Design of Electric Bike Controller Using Pulse Width Modulation (PWM)

By

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In closing, this project is dedicated to my family , friends and the future generation I am paving the way for my children.

ABSTRACT

As technology continuously evolves, we are moving towards the 4.0 industrial revolution, it is important to keep up with the pace of industrial evolution. Modes of transport throughout the ages have also evolved and have become more efficient. Bicycles have also evolved throughout the ages and are now electrically powered.

The introduction of electric bicycle has led to some of the most interesting applications of electric motors and power electronics. The brushless direct current motor is ideal for this application because of its high efficiency , better thermal management, silent operation and reliability. BLDC motors are also attractive in automotive applications as they offer desirable control. The control of these motors can be either sensored or sensor less depending on the application.

Another technique that usually accompanies control of brushless dc motors is the utilization of Pulse Width Modulation(PWM). This technique is used to limit the excessive starting current through current chopping and essentially controls the speed and the torque of the motor at the shaft. In this project , a prototype electronic controller will be designed and built. Sensored position control will be used by using Hall sensors ,while to vary the speed and torque PWM shall be used .The conversion of the automotive alternator into a BLDC (as AC machines can be converted into DC machines and vice versa) and insertion of the hall sensors shall be done to complete the sensored BLDC design.

To ensure success of this project, Hall sensors, the commutation and working principle of the BLDC were thoroughly studied. PWM was used to control the torque, current and ultimately this allowed variation of the speed to be possible.

This dissertation describes the design, development and implementation of a BLDC powered electric bike controller using PWM.

Keywords : brushless dc motor(BLDC), pulse width modulation (PWM), commutation, regenerative braking, Hall sensors(position sensors), SPDT relay (single pole double throw relay).

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CHAPTER 1: INTRODUCTION

1.1 Introduction and Context

In this present day and age, engineers and scientists are constantly trying to come up with innovative ways to solve societies' problems. It has always been known through various experiments in both practical and experimental physics that energy is not lost but it is converted to other forms of energy. This phenomenon of energy conversions has played a crucial role in the evolution of electrical vehicles and the power electronic devices concerned. A good example of this is regenerative braking or kinetic energy recovery. This type of technology is common in applications that involve electric motors whereby there is need for energy to be harvested or need for the brake pads to be prolonged. However, for regenerative braking in motors to be meaningful, another common technique called Pulse Width Modulation is used (PWM). This technique allows the motor's speed to be controlled as desired while improving the overall efficiency and power-losses of the motor. Pulse width modulation is simply a control technique that enables one to control various aspects such as current ,voltage, torque ,speed of motors and much more in an energy-efficient manner. Existing applications for PWM include, but are not limited to:

- Variable speed fan controllers .
- VRF HVAC compressor drives .
- Hybrid and electric vehicle motor drive circuits.
- Pure Sinewave Inverters.
- Motor control.

Switched mode technology has made a positive impact in the world by almost halving the power consumption of applications that use motors. These include variable speed drives, inverter air conditioners, inverter refrigerators, inverter washing machines and many more. Through use of PWM , inverter air conditioners can consume less than half the energy that their non-inverter counterparts do in some cases [1]. PWM is used because the voltage of the appliances' motor is varied so that they only consume as much power as they need while lessening the usual consequence of burning off unused current as heat. PWM works by pulsing DC current and varying the amount of time that each pulse stays 'on' to control the amount of current that flows to a device such as a motor. The use of PWM becomes attractive because only on/off time is modulated, rather than the power, this allows us to do some things we were not able to do before. Initial power required to start the motor turning can be supplied by applying modulated voltage and current. This greatly reduces the excessive starting current and high torque. This is attractive because short bursts of full power are used to 'boost' the motor, and then let the motor 'glide' under its own inertia thus only using the power that is needed hence less power dissipated. Thus, by varying the duty cycle, the average of the signal approximates the level of the analog DC voltage needed to drive the motor at the same speed. This makes varying of the speed of the motor possible without 'blocking' some current and generating waste heat.

Regenerative braking is one of the standout innovations that utilises power electronic devices to make respective energy conversions and it is very important to fully understand what regenerative braking is and the working principle behind it. Regenerative braking also sometimes known as electrical braking is an energy recovery technique which involves the conversion of mechanical energy (kinetic) to electrical energy. A moving vehicle or an electric motor-based machine under motion has a lot of kinetic energy and when the brakes are applied, that energy therefore must go somewhere. In most cases, in the past many designers used and continue to use the traditional way of braking which is friction based and this often leads to a lot of energy being wasted as dissipated heat and leads to wear of the brake pads [1]. Thus, in regenerative braking the electric motor acts as a generator when under braking. The motor acts as a generator as it is now converting the mechanical/kinetic energy that would have been lost as heat into electrical energy that can be stored in a separate battery, super capacitor or can simply be used to recharge the battery through further manipulation of power electronics. This stored energy if large enough, can be used to restart or speed up the motor without having to tap into its own energy reservoirs.

Regenerative braking is performed by transferring the mechanical energy from the wheels or motor shaft to an electrical load. This whole dynamic sorely depends on the motor's ability to operate in reverse function as a generator. Regenerative braking has become quite common in the modern times as it is widely used in e-bikes, electrical vehicles, hybrid electrical vehicles, industrial machines and in Formula One amongst other countless applications. In Formula One it is known as the Kinetic Energy Recovery System (KERS) and up to 120KW / 160bhp of power can be harvested and sent to the drivetrain from the energy reservoir [2] and the power units that are used are known as the Motor Generator Unit-Kinetic or simply MGU-K because the cars are hybrid electric [2]. In most Ev's and HEVs, the induction motor is used while in e-bikes the brushless dc motor-based hub motor is widely used. The working principle of the motor-generator unit is generally the same with the only difference being the type of motor used and the type of power electronic convertors used. The block diagram below shows or illustrates this working principle:

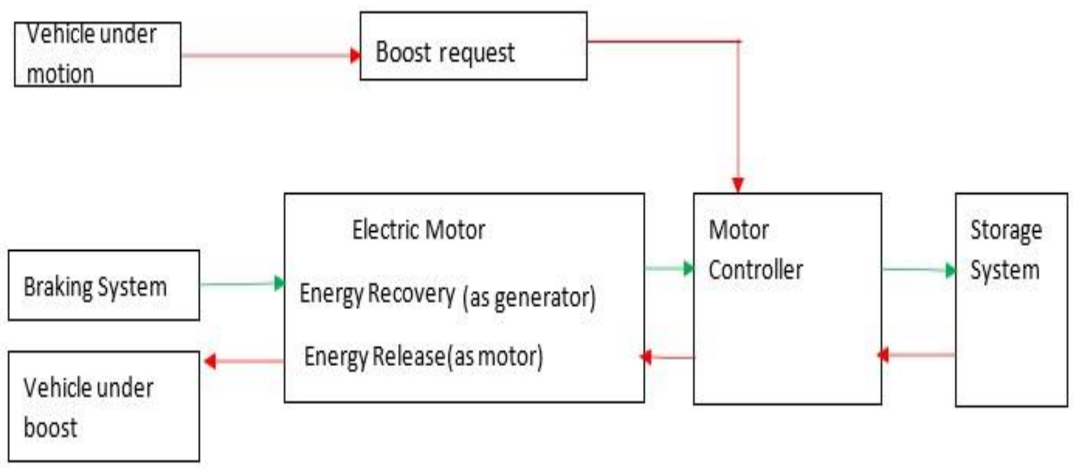


Figure 1: Regenerative braking block diagram

The principle behind Regenerative braking is that when an electric motor runs in one direction, it converts electrical energy into mechanical energy that can be used to perform work such as turning the wheel and when the motor runs in the opposite direction it becomes an electric generator. When the wheels spin without acceleration, the rotation induces a reverse flow of energy producing a generator effect[3]. A back emf is induced in the motor. Back electromotive force (BEMF) is a voltage that appears in the opposite direction to current flow because of the motor´s coils moving relative to a magnetic field[4]. It is this voltage that serves as the principle of operation for regenerative braking. The back EMF is directly related to the speed of the motor, so knowing the value of back EMF allows us to calculate the speed of that motor. Thus, with the use of appropriate convertors this energy can therefore be sent to a reservoir such as a battery or bank [5]. The use of this type of braking is gaining traction as it has been proven that is it quite fuel efficient(vehicles), reduces wear and tear.

1.2 Problem Statement

People of all ages take up cycling or bike riding as a hobby and some have even taken it as their main mode of transport. Therefore, in doing so, people tend to end up cycling over 50km per day. It therefore becomes a challenge to cycle everyday up to 50km and it is also strenuous to the elderly as this activity puts a lot of pressure on the leg muscles(quads). This also becomes quite the challenge if one must cycle up a hill or must cycle against wind. This then results in the cyclist expanding a lot of energy by just trying to overcome the uphill force and the wind force. This is a problem especially in areas that are uphill or have a lot of wind and as a result people end up falling out of love with cycling or the sensation of cycling as it is generally a strenuous activity to cycle in uphill and in windy areas. This then discourages people in taking up cycling as a hobby thus the culture that we all grew up to of bicycle riding and outdoor adventures is slowly dying because of this. Using a bicycle sometimes is a release in a country as it reduces the number of cars that manoeuvre around areas such as the CBD. A person can just leave their car parked somewhere and hop onto a bicycle and they are able to manoeuvre around without using their cars. This reduces air pollution, traffic jams and crimes such as hijacking . In most first world countries and developing countries such as Switzerland and China are in the top 10 for having the most bicycles per capita because they understand and acknowledge this problem of a lot of cars thus causing traffic [5][6].

Therefore, in closing, a lot of people are starting to opt out of cycling because of uphill areas, windy areas and most importantly they are falling out of love with the culture of outdoor adventures because of this.

1.3 Projective Objective

The objective of this project is to provide a solution to the underlying problems that have been mentioned in section 1.2. Thus, the main objective of this project is to design, build and test an electronic controller for an electric bike prototype. It is also important to note that the project shall also have multiple sub-objectives as this project shall be carried out under the divide and conquer rule. The main and primary objective is to ensure that the controller can drive the electric motor which in turn drives the bike while the secondary objective is attempt regenerative braking capability. To ensure success of the project the sub objectives entail choosing the best ways to make the system more efficient, obtaining the best results and these sub-objectives include:

- Appropriate selection of electric machine (motor).
- Selection of appropriate power electronics components and devices.
- Understanding Pulse Width Modulation (PWM) and determining the optimal switching frequency for the motor .
- Designing the electric motor speed controller using PWM and writing the accompanying software.
- Setting up the microcontroller to specified parameters .
- Understanding the different ways in which regenerative braking can be enforced.

1.4 Scope of Project

The scope of the entails the specific tasks that need to be completed and the work that must be accomplished to deliver the project. The specific components needed, budget and time that will be needed to solve the problem;

- The project must be within the budget of R1500 .
- The speed of the motor must be variable.
- The power electronics must be able to handle the power consumption by the motor.
- A clear idea on how regenerative braking is ideally implemented.

1.5 Methodology Overview

A proper and professional methodological approach which adheres to engineering principles shall be used for the purposes of completing this project. This will be fundamental especially if the project is taken up any further to master's level or an individual wants to take it further. If any challenges are faced during the completion of the investigation, these methods can be followed again to help solve the problem. These are the recommended steps that must be followed to ensure chronological solving of the problem:

1.5.1 Problem Identification

The designer shall be required to extensively and explicitly understand the problem, the implications of the problem to the society and the environment and understand the steps required to formulate an appropriate solution.

1.5.2 Requirements and Specifications

The specifications of the project should be clear and concise. This is what will guide the project and will determine the quality and scope of the project.

1.5.3 Background Research

This shall be done in the form of a literature review were similar problems and solutions will be thoroughly investigated. This section will also introduce the equations and assumptions that are most likely to be used in modelling the problem mathematically and it will also extensively look at closely related circuitry and software packages.

1.5.4 Design and Building Model

This is the stage at which the prototype will be designed, and several parameters established using several software packages. Software and hardware development shall commence.

1.5.5 Model Testing

The model which has been developed shall be tested through excessive testing to observe if all requirements and specifications are met by the prototype.

1.5.6 Clarification of Requirements Specifications and Test Acceptance

When the testing is concluded, a test acceptance procedure shall be conducted to compare the results to the specifications and expectations.

1.5.7 Conclusion and Presentation of Results

The investigation must show the number of tests done were enough to conclude a successful investigation. Any issues, difficulties and short comings must be included, and an engineering conclusion must be drawn on these short comings.

1.6 Project Deliverables

This project is a design, build and test-based investigation. The main objective of this project is to design and build an electronic controller for an electric bike prototype.

1.6.1 Project Investigation Presentation

A full detailed formal presentation outlining the basis of the project, investigation process, findings and final recommendations or improvements.

1.6.2 Project Report

A well detailed mini dissertation report must be presented at the end of the project to document the life cycle of the project and its findings. Suggested outline for a mini dissertation:

- Introduction
- Problem Statement.
- Requirements Analysis.
- Literature Study.
- Design.
- Experimental Design.
- Testing
- Results and Analysis.
- Conclusion.

1.6.3 Prototype Presentation

The final design prototype shall be presented on project day.

CHAPTER 2: REQUIREMENTS ANALYSIS

2.1 Introduction

In the previous chapter the idea of Pulse Width Modulation was introduced and discussed together with its working principle. The advantages and the reasons why Pulse Width Modulation or Switched Mode Technology is preferred were also discussed and supported. The problem was also defined, analysed and understood. In this chapter more focus is going to be on the constraints, implications and impact of the project both *society to project and project to society*. The chapter will also discuss more on the requirements of the design and the general specifications to ensure that the design is indeed the solution to the problem. However, for completeness, some literature that is concerned with motor equations might be briefly to further understand to move towards solving this problem.

2.2 Identified Issues and Constraints

2.2.1 Technical

In the development of the prototype, it might be quite a challenge to get the optimal switching frequency that will satisfy the motor used and to control the speed of the motor in a satisfactory manner. Since the controller will be built and tested on a Veroboard instead of a PCB, various issues will arise. This is problematic especially in this case since we are going to be switching at high frequencies thus the resulting consequence will likely be Electromagnetic Interference(EMI). Therefore, this will likely be one of the biggest challenges that will be encountered in this project.

2.2.2 Financial and Economic

- This entire project has been allocated a budget of R1 500.

2.2.3 Social

- It might encourage some members of the society to enjoy the sensation of cycling without having to put any mechanical cycling effort
- Get the public to appreciate the importance of regenerative braking as an agent of fuel efficiency

2.2.4 Legal

- N/A

2.2.5 Safety

- Must be safe to use. Since this is most likely to be a high current application, the necessary safety precautions must be observed during building and testing.
- Minimize the use of naked wired so that it is safe for everyone to use.

2.2.6 Environmental Impact

- There is no damage or harm to the environment caused by this project

2.2.7 Ethical Considerations

- The ECSA code of conduct shall be obeyed and as such the project doesn't pose any threat or harm to society.

2.3 Requirements Specifications

2.3.1 Technical Requirements

- An electric motor shall be used as the propulsion system of the bike.
- PWM shall be used to control the motor.
- The design must be able to handle an input voltage range of atleast12V and input currents up to 65A.

2.3.2 Quality and Performance Requirements

- The design shall operate at least the rated specified power and rpm .
- The design must show the success or the advantages of PWM through its efficiency.
- The speed must be variable as per duty cycle.

2.3.3 Financial Requirements

- The project's maximum expenditure shall be capped at R1 500 as per university regulations.

2.3.4 Social Requirements

- The design shall raise awareness on the importance of regenerative braking in relation to fuel efficiency

2.3.5 *Legal Requirements*

- The design must be within the legal legislations of South Africa

2.3.6 *Environmental Requirements*

- The design shall be environmentally friendly as there are no carbon emission or any waste disposals

2.3.7 *Safety Requirements*

- The design must be safe to use i.e. all naked wires shall be insulated.

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction and Overview

In the previous chapters the concepts of speed control ,switch mode technology and regenerative braking were discussed. The importance of motor control was briefly highlighted in the previous chapters together with principles which govern it. In the previous chapters the problem statement, scope and the objectives where defined and it was then established that switch mode technology (PWM) is one of the key ingredients in controlling motors, whether be it in speed control or regenerative braking as it all boils down to the quick switching and manipulation of electronic switches. The main objective of this chapter is to provide an overview of this control technique and the principles which governs it , similar work and difficulties faced in past similar work. This chapter is going to give the theoretical background of motor control especially that of a Brushless DC Motor (BLDC) and regenerative braking and the different methods used in implementing it. In this chapter, the working principle of the BLDC motor, how it commutates and the different ways of achieving regenerative braking will discussed at length.

3.2 Theory and Methods

To solve the problem that was stated, one must fully understand and fully appreciate the working principle and the laws of physics that govern the BLDC Motor, the power electronics used and the software incorporation. This is essential because by understanding this working principle, it is then clear on how the software and coding for the controller will be structured and written. It is also important to understand the regenerative braking working principle and how this energy can be harvested with respect to the BLDC Motor. This is essential as it makes coding for the problem manageable and approachable.

3.2.1 Understanding the Brushless DC Motor (BLDC)

A brushless dc motor is a type of electric motor which is electronically commutated. This means that this type of motor requires electronic assistance so that it can commutate(rotate). A brushless dc motor can be viewed as a 3-phase motor whereby a controller is required to provide a series of current pulses to the respective windings of the motor at a certain and specific time. This is done by a power electronics converter called an inverter. An inverter takes DC source as an input and outputs an AC source which is the one that is used to energize and excite the windings. The use of brushless dc motor as technology has evolved has become so instrumental and crucial such that they have found applications in day to day usable devices such as in computers(disk drives and printers) , hand held power tools(drillers)[7] and most importantly for the purposes of this project, they have found their way recently as propulsion systems for electric vehicles, hybrid electric vehicles , electric bicycles , electric motorbikes and many other automotive applications. A good example of electric motor prominence and use is in Formula One racing as they are used and play a prominent role in the propulsion system as these cars are hybrid cars. This therefore becomes very advantageous to the purposes of this project as these motors can deliver high torque with good speed response [8]. Thus, due to their construction and structure, BLDC motors have high energy efficiency and good thermal characteristics, which is what is required for this project.

3.2.2 Working Principle of BLDC Motor

Before understanding how BLDC commutation works ,it is important to first understand how brushed motor commutation works. It is important to really appreciate and acknowledge the superiority of brushless motor commutation. A brushed motor has permanent magnets at the outside of its structure with a spinning armature on the inside [9]. The permanent magnets that are on the outside are known as the stator and the armature that rotates is an electromagnet known as the rotor. In a brushed DC motor, the rotor spins 180° when an electric current is run to the armature. To go any further, the poles of the electromagnet must flip. The brushes, as the rotor spins, contact the stator, flipping the magnetic field and allowing the rotor to spin a full 360° [9].

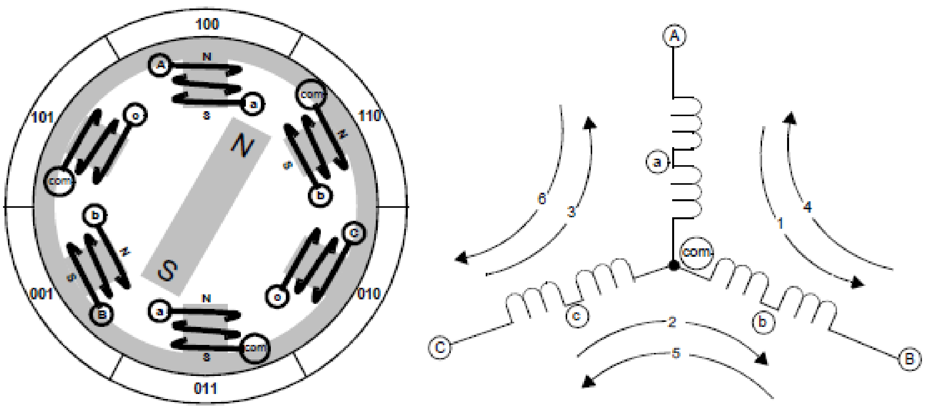


Figure 2: Simplified anatomy of BLDC motor [4]

In the illustration above in figure 2, a BLDC motor consists of 3 electromagnetic circuits connected at a certain point which is known as the neutral point. Thus, each electromagnetic circuit is split at this neutral point which is the centre thus allowing the rotor which is the permeant magnet to move in the middle of the induced magnetic field. A lot of BLDC motors are in star topology and as a result they are driven by energizing 2 phases out of the 3 at a time. However, in a brushless direct current motor there is no need for brushes to flip the electromagnetic field. In a BLDC motor the stator is now the electromagnet while the rotor is the permanent magnet. Therefore, there is need for electronic assisted commutation to continuously flip and change the electromagnetic field to keep the motor spinning.

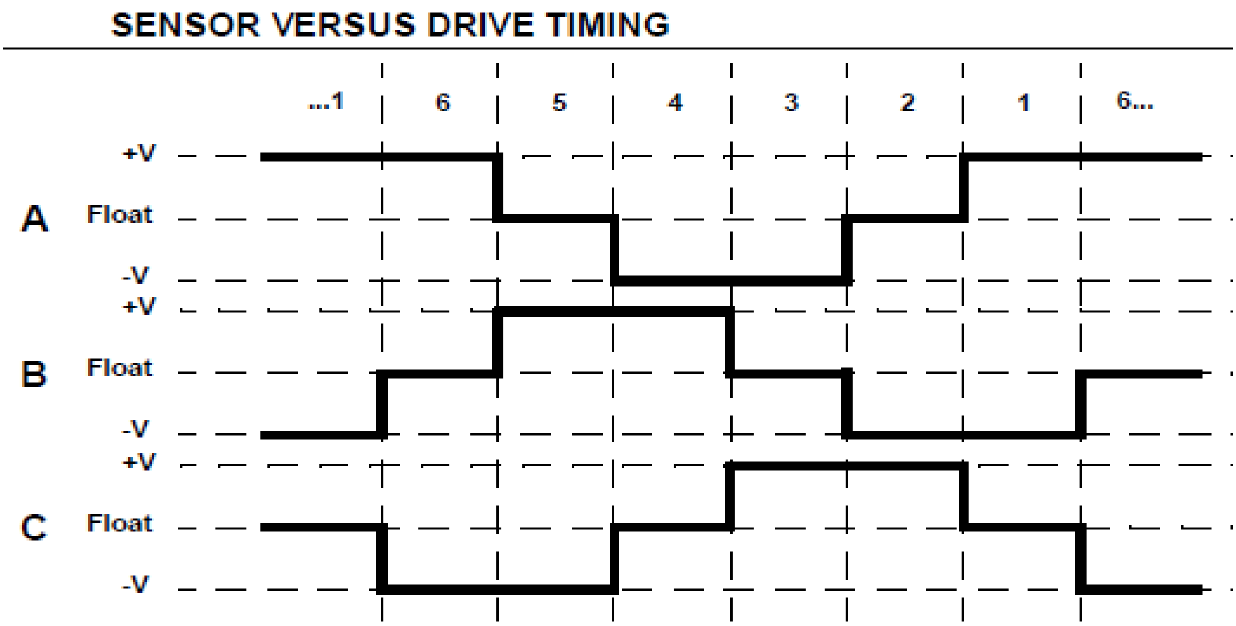


Figure 3: Sensor vs Drive timing diagram [10]

The timing diagram that is shown above in figure 3 shows the 6 commutation steps that define the rotation of the motor. The configuration shown in Figure 2 is that which would be realized by creating an electric current flow from terminal A to B which is indicated as path 1 in Figure 1. The rotor can be made to rotate clockwise 60 degrees from the A to B alignment by changing the current path to flow from terminal C to B which is indicated as path 2 in Figure 1. This magnetic alignment is used only for illustration purposes because it is easy to visualize. Practically, the maximum torque is obtained when the rotor is 90° away from alignment with the stator magnetic field [10]. Thus, with the above being said, it is important to note that the key to BLDC commutation is to sense where the rotor is positioned and then energize the respective phases that produce the most amount of torque. The rotor travels 60°(electrical) per commutation step hence 6 commutation steps since an electrical revolution is 360°. Thus, the appropriate current path of the stator is activated when the rotor is 120° from alignment with the corresponding stator magnetic field and deactivated when it is 60° from alignment at which the next phase is energized. This process repeats hence commutation is achieved. Using Figure 1 as reference, commutation of the rotor would be at the completion of the current path 2 and at the beginning of current path 3 for clockwise rotation and therefore by electrically commutating the rotor through the 6 different steps at the precise moments allows the rotor to achieve one complete electrical revolution [9][10]. Therefore the 2 most common ways to achieve BLDC commutation is through 2 certain methods. These are the Sensored and Sensor less commutation methods.

