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BLDC DRIVE FOR ELECTRIC VEHICLE WITH REGENERATIVE BRAKING- SHELL ECO MARATHON

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

PROBLEM STATEMENT

The world is exhausting its reserves of fossil fuels, a concern that necessitates increasing the use of alternatives based on renewable energy. A viable alternative is presented through green electric vehicles that are already being used in the automobile industry to accelerate sustainable transport. This makes battery-electric vehicles a prospective solution to the existing energy crisis, especially in the developing countries where non-renewable energy resources are limited and the demand for environmentally friendly alternatives in on the rise in order to avert the adverse affects of global warming and air pollution. However, various developments need to be carried before electric vehicles become mainstream. While a green alternative to fossil fuels is essential to combat the growing environmental and resource management issues, electric vehicles also increase energy efficiency. An internal combustion engine can reach up to 40% efficiency at maximum, while an electric motor can easily reach up to an efficiency of 80-85%. Moreover, the technology utilized in the design of battery-electric vehicles curbs noise pollution due to the relatively smooth drive maintained by its electric motors.

The current plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (EVs) achieve a much better economy in comparison to that achieved by the conventional vehicle. Moreover, they are cheaper to run. Cost comparisons to run an EV (Tesla Model S and Nissan Leaf to be specific) have been conducted by various online blogs and they all prove that it is significantly cheaper to run than an ICE powered vehicle. [1]

Another area where electric motors outperform the combustion engine is torque. An engine takes some time to hit peak torque and that time can only be minimized. An electric motor can provide peak torque at zero RPM, which leads to far greater acceleration. This has enabled Tesla to put supercars of today to shame right off the line, but as can be seen in many tests, at higher speeds, Tesla loses because of the fixed gear ratios.

One argument that some people make is that even if an EV could be more efficient, the carbon footprint is significant due to two main reasons, batteries and energy source. Batteries use lithium and mining lithium pollutes the environment. This when compared with the carbon footprint of conventional cars over their lifespan has been proved by most to be lower. The energy source required in proving an electric car's full potential in efficiency should ideally be renewable. However, even if the energy source were an internal combustion engine, that engine would be significantly efficient than a car's engine because of several reasons, one of them being that it runs on a constant speed, hence there are no transients. An American company called VIA trucks has employed this behavior. Their trucks run an engine at a constant speed as the power source but the drive train is electric, which results in a very high MPG rating. [2]

Today, electric cars are making a comeback. With Tesla's Model 3 launch recently [3], electric cars will be in the mass market shortly, competing with mainstream cars. The reason is advancement in battery technology and solid-state circuits. We know the fossil fuels are limited. One research says it could be as early as forty years when we run out of oil [4]. EVs are the solution to this problem. That is exactly the idea behind this research. We want to perfect the driving circuit for the electric motor and make it useable on an electric car.

An electric car, like a combustion engine powered car, has many parts. The defining character is the replacement of the engine by an electric motor, and fuel by batteries. Motors come in different sizes and configurations. The EPS cluster at the EE department has already successfully implemented driving circuits for a single and a three-phase AC induction motor. Generally, AC induction, AC synchronous and DC brushless (BLDC) motors are used in the electric vehicle industry. We will be designing a circuit for a brushless DC hub motor.

Our aim is to make a working drive for a BLDC motor. BLDCs are used in many hybrid cars and when compared to AC induction motors, produce a lot less heat within the rotor, can be driven via a simpler circuit, because making AC from a DC battery is a complicated process [5]. BLDCs are stable. There have been two senior year projects on brushless DC motors; however, a successful driving circuit is yet to be designed. Depending on the availability of time, we will design a circuit for sensor less control of a BLDC. The reason is that the hall sensors used in such a motor are fragile and expensive, and sensor less control is more reliable and robust [6]. The IEEE symposium on sensor less control for electrical drives (IEEE SLED) is held every year focused on this purpose [7], [8]. The basic idea behind the brushless control is to use the back EMF from the coils to detect the position of the rotor, which in the sensor based case, is done via hall sensors.

