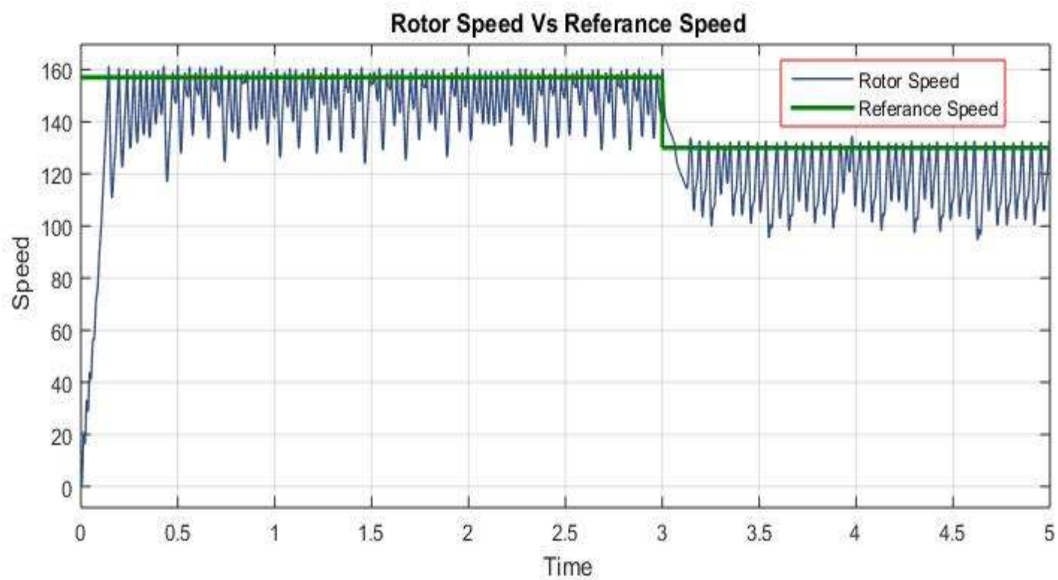


Figure 4-13: Rotor speed Vs reverence speed

4.1.10. Torque

The torque associated with induction motor is high because the starting torque of the induction motor is high as shown in the figure 3-14. The torque required by the Bajaj is around 52Nm, after the motor rotate and start drive the vehicle comes to zero to minimized losses.

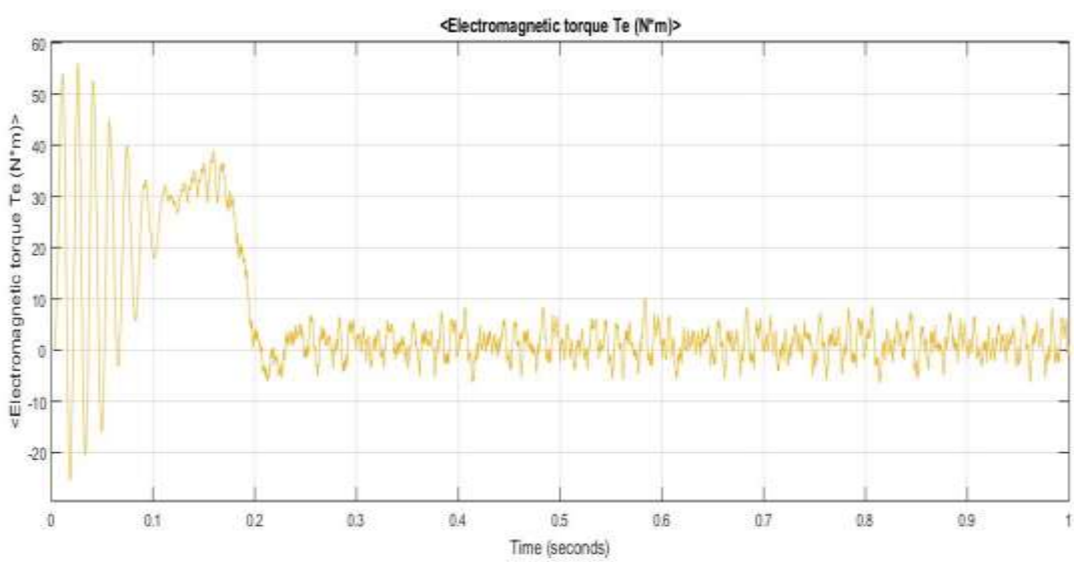


Figure 4-14: Electromagnetic torque

4.1.11. The torque-speed curve (At 50Hz)

The combined speed and torque curve are shown in figure 4-15 below. This shows combined characteristics of both speed (X-axis) and toque (Y-axis). The motor is operating at 50 Hz frequency. If the switching of IGBTs is made for less time there reduces frequency. The speed and torque at 10 Hz are shown below these values are less than initially calculated at 50Hz.

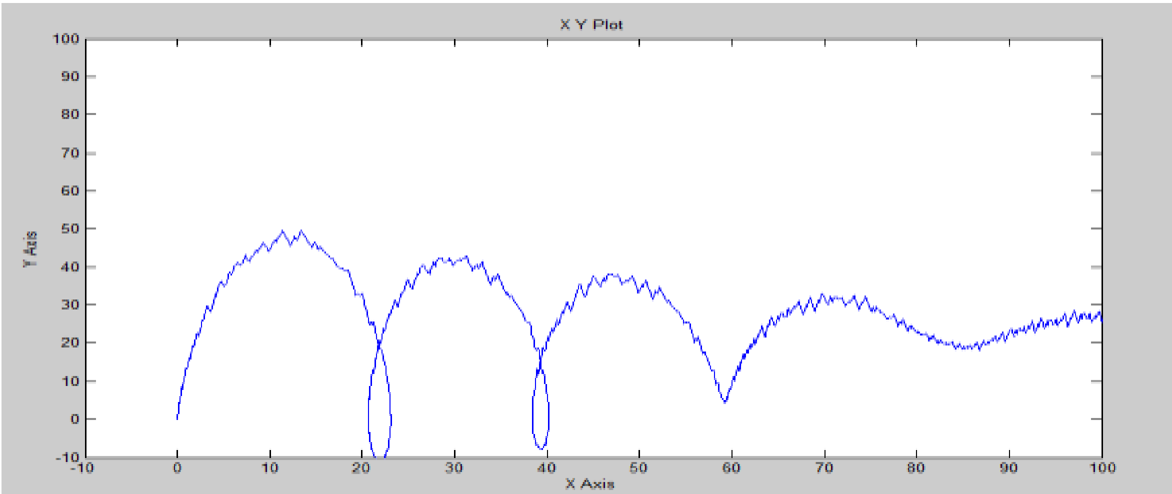


Figure 4-15: Torque speed curve at 50Hz

4.1.12. The torque-speed curve (At 10Hz)

The toque speed curve of induction motor at 10Hz is represented as in shown in figure 4-16 below. When its frequency is minimized the switching time is increased this cause reduction magnitude of torque- speed curve.

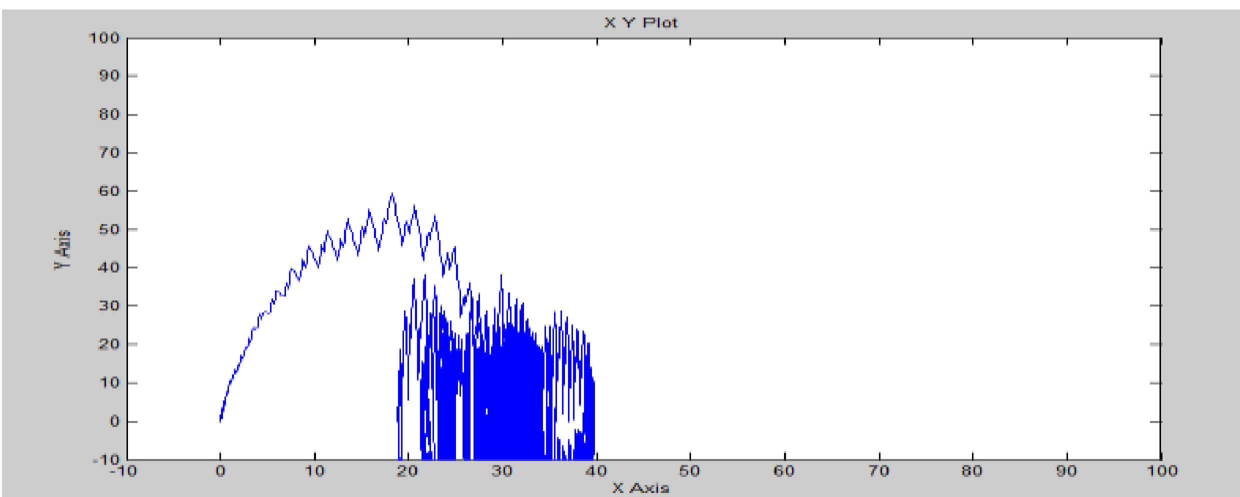


Figure 4-16: Torque speed Curve at 10Hz

4.1.13. Motive force verses approaching angle

There are three main force which act on the Bajaj when it travels at constant speed. but while the vehicle is accelerating or decelerating the effect of the force due to the inertia also act up on the vehicles. Gradient force increases when the approaching angle is increase. Aerodynamics force is constant if the speed of the vehicle is assumed to be constant. The total motive force with each component of the force acting on the vehicle is shown on the figure 4-17. We assumed the vehicle speed when move up is $25^{km}/_{hr}$ and velocity of the air also assumed equals to zero.

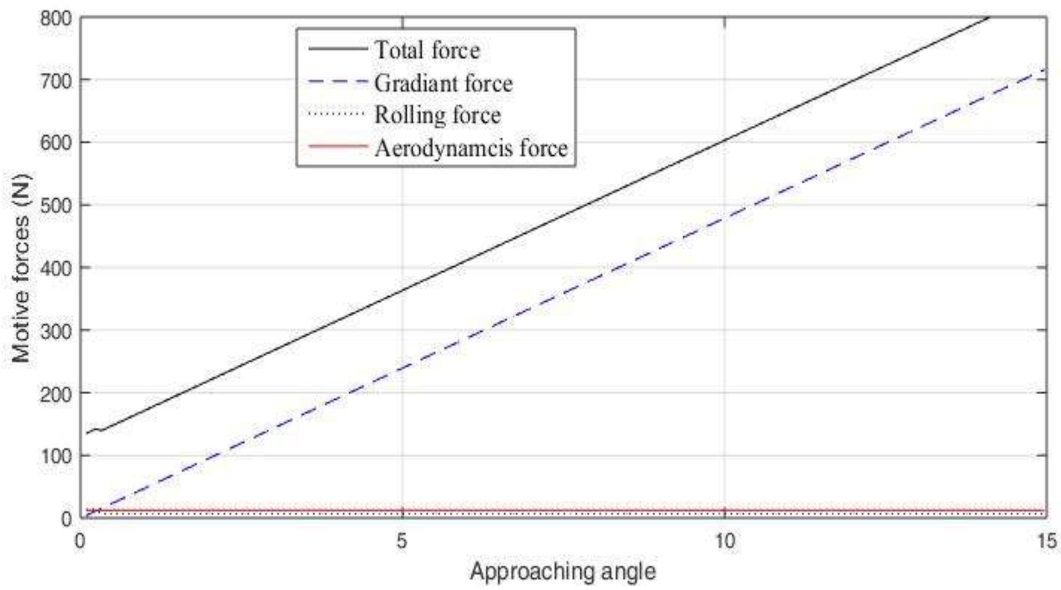


Figure 4-17: Motive force verses Approaching angle

4.1.14. Motor power consumption with respect to approaching angle

The maximum reactive power is supplied when the Bajaj is clamping the hill of maximum approaching angle which is 7.67 degree with its full load at the speed of 25 $^{km}/_{hr}$. The reason why the speed of the Bajaj is reduced while clamping the hill is to increase torque with limited power supply of the battery and limited power output of the motor. Figure 3.9 show the power needed to be supplied by the motor to drive the Bajaj at constant speed of 25 $^{km}/_{hr}$ with verses approaching angle. Figure 4-18 show that the relationship between total power consumption and approaching angle.