Sensor less Commutation

In this type of commutation, since there are 3 phases and of which 2 are always energized per commutation step, it is then possible to determine when to commutate by sensing the induced voltage that arises in the floating phase winding. This voltage is known as the Back EMF(BEMF).This is done using an analog filter which detects the zero switching. At zero switching it is when the BEMF of the unexcited winding reaches half of the dc bus voltage. Therefore, the time it takes to reach this voltage is the average time that is required for each commutation step. Thus, this process is repeated for the 6 commutation steps. However, this method of commutation has major drawbacks. The major disadvantages for sensor-less motor control are that the motor must be moving at a minimum rate to generate enough BEMF which will be sensed for feedback, rates faster than ideal rate will result in discontinuous motor response and any abrupt changes to the motor load can result in the BEMF loop going out of lock [9][10]. Thus, the disadvantages of Sensor less control show that this method is not dynamic enough especially if this is implemented in an application where the speed is being continuously varied i.e. an electric bike or electric vehicle. Therefore, another method of commutation was investigated.

Sensored Commutation

A better way of commutating a BLDC is by using the technique of sensored control. The best way to know when to commutate is by using position sensors and in this case, these are the hall effect sensors. These sensors are governed by the hall effect, which states that when a current carrying conductor is placed in a magnetic field, a voltage is induced in a direction that is perpendicular to both the current and the magnetic field [12]. Most BLDC motors come with Hall sensors, but some don't thus one can modify their BLDC motor by placing position sensors such as shaft encoders or Hall sensors on the none driving end of the motor, or simply embed them onto the stator. In this scenario, Hall sensors were investigated at length. The type of Hall effect sensors used in automotive applications is the bipolar latching hall effect sensors.

Whenever the rotor magnet passes near the hall sensors, these sensors give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined in terms of 0s and 1s. Based on the Hall sensor's characteristics they can be placed at 120° phase shift to each other since the timing diagram of the sensors must resemble that of 3-phase AC which is also at 120° phase shift with each other. Therefore, the commutation sequence will be based on the phase shift.

Each commutation step has one of the winding energized with positive power (current flows into winding), the second one energized negative (current leaving winding) and the third is left floating(unenergized). Thus, torque is then produced because of the interaction between the magnetic field created by the stator and the rotor. Theoretically peak torque is realized when the two fields are perpendicular to each other and falls as the two fields move together. To keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field. What is known as "Six-Step Commutation" defines the sequence of energizing the windings [11].

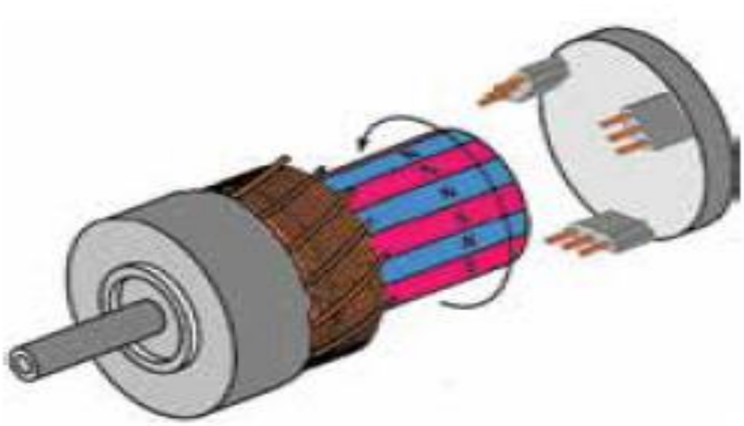


Figure 4 : BLDC motor with three Hall sensors [12]

The rotating permanent magnet moving across the front of the Hall sensors causes then to change states with respect to the North and South poles.

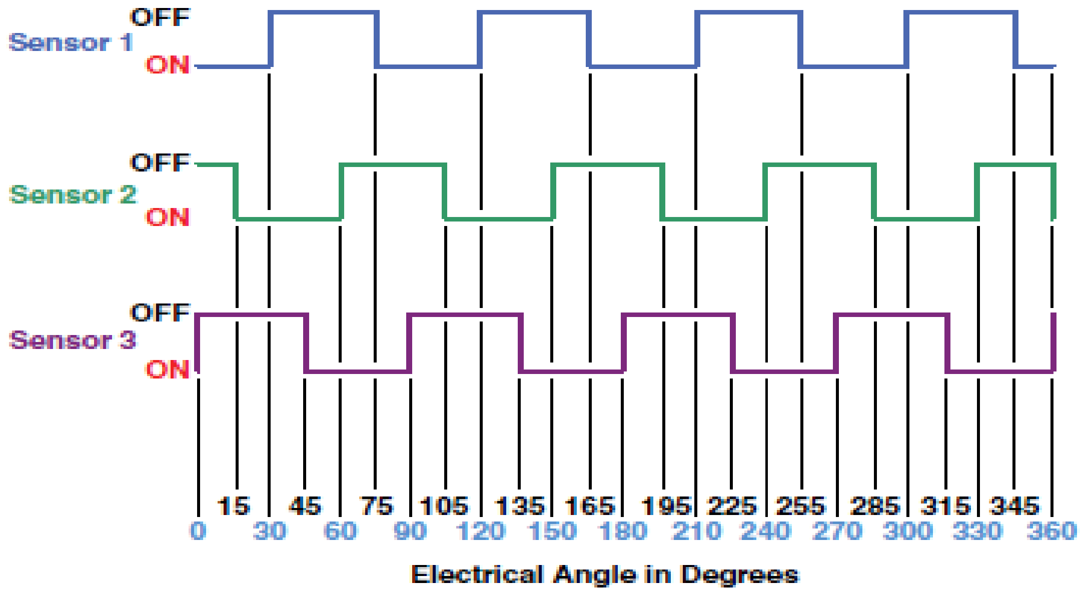


Figure 5 : Hall sensor IC's timing diagram [12]

The illustration above shows the timing diagram of an 8-pole magnetic BLDC motor. The south pole is 90° from the next pole. When the three Hall sensor are placed 30° apart, the first sensor will operate at 30°, the second at 60° and the third at 90°. This is true for when they are also placed at 60° intervals (60°,120°,180°). When the North pole passes the Hall sensor ICs, they will release. Each North pole of the rotating eight-pole magnet is 45° from the adjacent South pole. Each sensor IC will release at 45° after operating. Thus, the Hall sensors will give the out a signal in terms of binary for the rotor position by giving the polarity. This information is then sent a logic circuit which then allows commutation by then switching on and off the appropriate phases.

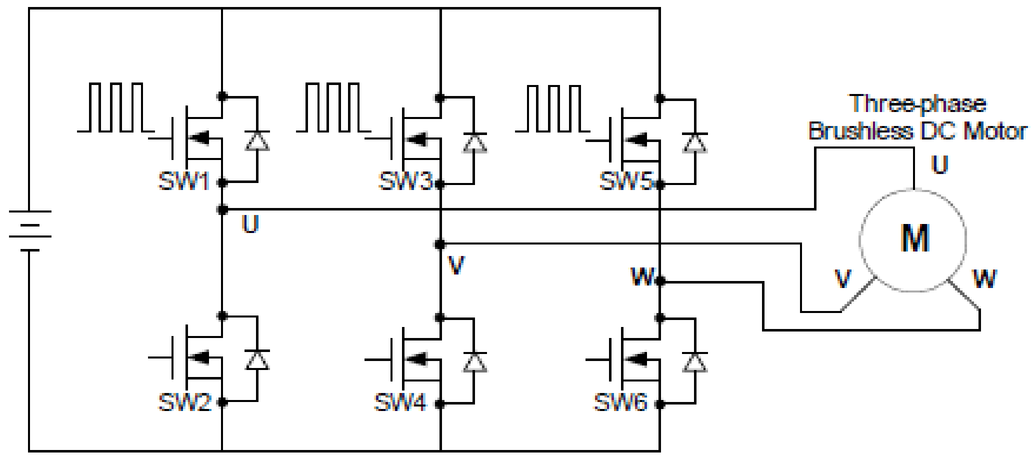


Figure 6 : BLDC driving circuit [13]

The circuit above shows how this switching takes place. Each phase is connected to a half bridge, hence together it forms an inverter circuit. This is comprised of 6 electronic switches(transistors), these can be IGBTs or MOSFETs. The high-side switches are controlled using pulse-width modulation (PWM), which converts a DC voltage into a pulsed voltage, which easily and efficiently limits the starting current, control speed and torque. Generally, raising the switching frequency increases PWM losses, though lowering the switching frequency limits the system's bandwidth and can raise the ripple current pulses to the points where they become destructive or shut down the BLDC motor driver [8].

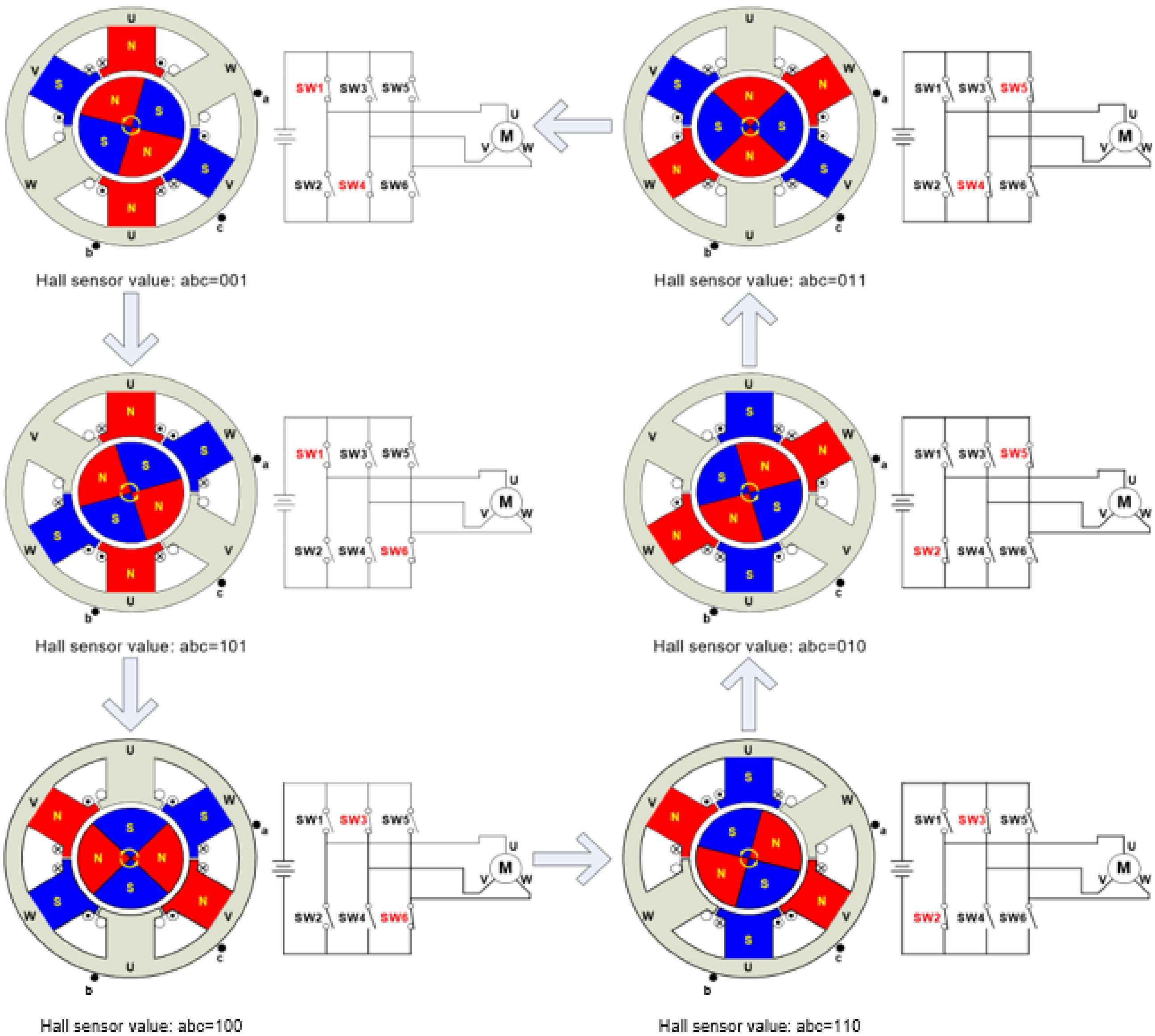


Figure 7: BLDC motor commutation sequence [13]

The diagram above shows the commutation sequence for the BLDC motor across all 6 commutation steps in the counter clockwise direction. The phases are in star connection and the Hall sensors A,B and C are 120° apart mounted on the stator. In synchronous mode, the phase current switching updates every 60°. For each step, there is one motor terminal driven high, another motor terminal driven low, with the third one left floating. Individual drive controls for the high and low drivers permit high drive, low drive, and floating drive at each motor terminal. However, one electrical revolution(6 commutation steps) does not correspond to a complete mechanical revolution. The number of electrical cycles to complete a mechanical rotation is determined by the number of poles of the motor. Every rotor pole pair requires one electrical cycle in one mechanical rotation. So, the number of electrical cycles is equal to the rotor pole pairs. [13].

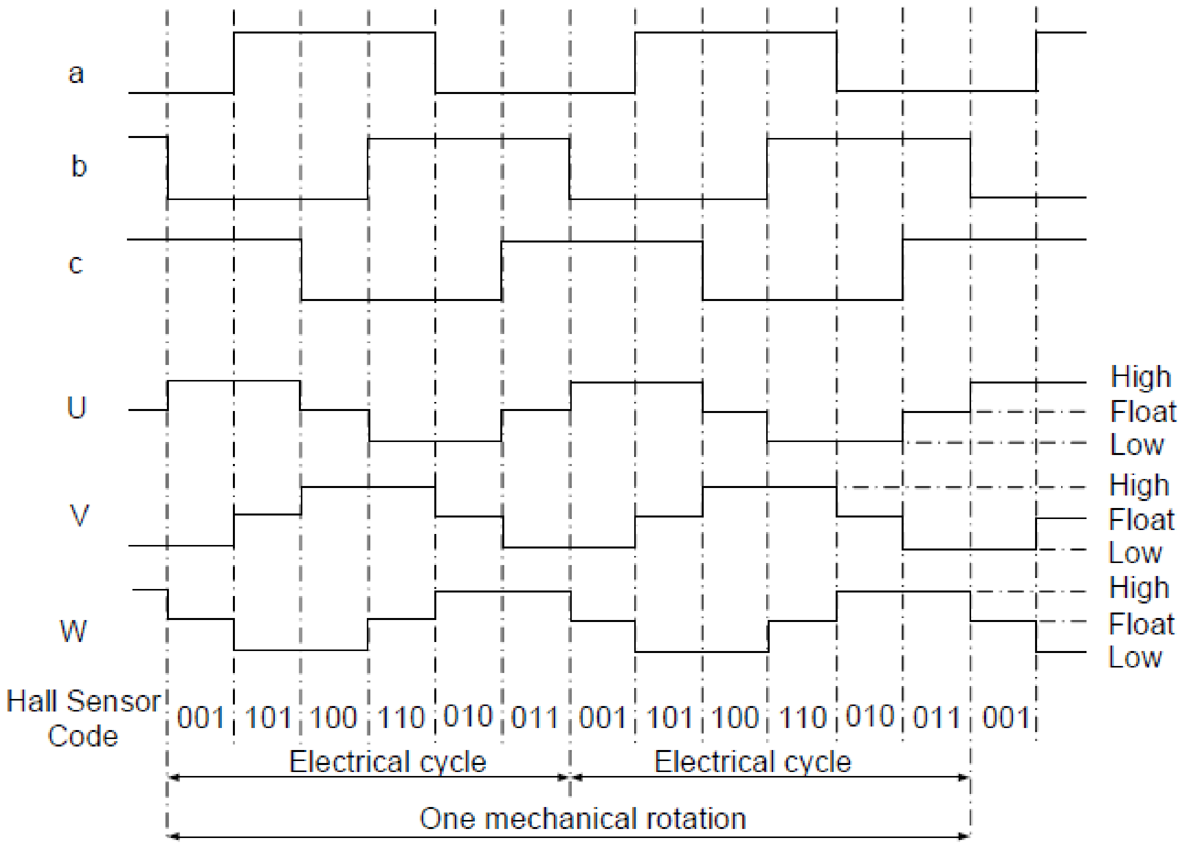


Figure 8 : BLDC motor Hall sensor IC's drive timing [13]

The illustration above shows the phases W,U AND V as either energized or left floating based on the Hall sensor signal. To vary the rotation speed, the duty cycle of PWM signal is varied. Generally, the PWM frequency should be at least 10 times higher than the maximum motor rotation frequency. The PWM frequency can also be determined making use of the per phase time constant. Knowing the inductance and resistance of the motor will allow for the time constant to be calculated and then it can be used to calculate the ideal PWM frequency. An advantage of PWM is that if the bus voltage is much higher than the motor-rated voltage then limiting the duty cycle of PWM to meet the motor rated voltage controls the motor.

Therefore, these fundamentals above now allow the software development to commence as we now have an idea on how to write the program that facilitates commutation and the controlling of the motor by varying the PWM duty cycles.

3.2.3 Understanding the Power Electronics

Now that basic understanding of how the BLDC works together with the sensors has been established, the next logical step is understanding the power electronics that are used in this application. The switching circuit is comprised of 6 switches of which in this case will be the MOSFETs. It is important that one fully understands how MOSFETs work and how they are driven for switching applications. This is because when switching, the gate of the MOSFET acts as a capacitor. This is because at the gate of the MOSFET there is a parasitic input capacitance that needs to be charged and discharged at fast rates. If this is done correctly then the input gate capacitance will charge and discharge rather fast therefore fully turning on and off the mosfets at the required times. This greatly decreases switching losses and the rise and fall time edges are decreased. Failure to drive the MOSFETs properly will lead to excessive power dissipation in the MOSFET, increased possibility of shoot-through during switching and $\frac{dV}{dt}$ failure. These problems can be avoided by understanding the driver needs of a MOSFET.

3.2.4 Mosfet Drivers

It is important to drive the MOSFET's gate with a high gate voltage to quickly charge the input gate capacitance and the on resistance between $V_{ds}(R_{ds-on})$.The Power MOSFET forms a resistive channel between drain and the source. Thus, the power dissipated in this respect will be :

$$\boldsymbol{P_{LOSS} = Irms^2 * R_{DS-ON}}$$

where :

$$\boldsymbol{R_{DS-ON} = drain\ to\ source\ on\ state\ resistnace.}$$

$$\boldsymbol{I_{rms} = drain\ to\ source\ rms\ current}$$

Thus, as suggested by many datasheets, V_g should always be at least 10V to try and minimize the switching losses.

3.2.5 Pulse Width Modulation drive schemes

Since PWM is used to control the motor, it is important to note that there are several ways in which PWM can implemented in this application. There are two common schemes that are usually used to implement PWM which are:

- **Unipolar Pulse Width Modulation drive** – in this technique the motor phases are switched in such a way that one of the phases returns current while PWM modulation is happening in the complementary phase.
- **Bipolar Pulse Width Modulation drive –** in this technique we have the voltage passing through the two phases as being modulated with the PWM, both the input and output of current are being modulated.

Both PWM switching techniques have advantages and disadvantages.

Table 1 : Comparison of PWM techniques.

Unipolar	**Bipolar**
Reduces electromagnetic noise	Recommended approach for sensor less control since this technique increases the BEMF in the circuit. This BEMF is then used as feedback.
DC bus ripple is reduced	Has zero-point voltage at 50% duty cycle, thus more time to sense BEMF.

The PWM can either be complementary or independent. For independent PWM, the high-side and the low side switches in the same phase are operated independently as the BLDC traverses through the sequence. If the high-side is performing PWM then the low-side is off. The MOSFETs in the same phase should never be on at the same time as this will lead to a shoot through between the drain and source thus permanently damaging the MOSFETs. Independent PWM mode is ideal if the BLDC is to operate in the 2 of the 4 quadrants of motor operation.

In complementary mode the high-side and low-side switches are operated inversely However this mode is more challenging and require hours of research and significant knowledge of electronics. This is because as the PWMs for each phase are operated inversely thus a dead-time insertion must be performed so that the 2 MOSFETs of the same bridge are never on at the same time. In some cases, doing it in software alone is not enough thus further discrete electronic components are needed to surely guarantee this. Independent and Complimentary PWM operate in the 2 and 4 quadrants respectively.