Chapter 2

BACKGROUND AND RELATED WORK

Electric vehicles are older than traditional vehicles. Sometime between 1832 and 1839 (the exact year is uncertain), Scottish businessman Robert Anderson invented the first crude electric carriage. In 1865 and then again in 1881 the storage battery technology was greatly improved and in turn enabled the electric vehicles to become a feasible, usable technology. It was 1884 when Benz patented the first gasoline powered car (The Benz Patent Motorwagen). Due to the limitation of fossil fuels back then, popularity of electric vehicles kept increasing. In early 1900s, there were actually more electric cars than gasoline powered vehicles. Oldsmobile and Studebaker were the first two successful manufacturers of electric vehicles. High cost, low speed and short range of electric batteries were the main reason of electric vehicles dying out gradually. Other reasons of advancements in gasoline engines such as the invention of electric starter, which solved the problem of hand cranking in gasoline powered vehicles [9], [10].

Since we know that fossil fuels are limited, an alternative must be developed [11]. They are dangerous for the environment too, because every time an engine starts, it hurts the environment. Thankfully, we have the basic concept and just need to refine it. With the advancements in battery technology and improved energy density, General motors developed a car called EV1 which was totally electric in 1996. But soon they stopped the production in 1999. With more research in battery technology and solid-state circuits, increased energy density and invention of lithium based batteries; EVs seem to make a comeback. Today, many automakers are making EVs namely Nissan Leaf, Renault Zoe, all models of Tesla and the list goes on. With minor differences, all EVs today either use a brushless DC, Synchronous AC or an Induction AC motor to power the wheels, and a lithium battery to power the motor. Lithium based batteries have a higher energy density when compared to lead acid ones but are expensive too. Some cars, like Honda FCX Clarity use a fuel cell rather than a battery and generate on board electricity rather than storing it [12], but the generation and purification of hydrogen is a complicated and not so energy efficient process. Apart from this, Gasoline-Electric Hybrids also use the same types of electric motors.

There have always been tradeoffs when comparing the two widely used motor types, BLDC and BLAC. When comparing the two, one is most concerned with efficiency and the torque-speed characteristics.

2.1: Efficiency Comparison between Brushless DC Motor and Brushless AC Motor Considering Driving Method and Machine Design

A research paper published in IECON 2011 shows that a BLDC machine can have a higher fundamental magnetic flux component than BLAC machine when the same maximum energy product magnet is used under the same stator and rotor geometries. Simulation results show that of course BLAC drive was better for the BLAC machine. However, for the BLDC machine, the BLDC drive achieves as high efficiency as the BLAC machine because of utilizing the harmonics. These results indicate that BLDC machine with BLDC drive has a potential to realize high efficiency and low costs. The experimental results show that the BLDC drive is am effective driving method since it can easily decrease the inverter loss compared to the loss of BLAC drive. Additionally, high duty factor region i.e. low DC link voltage optimizes the BLDC drive. Therefore, a BLDC machine with a BLDC drive has the highest total efficiency in these machines and drives combination in the experiment. These results give the considerable choice to select the machine and its driving method to achieve high efficiency and cost reduction. [13]

2.2: Torque-Speed Characteristics of Interior-Magnet Machines in Brushless AC and DC Modes, with Particular Reference to Their Flux-Weakening Performance

The torque-speed characteristics of BLDC and BLAC are compared in another paper published in IPEMC 2006. In this paper, torque-speed characteristics of a 3-phase permanent magnet brushless machine, having an interior permanent magnet rotor and an essentially sinusoidal back EMF waveform, are determined experimentally when the motor is operated in brushless AC (BLAC) mode, with 3-phase, sinusoidal current waveforms, and in brushless DC (BLDC) mode with both 2-phase, 120deg conduction and 3-phase, 180deg conduction rectangular current waveforms. The performance is compared on the basis of (i) the same peak phase current, (ii) the same torque in the constant torque-operating region, and (iii) the same RMS phase current. The results show that while 2-phase, 120deg BLDC operation resulted in the highest torque capability for the same peak current and BLAC operation resulted in the highest specific torque per RMS current when operating below the base-speed, 3-phase, 180deg BLDC operation generally results in the best performance in the flux-weakening region. [14]