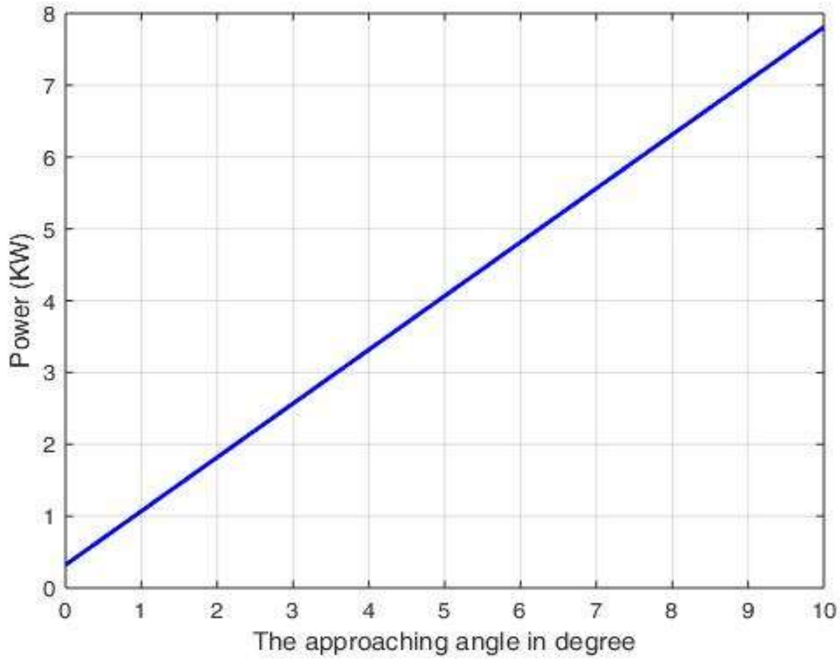
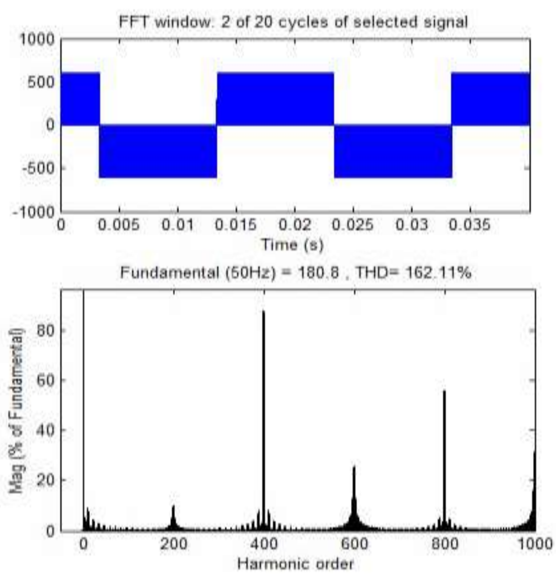


Figure 4-18: Motor power consumption with respect to approaching angle

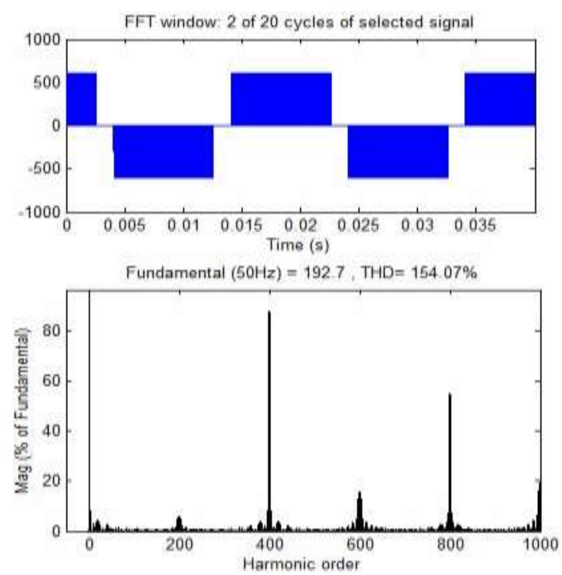
4.1.15. Comparison simulation results of SPWM and SVPWM

Space vector Modulation Technique has become the most popular and important PWM technique for Three Phase Voltage Source Inverters for the control of AC Induction motor. In the following figures show the wave forms of SPWM and SVPWM techniques using FFT analyzing by varying its modulation index.

<u>Modulation index = 0.4:</u>

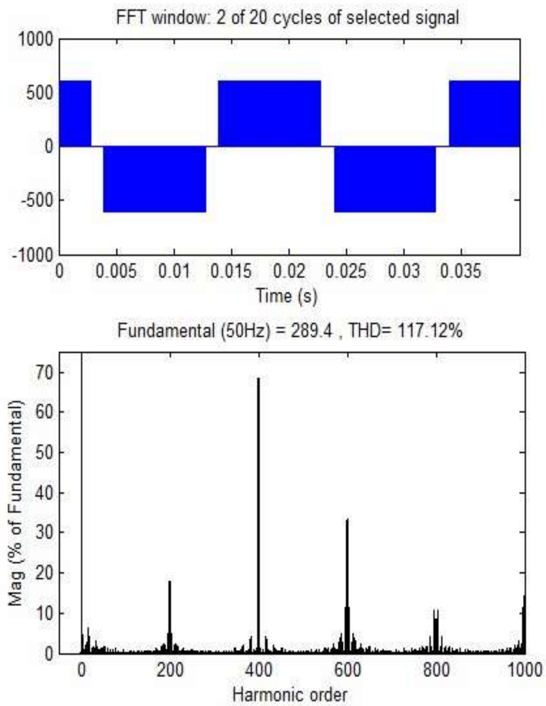


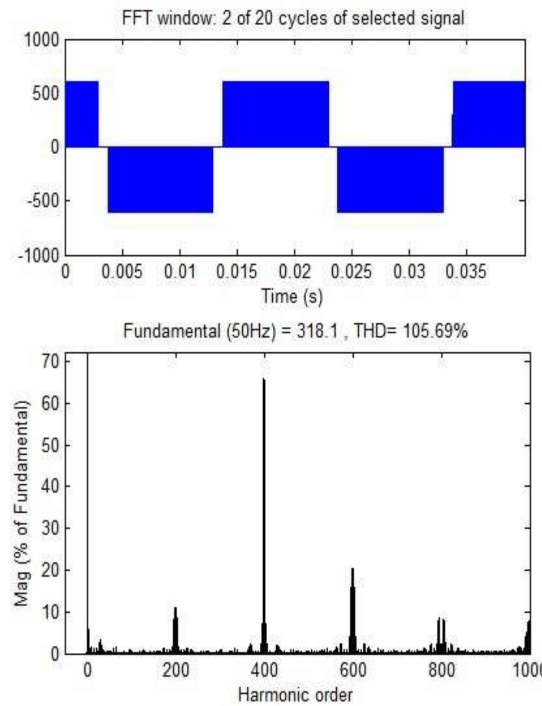
(A) SPWM



(B) SVPWM

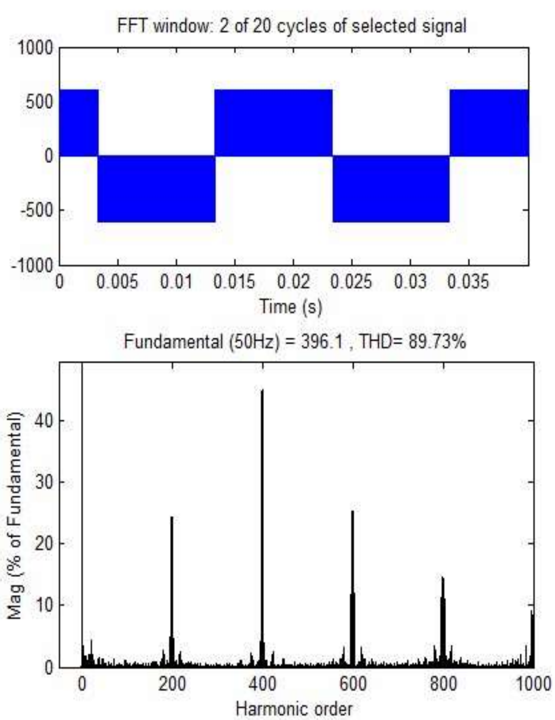
Modulation index = 0.6:

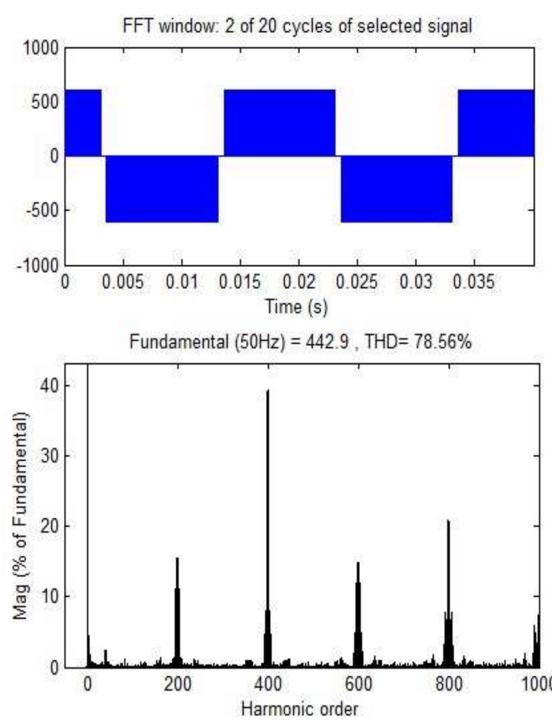




(A) SPWM (B) SVPWM

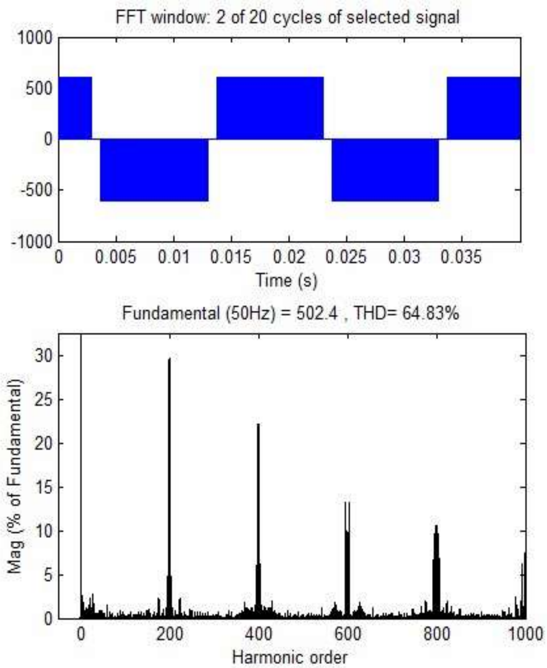
Modulation index = 0.8:

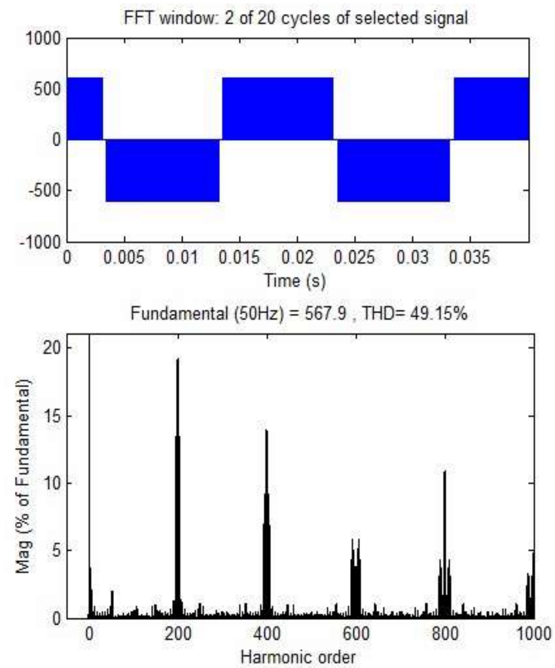




(A) SPWM (B) SVPWM

Modulation index = 1:





(A) SPWM (B) SVPWM

In Table 4-1 below SVPWM gives 15% enhanced fundamental output with better quality i.e. lesser when THD compared to SPWM.

Table 4.1: Comparisons between SPWM and SVPWM by varying modulation index.

Technique	**SPWM**		**SVPWM**	
M. I. (M)	**Output line voltage (peak) volt**	**THD** (%)	**Output line voltage (peak) volt**	**THD** (%)
0.4	180.80	162.11	192.70	154.07
0.5	266.50	123.35	312.20	108.78
0.6	289.40	117.12	318.10	105.69
0.7	369.20	94.52	436.60	81.19
0.8	396.10	89.73	442.90	78.56
0.9	472.90	70.69	552.30	53.62
1.0	502.40	64.83	567.90	49.15

4.2. Proteus simulation result

4.2.1. Driver circuit output

PWM is generated by Arduino which is in mA and signals is in +5v as this current and voltages is not enough for IGBT's to run for this purpose we need a driver circuit for IGBT's on or OFF. this driver circuit will convert the Arduino signal to +12v meaning that PWM which is in +5v will convert to PWM of +12v which can easily turn on the IGBT's and second will use Optcoupler to the purpose of using them is that help in avoiding the reverse current as we know that current more than +25mA will burn the internal chip of microcontroller so we will use for controller safety. Figure 4-17 show that the gate signals generated from the driver circuit to on and off switches on the inverter in order to run induction motors.

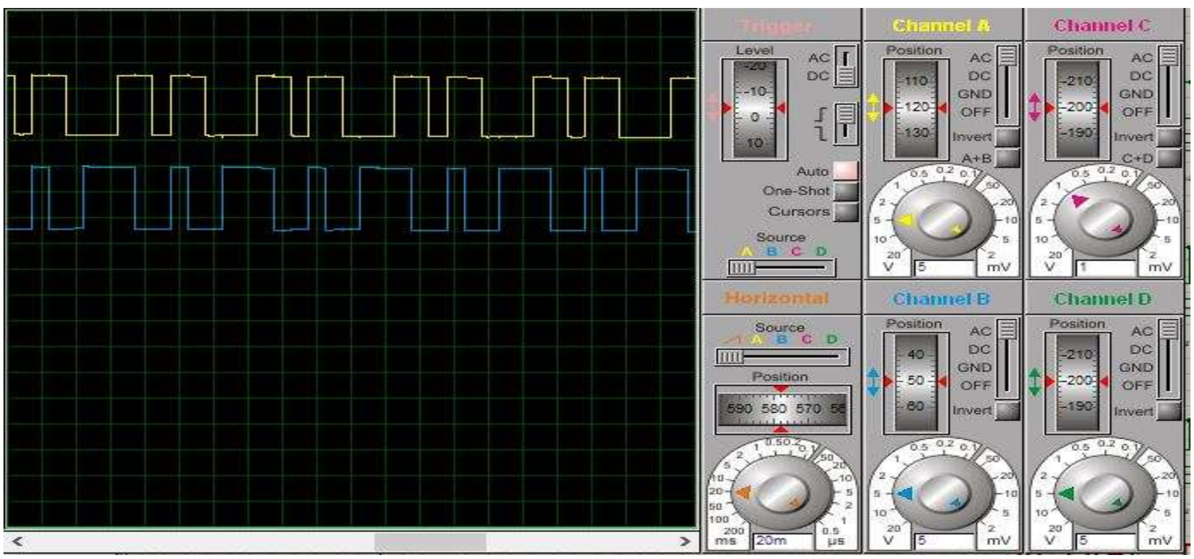


Figure 4-19: High side and Low side wave form of driver circuit in one leg

4.2.2. Three phase inverters output

In Proteus phase inverter is made by using CONTROLLER ARDUINO MEGA 2560. This uses six IGBT switches that are turned on and off by using pulse width modulation. The turn on and off of the IGBTs give rise to three phase output from single phase input. The IGBT used is 4PC40UD. These are high speed switching devices that turn on and turn off by sequence to produce three phase output. The inverter is simulated and switching of inverter is indicated with LEDs. The switching with LED positions is shown as in figure below. The LEDs turn on and turn off as directed with pulses resulting from pulse width modulation. The oscilloscope is used to observe the three-phase output.

The programming used for driving IGBTs is done in Arduino software. This produces pulse that drives the inverter. Three phase output is generated as an output of inverter. This output is further used to drive the three-phase motor which drives the load. The three-phase output resulted from the output of this circuit is shown in figure below.

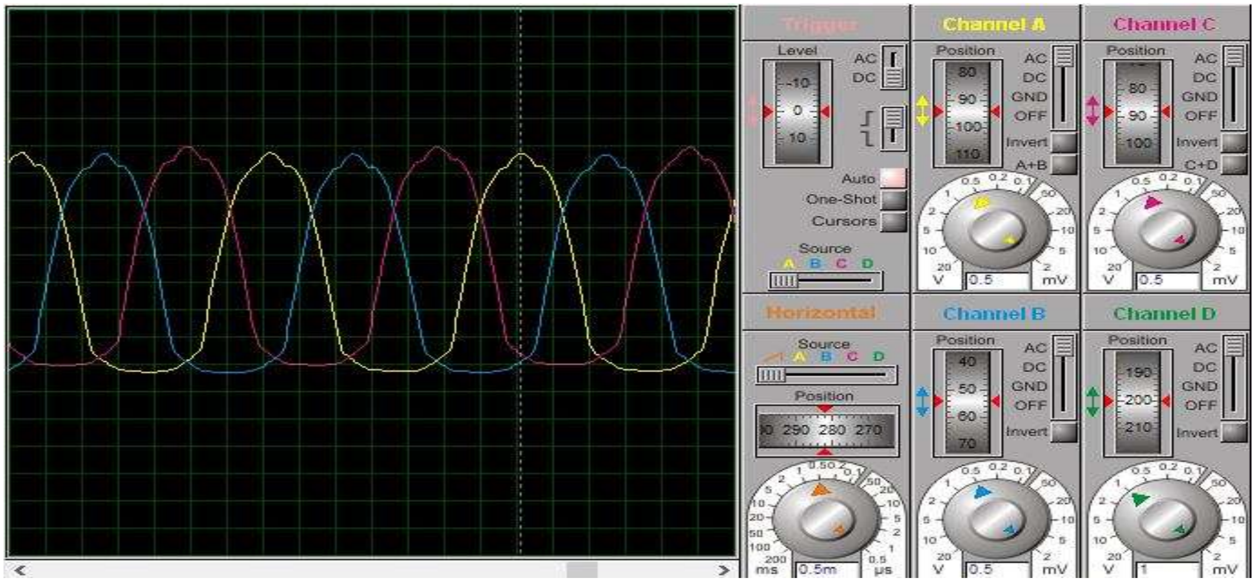


Figure 4-20: Three Phase Output

4.2.3. Forward and reverse direction rotate of motor

The push button in the control circuit is used to run the motor speed up, speed down, forward, reverse direction by due to the changing of switching pulse of IGBT gate signals. The following figure 4-21 and figure 4-22 show that the output wave result when the motor run forward and reverse direction respectively.