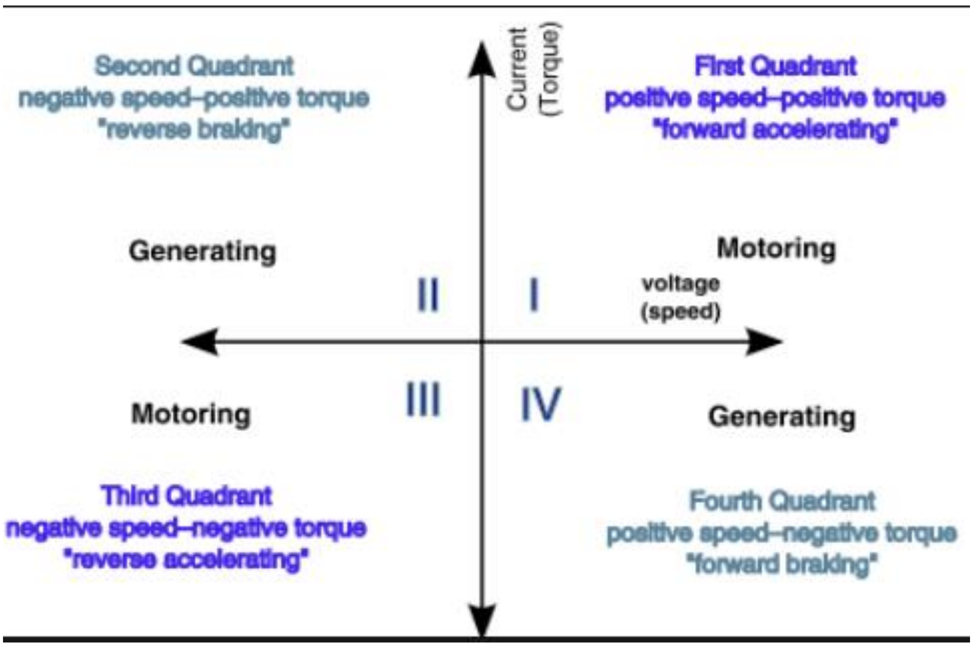


Figure 4 : 4 quadrants of motor operation [20]

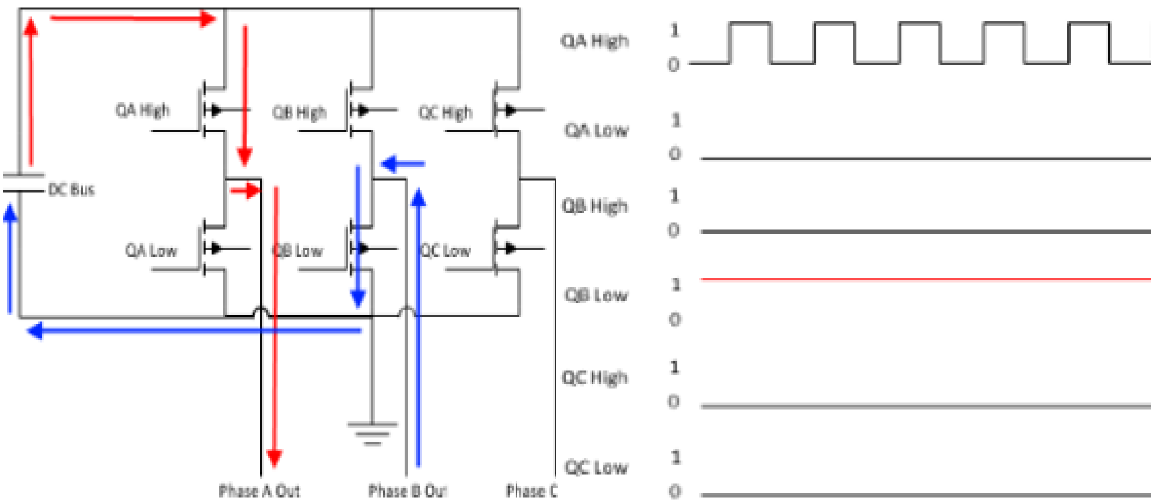


Figure 10 : Independent switching driving scheme [20]

Thus, due to simplicity of implementation and time constraints, in this project independent PWM technique is used.

3.2.6 Regenerative Braking of BLDC Motor

Regenerative braking is an energy recovering system mechanism which slows a vehicle or object by converting its kinetic energy into a form which can be either used immediately or stored until needed. In this mechanism, the electric motor uses the vehicle's momentum to recover energy that would be otherwise lost to the brake discs as heat. However, in practice, regenerative braking on its own is not enough to bring a vehicle to a standstill thus it must be used in combination with another braking system. During deceleration ,regenerative braking is achieved by reversing the current in the motor-battery circuit, thus acting as a generator returning the current flow into the supply battery. However, when there is low speed in the BLDC motor, winding BEMF cannot reach the voltage across the battery. In order to raise the BEMF to battery charging voltage then a boost converter might be of use. Due inductance presence in motor windings, these inductances of drive circuit can consist of the boost converter circuit. To achieve the recovery of energy, the high-side MOSFETs are all turned off and low-side MOSFETs have their duty cycles varied. By varying the PWMs the current is allowed to flow from the 3 phase windings back to the battery (via the freewheeling diodes of the MOSFETs) using a switching sequence as well Armature current of the BLDC motor and in which there is only one power switch is operated within each commutation state on bidirectional dc/ac converter switching signals. According to the principle of the volt-second balance, one can conclude that change in the equivalent inductor voltage is zero over one electric circuit[15].

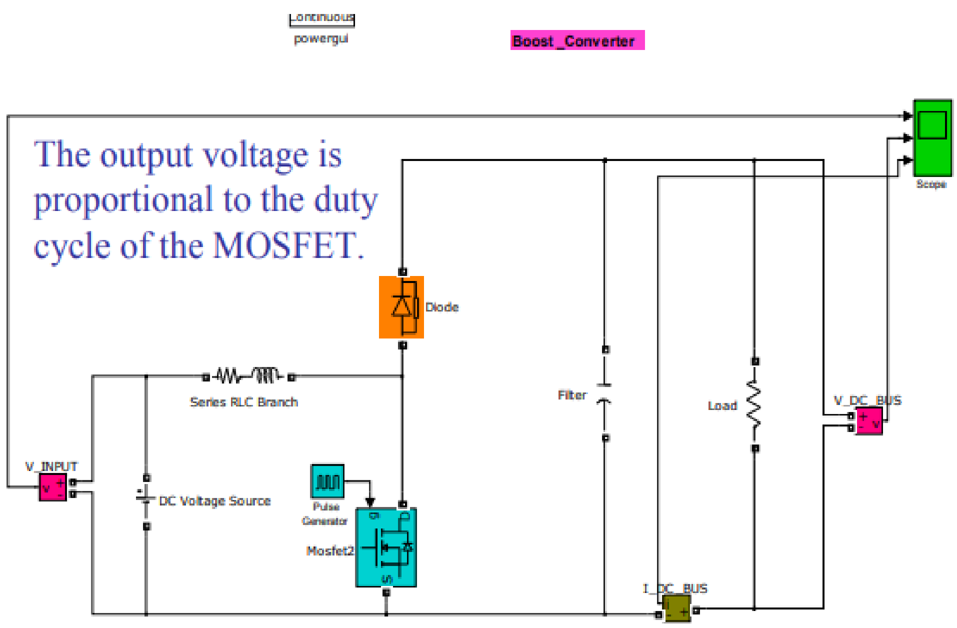


Figure 11 : Equivalent boost converter circuit of one winding when in regenerative braking mode[15]

The diagram above shows the equivalent circuit of a boost converter for one phase winding when the high MOSFET is turned off and the low MOSFET is controlled by PWM. The high MOSFET's body diode will conduct.

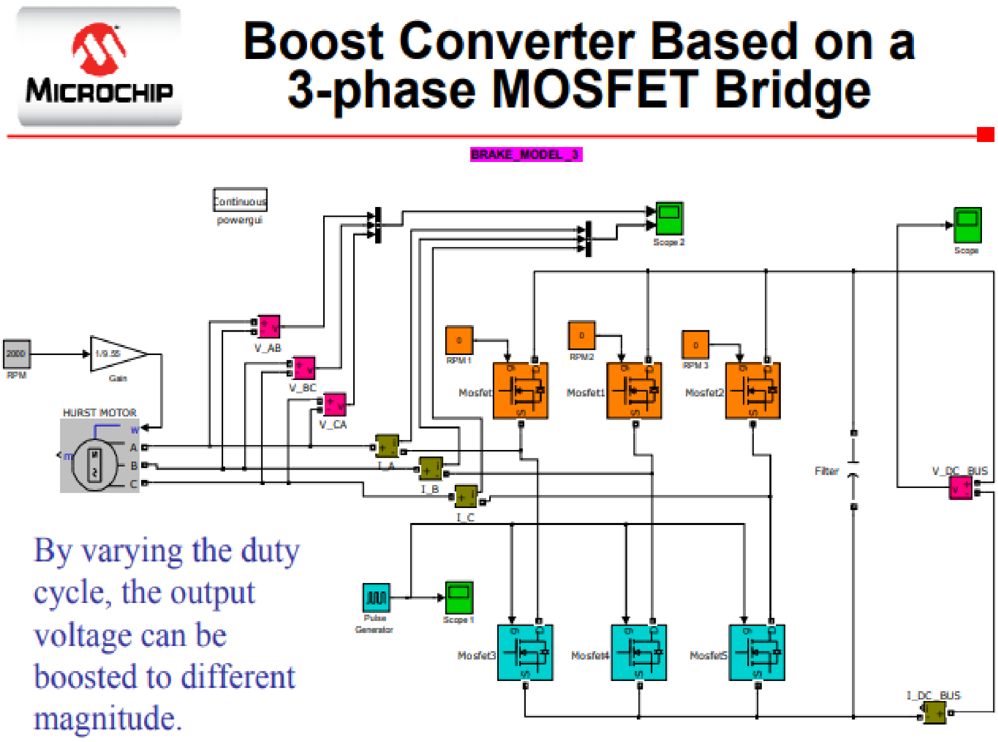


Figure 12 : Boost converter based on MOSFET drive circuit[15]

The diagram above shows an inverter after the high MOSFETS have been turned off. This now brings about 3 separate boost converter equivalent circuits one for each phase. Thus, this principle for the purposes of this project shall be used.

3.3 Similar Work

Jarrad Cody, Özdemir Göl, Zorica Nedic, Andrew Nafalski, Aaron Mohtar (MEng and PhD) from the University of South Australia wrote on their journal "REGENERATIVE BRAKING IN AN ELECTRIC VEHICLE" the fundamentals of BLDC control(Speed and Regen braking). In the journal it is stated that two separate modules (stages) are required to control a BLDC motor, a power module and a control module. A BLDC motor requires a DC source voltage to be applied to the its stator windings in a sequence to sustain rotation[18].

In the case of a BLDC motor the commutation sequence is shown in Table 1, with NC (Not Connected) designating the pairs of stator windings (phases) which are not energised during this commutation step. Table 2 shows the corresponding switching sequence.

Table 1. Forward Commutation Sequence

Forward/Clockwise Motoring Commutation Sequence						
Step	Hall A	Hall B	Hall C	Phase A	Phase B	Phase C
1	1	0	0	-V	+V	NC
2	1	0	1	NC	+V	-V
3	0	0	1	+V	NC	-V
4	0	1	1	+V	-V	NC
5	0	1	0	NC	-V	+V
6	1	1	0	-V	NC	+V

Table 2. Forward Switching Sequence

Forward/Clockwise Motoring Inverter Operation			
Step	PWM Switch	ON Switch	OFF Switch
1	B_High	A_Low	Remaining
2	B_High	C_Low	Remaining
3	A_High	C_Low	Remaining
4	A_High	B_Low	Remaining
5	C_High	B_Low	Remaining
6	C_High	A_Low	Remaining

Figure 13 : Commutation sequence for forward motoring[18]

- And the energized sequence of the first commutation step is illustrated below

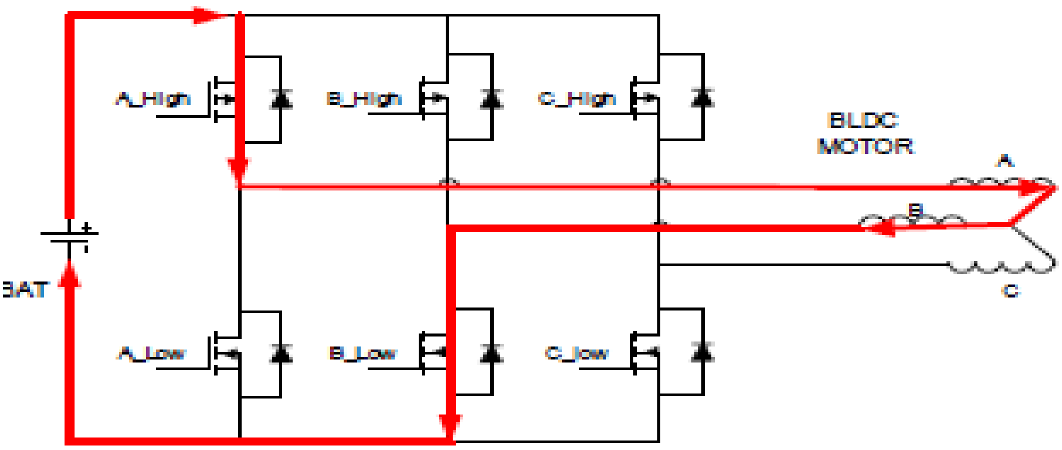


Figure 14 : Motoring current flow per step[18]

- It was then stated that a similar strategy for reverse motoring was also used as the tables below illustrate:

Table 3. Reverse Commutation Sequence

Reverse/Anticlockwise Motoring Commutation Sequence						
Step	**Hall A**	**Hall B**	**Hall C**	**Phase A**	**Phase B**	**Phase C**
1	1	0	0	+V	-V	NC
2	1	0	1	+V	NC	-V
3	0	0	1	NC	+V	-V
4	0	1	1	-V	+V	NC
5	0	1	0	-V	NC	+V
6	1	1	0	NC	-V	+V

Table 4. Reverse Switching Sequence

Reverse/Anticlockwise Motoring Inverter Operation			
Step	**PWM Switch**	**ON Switch**	**OFF Switch**
1	A_High	B_Low	Remaining
2	A_High	C_Low	Remaining
3	B_High	C_Low	Remaining
4	B_High	A_Low	Remaining
5	C_High	A_Low	Remaining
6	C_High	B_Low	Remaining

Figure 15 : Commutation sequence for reverse motoring[18]

The scheme that was used above is the independent PWM switching technique. Regenerative braking was achieved using a strategy called independent switching in conjunction with PWM. In independent switching all switches are turned off when applying regenerative braking. PWMs on the low switches were then varied to control the level of regenerative braking. Thus, during this mode, the direction of the current is reversed and the current flows back to the battery through the freewheeling diodes.

The figure below shows an example of the current flow when the winding pairs of the A and B phases are energized. In this example ,the current can flow through the freewheeling diode of the A High switch , through the battery and through the B low switch.

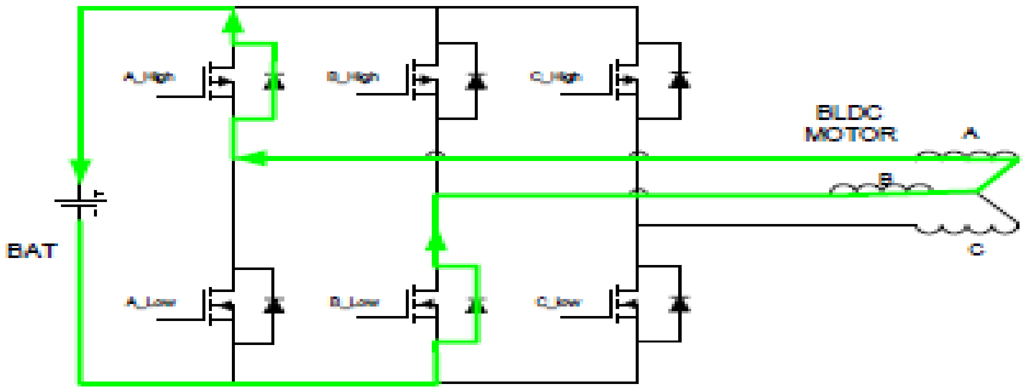


Figure 5 : Regenerative current flow for commutation step [18]

To control the level of braking, the PWM duty cycle is varied, which essentially toggles the current flow between regeneration and coasting. The maximum level of regeneration occurs when the low-side switches are all turned off. Figure 17 below shows the switching sequence applied during regenerative braking with independent switching. It is noted that the low-side switches are switched with PWM and all other switches remain off.

Forward/Clockwise Regenerative Inverter Operation			
Step	PWM Switch	ON Switch	OFF Switch
1	A_Low	NIL	Remaining
2	C_Low	NIL	Remaining
3	C_Low	NIL	Remaining
4	B_Low	NIL	Remaining
5	B_Low	NIL	Remaining
6	A_Low	NIL	Remaining

Figure 17 : Forward regenerative inverter operation [18]

Regenerative braking was also be applied whilst the vehicle is in reverse as shown in Table 6 below. The same method was used as in the forward mode, but the phases were energised differently. This switching sequence was determined by the control stage and using a forward/reverse switch interface.

Reverse/Anticlockwise Regenerative Inverter Operation			
Step	PWM Switch	ON Switch	OFF Switch
1	B_Low	NIL	Remaining
2	C_Low	NIL	Remaining
3	C_Low	NIL	Remaining
4	A_Low	NIL	Remaining
5	A_Low	NIL	Remaining
6	B_Low	NIL	Remaining

Figure 18 : Reverse regenerative inverter operation [18]

This was designed by the School of Electrical and Information Engineering, University of South Australia, Adelaide, South Australia, Australia for their Two-person Renewable Energy Vehicle(TREV) and the regenerative braking discussed in their journal was successfully tested and implemented in their final design. Below shows the images of their final TREV design and the TREV BLDC Motor Controller.

Figure 6 : TREV electric vehicle [18]

Figure 20 : TREV BLDC controller [18]

3.4 Tools, Components and Software

Properties of Microcontrollers

A suitable microcontroller must be selected to facilitate the switching of these MOSFETs . The switching is done with the aid of 3 PWM signals each switching at certain instances at very high frequencies. Thus, the need to be switching the individual switches requires the aid of a microcontroller which is powerful and easy to understand(time is a constraint, should the microcontroller prove challenging to configure). Thus, essentially a microcontroller that is best suited to BLDC motor control must be used to ensure fluency of the project.

The table below shows different possible selection criteria of the right microcontroller:

Table 2 : Microcontroller comparison.

Name of microcontroller	**Advantage**	**Disadvantage**
PIC family	-Fast execution speed. a wide variety of separate electronic components. Easily accessible.	-Due to its complex architecture, so is the development of the source code. -Microchip Application notes especially for BLDC motor is provided in assembly language(which is quite airy to understand, and it is a separate project on its own) [4].
Cypress PSoC with ARM Cortex	-Programmable analog and digital blocks in PSoC provide the flexibility to adapt to changing requirements quickly and easily. -Unmatched integration makes PSoC the fastest way to reduce the size, weight, and power requirements of any product. -Developing embedded systems with advanced analog sensing, monitoring, and control is simple with built-in programmable analog features.	-Due to its complex architecture, so is the development of the source code. -Expensive.
Microchip ATmega 328p /Arduino	-Relatively simple to use and interfacel[17]. -Ideal for complex coding(i.e. this project).	-Slow processing power.

From the table above a suitable microcontroller can be selected. Thus, the components and tools required are as follows:

- BLDC Motor
- Hall sensor ICs
- Microcontroller (ATmega328P/Arduino Uno)
- Programmer for the respective chosen microcontroller.
- Power source(12V battery)
- 6 MOSFETs and heat sinks
- Drivers for the MOSFETs
- Resistors, Capacitors,
- Potentiometers
- Crystal Oscillator
- Programming IDE (AMTEL STUDIO 7 for ATmega / Arduino IDE)
- Veroboard/PCB
- Oscilloscope

3.5 Conclusion

The purposes of this chapter were to provide a theoretical background on how a BLDC works. This chapter offered an in-depth insight on this working principle and how the 6-step commutation works and how regenerative braking can be implemented in a BLDC motor. In this chapter , the components and software that shall be used were also briefly described.

The next chapter shall be the design chapter. The inverter drive circuit will be designed. The software will also be designed in terms of software flow diagram and the PWM frequency will also be designed.

CHAPTER 4 : DESIGN

4.1 Introduction and Overview

In the previous chapter, the theoretical background of brushless dc motors and the 6-step commutation sequence was discussed. The electromagnetic relationships were discussed and their role in BLDC commutation was understood. A method of feedback(knowing rotor position) was established as it was noted that using magnetic Hall sensors gives the highest accuracy. It was noted that in order to commutate the BLDC, it had to be done so using a power electronics converter called known as a three-phase inverter bridge with its switching sequence dependant on the output of the magnetic Hall sensors. It was also noted that regenerative braking could be achieved by switching off the high side MOSFETs and pulsing the lower side MOSFETs with PWM with variable duty cycle hence allowing the upper MOSFETs body diodes to conduct thus essentially forming a boost converter in the process. All of this was obtained through research and past work and in this chapter, a design for the controller suitable for this project shall be realised.

4.2 Design alternatives

Electrical machine alternatives

The obvious design alternative in this instance would have been to use an actual BLDC motor instead of using an alternator then convert it to a BLDC. This is because a BLDC has higher efficiency as compared to the alternator. A BLDC's rotor is a permanent magnet whereas that of an alternator is an electromagnet and must be energized via carbon brushes thus is less efficient. However, the alternator was chosen because it was much cheaper as a second hand than a BLDC motor.

Rotor location feedback sensor alternatives

An alternative to the hall sensor method would be to sense the BEMF in a method called the Zero-Crossing of the BEMF. This method is not favourable as it is only ideal in constant speed applications. It involves quite complicated software writing and it isn't necessarily the optimal solution even though it is cheaper as all that is needed component wise are resistors while in sensored commutation Hall sensors are used which are quite expensive with respect to the budget that was presented. However, sensored commutation using Hall sensors was selected as it provides more dynamic commutations at various speeds.

Microcontroller alternatives

In this project several other microcontrollers can be used. However, selection of a microcontroller could have a significance on the performance of the whole system. For example, there are some microcontrollers which are sorely dedicated to motor control especially BLDC and Variable Speed Drives(Induction motor). Other microcontrollers would suffice but would require significant register and timer manipulation in order to control the PWMs of the required phases in each commutation step. The table below shows a criterion on how the microcontroller was chosen especially for this project with respect to the research that was conducted in chapter 3.

Table 3 : Microcontroller decision matrix.

Decision factors	**ATmega 328P**	**dsPic30F2010**	**Raspberry Pi**	**PSoC 5 with arm cortex 3**
Score out of 5				
Motor control modules	3	5	4	5
Features	3	4	4	4
Cost	5	3	1	1
Efficiency	3	3	4	5
Memory	2	4	5	5
Availability	5	3	4	3
Weighted Score	**21**	**22**	**22**	**23**

From the table above it is clear to see that the PSOC would be the best microcontroller to use. The ATmega328p based Arduino shall be used as the preferred microcontroller as it is cheaper and easily available.

4.3 Detailed Design

In this design , as described in the previous chapters, a car alternator is used as the machine of choice(BLDC). Thus, to have a fully working system, the design has several sub systems which form one large system that permits a fully functioning project. Thus, the circuits that are to be designed are the control unit(microcontroller and peripheral circuit (hall sensor circuit) and the power stage (3-phase inverter bridge with drivers).The choice of microcontroller is the Arduino Uno (ATmega328P) and below shows a simplified hardware block diagram incorporating the primary hardware to facilitate speed control. The block diagram below was prepared and drawn using Microsoft Word shapes.

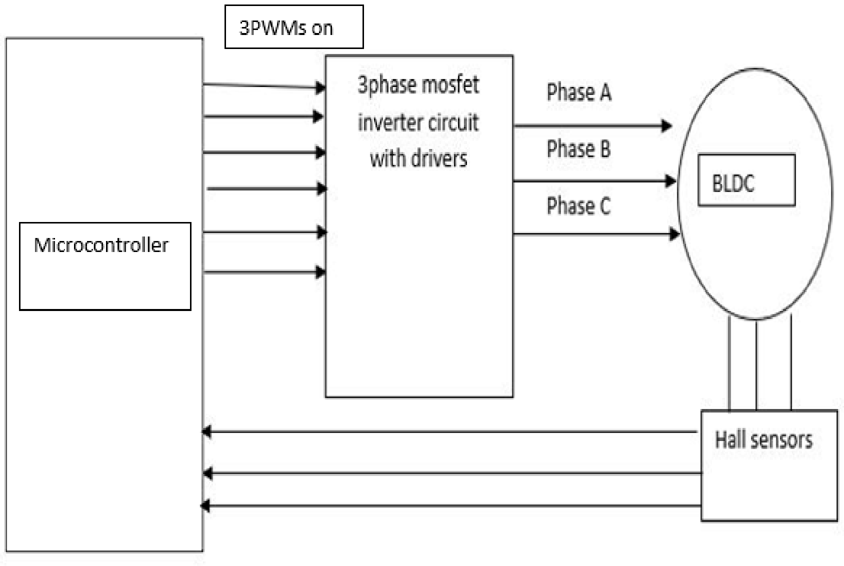


Figure 21: Simplified hardware setup of BLDC drive

From the block diagram above, several sub-system blocks combine to form the overall system. The Hall sensors provide the input signal based on the current rotor position. The states of the three Hall sensors is read by the microcontroller and based on the look-up table defined, the appropriate MOSFETs are energized using PWM and the BLDC then moves.