2.3: Low-Cost Sensor Less Control of Brushless DC Motors with Improved Speed Range

One problem in BLDC motors is position sensing. An easy way to do this is to use Hall-effect sensors, which generate voltage in response to a magnetic field. But these are not robust and are expensive, and the motor assembly gets complex. They also tend to malfunction when dirt and moisture enter the assembly. An alternative way to do this is by sensing the back-EMF produced by the stator coils. A research conducted at Oak Ridge National Laboratory, National Transportation Research Center at Knoxville, Tennessee concluded that getting rid of the Hall-effect sensors could significantly save cost as it reduces the overall number of components in the motor as well as the driving circuit [15]. One paper published in Optimization of Electrical and Electronic Equipment (OPTIM), 2010 shows that utilizing advanced variable speed driving circuits can improve the efficiency of residential electric motors. [16]

Keeping in view the above discussion, it is desirable to switch to a more robust, discrete component, sensor less control. However, due to time constraints we focused ourselves on our main purpose, which is to maximize the efficiency of a BLDC motor, and so we restricted to a sensored control using hall sensors.

2.4: BLDC Motor and Controller

A single brushless DC hub motor is being used for rear wheel traction. The motor is rated at 1.5 kW and 48V, providing a torque of 25Nm. A brushless DC motor is more efficient and reliable than a brushed DC motor. In a brush DC motor, carbon brushes are used to physically commutate, which wear out and need routine replacement. Since these physical connections can also cause sparking unlike in a brushless DC motor which makes it much more reliable.

In order to make a motor controller, we would first look into how the BLDC motor works. The rotor and stator of a BLDC motor are shown in the Fig.1. The rotor of a BLDC motor is a permanent magnet.

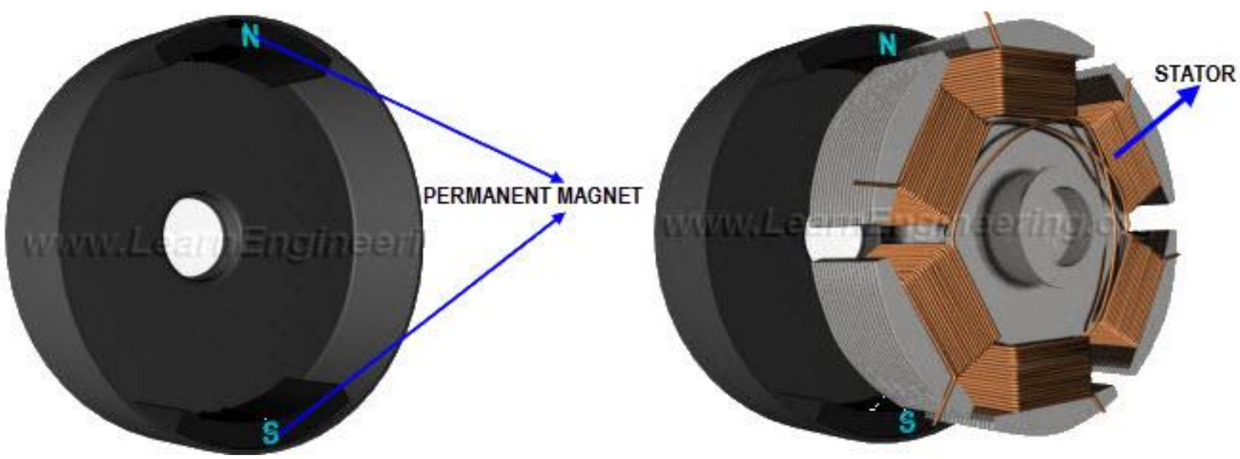

Fig.1 The Rotor of a BLDC is a permanent magnet; the stator has a winding arrangement [17]

The stator has a coil arrangement as illustrated. The internal winding of the rotor is illustrated in the Fig.2 (core of the rotor is hidden here). The rotor has three coils, named A, B and C.

Fig.2 The coil arrangement in a BLDC is shown here, with different color for different coils [18]

Out of these three coils, only one coil is illustrated in the Fig.3 for simplicity. By applying DC power to the coil, the coil will energize and become an electromagnet.