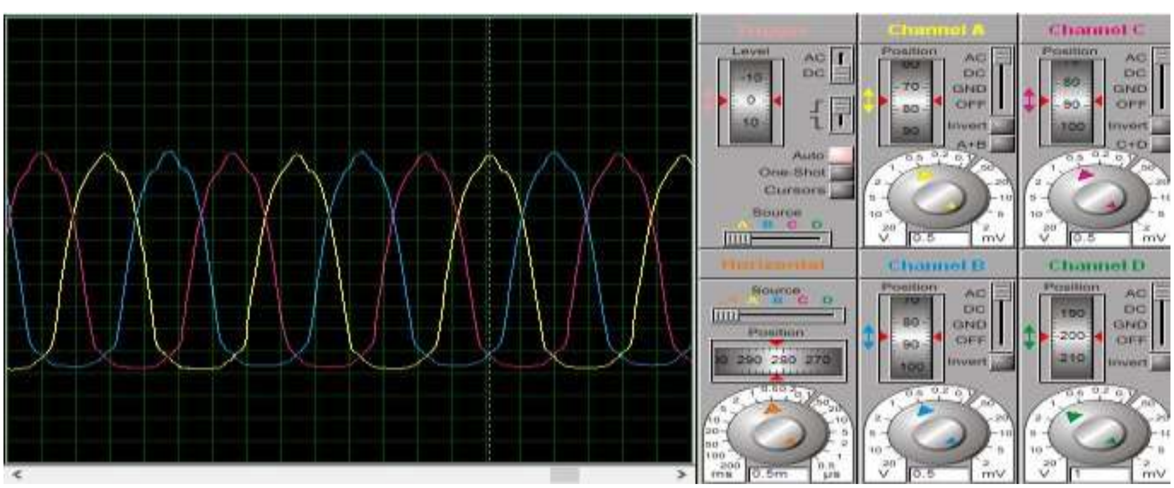


Figure 4-21: Wave form when the motor rotate forward direction

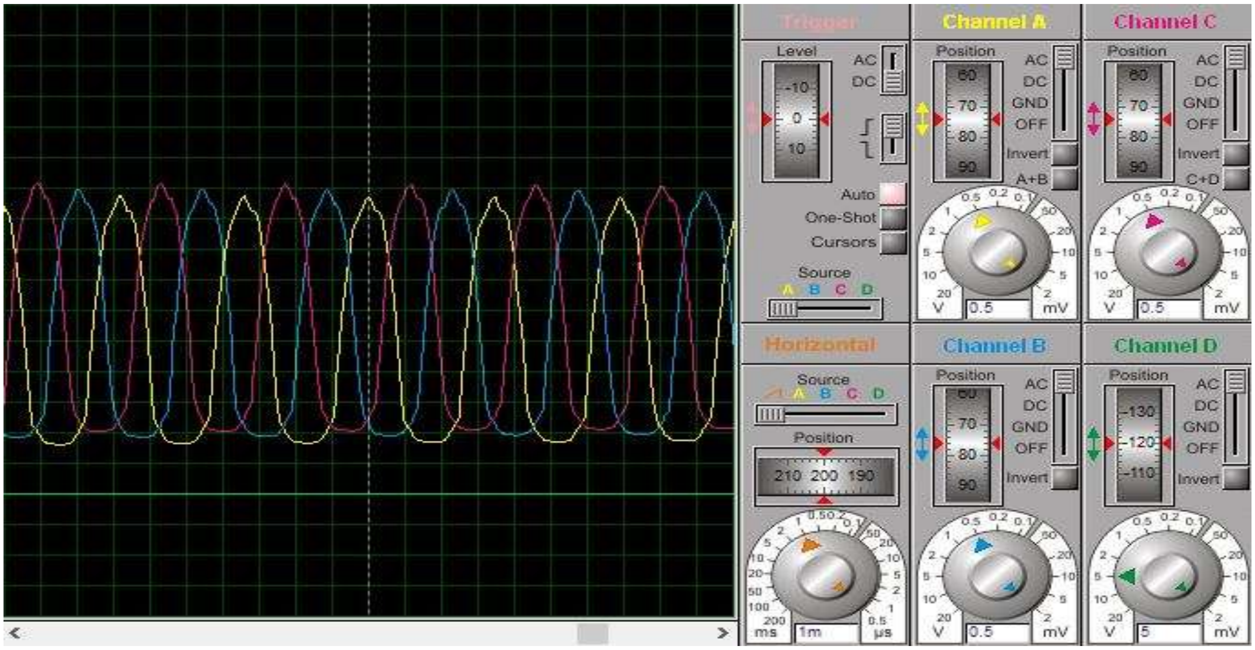


Figure 4-22: Wave form when the motor rotate reverse direction

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In this thesis space vector pulse width modulation-based induction motor with proportional integral control model is designed through MATLAB software and also tested successfully by evaluating the parameters like stator current, rotor current, torque and speed**,** it is due to its characteristics like good power factor, extremely rugged and high efficiency. This scheme leads to be able to control the speed of the motor by control the frequency and amplitude of the stator voltage. SVPWM control system design and implementation is uncomplicated and trouble free. These types of induction motors control system can be used in lathes, drilling machines, lifts, cranes, conveyors, industrial drives, agricultural and industrial pumps in addition to electric vehicle application. The modulation technique chosen for the thesis is space vector pulse width modulation, has good utilization of the DC link voltage, low current ripple and is relatively easy to implement in the hardware. These features make it suitable for high-voltage high-power applications, such as renewable power generation.

A design procedure for the EV propulsion system is presented based on the vehicle dynamics. This methodology helps to calculate the motor power rating according to the vehicle dynamics. It is observed that as the speed factor (i.e. ratio of vehicle maximum speed by vehicle base speed) is small, the power rating requirement is high. However, when the vehicles are at maximum speed its base speed and power rating is significantly decreases. But for higher value of the speed factor, when the vehicle base speed is increased for the same vehicle maximum speed, the power rating does not change significantly. A three-wheeler EV is developed for maximum speed of 50 km/hr.

5.2. Recommendation

In this thesis there are several ideas that can be discussed and analyzed, start from this work There are some o suggestions and recommendation for future work:

- ❖ Connect the FPGA to the inverter and test the modulation algorithm created in Lab VIEW. Because FPGA comes several benefits: Because of the lack of sequential execution, the FPGA accomplished more per clock cycle. The computing power is higher than for conventional DSP's, implementing a concept is easier and faster. Instead if weeks it takes hours, the programmable silicon eliminates fabrication costs and installation requirements, The FPGA does not use operating systems. This minimizes problems, because the communication with the hardware will be directly And Having the characteristic of being configurable makes it easy to adapt to future modifications.
- ❖ Try the space vector modulation strategy with unbalanced system: $V_{AO} + V_{BO} + V_{CO} \neq 0$
- ❖ Improve the two-level SVPWM within using LabVIEW. Because LabVIEW software has benefits considering the following two big differences from other programming languages which is Graphical programming is realized with help from graphical icons and directly compiled to machine code and data flow is transmitted in form of data (not lines of text). This makes it easier to control different executions done separately and consecutively.
- ❖ For tuning techniques used fussy logic, artificial neural network and other latest control techniques are used in addition to Ziegler-Nichols tuning rules.

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APPENDIX

Appendix A: Arduino Code for PWM three phase Inverter for induction motor drive

Code for PWM 3P Inverter for induction motor drive using Arduino Mega (2560).

```
//you can run Motor
//Forward
//Backward
//Speed Up Motor
//Slow Down Motor
// STOP Motor.
int led1 = 6; // Pulse 1
int led2 = 5; // Pulse 2
int led3 = 9; // Pulse 3
int led4 = 10; // Pulse 4
int led5 = 11; // Pulse 5
int led6 = 3; // Pulse 6

//Analogs Inputs
int F = A0; //Run Forward
int B = A1; //Run Backward
int U = A2; //Speed Up
int D = A3; //Speed Down
int S = A4; //Stop

int cont = 0;
int val;
void setup()
{
  // initialize the digital pin as an output:
  pinMode(led1, OUTPUT);
  pinMode(led2, OUTPUT);
  pinMode(led3, OUTPUT);
  pinMode(led4, OUTPUT);
  pinMode(led5, OUTPUT);
  pinMode(led6, OUTPUT);
  // initialize the analog pin as an inputs:
  pinMode(F, INPUT);
  pinMode(B, INPUT);
  pinMode(U, INPUT);
  pinMode(D, INPUT);
```

```
  pinMode(S, INPUT);
}
void loop()
{
  if ((digitalRead(F) == HIGH) && (digitalRead(B) == LOW) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == HIGH))
  {
    digitalWrite(led1, LOW);
    digitalWrite(led2, LOW);
    digitalWrite(led3, LOW);
    digitalWrite(led4, LOW);
    digitalWrite(led5, LOW);
    digitalWrite(led6, LOW);
    delay(1000);
    back();
  }
  if ((digitalRead(F) == LOW) && (digitalRead(B) == HIGH) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == HIGH))
  {
    digitalWrite(led1, LOW);
    digitalWrite(led2, LOW);
    digitalWrite(led3, LOW);
    digitalWrite(led4, LOW);
    digitalWrite(led5, LOW);
    digitalWrite(led6, LOW);
    delay(1000);
    forw();
  }
}
void forw()
{
  while (1)
  {
    if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == LOW))
    {
      digitalWrite(led1, LOW);
      digitalWrite(led2, LOW);
      digitalWrite(led3, LOW);
      digitalWrite(led4, LOW);
```

```
    digitalWrite(led5, LOW);
    digitalWrite(led6, LOW);
    break;
  }
  if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == LOW)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == HIGH))
  {
    cont = cont + 1;
    if (cont > 10)
    {
      cont = 10;
    }
  }

  if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == LOW) && (digitalRead(S) == HIGH))
  {
    cont = cont - 1;
    if (cont < 0)
    {
      cont = 0;
    }
  }
  if (cont == 0) {
    val = 10;
  }
  if (cont == 1) {
    val = 9.5;
  }
  if (cont == 2) {
    val = 9;
  }
  if (cont == 3) {
    val = 8.5;
  }
  if (cont == 4) {
    val = 8;
  }
  if (cont == 5) {
    val = 7.5;
```

```
}
if (cont == 6) {
  val = 7;
}
if (cont == 7) {
  val = 6.5;
}
if (cont == 8) {
  val = 6;
}
if (cont == 9) {
  val = 5.5;
}
if (cont == 10) {
  val = 5;
}
digitalWrite(led1, HIGH);
digitalWrite(led2, HIGH);
digitalWrite(led3, HIGH);
digitalWrite(led4, LOW);
digitalWrite(led5, LOW);
digitalWrite(led6, LOW);
delay(val);

digitalWrite(led1, HIGH);
digitalWrite(led2, LOW);
digitalWrite(led3, HIGH);
digitalWrite(led4, LOW);
digitalWrite(led5, HIGH);
digitalWrite(led6, LOW);
delay(val);

digitalWrite(led1, LOW);
digitalWrite(led2, LOW);
digitalWrite(led3, HIGH);
digitalWrite(led4, HIGH);
digitalWrite(led5, HIGH);
digitalWrite(led6, LOW);
delay(val);
```

```
  digitalWrite(led1, LOW);
  digitalWrite(led2, HIGH);
  digitalWrite(led3, HIGH);
  digitalWrite(led4, HIGH);
  digitalWrite(led5, LOW);
  digitalWrite(led6, LOW);
  delay(val);

  digitalWrite(led1, LOW);
  digitalWrite(led2, HIGH);
  digitalWrite(led3, LOW);
  digitalWrite(led4, HIGH);
  digitalWrite(led5, LOW);
  digitalWrite(led6, HIGH);
  delay(val);

  digitalWrite(led1, HIGH);
  digitalWrite(led2, HIGH);
  digitalWrite(led3, LOW);
  digitalWrite(led4, LOW);
  digitalWrite(led5, LOW);
  digitalWrite(led6, HIGH);
  delay(val);

  digitalWrite(led1, HIGH);
  digitalWrite(led2, LOW);
  digitalWrite(led3, LOW);
  digitalWrite(led4, LOW);
  digitalWrite(led5, HIGH);
  digitalWrite(led6, HIGH);
  delay(val);

  digitalWrite(led1, LOW);
  digitalWrite(led2, LOW);
  digitalWrite(led3, LOW);
  digitalWrite(led4, HIGH);
  digitalWrite(led5, HIGH);
  digitalWrite(led6, HIGH);
  delay(val);
}
```

```
}
void back()
{
  while (1)
  {
    if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == LOW))
    {
      digitalWrite(led1, LOW);
      digitalWrite(led2, LOW);
      digitalWrite(led3, LOW);
      digitalWrite(led4, LOW);
      digitalWrite(led5, LOW);
      digitalWrite(led6, LOW);
      break;
    }

    if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == LOW)
&& (digitalRead(D) == HIGH) && (digitalRead(S) == HIGH))
    {
      cont = cont + 1;
      if (cont > 10)
      {
        cont = 10;
      }
    }

    if ((digitalRead(F) == HIGH) && (digitalRead(B) == HIGH) && (digitalRead(U) == HIGH)
&& (digitalRead(D) == LOW) && (digitalRead(S) == HIGH))
    {
      cont = cont - 1;
      if (cont < 0)
      {
        cont = 0;
      }
    }
    if (cont == 0) {
      val = 10;
    }
    if (cont == 1) {
```

```
  val = 9.5;
}
if (cont == 2) {
  val = 9;
}
if (cont == 3) {
  val = 8.5;
}
if (cont == 4) {
  val = 8;
}
if (cont == 5) {
  val = 7.5;
}
if (cont == 6) {
  val = 7;
}
if (cont == 7) {
  val = 6.5;
}
if (cont == 8) {
  val = 6;
}
if (cont == 9) {
  val = 5.5;
}
if (cont == 10) {
  val = 5;
}
digitalWrite(led1, LOW);
digitalWrite(led2, LOW);
digitalWrite(led3, LOW);
digitalWrite(led4, HIGH);
digitalWrite(led5, HIGH);
digitalWrite(led6, HIGH);
delay(val);

digitalWrite(led1, HIGH);
digitalWrite(led2, LOW);
digitalWrite(led3, LOW);
```

```
digitalWrite(led4, LOW);
digitalWrite(led5, HIGH);
digitalWrite(led6, HIGH);
delay(val);

digitalWrite(led1, HIGH);
digitalWrite(led2, HIGH);
digitalWrite(led3, LOW);
digitalWrite(led4, LOW);
digitalWrite(led5, LOW);
digitalWrite(led6, HIGH);
delay(val);

digitalWrite(led1, LOW);
digitalWrite(led2, HIGH);
digitalWrite(led3, LOW);
digitalWrite(led4, HIGH);
digitalWrite(led5, LOW);
digitalWrite(led6, HIGH);
delay(val);

digitalWrite(led1, LOW);
digitalWrite(led2, HIGH);
digitalWrite(led3, HIGH);
digitalWrite(led4, HIGH);
digitalWrite(led5, LOW);
digitalWrite(led6, LOW);
delay(val);

digitalWrite(led1, LOW);
digitalWrite(led2, LOW);
digitalWrite(led3, HIGH);
digitalWrite(led4, HIGH);
digitalWrite(led5, HIGH);
digitalWrite(led6, LOW);
delay(val);

digitalWrite(led1, HIGH);
digitalWrite(led2, LOW);
digitalWrite(led3, HIGH);
```

```
    digitalWrite(led4, LOW);
    digitalWrite(led5, HIGH);
    digitalWrite(led6, LOW);
    delay(val);

    digitalWrite(led1, HIGH);
    digitalWrite(led2, HIGH);
    digitalWrite(led3, HIGH);
    digitalWrite(led4, LOW);
    digitalWrite(led5, LOW);
    digitalWrite(led6, LOW);
    delay(val);
  }
}
```