4.3.1 Software Flow Diagram Design

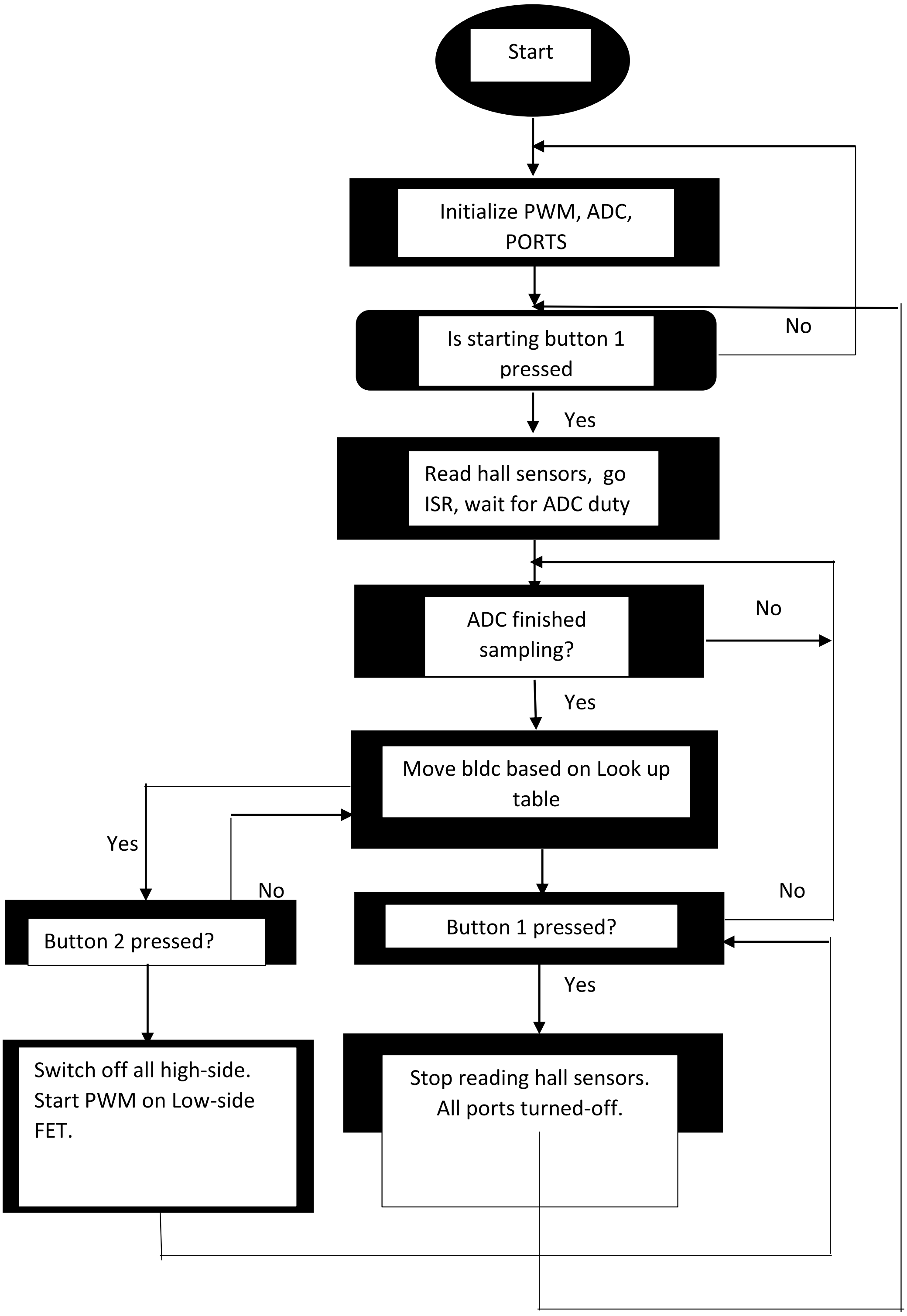


Figure 22: Software flow diagram

The flow diagram above shows how the software potion of the system shall work. The PWM directly controls the speed of the motor based on the voltage input, which is determined by the potentiometer, thus the duty cycle. After initializing the PWM, ADC and the pin change interrupts(Hall sensor input), the program waits for a signal such as a button press to start. When the start button is pressed, the Hall sensors are read and based on their value, the windings are energized based on the look-up table. The windings will be energized according to the state of the Hall sensors thus the motor starts spinning. The pins that the Hall sensors will be connected to will have their pin change interrupts enabled. The look-up table for commutation will then be attached to an interrupt service routine vector (ISR VEC). As the rotor spins, its position is changing and as it changes the pin change interrupt of the Hall sensors gets triggered. When they get triggered, the look-up table in the ISR VEC is read and the appropriate windings are energized. This process happens at very high speeds. This ensures that the correct windings are energized.

4.3.2 Design of Switching Sequence Lookup Table

In order to commutate the motor , a switching sequence must be defined or designed according to the type of the motor. The number of poles essentially define the commutation method that must be used. In this case the motor is a 6-pole motor thus the 120° commutation method shall be used. Therefore, to get the switching sequence that is suited to our motor let the drive circuit illustration below be considered:

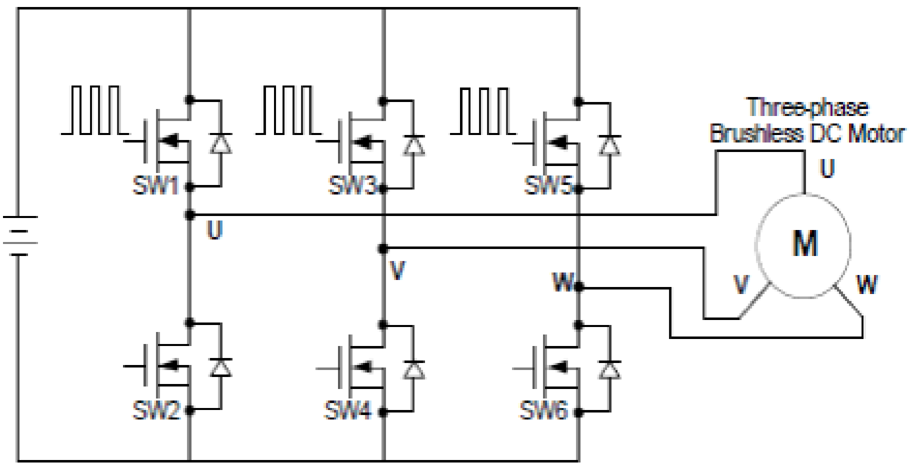


Figure 23: BLDC drive circuit [13]

From the circuit above and from first principles two phases out of the three phases must be energized per step. Therefore, this means that per commutation step, two MOSFETs shall be energized, one high-side and one low-side. MOSFETs from the same phase must never be on at the same time so that MOSFET shoot-through can be avoided.

Since there are 3 Hall sensors, per step the Hall sensor state is either a logic low or a logic high. Therefore, there are 8 possible states for the Hall sensors which are (000, 001, 010, 100, 100, 110, 011, 111). However, since the 120° method is used, the Hall sensors will never achieve the states 000 and 111 therefore this means that there are 6 possible states which are achievable. Therefore, per commutation step the binary numbers achieved in that step by the Hall sensors is attached to the pair of MOSFETs that need to be energized. Thus, the states of the Hall sensors will be used as feedback.

The image below shows the commutation lookup table for a 6-pole motor:

STEP	Hall Effect sensors			MOSFET switching					
	HALL 1	HALL 2	HALL 3	Drive SW1	Drive SW2	Drive SW3	Drive SW4	Drive SW5	Drive SW6
1	1	0	1	pwm	0	0	1	0	0
2	0	0	1	pwm	0	0	0	0	1
3	0	1	1	0	0	pwm	0	0	1
4	0	1	0	0	1	pwm	0	0	0
5	1	1	0	0	1	0	0	pwm	0
6	1	0	0	0	0	0	1	pwm	0

Figure 24 : Look-up table for commutation sequence

The table above shows the look-up table for a 6-pole motor. The table was drawn using Microsoft Word and the drive circuit in Figure 23 was used as the reference for the design. In the first step(101), it is seen that SW1 and SW4 will be energized with SW1 the one being pulsed with PWM and SW4 turning on. Step 2(001) sees SW1 and SW6 with SW1 being pulsed with PWM and SW6 turned on. The steps continue through to step 6 as the respective windings will be energized based on the binary value that is defined in the look-up table. The look-up table is attached to the interrupt service routine vector as a switch statement which has 6 cases.

4.3.3 Stage 1: Hall Sensors

- The Hall sensors that are used are bipolar switching Hall effect sensors. They give a logic high when they sense a South pole and stay in that state until they sense a North pole thus giving a logic low.
- This phenomenon is used to create a timing diagram of commutation steps which is analogous to the BEMF graphs.

- The microcontroller will receive inputs from the 3 Hall effect sensors which when inside the microcontroller will give a 3-digit binary number which corresponds to the phases that need to be energized.
- These Hall sensors provide the feedback for each commutation step and for each step it is a unique number.
- These binary numbers correspond to a specific high side low side mosfet pair per step. Since these sensors are used to sense the rotor position, they energize the respective phases per step in the stator thus creating a rotating magnetic field within the stator , hence BLDC rotation would be completed.

4.3.4 Stage 2 : Power Stage

The power stage consists of the power supply, the load (BLDC) and the driver circuit (3 phase inverter with drivers). The power stage can be driven by three synchronous MOSFET drivers (IR family) or one MOSFET driver to drive all the MOSFETs like the HIP4086 or by two drivers like the Microchip TC4469. Selection of these drivers is arbitrary to the designer. The motor voltage and current chopping is managed by PWM signals that are driven into the gate of the MOSFET.

In order to drive these 6 MOSFETs, driver IC's are used so that the MOSFETs can overcome the input gate capacitance in the quickest possible time thus allowing the MOSFETs to fully turn on. Basically, the drivers act as voltage amplifiers and as they take the PWM signal which from the microcontroller is between (3.3v-5v) and provide an output PWM which is between 10v-20v ,which in most cases is the recommended driving voltage for the gate. In most cases 3 driver IC's are used, each for a pair of MOSFETs in a phase. This offers favourable synchronized operation. This can also be achieved by using 2 Quad CMOS buffers/ drivers. Each drives the high-side and low-side independently. These are used in a configuration were the high-side is driven by P-type MOSFETs while the low-side is driven by N-type MOSFETs. In this project two MicrochipTC4469 driver IC's are used. The TC4469 device is a family of four-output CMOS buffers/MOSFET drivers with 1.2 A peak drive capability. Unlike other MOSFET drivers, these devices have two inputs for each output. The inputs are configured as logic gates AND/INV (TC4469). The TC4469 drivers can continuously source up to 250 mA into ground referenced loads. These devices are ideal for direct driving low current motors or driving MOSFETs in a H-bridge configuration for higher current motor drive . Having the logic gates onboard the driver can help to reduce component count in many designs. The TC4469 devices are very robust and highly latch-up resistant. They can tolerate up to 5 V of noise spiking on the ground line and can hand up to 0.5 A of reverse current on the driver outputs [11].

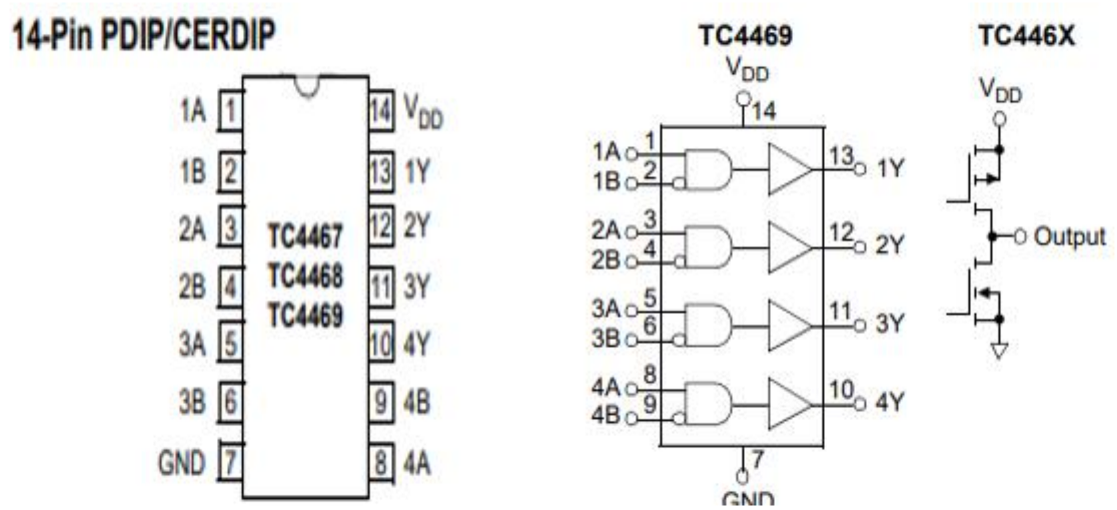


Figure 25: TC4469 MOSFET drivers

Two TC4469 drivers are used to drive the three phase MOSFET bridge since it is one of the recommended drivers for motor control application. This driver also offers simplicity of the overall circuit. This is because this driver can directly drive the P-Type MOSFETs as the driver can invert the PWM signal coming from the microcontroller. Since the P-channel MOSFETs were used in high side configuration it was important to find the MOSFET that offered the lowest $R_{ds(on)}$ resistance. Thus, upon traversing through various data sheets, the IRF4905 MOSFET was discovered. This is a good choice for a MOSFET for this application as $I_D = -74A \; and \; V_{DSS} = -55V \; at \; 25°C.$ The $R_{ds(on)} = 0.02\Omega$ which is even lower than some N-Type MOSFETs. The Input capacitance was seen to be $3400pF$ while the total gate charge was found to be $180nC$. Thus, with information, the MOSFET chosen for the high-side drive was the IRF4905.

For low-side driving, the IRF3205 N-Type MOSFET were chosen. The IRF3205 was found to be a good choice for this application as $I_D = 110A \; and \; V_{DS} = 55V \; at \; 25°C.$ The $R_{ds(on)} = 0.08\Omega$ which is safe and ideal for this application.

4.3.5 Hardware Circuit Design

For this design, the several components and software are used:

- TC4469 drivers -X2
- IRF3205 N-Channel MOSFETs -X3

- IRF4905 P-Channel MOSFETs -X3
- 330Ω resistor -X6
- 470Ω resistor(series gate resistors -X6
- 10kΩ resistor(pull-down resistors)-X6
- 0.1uF 50V ceramic capacitor(bypass) – X2
- 10uF 50V electrolytic capacitors(bypass) – X2
- MUR460 power rectifiers(Schottky diode) -X6
- 12V battery pack / Power supply(not limited)
- Easy EDA circuit design software

The circuit below was designed and drawn using Easy EDA circuit design software.

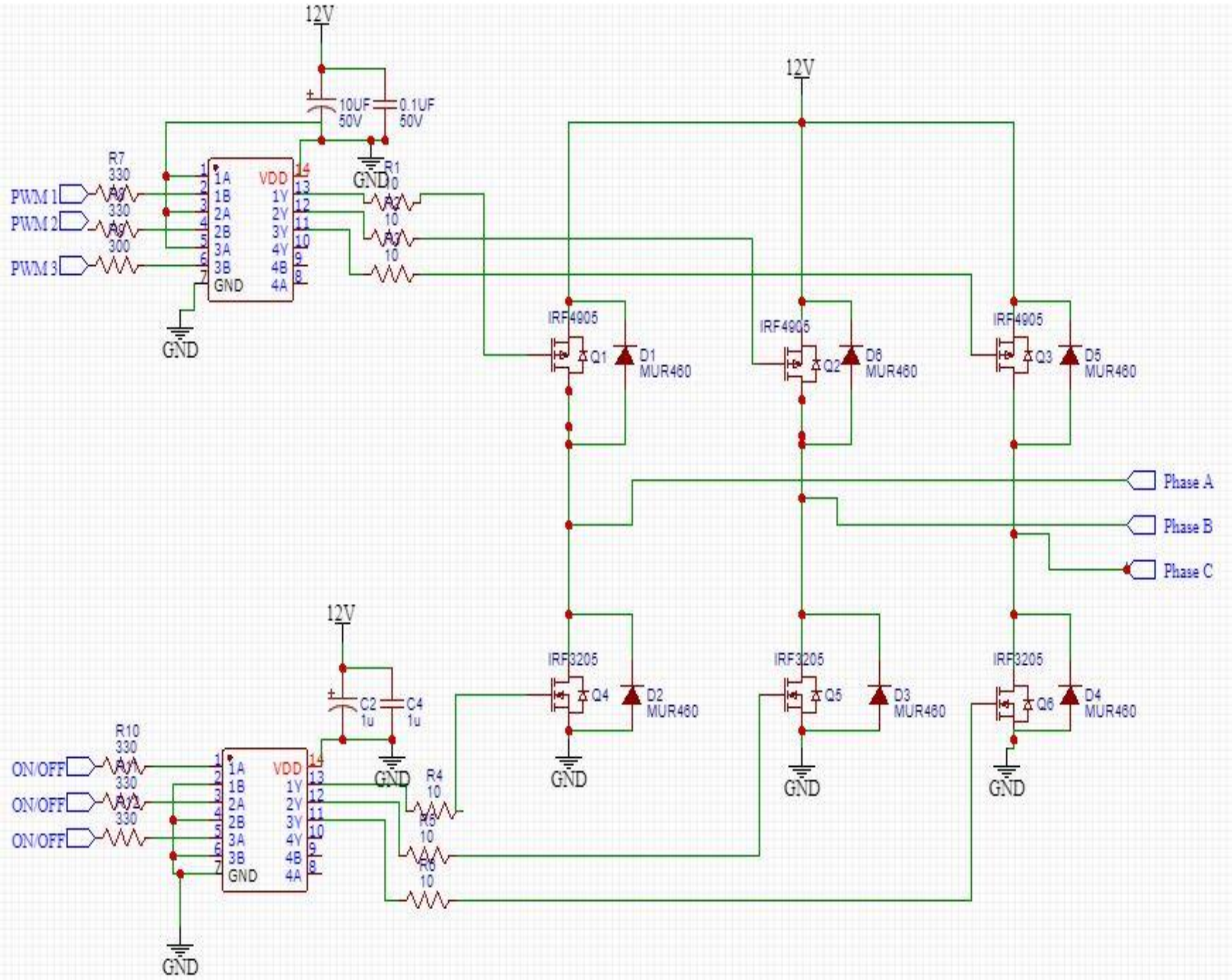


Figure 26: Designed three phase inverter bridge with drivers

The circuit diagram above shows the MOSFETs and drivers in connection. This is the circuit that will facilitate the commutation of the motor. It is important to note that regenerative braking can also take place by sorely using this configuration. This can be done by turning off all the high side mosfets and start Pulse Width Modulating the low side mosfets at several duty cycles. The low side mosfet, the stator windings act as inductor and the body diode of the high side mosfets form an equivalent of a boost converter.

4.3.6 Design of Switching Frequency

In order to see the effect of switching frequency and thus choosing the optimal switching frequency, several parameters of the motor had to be known. The time constant $\boldsymbol{\tau}$ had to be known.

$$\boldsymbol{\tau} = \frac{\boldsymbol{L}}{\boldsymbol{R}}$$

were **L** being the per phase inductance while **R** is the per phase stator resistance.

An RLC meter was used to measure **L** and **R**. This was done by taking the measurements between two phases and dividing by 2. The per phase inductance was found to be **0.0105mH** while the per phase resistance was found to be **0.1Ω.** A general rule of thumb in designing the switching frequency is that the time constant $\boldsymbol{\tau}$ must be significantly longer than the period of the switching frequency.

Thus, finding the time constant :

$$\boldsymbol{\tau = \frac{L}{R} = \frac{0.0105m}{0.1} = 105\ uS}$$

The time constant therefore determines the minimum PWM frequency that must be used. Since the whole essence of using PWM is to have an energy efficient system, the time constant should be significantly longer than the PWM period so that most of the voltage is dropped across the inductance rather than the resistance. This greatly reduces I^2R losses, smooths out current flow and lowers the peak current. Losses in other parts of the circuit are also minimized.

Since $\boldsymbol{\tau = 105uS}$, then minimum acceptable frequency :

$$\boldsymbol{F_{PWM} = \frac{1}{\tau} = \frac{1}{105u} = 9.6\mathrm{KHz}}$$

The ideal switching frequency is therefore 3 to 4 times larger than the minimum frequency. Therefore, any frequency within this range would be acceptable.

$$\boldsymbol{F_{PWM\ IDEAL} = 28.8 - 38.4KHz.}$$

Thus, the ideal frequency that will be used is 31KHz as it lies within the range that is stated above. An LT Spice simulation was carried out to compare the effects that the two frequencies have on the motor in terms of peak and average currents. To do this an equivalent circuit consisting of an inductor , resistor and voltage source(BEMF) was constructed in LT Spice and the per phase resistance and inductance that was previously measured was used and the L and R values. For simplicity, a 50% duty cycle was used while the value of BEMF was assumed to be 80% of the average voltage. This was then simulated and below were the findings:

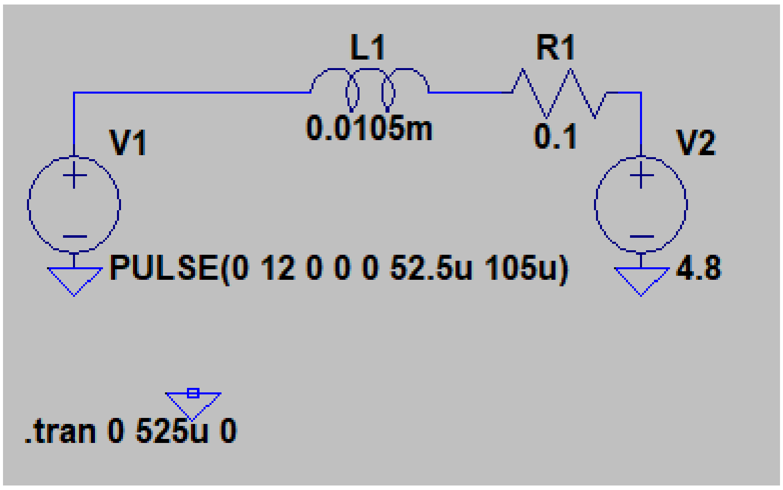


Figure 27: Per phase equivalent circuit of motor

The above circuit was simulated, and the results for 9.6KHz are shown below :

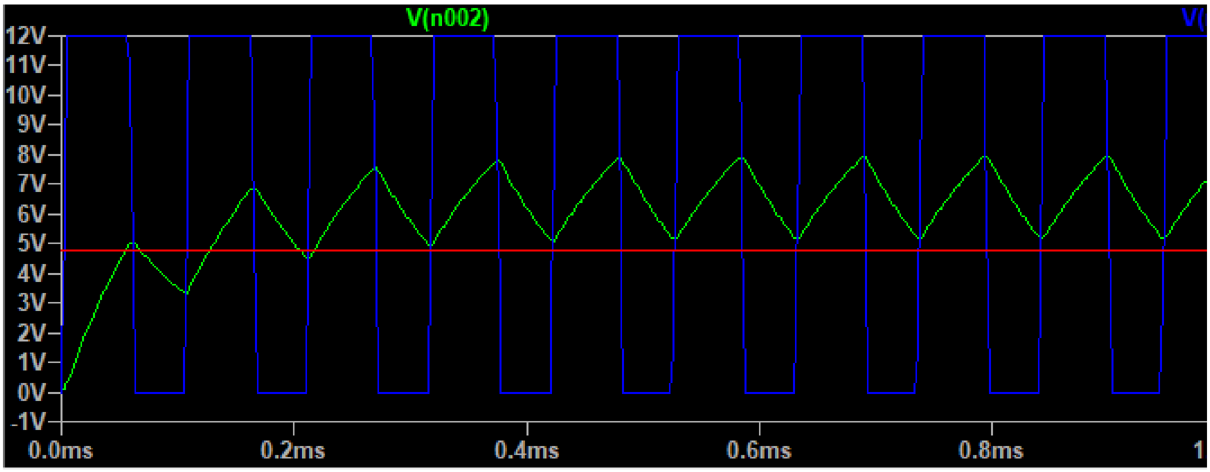


Figure 28: Inductor voltage at 9.6KHz 50% duty cycle

This shows the inductor voltage at the 12V supply at 50% duty cycle. Therefore, the average voltage is 6V.