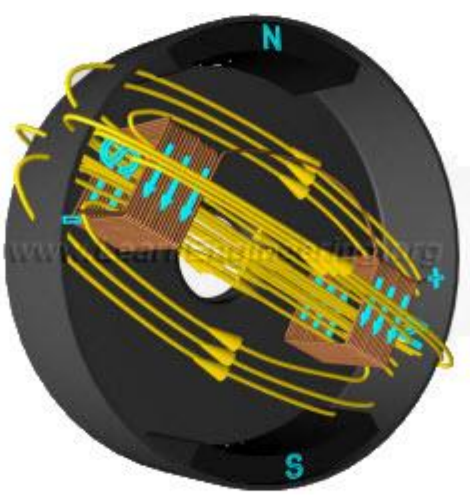

Fig.3 The coil energized by a DC power source becomes an electromagnet [19]

The operation of a BLDC is based on the simple force interaction between the permanent magnet and the electromagnet. In this condition, when the coil A is energized, the opposite poles of the rotor and stator are attracted to each other (The attractive force is shown in green arrow). As a result, the rotor poles move near to the energized stator.

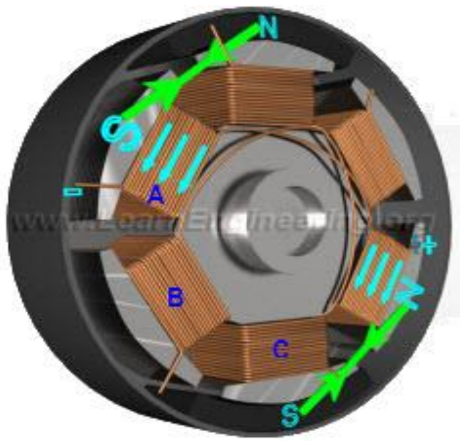

Fig.4 The rotor moves towards the energized coil, due to the attractive force [20]

As the rotor nears coil A, coil B is energized. As the rotor nears coil B, coil C is energized. After that, coil A is energized with the opposite polarity (compare the last part of Fig.5 with Fig.4).

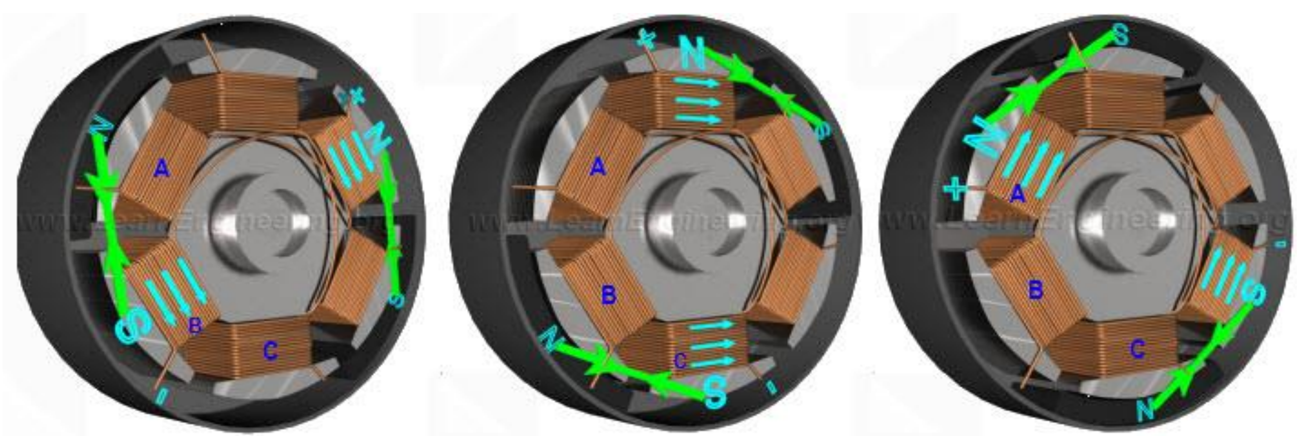

Fig.5 In a BLDC, as the rotor nears the energized coil; the next coil is energized [21]

This process is repeated, and the rotor continues to rotate. The DC current required in each coil is shown in the following graph.