Appendix B: MATLAB code for analyzing Figure

MATLAB code for the analysis motive force versus approaching angle of the vehicle (**Figure 3.14)**

```
fric=0.01; %  Friction coefficient

g=9.81; %  gravitational acceleration

a=0.5;  %  Acceleration (m/sec)

r=0.1;  %  Radius of the wheel in meter

K_friction=0.001;  %  Coefficient of friction by considering the asphalt road

F_tot=0;

vkph=50;  %  Speed of the rotor in Km/hr

Tot_effcen.M=0.98;  %  Efficiency

Adnsty=1.2;  %  Kd/m3

Af=0.53;  %  Frontal area of the car (m2)

vo=0;  %  Air velocity in m/s

Cw=0.2;    %  Initial condition

apangle=0;

apangle1=15;

d_apangle=0.5e-2;   %  unit step increment

apangle_final=15; %  final value in degree

x=1 ;n=1;

while(apangle<apangle_final),

   vmps=50*(1000/3600);

   theta=apangle*(0.8*pi/360);

FA=0.5*Adnsty*Cw*Af*(vmps+vo) ^2;

if apangle<=50*d_apangle;

    statfric=0.001;

else

    statfric=0;

end
```

```
Frolling=m*g*(K_friction+statfric)*cos(theta);
Fgradient=m*g*sin(theta);
F_tot=Frolling+Fgradient+FA+m*a; % Total force (Nm)
apangle=apangle+d_apangle;
apangle1=apangle1+d_apangle;
if x>16,
   F_totn(n)=F_tot;
   Fgradientn(n)=Fgradient;
   Frollingn(n)= Frolling; %Power in KW
   FAn(n)=FA;
   apanglen(n)=apangle;
   n=n+1;
   x=1;
end
  x=x+1;
end
figure(1);
plot(apanglen, F_totn,'k',apanglen,Fgradientn,'b--',apanglen,Frollingn,'k:',apanglen,FAn,'r')
axis([0 15 0 800]);
grid
xlabel('Approaching angle')
ylabel('Motive forces (N)')
```

MATLAB code for the analysis motive forces vs speed of the car in Km/hr **(Figure 3.15)**

```
clear all; close all;
m=700;
fric=0.01;
g=9.81;
a=0.5;
```

```
r=0.1; % Radius of the wheel in meter
K_friction=0.01; %Coefficient of friction by considering the asphalt road
r=0.1;
F_tot=0;
vkph=50; %speed of the rotor in Km/hr
Tot_effcen.M=0.98;
Adnsty=1.2; %Kd/m3
Af=0.53; %area in m2
vo=0; %air velocity in m/s
Cw=0.3;
%Initial condition
apangle=0;
Vkph=0;
Vkph1=0;
d_Vkph=1e-2; %unit step increment
Vkph_final=50; %final value in degree
x=1;
n=1;
while(Vkph<Vkph_final),
    vmps=Vkph*(1000/3600);
    theta=apangle*(2*pi/360);
FA=0.5*Adnsty*Cw*Af*(vmps+vo)^2;
if  Vkph<=50*d_Vkph;
     statfric=0.1;
else
     statfric=0;
end
Fac=m*a;
```

```
Frolling=m*g*(K_friction+statfric)*cos(theta);
Fgradient=m*g*sin(theta);
F_tot=Frolling+Fgradient+FA+Fac; % Total force (Nm)
Vkph=Vkph+d_Vkph;
Vkph1=Vkph1+d_Vkph;
if x>16,
   F_totn(n)=F_tot;
   Fgradientn(n)=Fgradient;
   Frollingn(n)= Frolling;  %Power in KW
   FAn(n)=FA;
   Facn(n)=Fac;
   Vkphn(n)=Vkph;
   n=n+1;
   x=1;
end
  x=x+1;
end
figure (1);
plot(Vkphn, F_totn,'k',Vkphn,Fgradientn,'k',Vkphn,Frollingn,'k:',Vkphn,FAn,'r',Vkphn,Facn,'r--
','LineWidth',1.3)
axis([0 50 0 800]);
grid
xlabel('Speed of the car in Kmph')
ylabel('Motive forces (N)')
set(gca, 'FontName','TimesNewRoman')
set(gca, 'FontSize',12)
```

MATLAB code for the analysis of Power required to drive EV vs departure angle of the road in degree (Figure 3.16)

```
clear all; close all;

m=700;

fric=0.01;

g=9.81;

a=0;

r=0.1; % Radius of the wheel in meter

c_ofriction=0.001; %Coefficient of friction by considering the asphalt road

d=0.1;

v=25; %speed of the rotor in m/se

Tot_effcen.M=0.98;

Adnsty=1.2; %Kd/m3

Af=0.053; %area in m2

vo=0; %air velocity in m/s

Cw=0.3;

%Initial condition

angleR=0;

angleR1=0;

d_angleR=1e-6; %unit step increment

angleR_final=15; %final value in degree

x=1;

n=1;

while(angleR<angleR_final),

   Fadyna=0.5*Adnsty*Cw*Af*(v+vo)^2;

   theta=angleR*0.5*pi/360; %Degree to radian conversion

F_tot=m*g*(sin(theta)+c_ofriction*cos(theta))+Fadyna+m*a; % Total force(Nm)

Power=F_tot*v; %W

Torque=(Power*r/v)/0.98; % Nm
```

```
angleR=angleR+d_angleR;
angleR1=angleR1+d_angleR;
if x>16,
    F_totn(n)=F_tot;
    Torquen(n)=Torque;
    Powern(n)=Power/1000; %Power in KW
    Fadynan(n)=Fadyna;
    thetan(n)=angleR;
    n=n+1;
    x=1;
end
  x=x+1;
end
figure(1);
plot(thetan,Powern,'b','LineWidth',2);
axis([0 10 0 8]);
xlabel('The approaching angle in degree')
ylabel('Power (KW)')
```