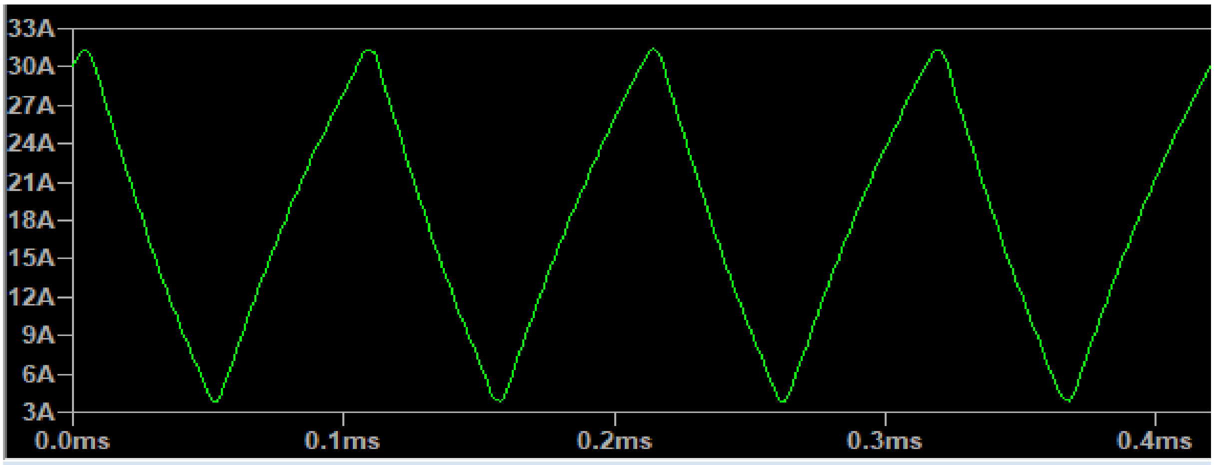


Figure 29: Inductor current at 9.6KHz at 50% duty cycle

The simulation results show that by using the minimum PWM frequency of **9.6KHz** based on the time constant $\boldsymbol{\tau}$ will yield peak currents of up to **32A** while the average current is $\boldsymbol{I_{avg} = \frac{I_{max} - I_{min}}{2} = \frac{32-4}{2} = 14A.}$ This means that the average current at 50% will be **14A** while the peak current reaches up to **32A**.

- The simulation was run again with the circuit parameters adjusted for operation at a frequency of 31KHz and a duty cycle of 50%. The images below show these results:

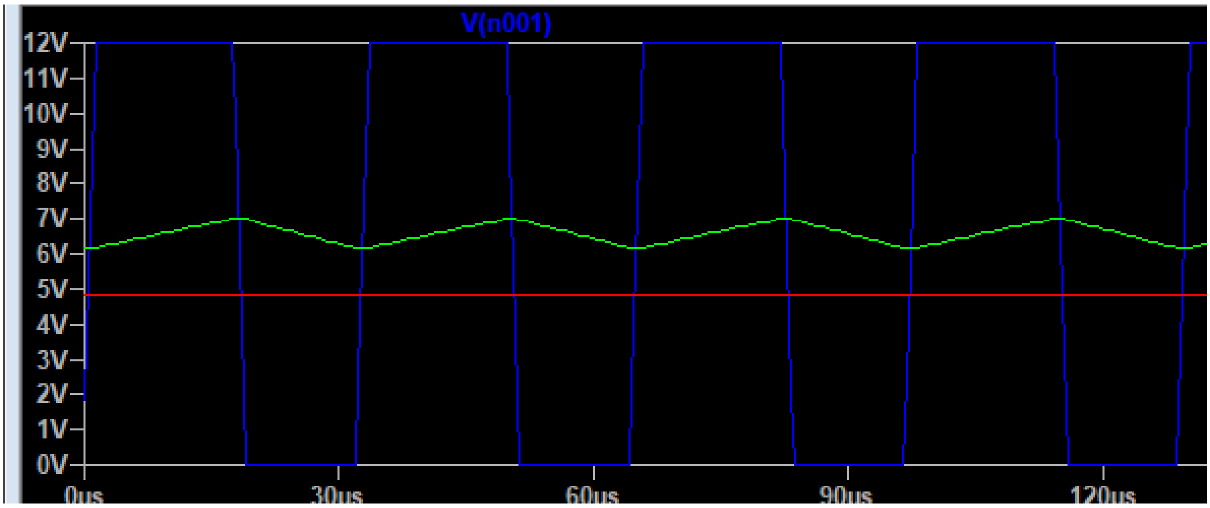


Figure 30: Inductor voltage at 31KHz at 50% duty cycle

- At 31KHz shows more stable inductor voltage.

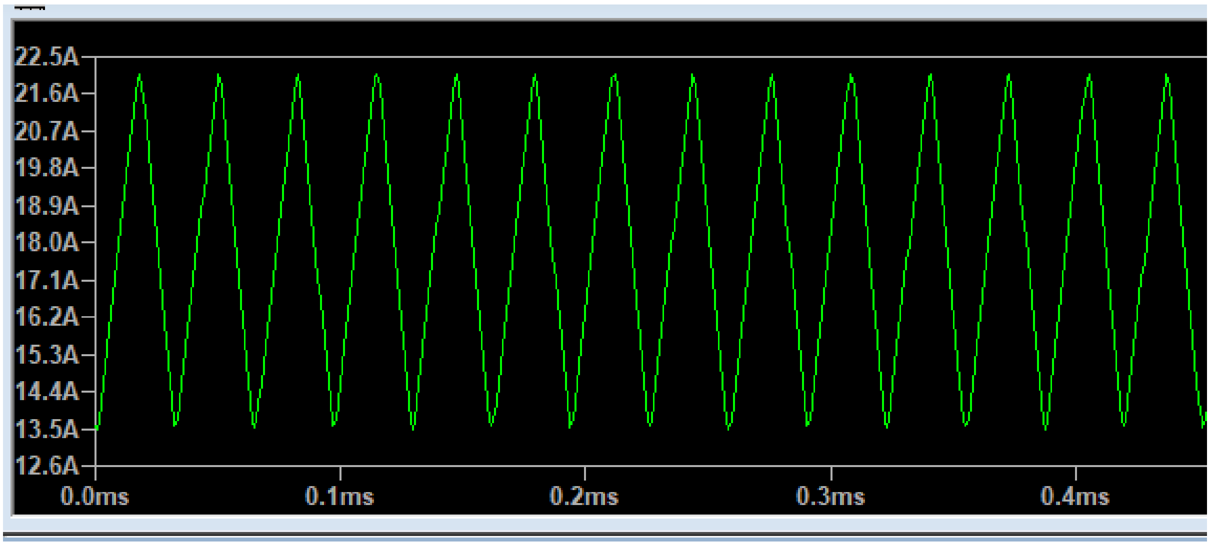


Figure 31: Inductor current at 31KHz at 50% duty cycle

While at 31kHz the peak current appears to be at about **22A** while the average current is $I_{avg} = \frac{Imax-Imin}{2} = \frac{22-14}{2} = 4A.$

These results agree with what is known theoretically. The peak and average current greatly reduces as the switching frequency is increased. Thus in the final design 31KHz was chosen as the switching frequency.

CHAPTER 5 : TEST EVALUATION AND STRATEGY

5.1 Introduction

This chapter discusses the system and its subsystems, detailing test and evaluation strategies. This chapter will include experiment design and test strategy. This will be dominated by functionality experiments on the characterises of the motor and the gate pulses of the MOSFETs used in the controller. This will cover expected output results. The design in this chapter is based on the requirements and specifications in chapter 2. It will also give details on the performance test and the evaluation of how the prototype works. For every experimental setup that will be done will be given in details, that is a detailed discussion on the equipment used, experimental setup and any graphical representation if any.

5.2 Experimental Design

5.2.1 Experiment 1 : Checking correctness of common gate pulses of MOSFETs

Experiment Aim

The aim of this experiment is to investigate the PWM pulses seen at the gate and coupling this with the ideal series gate resistor.

Relation to Objective

Clean gate pulses seen by the gate constitute to proper driving of the MOSFET and gate ringing is eliminated thus false switching is avoided.

Equipment

- BLDC motor
- Digital Oscilloscope
- Controller

Setup

- Connect the motor to the controller and the power supply.
- Connect one oscilloscope channel then connect the positive probe to the gate and the ground probe to ground.

Procedure

1. Connect the controller to the motor and power supply
2. Run the motor using the desired potentiometer setting for speed.
3. Connect the probes of the oscilloscope to the gate and ground reference.
4. Save what it seen in the oscilloscope.

Uncertainty and Control

The gate pulses waveforms will be measured at all the gates that receive the PWM signal.

Expected Results

Acceptable gate pulses with minimum noise.

5.2.2 Experiment 2 : Testing of correctness of switching sequence

Experiment Aim

The aim of this experiment is to test the correctness of the switching sequence.

Relation to Objective

The Hall sensors provide feedback in relationship to the rotor's position. A unique 3-digit binary number per commutation step corresponds to which MOSFETs need to be excited.

Equipment

- Power supply
- BLDC motor
- breadboard
- 6 green LEDs
- Arduino UNO
- Connecting wires

Set up and Procedure

- Set up the 6 LEDs as in the same configuration as the 6 MOSFETs. The inputs of the six LEDs should be connected into the microcontroller as would the MOSFETs.
- Connect the Hall sensors from the motor into the microcontroller and power the sensors.
- At this point the software must have been written. Upload and run the code.

- Once the sensors have been connected and powered, rotate the shaft of the motor slowly and observe the LEDs switching in the same sequence as the MOSFETs would. If the sequence is wrong, correct in the code and repeat the steps until satisfactory.

Expected Results

The expected results are to see the LEDs switching in the same sequence as the one defined for the MOSFETs.

5.2.3 Experiment 3 : Determination of Current , Input power

Experiment Aim

The aim of this experiment is to determine the current drawn by the motor and thus the input power at different duty cycle settings.

Relation to objective

It is important to know the input current and power so that other parameters and overall efficiency can be determined.

Equipment

- BLDC motor
- Power source
- Shunt resistor
- Multi meter

Procedure

- Connect the shunt resistors in series with the power source.
- Measure the voltage drop across the resistor at different duty cycle settings.
- Measure the voltage drop in the resistor and divide by the shunt resistance to find the current.

5.2.4 Experiment 4 : Determination of revolutions per minute

Experiment Aim

The aim of this experiment is to find the revolutions per minute of the BLDC motor under different duty cycle settings.

Equipment

- BLDC motor
- Power source
- Motor controller
- Oscilloscope

Procedure

- Run the motor at intended duty cycle
- Connect the probes at any 2 phases
- As the motor is running observe the waveform and the frequency that is seen .
- This frequency observed is the frequency of the rotating field and can be used to calculate the speed provided the number of poles in the motor is known.

5.3 Conclusion

This chapter gave an overview of the experiments that are likely to be conducted and the test strategies down to ensure a proper working system.

CHAPTER 6 : IMPLEMENTATION OVERVIEW

6.1 Introduction

In this chapter the actual implementation and construction of the hardware and software were explicitly discussed and illustrated. It shows a step by step process as to how the whole prototype was assembled. The issues faced both in the hardware, electronics and the software were discussed and how they were solved.

6.2 Hardware

6.2.1 Alternator to BLDC motor conversion

Originally, the automotive alternator is a 3-phase machine. It is used as generator in the car to charge the battery. The alternator usually generates up to 120A of AC which is then that is rectified by the rectifying diodes to give DC. A voltage regulator is used to give a steady DC output of 14.5V. The image below shows an exploded illustration of the automotive alternator working as a generator in the car.

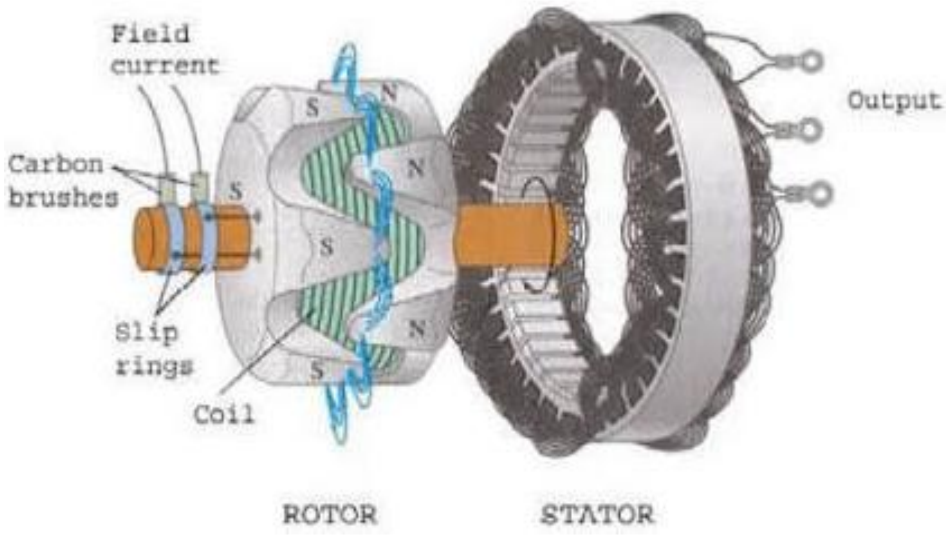


Figure 32: Exploded view of automotive alternator

The working principle of the alternator is quite simple. The rotor of the alternator is excited with DC field current. This produces a magnetic field around the rotor. When this rotor is rotated about the fixed stator, according to Faraday's law of induction, current is induced to the three stator windings which is 120° out of phase with each other. Since this generated current is AC, the rectifiers convert the AC to a DC supply which will charge the battery via the voltage regulator. To utilize this as a motor the rectifiers were removed from the stator and the 3 phase wires were accessed. This stator was wound as a star connection. The images below show how this was achieved.

Figure 33: Bosch automotive alternator (14.5V 65A).

The alternator was then opened to have a closer look inside and make the necessary adjustments in order to make it BLDC motor.

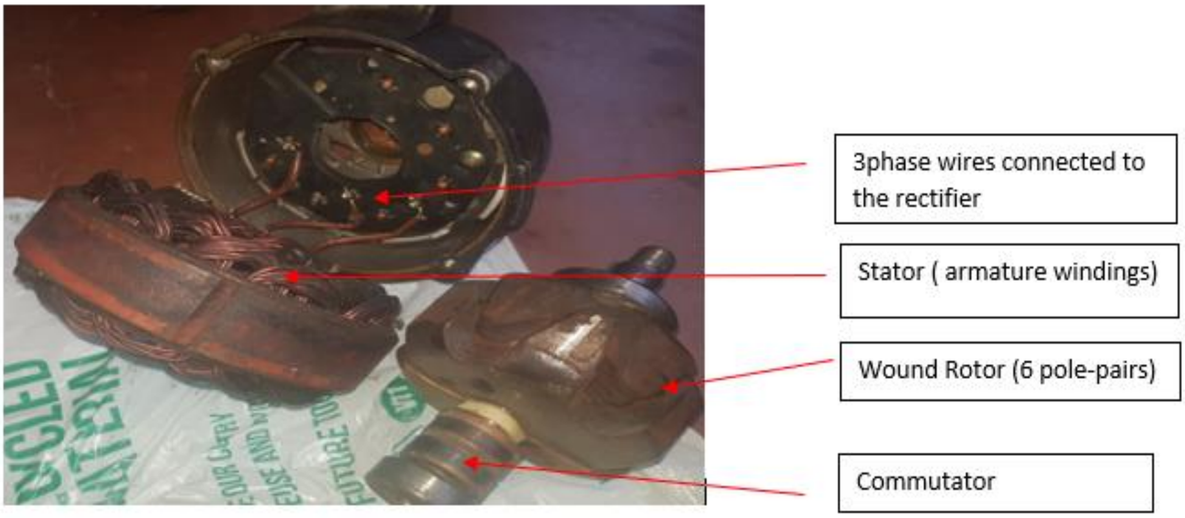


Figure 34 : Alternator showing the three phase wires from the stator connected to the full wave rectifier and the wound rotor with the commutator.

The three phase wires were then disconnected from the rectifiers. This now formed a sensor less BLDC motor as the 3phase wires now represent the input of the armature windings which will be pulsed in a special way in order to create a rotating magnetic field that the wound rotor (excited by a DC field current and now acts as the electromagnet with 6 pole pairs) will try and follow this rotating field thus running as a motor.

Figure 35 : Alternator to BLDC conversion

The field is excited by a DC power supply with the aid of carbon brushes via the commutator.

6.2.2 Insertion of Hall Sensors into the Alter-motor and Challenges faced

In most cases it would have been enough to run the newly modified motor using the sensor-less technique. Since it has already been discussed in the previous chapters that BEMF is induced in undriven phase during one of the drive phases thus can be used as feedback. However, this is not the ideal way to control these motors as was discussed in the Literature Review.

Thus, further modifications were made to the motor so that the location of the rotor could be known as a to provide the so called '***sensored control of the motor'***. The best way to achieve this was to use bipolar latching Hall effect sensors. These sensors give a logic 1 if they are exposed to a North pole and give a logic 0 if they are exposed to the South pole. In theory these Hall effect sensors must be 3 and spaced 120° electrically apart. In the commercial readymade bldc, these sensors are already calibrated 120° electrically apart and are already embedded in the stator. Thus, the biggest challenge in the modification was locating the ideal position of these sensors. This was even made more difficult by the fact that it is nearly impossible to embed these sensors inside the stator because the armature windings of the stator are closely packed together. However, the only place where the Hall sensors could have been realistically placed was at the base of the wound rotor. However ,there was another problem that was faced in doing this. The rotor magnetic field does not reach the bottom metal base of the rotor because the base is thick such that the magnetic field is unable to penetrate. In order to solve this problem external permanent magnets were placed at the bottom base of the rotor with each permanent magnet placed at the position were the magnetic flux is at its greatest relative to its analogous pole on the wound rotor.

The illustration below shows this:

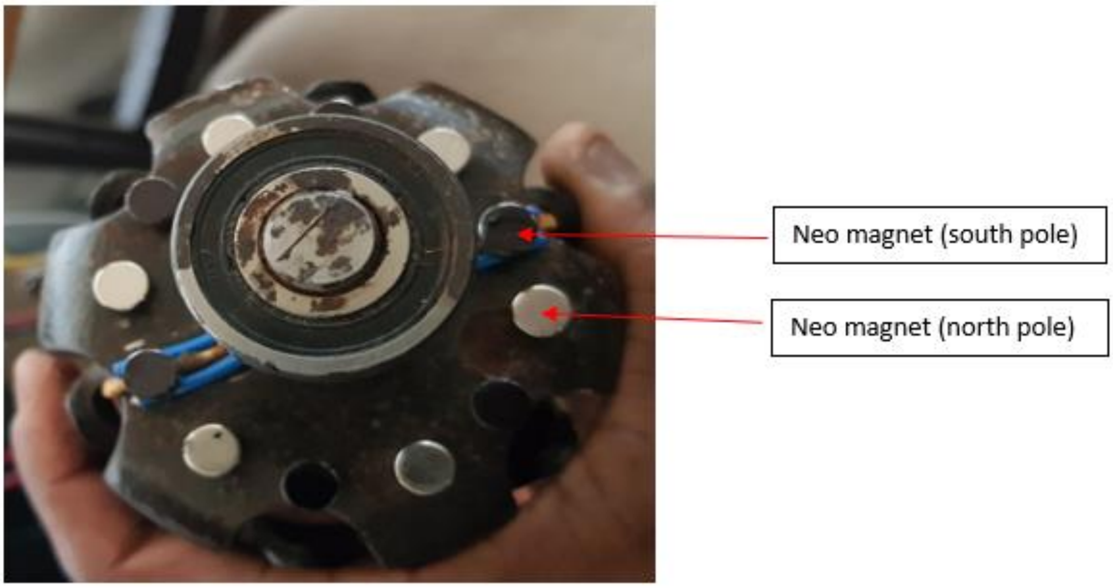


Figure 36: Permanent magnet placement onto the rotor base.

This modification made it easy to insert the Hall sensors to know the rotor position. The next step was to calibrate the position of the sensors relative to the magnets. To do this was simple. It is known that 2 phases are energized per commutation step, thus in order to align these sensor s correctly the following was done:

- A reference point at the top part of the casing of and the shaft of the motor was marked using a magic marker .
- The wound rotor was excited, and 2 phases of the stator were energized, and the rotor made a single step with the rotor locking up after this and the torque going to zero.
- At this precise point a second marking was made from the shaft refence point to the top casing of the motor.
- The angle between was then measured using a protractor and was established to be 12° with an allowable tolerance of 20% depending on the needs of the designer.

- This angle was then used as the spacing between the hall sensors relative to the axis of the rotor shaft.

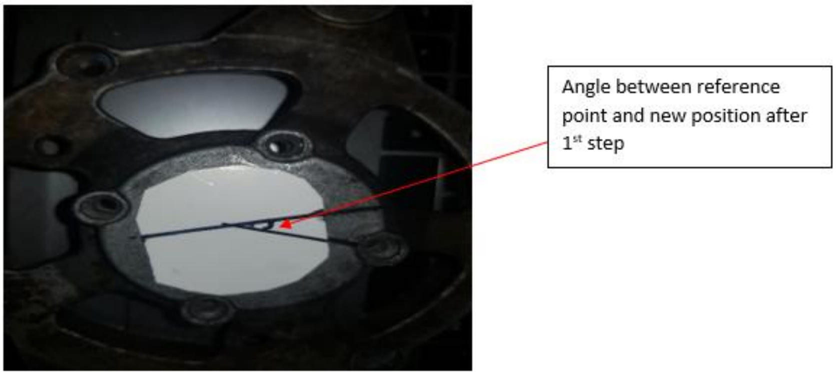


Figure 37: Mechanical angle per commutation step.