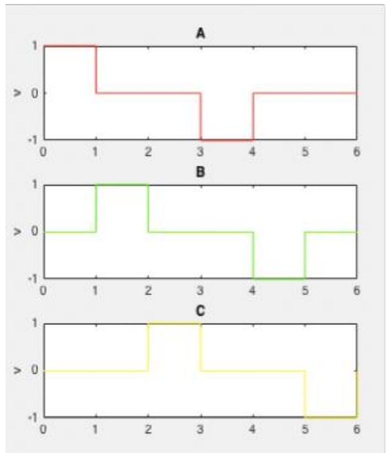

Fig.6 The DC voltage required in each coil is shown in this graph

Even though this motor works, it has one drawback. You can notice that, at any instant only one coil is energized. The two dead coils greatly reduce the power output of the motor. Here is the trick to overcome this problem. When the rotor is in this position, along with the first coil, which pulls the rotor, we can energize the coil behind it such a way that it will push the rotor.

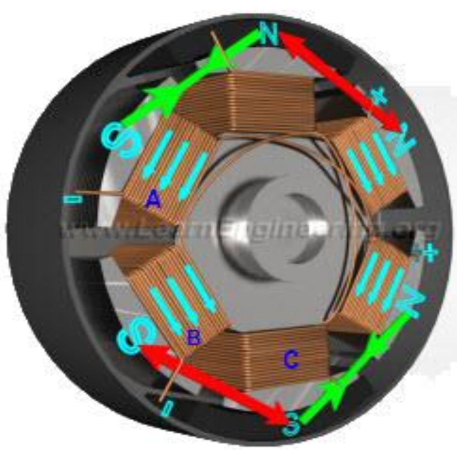

Fig.7 In practice two coils are energized in a BLDC motor [22]

For this, a same polarity current is allowed to flow through the second coil. The combined effect produces more torque and power output from the motor. The combined force also makes sure that a BLDC has a beautiful, constant torque nature. Such torque nature is difficult to achieve in any other type of motors.

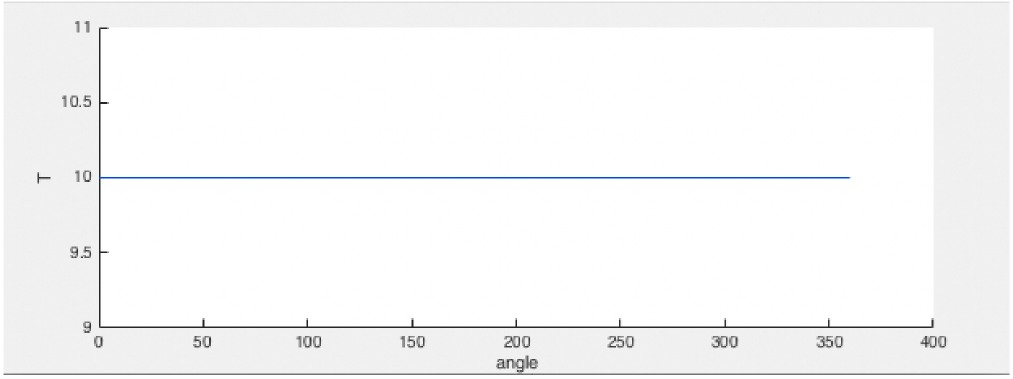

Fig.8 The BLDC has a constant torque nature as shown.

The current form required for the complete 360-degree rotation is shown in the graph below.

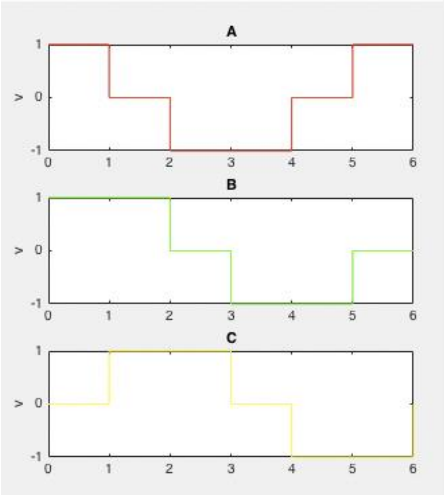

Fig.9 The voltage form required in each of the coil

With this new configuration coils need to be energized separately, but by making a small modification to the stator coil, we can simplify this process. Just connect one free end of the coils together, as shown in the Fig.10.