Appendix C: MATLAB Simulink Modeling

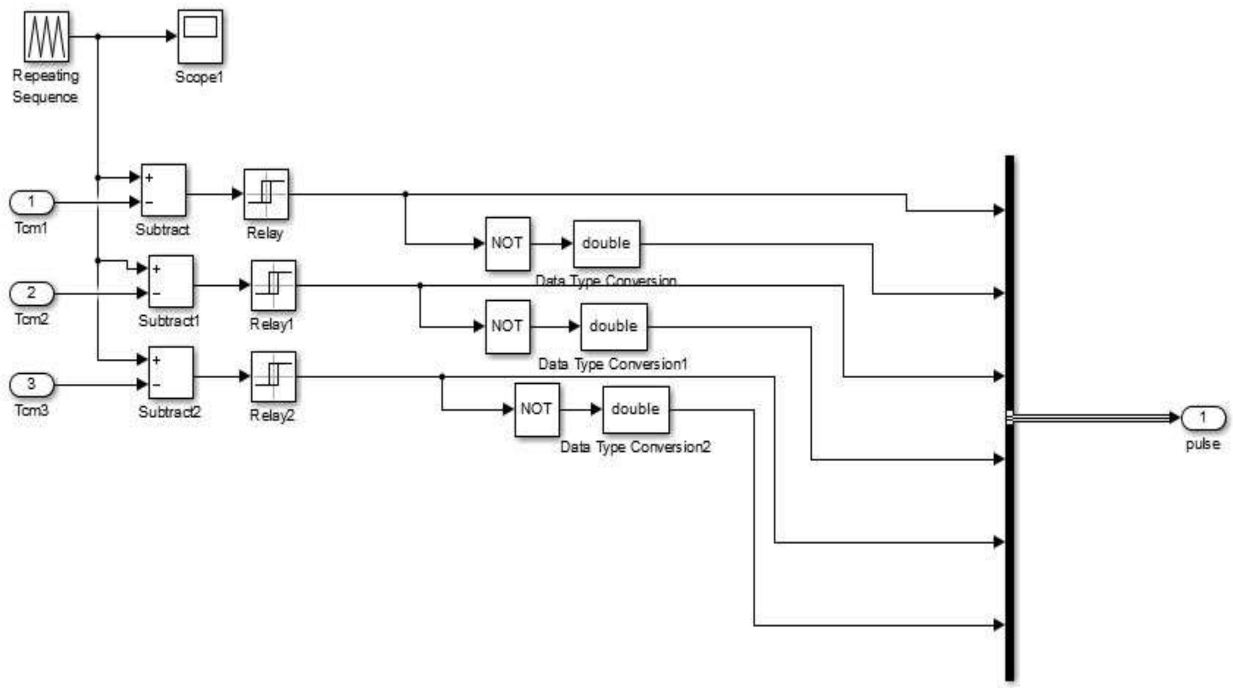


Figure A1: MATLAB Simulink subsystem model for generating SVPWM

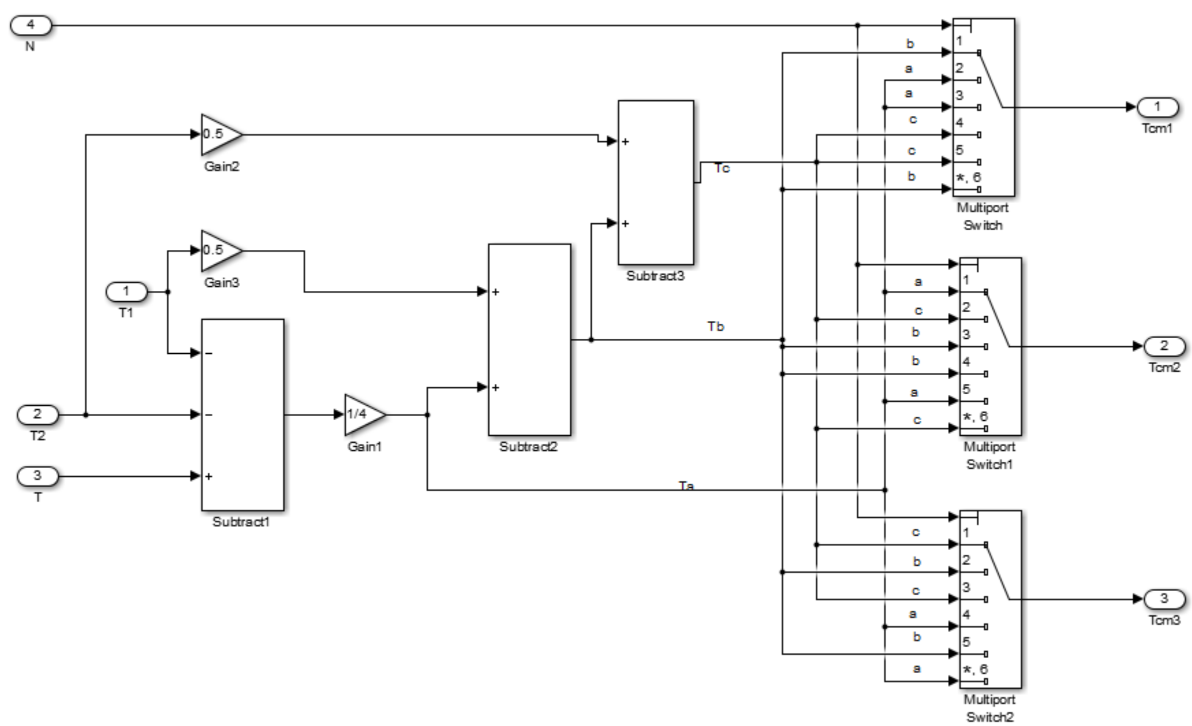


Figure A2: MATLAB Simulink subsystem model for calculating switching operating time

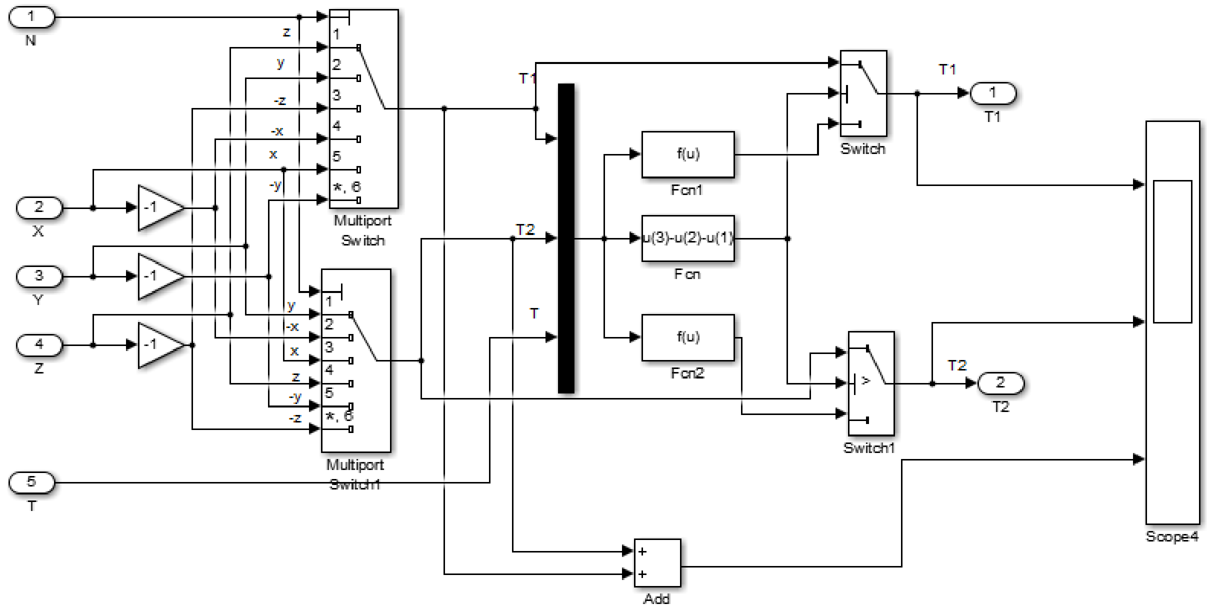


Figure A3 : MATLAB Simulink subsystem model for calculating operating time of the fundamental vectors