After the angle per step was established the next step was to prepare the Hall sensor circuit with each sensor being spaced out at an angle of 12° (mechanical). The Hall sensors used were the Honeywell SS411A bipolar Hall sensors and a 10kΩ resistor was placed between the input and output of the sensors. These resistors act as pull up and pull-down resistors so that they can quickly be pulled to Vcc or to GND depending on the state of the sensor. In order to come up the optimal placement scheme for the sensors, the radii of the alternator housing , the rotor and the circle created by the inserted magnets was determined. These radii were used to draw on a piece of paper then cardboard the end view of the alternator when looking at it from the end part. Once drawn , using the angle of 12° that was determined, the exact position of the sensors was drawn in and the cardboard was carefully cut out as drawn and the Hall sensor circuit was constructed. This constructed circuit was carefully inserted inside the alternator housing . The images below show a step by step process of how this was accomplished.

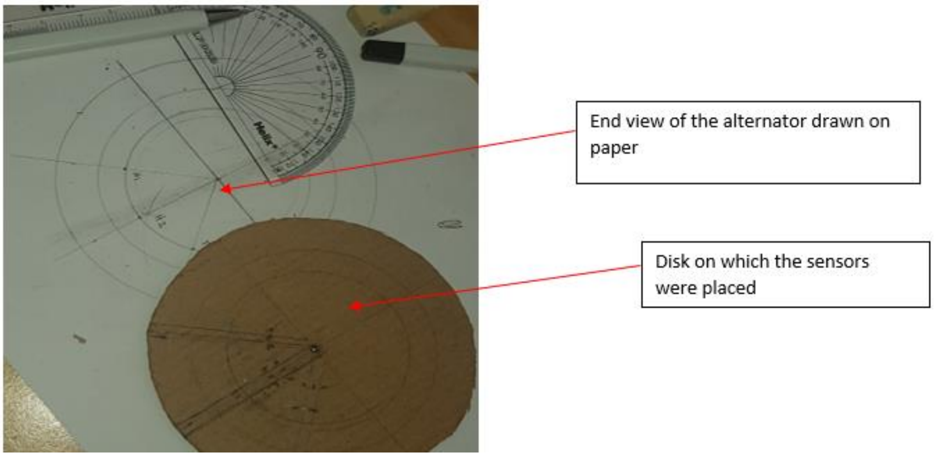


Figure 38 : Construction of Hall sensor disk

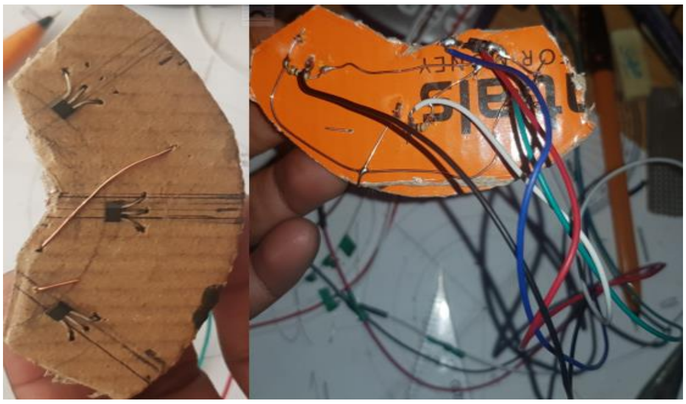


Figure 39: Hall sensor circuit.

Once this was done the final step with respect to the hall sensors was to insert them into the electrical machine.

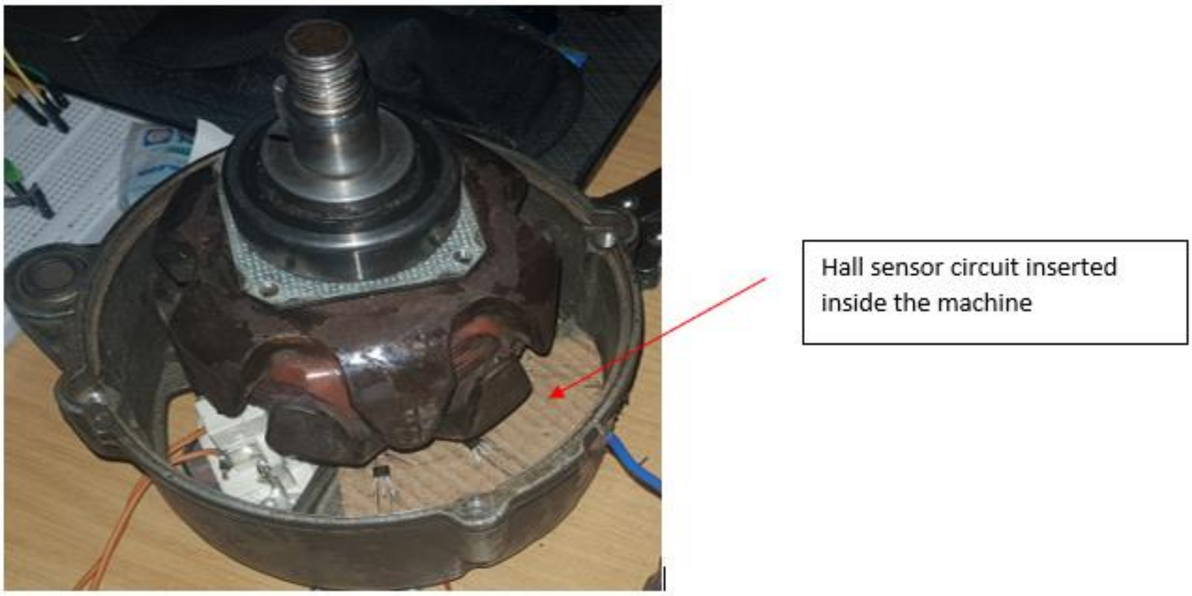


Figure 40 : Hall sensor circuit inserted inside the machine

6.2.3 Implementation of the Power Electronics

One of the key components or sub systems of this project is the power electronics. The power electronics that were used in this project were as per the designed in chapter 4. Due to the rather high cost of fabricating and manufacturing a PCB , the power electronics were laid out on Veroboard and then the components were soldered in together. The paths that carry the high currents were supplemented by adding thick copper wires that connect the sources and the drains of the MOSFETs to the 12V battery. These wires were then coated with soldering wire to ensure that they harden and the current carrying capabilities of these makeshift tracks are enhanced. Additional support and protection of the MOSFETs during current recirculation mode was implemented by inserting power rectifiers between the drain and source of the MOSFETs. This was done because the intrinsic body diodes are not able to handle the working current ,thus without these power rectifiers the MOSFETS were prone to avalanche mode failure and as a result the power rectifiers greatly improved this aspect of the design.

Below is an illustration of the circuit:

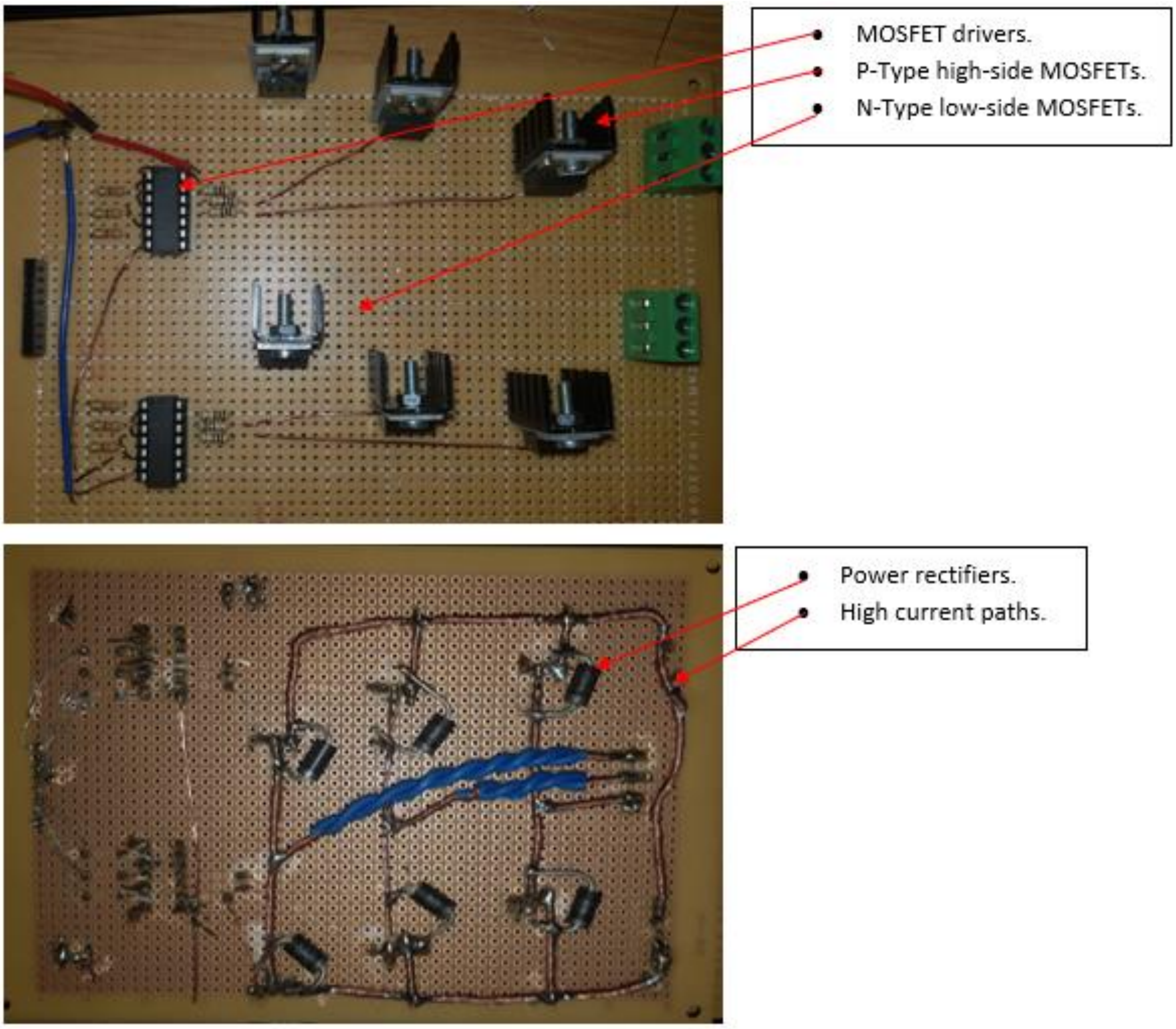


Figure 41: Power electronics circuit(Three phase inverter).

6.3 Software Implementation

Arguably the most important aspect of designing a good electronic motor controller is designing a control algorithm that will suitably and efficiently provide the appropriate and correct driving scheme to the MOSFETs in the inverter. Many designers find this the most challenging and time-consuming aspect of the entire project. This is because the software algorithm is the one which interfaces the several electronics , subsystems and motor and brings everything together to ensure a good overall working system. The software algorithm therefore allows a central hub to be created which interfaces the Hall sensors, the throttle/potentiometer and the power electronics (MOSFETs) in a systematic and intelligent manner. As was seen in the software flow diagram in the previous chapters the software design was guided by two crucial principles. Correctness and speed of execution of the program. The most important factor in the algorithm was the correctness of the software. This means that the defined or the read state of the 3 Hall sensors per commutation step had to switch the desired switching pair of the MOSFETs in that respective commutation step. Once this correctness was verified , the PWM for the gate drives was then set up. Lastly, the software was optimized by using direct port manipulation of the ATmega registers to set GPIO of the microcontroller, use of interrupt service routines so as to interrupt the main function whenever there was a state change in any of the 3 sensors thus switching the desired pair of MOSFETs , manipulation of the timer1 and timer2 registers to set up a PWM frequency of 31kHz and then using the 8bit analog to digital converter (ADC) to write the duty cycle into these timers' Output Compare register. The potentiometer's voltage value range of 0-5V was translated to 0-255 by the ADC with 0 represent 0% duty cycle while 255 represents 100% duty cycle. The software was written in C and C++ as the ATmega328p can support both languages.

6.4 Cost Summary and Bill of materials

The table below shows a cost summary of the components used in this project. Most of these components were acquired at MANTECH Electronics.

Table 4 : Bill of materials.

Component Name	Component Part No.	Supplier	Qty	Dimensions	Cost (R)
Bipolar Hall Effect Sensor	SS411A	MANTECH	3	3-30VDC	321.20
MOSFET P-C	IRF4905PBF	MANTECH	3	55V , 74A	55.02
MOSFET N-C	IRF3205	MANTECH	3	55V ,110A	36.29
Power Diode	MUR460RL	MANTECH	6	600V, 4A	21.31
Solder wire	-	MANTECH	3	2m	24.33
MOSFET drivers	TC4669CPD	MANTECH	2	-	53.60
12V 12Ahr battery	Forbatt	Boksburg China Shop	1	12V , 12Ahr	400.00
Automotive alternator	-	Private (2nd hand)	1	12V , 65A	450.00
Neo Magnets	-	RSE Components	12	3mm	144.50
Veroboard	-	MANTECH	1	100x300mm	57.58
Arduino Uno	-	Private (2nd hand)	1	-	190
TOTAL COST					**1753.83**

Sundry component expenses such as capacitors and resistors were excluded. It can be seen from the table above that this project cost at least **R1753.83**. This is **R253.93** over the allocated budget of **R1500**. The project cost this amount because the battery , the Hall sensors and automotive alternator were very expensive.

6.5 Conclusion

This chapter gave an overview of the construction and implementation process. The implementation of the power electronics , Hall sensor circuit and alternator to motor conversions was explicitly shown and discussed. A cost summary of the cost of the project was also given. The allocated budget for the project by the university was initially R1500 but due to the cost of components it was impossible to fit the whole project within that budget. The project cost at least **R1753.83.**

CHAPTER 7 : RESULTS AND ANALYSIS

7.1 Introduction and Overview

In this project, the objective was to design ,build and test an electronic speed controller for an electric bike prototype. This electric bike prototype would ideally use the brushless dc motor as its drivetrain while as already discussed in the previous chapters, the combination of the power electronics ,the sensor IC's and the microcontroller give rise to the electronic speed controller. Thus, the essence of this chapter is to provide the results and analysis of the several sub systems that make up this motor control system as set out by the test evaluation strategies that were outlined in chapter 5. In this chapter oscilloscope images and other supporting images were provided and discussed at length. Some calculations were performed, and graphs plotted for analysis.

7.2 Experimental and Test results

7.2.1 Testing of PWM from the microcontroller and the MOSFET drivers

Pulse Width Modulation(PWM) was used as the current chopping technique to limit and have more control of starting current and torque. This was done by applying limited voltage at start up at a certain PWM frequency and then varying the duty cycle as per potentiometer demand. Therefore, the high side P-Type MOSFETs were modulated while the low side N-Type MOSFETs were either on or off. The PWM frequency used was 31kHz. This was obtained after extensively going through the ATmega data sheet and configuring Timer1 and Timer2 to a phase correct PWM of 31kHz at a resolution of 8bits. The duty cycles of the PWMs is updated every time data is read off the ADC via the potentiometer setting.

Below shows an oscilloscope image of the high side PWM signal as seen by the gate;

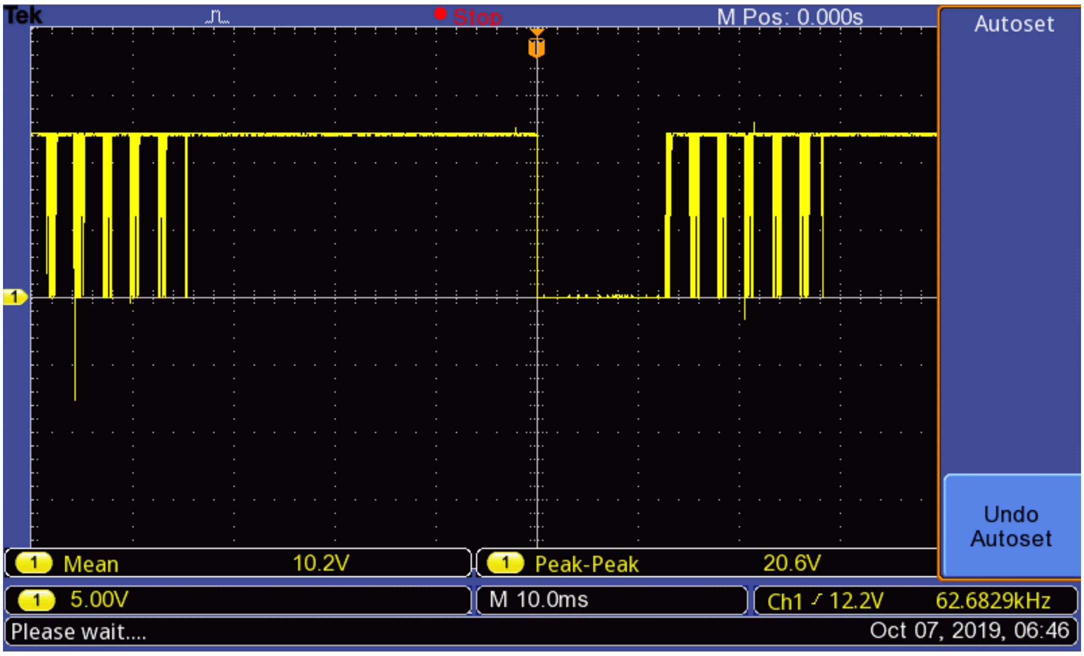


Figure 42 : PWM gate pulse of high-side MOSFETs.

Since the high side P-Type MOSFETs are the ones being pulsed, the PWM signal must be inverted and the driver voltage to the gate of these MOSFETs will swing between 0V and 12V thus Vgs will be either 0V or 12V . The image below from the oscilloscope shows this setting.

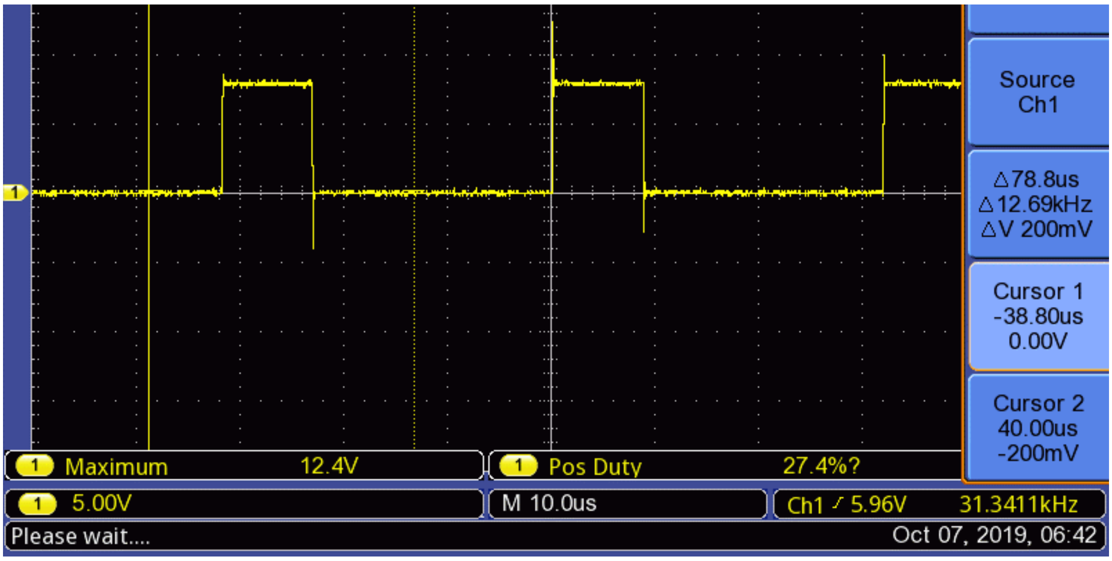


Figure 43 : Gate pulse at 31KHz.

The image shows the inverted signal. The PWM signal is inverted because the MOSFETs being driven are P-Type MOSFETs. Therefore, according to the image above the MOSFETs are off for 27.4% of the time and on for 72.6%.

7.2.2 Testing the correctness of the commutation / MOSFET switching sequence

Once the PWM was configured and the sensors installed into the electric machine, the next step was to derive the binary state machine that would determine the switching sequence of the MOSFETs in the inverter. Once this was derived the next step was to physically test this sequence's correctness in order to avoid a situation whereby the wrong switching sequence leads to the wrong MOSFTs switching thus potentially causing problems such as shoot-through etc. An LED test experiment was conducted to investigate the correctness of the state machine with respect to the MOSFET. Six LEDs were mounted on a breadboard to simulate the 6 MOSFETs of the inverter bridge. The LEDs were then connected to the microcontroller as outputs with each LED a simulation of each MOSFET. The Hall sensors were connected to provide the input signal. The images below show the setup of this experiment test :

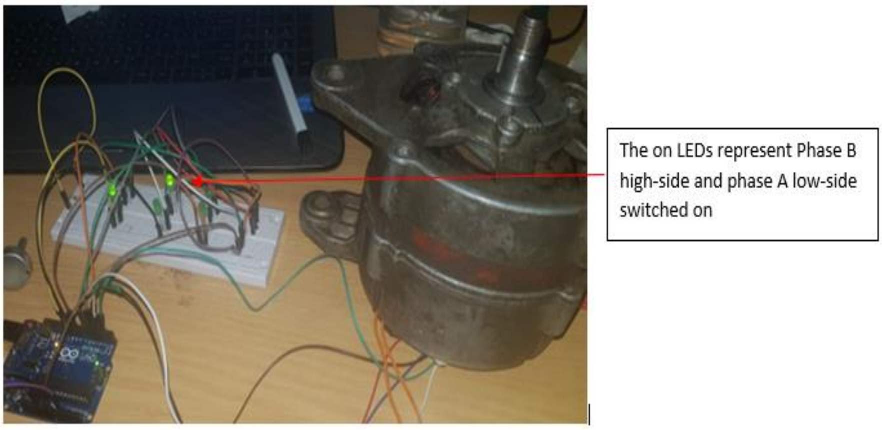


Figure 44 : Testing of switching sequence.

The shaft of the machine was rotated in a clockwise direction since the software was written for clockwise commutation. Approximately after every ~ 12° or so mechanically, a different pair of LEDs (one high-side one low-side) were switched on. This continued with 6 different LED patterns being seen. The LEDs switched on in accordance with the state machine and the required MOSFET position. This experiment was successful as the correct sequence was finally established and the code was optimized via the use of the LEDs before connecting to the inverter bridge.