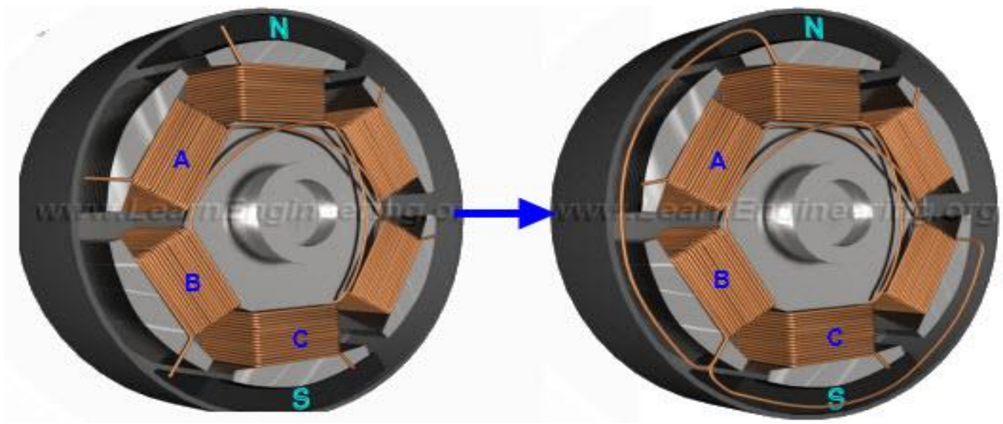

Fig.10 Connecting free ends of the coil together makes the BLDC voltage regulation much simpler [23]

When the power is applied between coils A and B, note the current flow through the coils. By comparing second part of the Fig.11 with Fig.7, it is clear that, the current flow is just like the separately energized state. [24]

Fig.11 Current flow with this configuration is same as that of the separately energized state [25]

Now for our controller to know which pair of coils is to be energized, we need to know the orientation of the rotor. For this purpose, we use three Hall effect sensors. The controller collects the data from the sensors to decide which coils need to be energized for the rotor to rotate continuously.

2.5: Regenerative Braking System

Regenerative braking plays a vital role in increasing the driving range of battery electric vehicles, contributing to elevated energy efficiency. "Long time for charging battery pack and short distance of driving range are the major problems for EVs. Effective battery utilization and advanced motor control have become an important issue" for them. Battery electric vehicles normally use mechanical brakes to provide deceleration. This is done by increasing the friction in the wheels, leading to loss of kinetic energy. Regenerative braking converts this kinetic energy (from the rotating system) into electrical energy that can charge the vehicle batteries [26].

"Regenerative braking is the process of feeding energy from the drive motor back into the battery during the braking process, when the vehicle's inertia forces the motor into generator mode" [27]. For battery-powered systems like electrical vehicles, regenerated energy (current) flows in the opposite direction to charge the batteries. The method is obtained by reversing the current in the circuit when the vehicle decelerates, "taking advantage of the motor acting as a generator, redirecting the current flow into the supply battery" [28]. The voltage is positive w.r.t motion, but the current flows from the system to the source, which is the opposite of what happens in the motor mode [29].

There are several ways to implement the regenerative braking system, including the use of ultra-capacitors along with DC-DC converters [30], incorporating fuzzy logic and PID control to the design system [31], utilizing electronic gearshift technology [32] and making use of independent switching coupled with PWM [33]. One such implementation method is where the circuit used to perform electronic switching using an inverter can be used with specific modifications to the switching mechanism to implement regenerative braking. Jarad Cody proposes a method that uses “independent switching in conjunction with pulse-width modulation” to implement the system. “In independent switching, all electronic switching devices are off while applying regenerative braking. The bottom switching devices are on for the 120-degree portion of the cycle. In this mode, the energized windings allow the current to flow through the low side of the PWM switch and through the freewheeling diode of the low-side high phase switch. Thus no current flows from the BLDC machine to the supply battery. During regenerative braking, current in the winding is reversed and supplied back into the battery. In this mode, all switches are turned off and the current can flow back through the freewheeling diodes”. However, after having implemented basic braking, there is a need to control its level. This is done by varying the PWM duty cycle, “which essentially toggles the current flow between regeneration and coasting”. Maximum regeneration can be attained with all the low-side switches turned off, and the “duty cycled varied from high to low”. The potentiometer used to control the PWM of the low-side switches is used to set the level of braking [34].