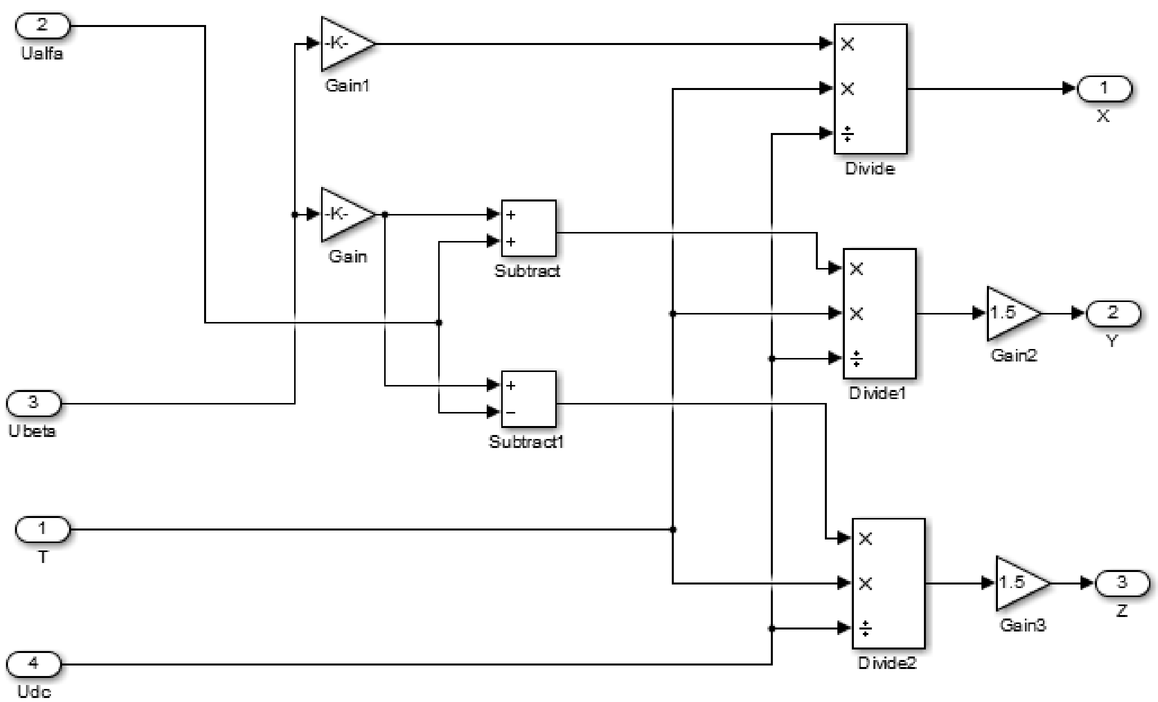


Figure A4: MATLAB Simulink subsystem model for calculating X, Y, Z

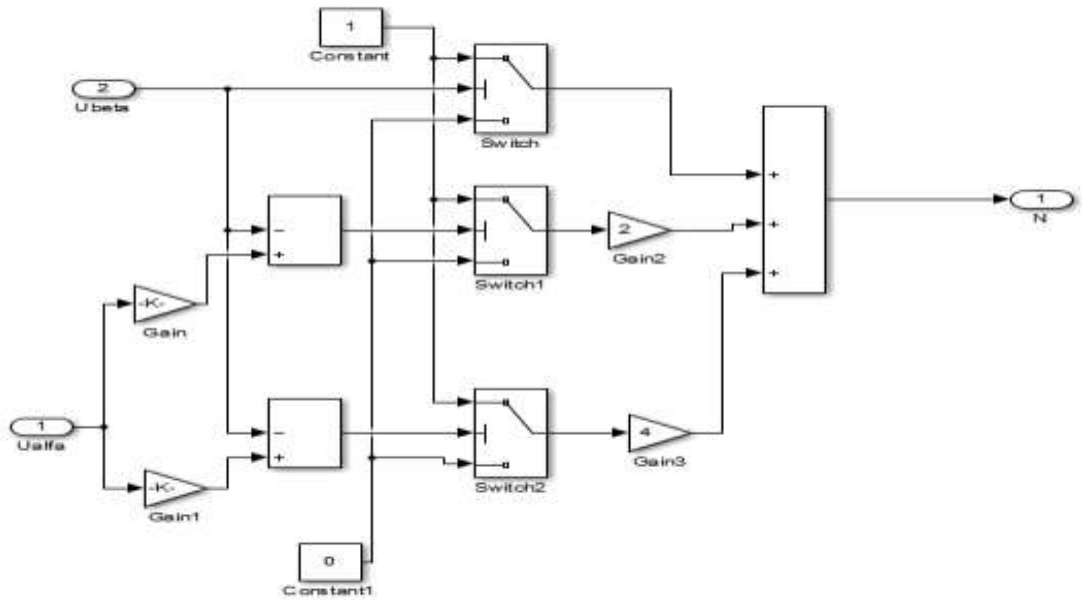


Figure A5: MATLAB Simulink subsystem model for sector judgment

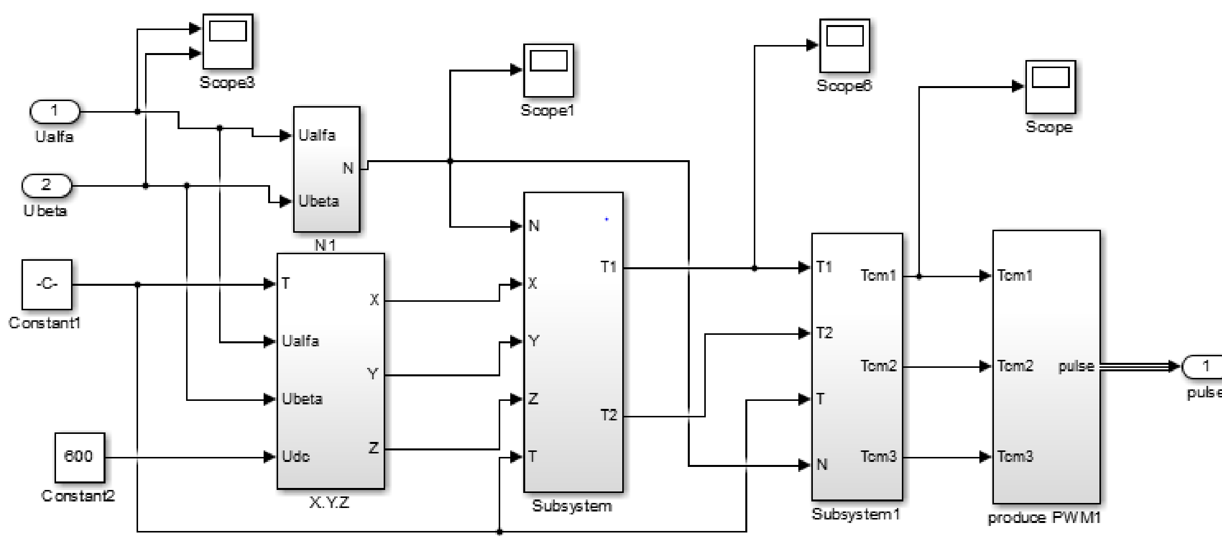


Figure A6: MATLAB Simulink subsystem model for the generation of gate pulse

Appendix D: Protous Simulation Design

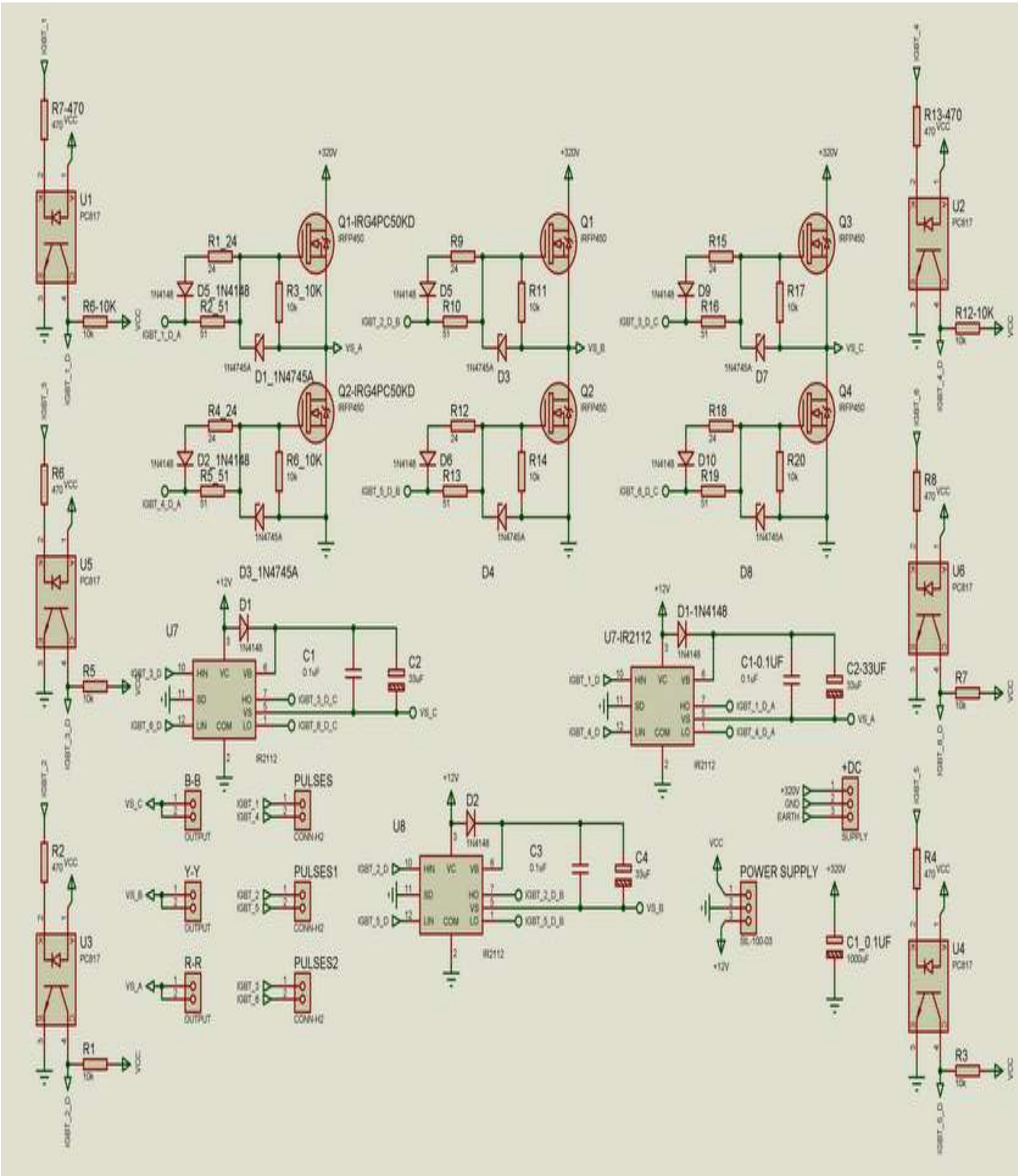


Figure A7: Schematic for Speed control 3 Phase

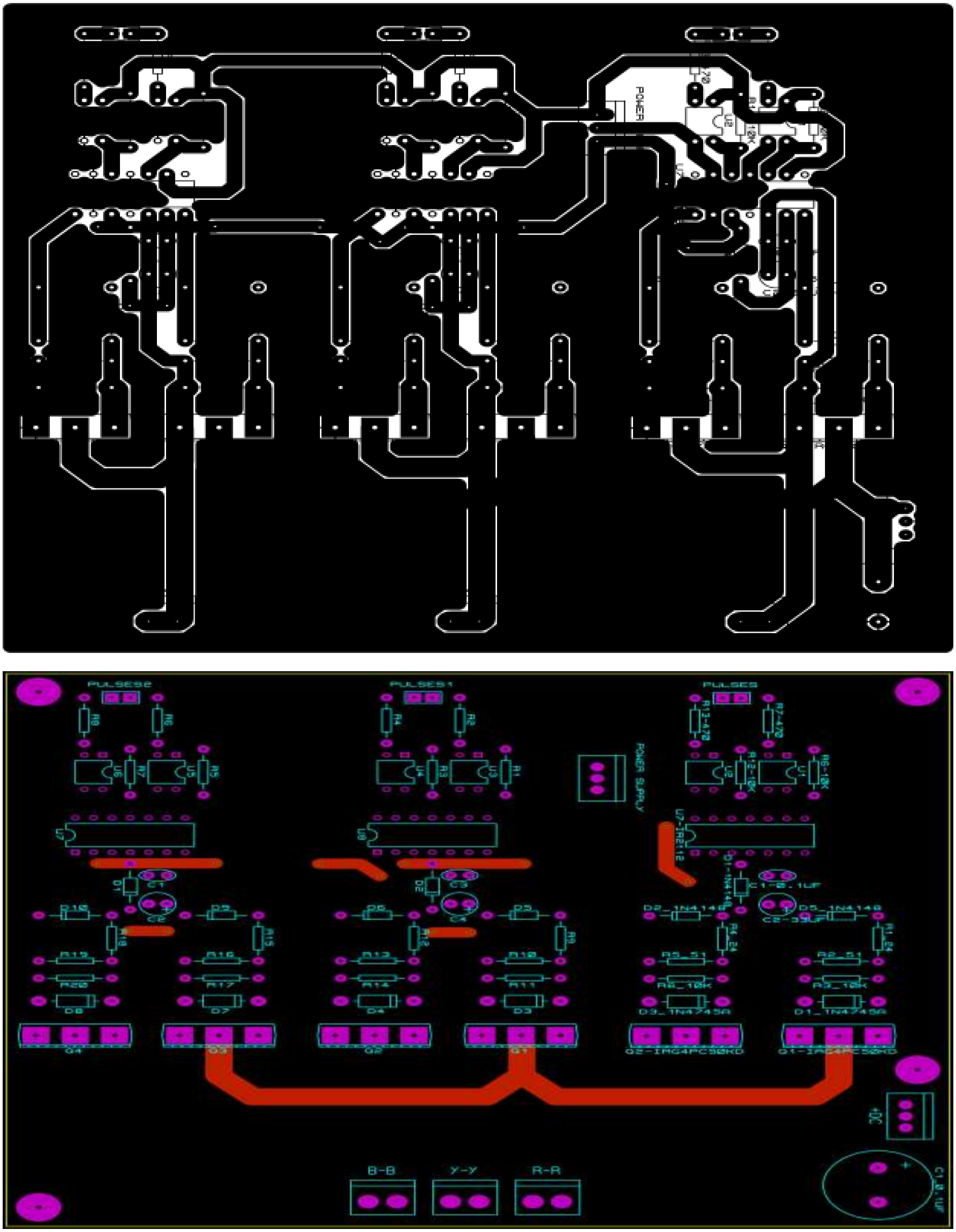


Figure A9**:** Top & Bottom layer pictures of PCB for control 3 Phase IM

Appendix E: Data sheet and characteristics electrical component used in the thesis