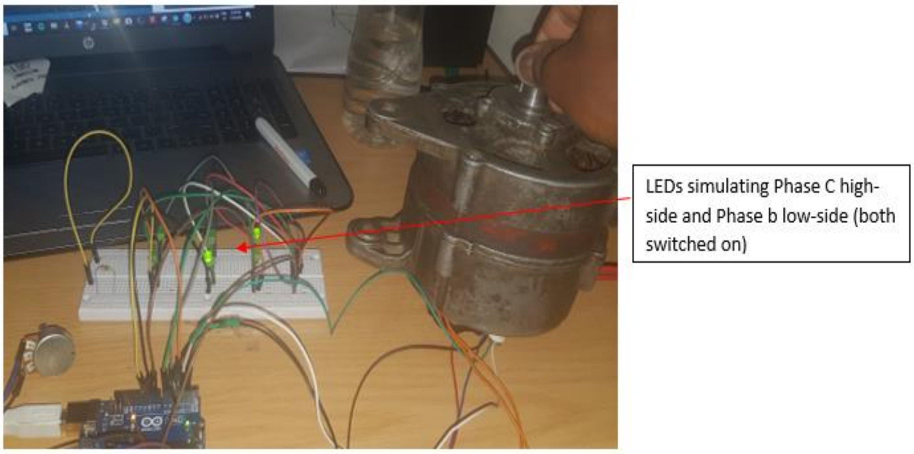


Figure 45 : Testing of switching sequence

7.2.3 Input Power

In order to measure the power drawn by the motor, several parameters had to be measured. To do this the currents at different duty cycles had to be determined. The circuit was connected, and the resistor was placed in series with the 12V supply and the input to the inverter.

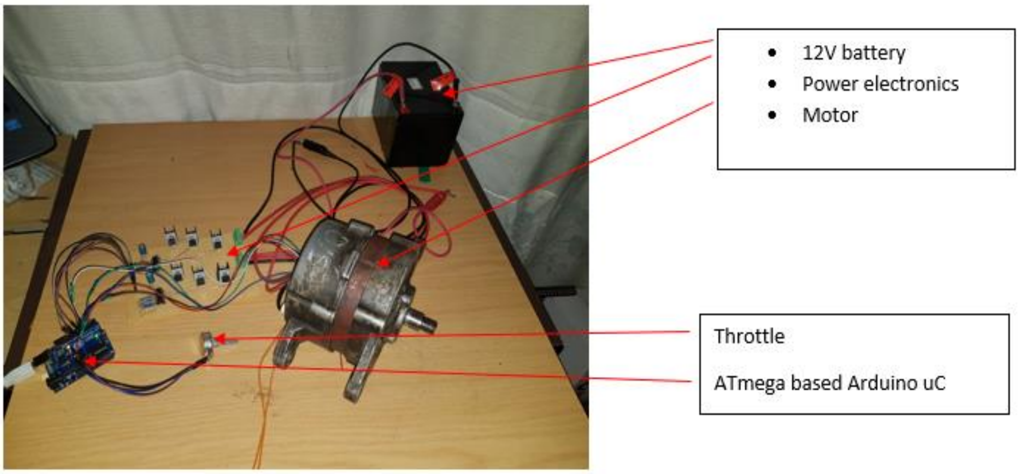


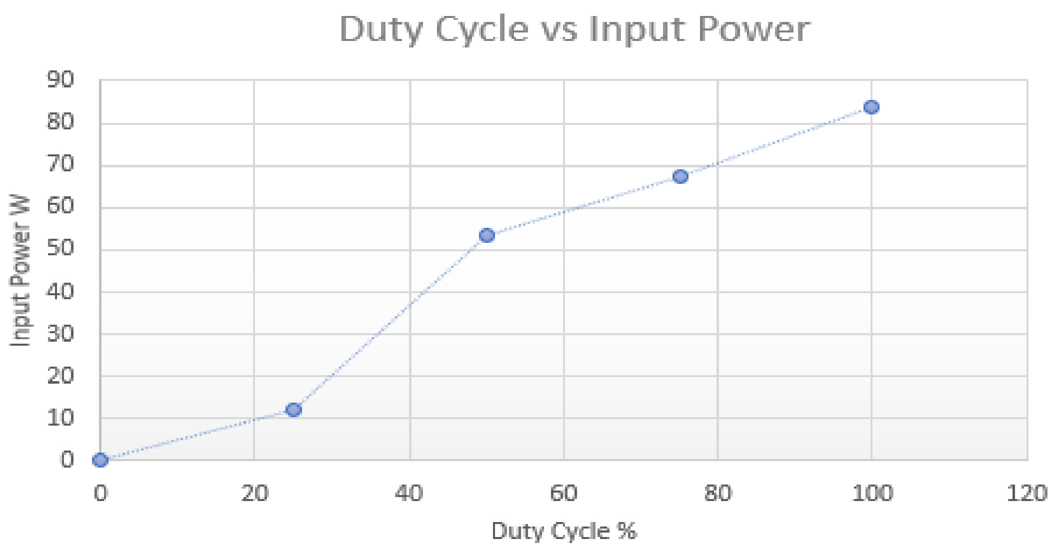
Figure 46: Set up during testing

Since the input voltage is known, the only parameter left to investigate was the current. This was done at no load. However, since PWM is being used, the current seen is likely to be a square wave thus using a normal multi meter will not give the true rms value of the current. Thus, to bypass this a shunt resistor was placed in series with the battery and the voltage drop across that resistor was measured and those values were used to determine the current by using Ohm's law.

Table 5 : Table showing the different current and power levels as per duty cycle setting.

Throttle Level	Voltage (V)	Average Current (A)	Input Power (W)
0	12	0	0
25	12	3.2	12.32
50	12	4.33	53.34
75	12	5.48	67.51
100	12	6.79	83.65

With this information a graph relating the throttle level/duty cycle and the input power was drawn as shown below:



From the above graph the input power increased with increase in duty cycle. This was to be expected as the essence of PWM is to reduce input power levels as per duty cycle setting by the designer. Thus, at no load it was clear to see that the power consumed by the motor was approximately **83.65W.**

7.2.4 Revolutions Per Minute

In any automotive application, a one of the most fundamental and key parameters is the speed. The speed can be deduced from the rpm of a motor. To measure the speed thus the rpm of a motor the following equations were used:

$$F_{motor} = \frac{1}{T_{motor}},$$

were F being the frequency of the rotating magnetic field in the stator measured between 2 phases and T is period of this frequency.

$n_e = 60 f_{motor}$,

were n_e *is the speed of rotating field in the stator.*

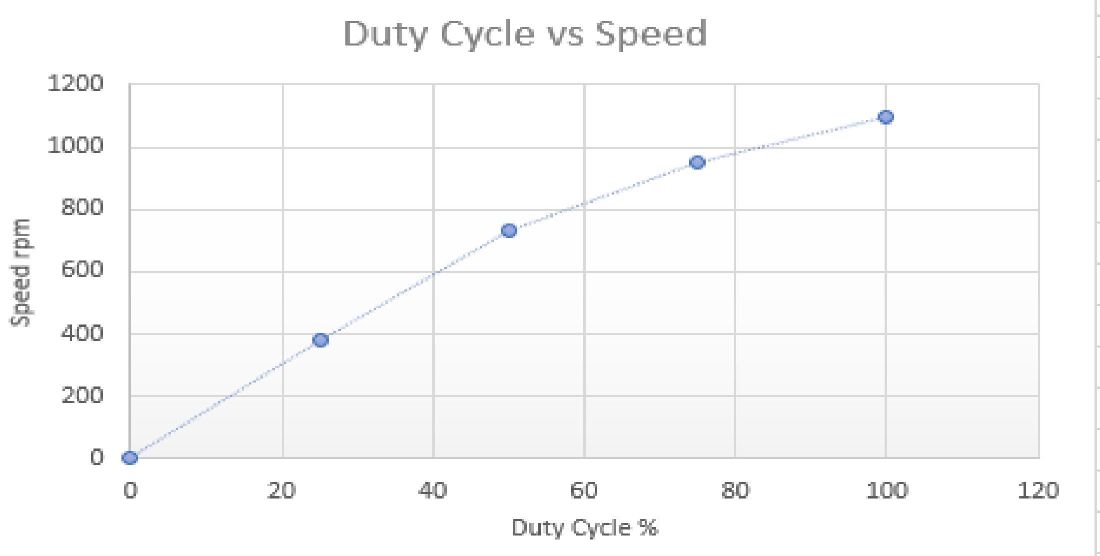
$n = \frac{n_e}{p}$ were n being the mechanical revolutions per minute while p is the number of poles of the motor.

Results for the rpm were taken at different duty cycle settings.

Table 6 : Table showing the RPM at different duty cycle settings.

Duty Cycle / Throttle Level	**Frequency of electric field F_{motor} (Hz)**	**Speed of rotating field n_e (rpm)**	**Speed of shaft at no load n (rpm)**
0	0	0	***0***
25	38.1	2286	***381***
50	73.2	4392	***732***
75	95.4	5724	***954***
100	109.5	6570	***1095***

- Again, the duty cycle can be related to the speed . The graph relating this shown below:



From the graph above, the increase in speed takes a linear form up until around the 50% duty cycle setting. From about 60% this linear relationship is lost and as the graph start to curve as it approaches at 100%. Therefore at 100% duty cycle is the maximum speed of the motor at

1095 rpm. From the graph above it can be concluded that the base speed will be experienced at 100% duty cycle at 1095rpm.

The next step was now to find the relationship between angular speed ω and the duty cycle. The angular velocity can be determined because the speed(rpm) is now known for all the duty cycle settings. By using the following equation, the angular velocity of the motor can be deduced at various duty cycle settings.

We know that $\boldsymbol{\omega} = \frac{\boldsymbol{2\pi n}}{\boldsymbol{60}}$ were **n** is the speed thus:

Table 7 : Table showing the angular velocity and RPM at different duty cycle settings

Duty Cycle	**RPM**	**Angular velocity ($rads^{-1}$)**
0	0	0
25	381	39.898
50	732	76.654
75	954	99.903
100	1095	114.668

7.2.5 Mechanical Power and Torque

The input power at no load (the rotor as the load) was determined for various duty cycle settings. The phase resistance was measured by making use of the RLC meter. The two probes of the RLC meter were placed on 2 phases of the stator and the value of the resistance found was divided by 2 to get the per phase resistance. The per phase stator resistance found to be **0.1Ω**. Thus, neglecting power loss in the bearings and friction, the power dissipated can be deduced. Using the equation:

$\boldsymbol{P_{mech} = P_{in} - P_{statot-loss}}$ **were** $\boldsymbol{P_{stator-losses} = 3I^2R}$ were **R** is the per phase resistance.

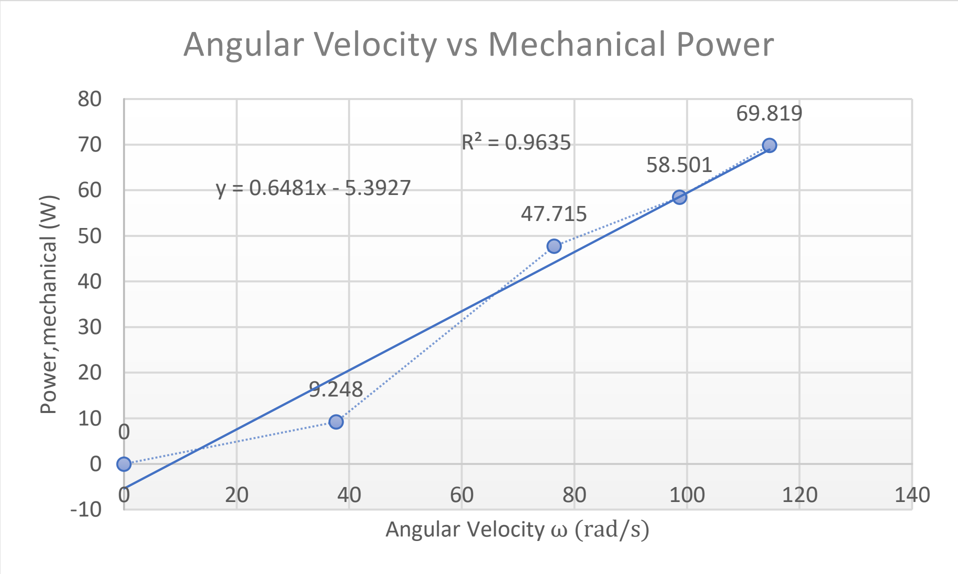
There were difficulties in obtaining the other losses thus they were neglected, and stator losses were the ones that were focused on.

Table 8 : Table showing input, mechanical and power losses at different duty cycle settings

Duty Cycle/Throttle	$\boldsymbol{P_{in}(W)}$	$\boldsymbol{P_{stator-loss}}$	$\boldsymbol{P_{mech}}$
0	0	0	0
25	12.32	3.072	9.248
50	53.34	5.625	47.715
75	67.51	9.009	58.501
100	83.65	13.831	69.819

It is clear now that from the information that was deduced empirically, other important parameters could be determined as well. The average torque was found by making use of the following relationship in the equation below:

The equation $\boldsymbol{P_{mech} = \tau\omega}$ suggests a linear relationship. Upon closer inspection it can be deduced that $\boldsymbol{P_{mech} \alpha\ \omega}$ thus in other words meaning that Power is directly proportional to the angular velocity. Thus, since torque was not known, a graph of $\boldsymbol{P_{mech}\ vs\ \omega}$ was plotted with the gradient obtained being the value for the torque of the shaft at no load (rotor acts as the load).

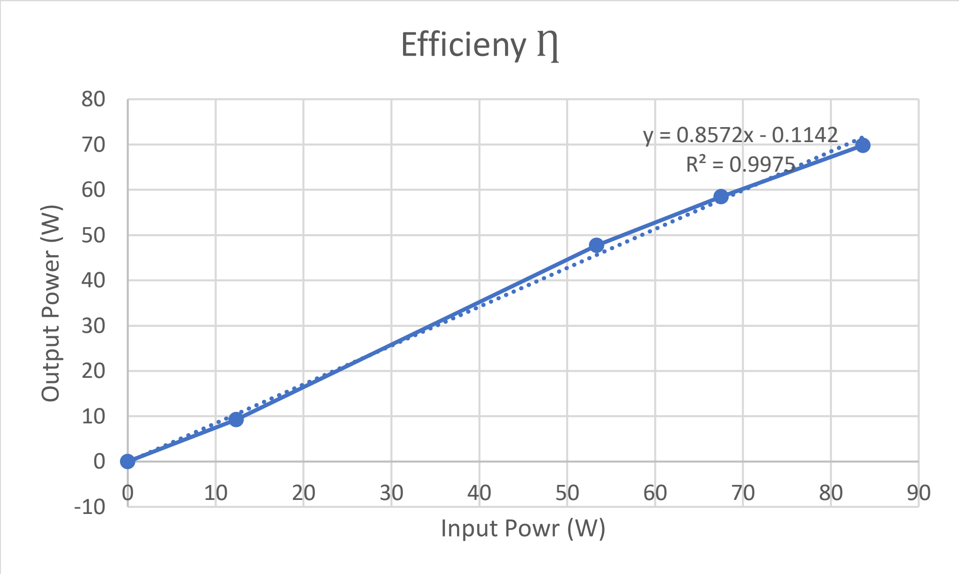


The graph above shows the relationship between the angular velocity and the mechanical power. It can be noticed that from the graph , the R^2 value is 0.9635 which is closer to 1.This suggest a linear relationship. Again, by looking at the gradient it could be concluded that at no load, the rated torque is **0.6481Nm**. However, one should also note that this value isn't overly accurate as other losses which couldn't be obtained via lab experiments were neglected. Therefore, to account for these losses that couldn't be determined, a fudge factor of 0.95 was attributed to the torque. Thus,

Torque = 0.95*0.6481 = **0.6157Nm**

7.2.6 Efficiency

In power electronics, efficiency is one of the most important factors in any design. A high efficiency means that the power dissipation and thermal management across the whole system is at a minimum and good respectively. Again, to calculate the efficiency, it was done under no load to the shaft (rotor acting as load). Since the input power was determined earlier and the mechanical power (output power) were determined it was simple to determine the efficiency. An elegant way to do this was to plot the graph that pitted input power against output power(mechanical power).



The graph above has R^2 value of 0.9975. This is very close to 1 therefore this graph suggests a linear relationship. The efficiency was therefore the gradient which is 0.8572.

However, since some loses couldn't be deduced a fudge factor of 0.95 was used to compensate for this. Thus η =**0.95*0.8572 =0.81434** = **81.4% .** This is reasonably acceptable as most motors are in and around this efficiency.

7.3 Conclusion

From the results and motor characteristics that were obtained above, it could be seen that the motor controller was working as expected with respect to PWM and the first quadrant of motor control. This chapter gave an overview on the tests performed. The graphs plotted were used to interpret and further affirm the attractiveness of using PWM and how PWM is used as a current chopping technique.

CHAPTER 8 : DISCUSSION AND CONCLUSION

8.1 Introduction

The purpose of this chapter was to evaluate the overall project and establish whether all the objectives of the project were met with respect to the problem statement and specifications met. The previous chapter gave the experimental results and the tests performed and these were discussed to rubber stamp whether the project was a success. Implementation difficulties and short comings of the project were discussed. Recommendations and corrections for future were highlighted.

8.2 Achievement of Objectives

The main objective, which was to design , build and test a PWM electronic controller for an electric bike prototype was successfully achieved. As stated in the specifications, this controller was able to limit the starting excessive current as this was seen in the previous chapter. The speed was variable as the PWM duty cycle was varied and updated every time the potentiometer or throttle was adjusted. The automotive alternator was successfully converted into a brushless dc motor. This was done by placing small permanent neo magnets at the end part of the rotor. Hall sensors were then spaced out accordingly with respect to these magnets so that the rotor could be located thus facilitating the switching. Therefore, in that respect this the project was a success.

8.3 Implementation Issues

8.3.1 MOSFET Failure

There were a lot of issues that were faced during the design ,implementation process and testing of the controller. The biggest issue that was faced was the constant failure of the switching MOSFETs while the motor was running. To try and debug this problem the per phase simulations were performed on LT Spices to get a better idea of the behaviour of the peak currents during switching. Initially the switching frequency that used was $9.6kHz$ as was defined by the time constant. When this was simulated , it was noted that the peak currents in the motor windings could get as high as 32A. Thus, this made sense as to why the MOSFETs had failed. This is because the first batch of MOSFETs that were used were the N-Channel IRF540. These have ratings of 100V and current of 31A. However, it is important to note that these ratings are true when the MOSFETs are operating at room temperature and as the temperature increases, the drain to source current capability decreases.

Therefore, the next step was to replace these MOSFETs with more robust ones. Next up were the IRF3205 with ratings of 55V and 110A at room temperature. These were configured on the high-side and low-side using the driver series IR2101. The switching frequency was left at $9.6kHz$ to compare and see if the same problem experienced with the IRF540s would resurface. Upon further testing the MOSFETs seemed to respond favourably as the duty cycle was varied. The MOSFETs on the high-side configuration then failed as the controller was operated at 100% duty cycle. This failure was because the IR2101's high side output needs to be bootstrapped thus allowing the bootstrap capacitor to discharge onto the source of the high-side MOSFET essentially creating a floating ground, the high side MOSFET should always operate in PWM mode so that the configuration works. Therefore, the high-side PWM duty cycle should never be 100% otherwise the capacitor will not charge and discharge thus no floating ground is created. This led to a shoot through in the inverter.

The MOSFETs were then checked via the diode test of the multi-meter to investigate which MOSFETs had failed. It was discovered that all the high-side MOSFETs had failed. The inverter circuit was then redesigned , with the final design being the one that is seen in chapter 4. TC4469 drivers were used together with P-type channel MOSFETs(IRF4905) for high-side driving. The phenomena of current recirculation in a drive circuit was investigated. When a specific MOSFET is turned off the current tends to flow in the freewheeling diode as it decays towards zero. In some cases, this current doesn't decay as fast as one would want and with time the freewheeling paths stop functioning properly. If the freewheeling paths do not work properly then power will want to dissipate via the MOSFET, thus excess current builds up as a result and with time this leads to the MOSFET failing. This is one of the problems which were faced. To solve this problem, external power rectifiers were placed between the drain and source of each MOSFET to improve current recirculation thus increasing reliability of the MOSFETs. Once this was done , the controller was able to work for prolonged periods as the testing described in the previous chapter commenced using the final design.

8.3.2 Electromagnetic Interference

Another issue faced was EMI in the circuit. This was made apparent by the fact that this was a high frequency application. The effect of stray inductance, large loops of the high current carrying paths often triggered false switching at the gates of the MOSFETs . This greatly hampered and hindered the performance of the controller and ultimately hampered the circuit from fulfilling its potential. Thus, after consultation with EMI and EMC expert and University lecturer Dr De Beer, it was recommended that the circuit layout should be redesigned by reducing the size of the loops, and by placing the drivers and series gate resistors as close as possible to the gates of the MOSFETs. This was done when the final circuit was laid out and soldered.

8.3.3 Position Sensors

Finding the optimal Hall sensor position was one of the biggest challenges that were faced. Theoretically and experimentally, as was discussion in Chapter 6 the angle of spacing of these sensors was established but in practice there were some blemishes. This is because external permanent magnets were placed at the end part of the rotor. Therefore, due to the small size of these magnets, they did not exactly correspond to the electromagnet that was formed by exciting the rotor. When the small magnets were placed at the end part of the rotor, there were some gaps within each magnet as seen in chapter 6. Therefore, it was noted that the magnetic flux formed about the gap was not uniform throughout the magnets. This means that the greatest and most pronounced flux was experienced directly on the face of the magnet and as one moves towards the gap, the flux becomes non-uniform. This was problematic as this also caused premature or delayed latching of the hall sensors. This resulted in the motor jittering. To solve this problem, the disk that contained the Hall sensors was advanced and retarded by means of trial and error until the ideal position was found.

8.4 Short Comings

In this project, the secondary objective of performing regenerative braking was unsuccessful. This was because of various reasons. The biggest reason for this was because of the time constraints. The amount of time spent debugging and fixing the implementation problems that are mentioned meant there was not enough time to design , implement and fully test for regenerative braking . Repeated failure of MOSFETs, issues related EMI, premature and delayed latching of the sensors provided their own challenges. When these issues had been fixed, an attempt to perform regenerative braking was made. This was done using the variable switch regenerative braking technique. In this technique, either one or two low-side switches are applied PWM. This technique would only work in short bursts but when prolonged, the high-side MOSFETs and its respective driver failed. This was taken to LT Spice to try and understand what the problem was, and it was noted that the high voltage spikes and reverse inductor current were the culprits for this. This current can ideally peak at about 14A which is rather high as the battery’s recommended maximum charging current is 3.6A. Once this failed , one final attempt was made to perform regenerative braking. A boost converter from MANTECH Electronics was acquired. The converter had an input voltage range of 2-12V and an output range of 12V-24V. This was tested by making a connection between the boost converter and the inverter via two SPDT relay switches. Again, this was tested and the MOSFETs failed. Through extensive research it was noted that the likely cause of these failures during regenerative braking mode was due to $^{dv}/_{dt}$ failure. This failure is caused by large inductive spikes getting onto the drain of the MOSFET thus coupling together with internal capacitance of the gate. When this energy is large enough, the voltage at the gate rises above the maximum allowable threshold thus the MOSFET fails instantly. This type of failure is very common in motors especially when the motor acts as a generator. Restricted budget also hindered further testing especially under loading. This is because further modifications to the shaft and materials would have to be acquired which cost money.

8.5 Recommendations

A ready-made BLDC motor with either hall sensors or shaft encoder already embedded into it or a hub motor would be a better choice for the electric machine. Anyone who would like to take this project further or improve on it, using a PCB to lay the controller circuit on would be favourable as EMI is greatly reduced. Extensive research into MOSFETs must be made. Closed loop control with under voltage protection and fault detection would make this project more complete.

8.6 Achievement of ECSA Outcomes

This project was guided by the Exit Level Outcomes that are set out by ECSA. Below are the ELOs that were assessed and a short description how they were satisfied.

8.6.1 Exit-level Outcome 1:Problem solving

This outcome was met and satisfied by successfully designing and testing a BLDC PWM based electronic controller for an electric bike application. Thus, the primary objective was satisfied.

8.6.2 Exit-level Outcome 3: Engineering design

To satisfy this outcome, creativity and innovation was required. This outcome was satisfied by spending countless hours studying microchip data sheets and application notes. This then led to the utilization of PWM to control and limit the average power and most importantly the varying the speed by adjusting the duty cycle. This outcome was also satisfied by successfully designing the software for the controller and the design of the optimal switching frequency using engineering the software LT Spice.

8.6.3 Exit-level Outcome 4: Investigations, experiments and data analysis

This outcome was satisfied by the contents in chapter 6 and 7. The led experiment that was conducted to determine the correct switching sequence and the experiment of finding the hall sensor angle spacing by energizing any two winding and measuring this angle from a reference point also satisfied this outcome. The graphs plotted were used to interpret and deduce important information about this project.

8.6.4 Exit-level Outcome 6: Professional Communication

This outcome was satisfied by various submissions of deliverables, a mini-dissertation and a power-point presentation of the project to fellow students and external examiners.

8.6.5 Exit-level Outcome 9: Independent learning ability

During the life cycle of this project I learnt so much about MOSFETs, switched mode technology, electric vehicles, regenerative braking, the importance of proper circuit layout and various conditions in which MOSFETs fail.

8.7 Future work

As this project is concluded, it is rather a great shame that regenerative braking wasn't successfully implemented into the final system design. More research will have to be put into understanding the MOSFET further. Scope for future work includes closed speed control , under voltage protection, a battery management system and reliable regenerative braking of the motor. An optimization technique that would likely be used is the complementary PWM technique for speed control and regenerative braking. This will further improve and increase the efficiency.

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APPENDIX

Software code

```
#define hall1 2

#define hall2 3

#define hall3 4

int stepstate;

bool hallstate1;

bool hallstate2;

bool hallstate2;

byte Throttle;

int HallVal;

int start_motor = 12; //Start button

int regenbrake_motor = 13; //Stop button

int start_,motor = 0;

int regenbrake_motor = 0;


//This interrupt vector will run whenever there is a change of state in any of the hall sensors

// I wrote this piece of code using interrupts based on the Lookup table designed


ISR(PINT2_vect){
   if ((hallstate1 == 1) && (hallstate2 == 0) && (hallstate3 == 1)) {
    stepstate = 1;
  }
  if ((hallstate1 == 0) && (hallstate2 == 0) && (hallstate3 == 1)) {
    stepstate = 2;
  }
  if ((hallstate1 == 0) && (hallstate2 == 1) && (hallstate3 == 1)) {
    stepstate = 3;
  }
  if ((hallstate1 == 0) && (hallstate2 == 1) && (hallstate3 == 0)) {
    stepstate = 4;
```

```
 }
 if ((hallstate 1== 1) && (hallstate2 == 1) && (hallstate3 == 0)) {
   stepstate = 5;
 }
 if ((hallstate1 == 1) && (hallstate2 == 0) && (hallstate3 == 0)) {
   stepstate = 6;
}
}
//The functions below control how the phases A, B AND C will be energized
// I wrote these functions through use of port manipulation
void Energize_Phase_A_high_B_low(){
 PORTB = B00000010;
 PORTD = B01000000;
 TCCR2A =  0;           // Phase A high_side PWM
 TCCR1A =  0x81;        //
}
void Energize_Phase_A_high_C_low(){
 PORTB = B00000010;
 PORTD = B00100000;
 TCCR2A =  0;           // Phase A high_side PWM
 TCCR1A =  0x81;        //
}
void Energize_Phase_B_high_C_low(){
 PORTB = B00000100;
 PORTD = B00100000;
 TCCR2A =  0;           // Phase B highside PWM
 TCCR1A =  0x21;        //



}
void Energize_Phase_B_high_A_low(){
 PORTB =  B00000100;
```

```
 PORTD =  B10000000;
 TCCR2A =  0;           // Phase B highside PWM
 TCCR1A =  0x21;        //
}
void Energize_Phase_C_high_A_low(){
 PORTB = B00001000;
 PORTD = B10000000;
 TCCR1A =  0;           // Phase C highside PWM
 TCCR2A =  0x81;        //
}
void Energize_Phase_C_high_B_low(){
 PORTB = B00001000;
 PORTD = B01000000;
 TCCR1A =  0;           // Phase C highside PWM
 TCCR2A =  0x81;        //
}
//This function below loads and updates the duty cycle as per potentiometer setting
// I wrote this piece of code to calibrate the PWM duty cycle. Timer compare output registers were used
void Duty_Cycle_Setting(byte duty_cycle){
 OCR1A  = duty_cycle;              // loads and updates the Phase A PWM duty cycle
 OCR1B  = duty_cycle;              // loads and updates the Phase B PWM duty cycle
 OCR2A  = duty_cycle;              // loads and updates the Phase C PWM duty cycle
}

void move_motor(){

 //This is the commutation sequence for the BLDC
 switch(stepstate){
  case 1:
   Energize_Phase_A_high_B_low();
   break;
```

```
  case 2:
    Energize_Phase_A_high_C_low();
    break;
  case 3:
    Energize_Phase_B_high_C_low();
    break;
  case 4:
    Energize_Phase_B_high_A_low();
    break;
  case 5:
    Energize_Phase_C_high_A_low();
    break;
  case 6:
    Energize_Phase_C_high_B_low();
    break;
  default:
    PORTD = 0;
    break;
 }
}

void regen_braking(){
  //This is the regenerative braking function
```

//This is the section where I attempted regenerative braking. The switching frequency I used was 1kHz at 90% duty cycle.

```
 digitalWrite(6, HIGH);
 delayMicroseconds(900); // 90% duty cycle @ 1KHz
 digitalWrite(6, LOW);
 delayMicroseconds(100);

  }
```

```
void setup() {
// I defined the direction of the I/O pins
  DDRD = B11100000; //configures pin 7,6,5 as ouputs and the rest as inputs
  DDRB = B00001110; //configures pin 9,10,11 as outputs
  // below is the Timer1 module setting to get 31kHz PWM
  TCCR1A = 0;
  TCCR1B = 0x01;
  // below is the Timer2 module setting to 31kHz PWM
  TCCR2A = 0;
  TCCR2B = 0x01;
 // ADC module configuration
  ADMUX  = 0x60;                    // Configures ADC module and select channels 0 as
potentiometer/Throttle input
  ADCSRA = 0x84;                    // Enable ADC module with 16 division factor (ADC clock = 1MHz)
// I defined and set the pin change interrupts for the hall sensors.
  PCICR |= (1 << PCIE2);     //enable PCMSK2 scan
  PCMSK2 |= (1 << PCINT18);  //Trigger state change interrupt on hall1
  PCMSK2 |= (1 << PCINT19);  //Trigger state chenge interrupt on hall2
  PCMSK2 |= (1 << PCINT20);  //Trigger state change interrupt on hall3
  hallstate1 = digitalRead(hall1);
  hallstate2 = digitalRead(hall2);
  hallstate3 = digitalRead(hall3);
  HallVal = (hallstate1) + (2*hallstate2) + (4*hallstate3); // Computes the 3digit binary code as a
decimal number which is the stepstate
  stepstate = HallVal;
  //bldc_move();// 1st BLDC steppinMode(ledPin, OUTPUT);      TT,M
  pinMode(start_motor, INPUT);
pinMode(regenbrake_motor, INPUT);
}

void loop() {
  ADCSRA |= 1 << ADSC;             // Start sampling
```

```
  while(ADCSRA & 0x40);           // Wait for sampling to be completed
  Throttle = ADCH;                //Read the sampled discrete values
  Duty_Cycle_Setting(Throttle);    //Duty cycle updates as per throttle demand
 motor_status = digitalRead(start_motor);
regen_status = digitalRead(regenbrake_motor);

if (motor_status == HIGH )
{ move_motor();}
else {PORTD=0;
PORTB=0;};

// THE regenerative braking section was commented out after repeated MOSFET failure during testing
//if (motor_status == HIGH && regen_staus == HIGH)
//{regen_braking();
//PORTB=0;};

}
```

ATmega328p data sheet

In this project, the datasheet was one of the most important pieces literature that governed and guided the design of this project.

The most important data sheet that I used was the ATmega328p data sheet which served as a guideline in writing the software and correctly setting the PINs , the interrupts and configuration of PWM and the ADC.

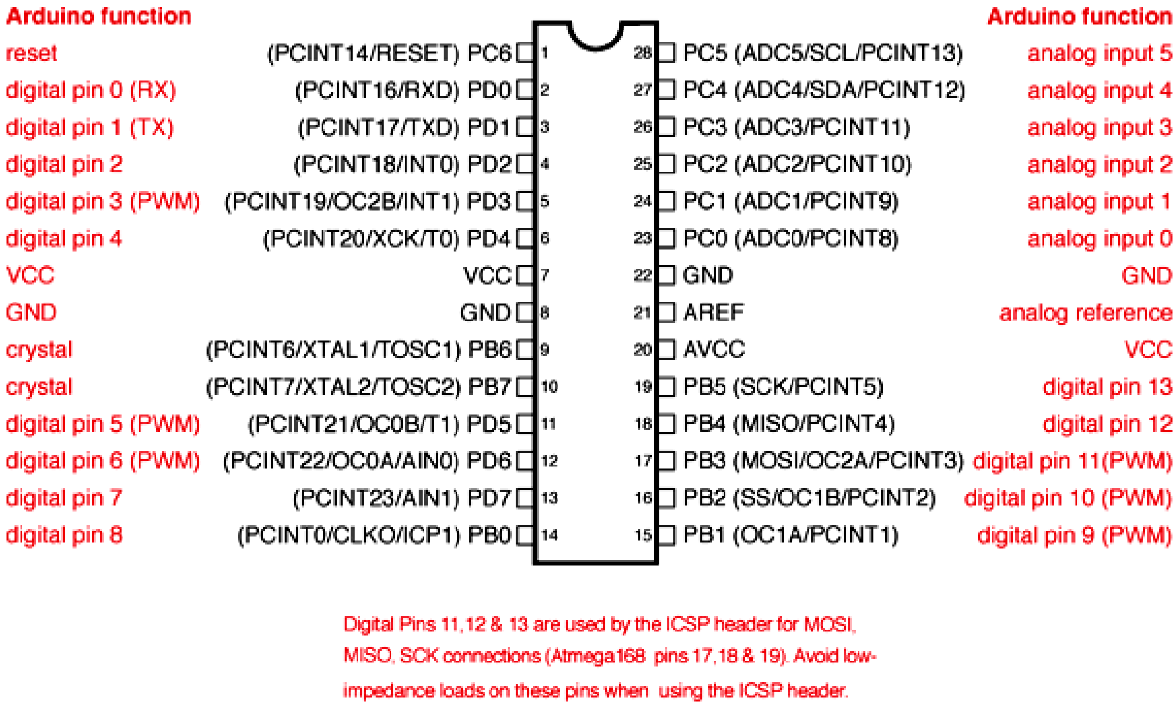

Figure 47: Arduino to ATmega pin mapping [23]

To fully optimize the code instead of using the Arduino built in functions, port manipulation was used instead, and the image above shows the PIN mapping analogous to the Arduino.

13.2.6 PCMSK2 – Pin Change Mask Register 2

Bit	7	6	5	4	3	2	1	0	
(0x6D)	PCINT23	PCINT22	PCINT21	PCINT20	PCINT19	PCINT18	PCINT17	PCINT16	PCMSK2
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7:0 – PCINT[23:16]: Pin Change Enable Mask 23...16**

Each PCINT[23:16]-bit selects whether pin change interrupt is enabled on the corresponding I/O pin. If PCINT[23:16] is set and the PCIE2 bit in PCICR is set, pin change interrupt is enabled on the corresponding I/O pin. If PCINT[23:16] is cleared, pin change interrupt on the corresponding I/O pin is disabled.

Figure 48 : PCMSK2 register [23]

- Pin Change Mask Register was used to setup the pin change interrupts as seen in the code.

14.4.2 PORTB – The Port B Data Register

Bit	7	6	5	4	3	2	1	0	
0x05 (0x25)	PORTB7	PORTB6	PORTB5	PORTB4	PORTB3	PORTB2	PORTB1	PORTB0	PORTB
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

14.4.3 DDRB – The Port B Data Direction Register

Bit	7	6	5	4	3	2	1	0	
0x04 (0x24)	DDB7	DDB6	DDB5	DDB4	DDB3	DDB2	DDB1	DDB0	DDRB
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 49 : Port B data register and Port B data direction register [23]

14.4.8 PORTD – The Port D Data Register

Bit	7	6	5	4	3	2	1	0	
0x0B (0x2B)	PORTD7	PORTD6	PORTD5	PORTD4	PORTD3	PORTD2	PORTD1	PORTD0	PORTD
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

14.4.9 DDRD – The Port D Data Direction Register

Bit	7	6	5	4	3	2	1	0	
0x0A (0x2A)	DDD7	DDD6	DDD5	DDD4	DDD3	DDD2	DDD1	DDD0	DDRD
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 50: Port D data register and Port D data direction register [23]

Instead of using the Arduino pinMode function, the Port B and D registers were used instead to define the pins as I/O and whether they are high or low. Using port manipulation increases execution speed and optimizes the whole system.

16.11.1 TCCR1A – Timer/Counter1 Control Register A

Bit	7	6	5	4	3	2	1	0	
(0x80)	COM1A1	COM1A0	COM1B1	COM1B0	–	–	WGM11	WGM10	TCCR1A
Read/Write	R/W	R/W	R/W	R/W	R	R	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

- **Bit 7:6 – COM1A1:0: Compare Output Mode for Channel A**
- **Bit 5:4 – COM1B1:0: Compare Output Mode for Channel B**

16.11.2 TCCR1B – Timer/Counter1 Control Register B

Bit	7	6	5	4	3	2	1	0	
(0x81)	ICNC1	ICES1	–	WGM13	WGM12	CS12	CS11	CS10	TCCR1B
Read/Write	R/W	R/W	R	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 51: Timer1 control registers A and B [23]

The two timer control registers seen above were configured with no prescaler mode to give a PWM frequency of 31kHz. The **COM1A1:0** and **COM1B1:0** control the Output Compare pins (**OC1A** and **OC1B** respectively) behaviour. If one or both **COM1A1:0** bits are written to one, the **OC1A** output overrides the normal port functionality of the I/O pin it is connected to. If one or both COM1B1**:0** bit are written to one, the **OC1B** output overrides the normal port functionality of the I/O pin it is connected to. However, the Data Direction Register(DDR) bit corresponding to the **OC1A** or **OC1B** pin must be set in order to enable the output driver. When the **OC1A** or **OC1B** is connected to the pin, the function of the **COM1x1:0** bits is dependent of the **WGM13:0** bits setting.

The table below taken from the datasheet shows the COM1x1:0 bit functionality when the WGM13:0 bits are set to the fast PWM mode [23].

Table 16-2. Compare Output Mode, Fast PWM[1]

COM1A1/COM1B1	COM1A0/COM1B0	Description
0	0	Normal port operation, OC1A/OC1B disconnected.
0	1	WGM13:0 = 14 or 15: Toggle OC1A on Compare Match, OC1B disconnected (normal port operation). For all other WGM1 settings, normal port operation, OC1A/OC1B disconnected.
1	0	Clear OC1A/OC1B on Compare Match, set OC1A/OC1B at BOTTOM (non-inverting mode)
1	1	Set OC1A/OC1B on Compare Match, clear OC1A/OC1B at BOTTOM (inverting mode)

Figure 52 : Output compare register [23]

Thus, the PWM frequency was set by making use of these registers.

Initial design of the power stage

The power stage of the controller was initially designed using IRF540 MOSFETs and the high-side low-side driver IR2101. The IR2101 was used so that one type of MOSFET could be used through-out. The IR2101 requires a bootstrap capacitor so as to provide a reference source voltage to the high-side MOSFETs. This will ensure that Vgs is always greater than 10V and below 20V as recommended by the datasheets of all power MOSFETs. The bootstrap capacitors were selected to be 3.3uF while the fast switching diodes(1N4148) were used as the bootstrap diodes[22]. Below shows the schematic that was designed using the software package EASY EDA.

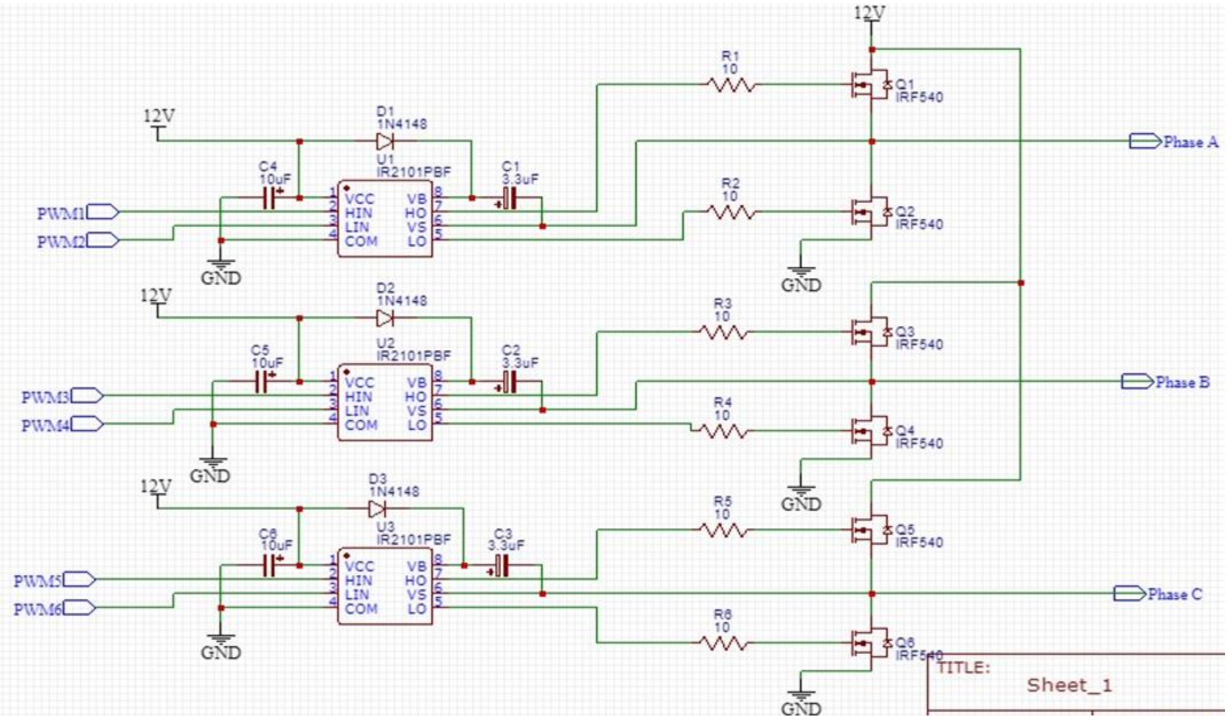

Figure 53: Power stage inverter circuit based on IR2101 gate drivers

The circuit was then constructed as the image below illustrates:

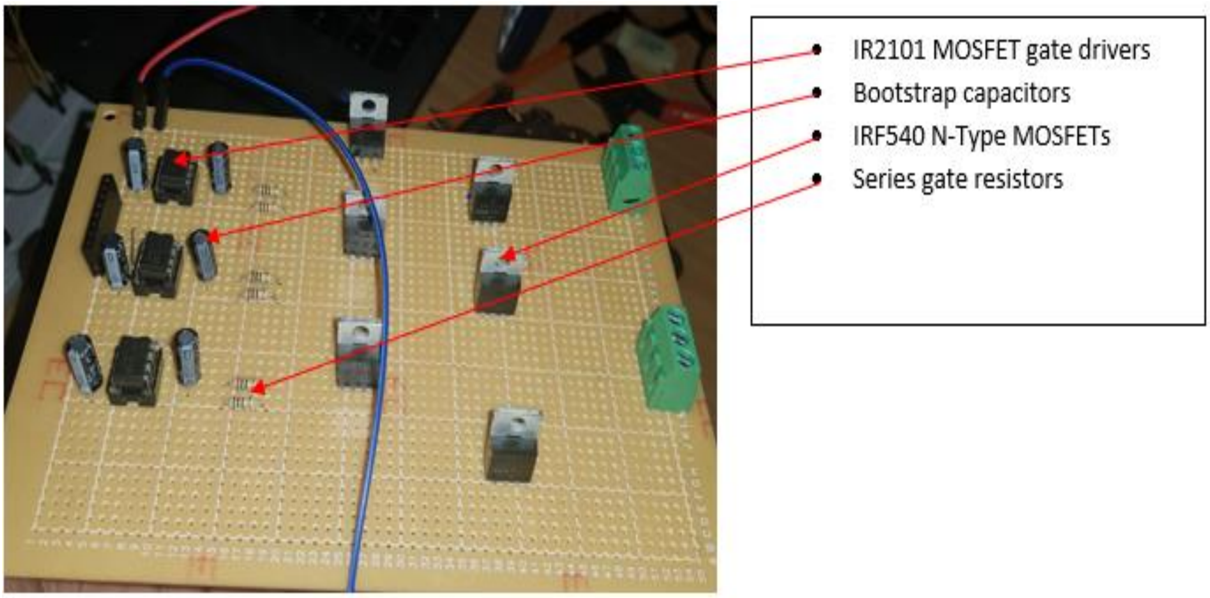

Figure 54: BLDC driver circuit based on IR2101

The driver circuit based on the IR2101 was constructed as shown above. This was the circuit that was initially designed and were a lot of MOSFET failures were experienced. The high side MOSFETs failed whenever the controller was operated at 100% duty cycle as was discussed in chapter 8. Due to these difficulties the final design used and tested on is the one that is seen in chapter 4 that is based on the P-channel MOSFETs and the TC4469 drivers. All the tests performed, and the results obtained in chapter 7 were acquired using the controller that was designed in chapter 4.

Initial layout of the Hall sensor circuit

The Hall sensors were initially laid out as was described in chapter 6. However, the Hall sensors were placed in such a way that they were curving away from the permanent magnets instead on curving towards the magnets. Even though 20° was the angle of spacing, the angles between the 3 were not equal. This was because of human error when laying out the Hall sensors. The illustration below shows this circuit.

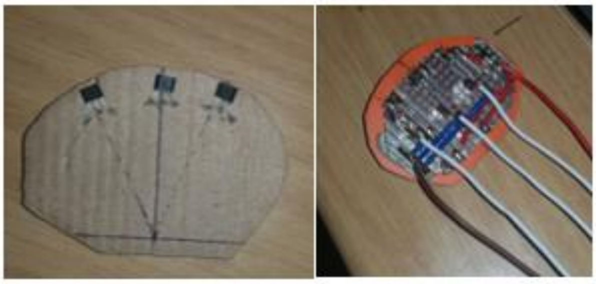

Figure 55 : Initial Hall sensor circuit

This layout caused the Hall sensors to latch prematurely, thus greatly reducing the performance. To solve this, a new Hall sensor circuit was prepared and constructed step by step as was shown in chapter 6. This improved the performance of the system.