Table A1: Absolute Electrical Ratings of 4P40UD IGBTs[L1]

	Parameter	Max.	Units
V_{CES}	Collector-to- Emitter Voltage	600	V
I_C @ $T_C = 25℃$	Continuous Collector Current	40	A
I_C @ $T_C = 100℃$	Continuous Collector Current	20	
I_{CM}	Pulsed Collector Current 1	160	
I_{LM}	Clamped Inductive Load Current 2	160	
I_F @ $T_C = 100℃$	Diode Continues Forward Current	15	
I_{FM}	Diode Maximum Forward Current	160	
V_{GE}	Gate-to- Emitter Voltage	± 20	V
P_D @ $T_C = 25℃$	Maximum Power Dissipation	160	W
P_D @ $T_C = 100℃$	Maximum Power Dissipation	65	

The Typical Output Characteristics is

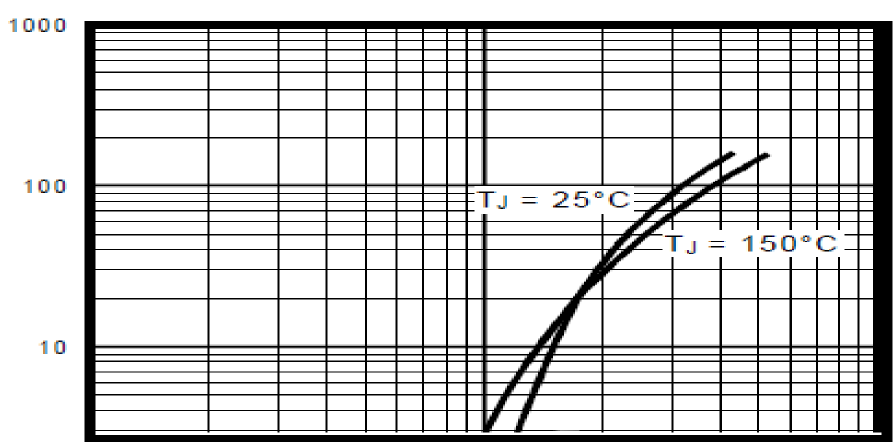


Figure A10: Graph between Collector to Emitter Voltage and Current of [L1]

Pin Description of IR2110 is

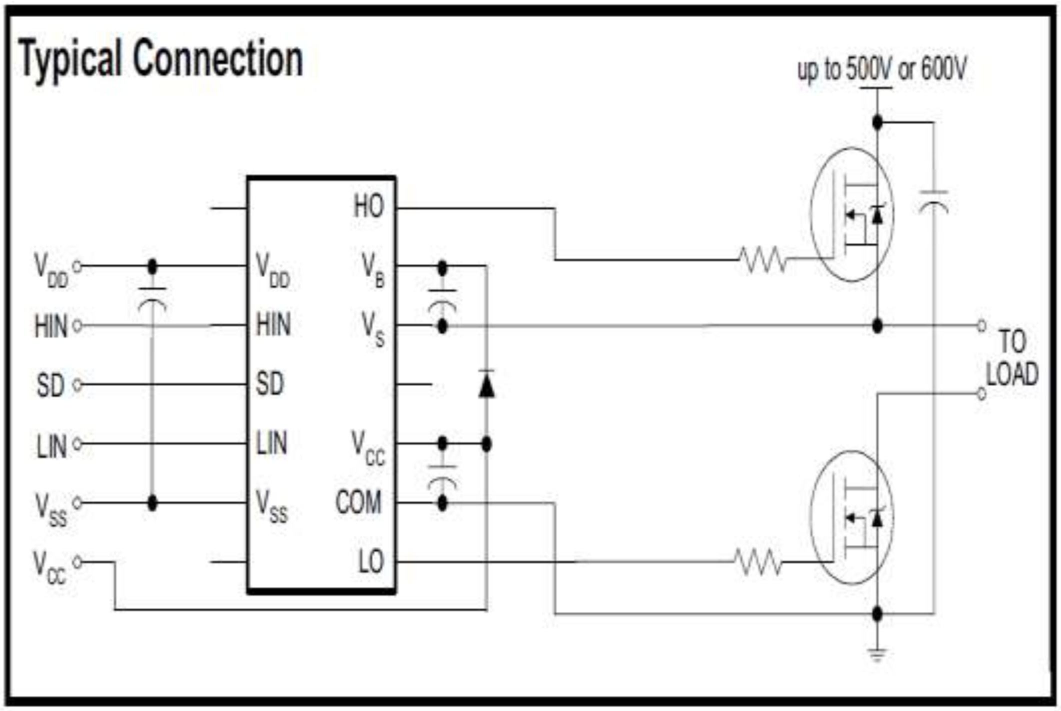


Figure A11: Connections of IR2110 with Pin Description

Table A2: Abbreviations of IR2110 Ports [L1]

Symbol	**Description**
V_{DD}	Logic supply
HIN	Logic input for high side gate driver output (HO), in phase
SD	Logic input for shutdown
LIN	Logic input for low side gate driver output (LO), in phase
V_{SS}	Logic ground
V_B	High side floating supply
HO	High side gate driver output
V_S	High side floating supply return
V_{CC}	Low side supply
LO	Low side gate driver output
COM	Low side return

Table A3: Maximum Ratings of IR2110 [L1]

Symbol	Definition	Min.	Max.	Units
V_B	High side floating supply offset voltage (IR2110)	-0.3	625	
	(IR2113)	-0.3	625	
V_S	High side floating supply offset voltage	V_B-25	V_B+0.3	V
V_{HO}	High side floating output voltage	V_s-0.3	V_B+0.3	
V_{CC}	Low side fixed supply voltage	-0.3	25	
V_{LO}	Low side output voltage	-0.3	V_{CC}+0.3	
V_{DD}	Logic supply voltage	-0.3	V_{SS}+25	
V_{SS}	Logic supply offset voltage	$V_{CC}-25$	V_{CC}+0.3	
V_{IN}	Logic input voltage (HIN, LIN, SD)	V_{SS}-0.3	V_{DD}+0.3	

Lead Assignment and Mechanical Structure of IR2110 is describe in the below diagram

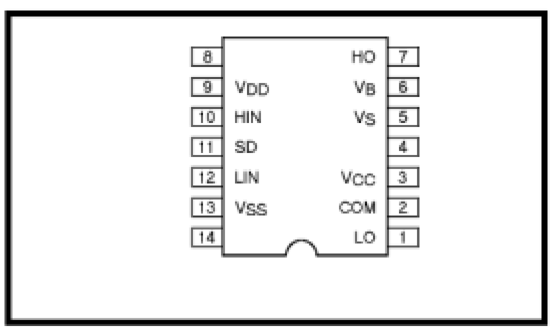
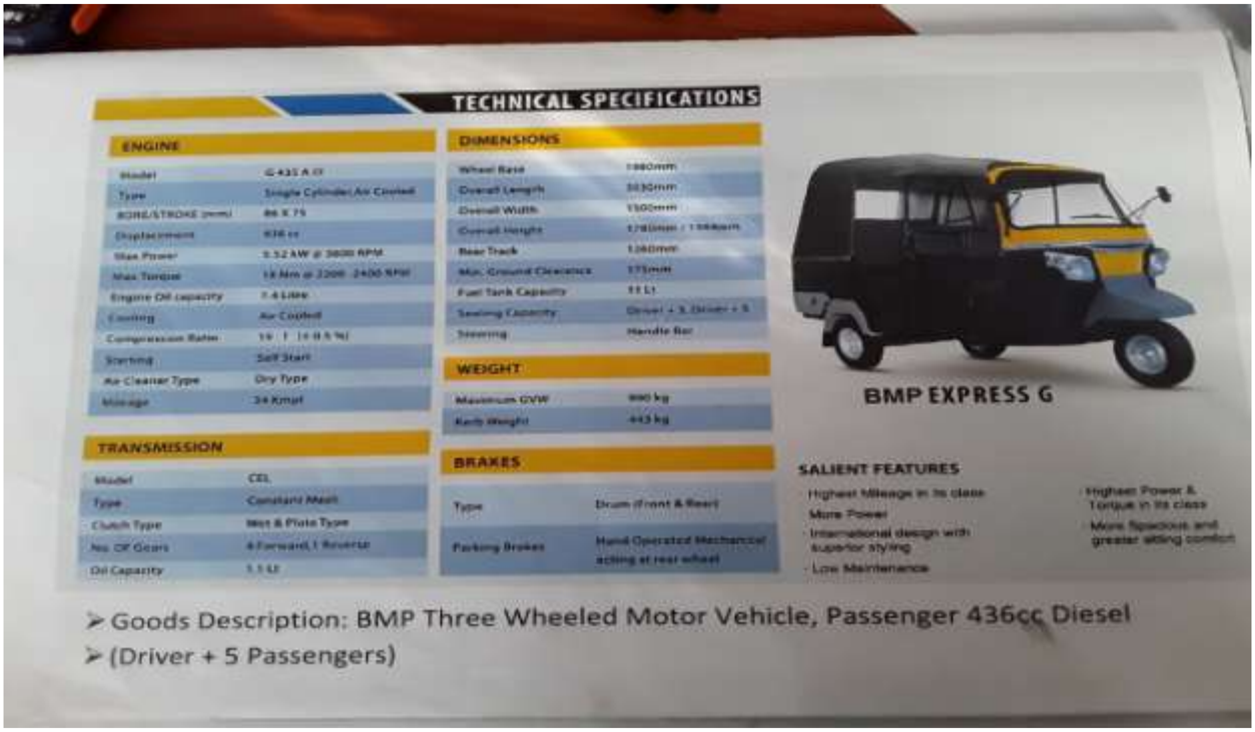


Figure A12: 14 Pin Lead IR2110 [L1]

Appendix F: Collected data from Hora trading

Different types of Bajaj that are fabricated by Hora trading



Bajaj specification from Hora trading that are selected for our work.

Parameter	Symbol	Value
Maximum power	P	7.52kw@3600rpm
Wheel base	B	1980mm
Overall length	L	3030mm
Overall width	W	1500mm
Overall height	H	1780mm
Vehicle mass	m	700 Kg
Air density	ρ	1.23 Kg/m^3
Frontal area	A	$0.35m^2$
Tyre radius	*R*	0.1m