Regenerative braking is not operative at “all times, e.g., when the battery is fully charged, braking needs to be provided by dissipating the energy in a resistive load. Therefore, the mechanical brake in the EV is still needed” [35]. A mechanical brake system is also needed to ensure safety in case of an electrical failure.

2.6: Batteries and Battery Management System

A 48V lithium ion battery powers the entire EV system. A battery management system designed specifically for the electric vehicle protects and manages the lithium ion battery for optimum usage. It protects the battery by preventing it to operate outside its safe operating zone by monitoring the following;

i. The maximum charging or discharging current
ii. Over-voltage during charging and under voltage during discharging.
iii. Depth of discharge and state of charge
iv. Thermal state
v. Monitors health of each cell

Ensures cell balancing to maximize the usable capacity of the battery.

2.7: Shell Eco Marathon Guidelines

The prototype design was implemented and optimized to work under the given design constraints set by Shell Eco Marathon rules.

Test 1: Driver and Vehicle's weight

- Minimum: 50kg
- Maximum vehicle weight without the driver: 140kg
    - Achieved: 50kg

Test 2: Vehicle Dimensions

- Vehicle maximum height must be less than 100 cm
- Vehicle track width must be at least 50 cm
- Ratio of height divided by track width must be less than 1.25
- Vehicle wheelbase must be at least 100 cm
- Maximum total vehicle width must not exceed 130 cm
- Maximum total length must not exceed 350 cm

Test 3: Seat Belts

- For Prototype cars this will be done by raising the vehicle with the Driver on board using the safety harness buckle as the lifting point, this must be capable of withstanding 1.5 times the Driver's weight
- Five mounting points to maintain the Driver securely in his/her seat. The five independent belts firmly attached to the vehicle's main structure and fitted into a single buckle, topmost straps at an angle of at least10° below the shoulder line

Test 4: Turning Radius

- The turning radius must be 8 m or less

Test 5: Horn and Visibility

- Pitch greater than or equal to 420Hz, emit a sound greater than 85dBA, when measured from a horizontal distance of 4m
- Direct arc of visibility ahead and to 90° on each side of the longitudinal axis of the vehicle
- Rear-view mirror on each side of the vehicle, each with a minimum surface area of 25 cm^2
- Checked in order to assess on-track safety by using 60 cm high poles spread out every 30° in a half-circle, with a 4 m radius in front of the vehicle.

Test 6: Driver to Vacate Vehicle

- Fully harnessed driver to be able to vacate their vehicles at any time without assistance in less than 10 seconds
    - Achieved: 6 seconds

Test 7: Brakes

- Two independently activated brakes or braking systems
- One system has to act on all front wheel(s), the other on all rear wheel(s)
- The right and left brakes must be properly balanced
- The vehicle will be placed on an incline with a 20 percent slope with the Driver inside. The brakes will be activated each in turn. Each system alone must keep the vehicle immobile

Test 8: Safety Features

- Edges
- No spaghetti wiring- Used connectors
- Strength of frame and chassis
- Driver comfort
- Roll bar- extends 5 cm around the Driver's helmet when seated in normal driving position with the safety belts fastened, capable of withstanding a static load of 700 N (~ 70 kg) applied in a vertical, horizontal or perpendicular direction, without deforming
- Protection for Lithium Ion Battery
    - Consisted of an internal Battery management system, catering to over or under voltage protection, over current protection, short circuit, and overheating
    - Protective Fire Blanket
    - Metal casing in case of leakage

Test 9: Electrical Components

- Kill Switches (inside and outside)
- Motor drive

- Joule Meter
- Dead man’s switch

Chapter 3

DESIGN METHODOLOGY AND TOOLS

3.1: SYSTEM LEVEL DESIGN

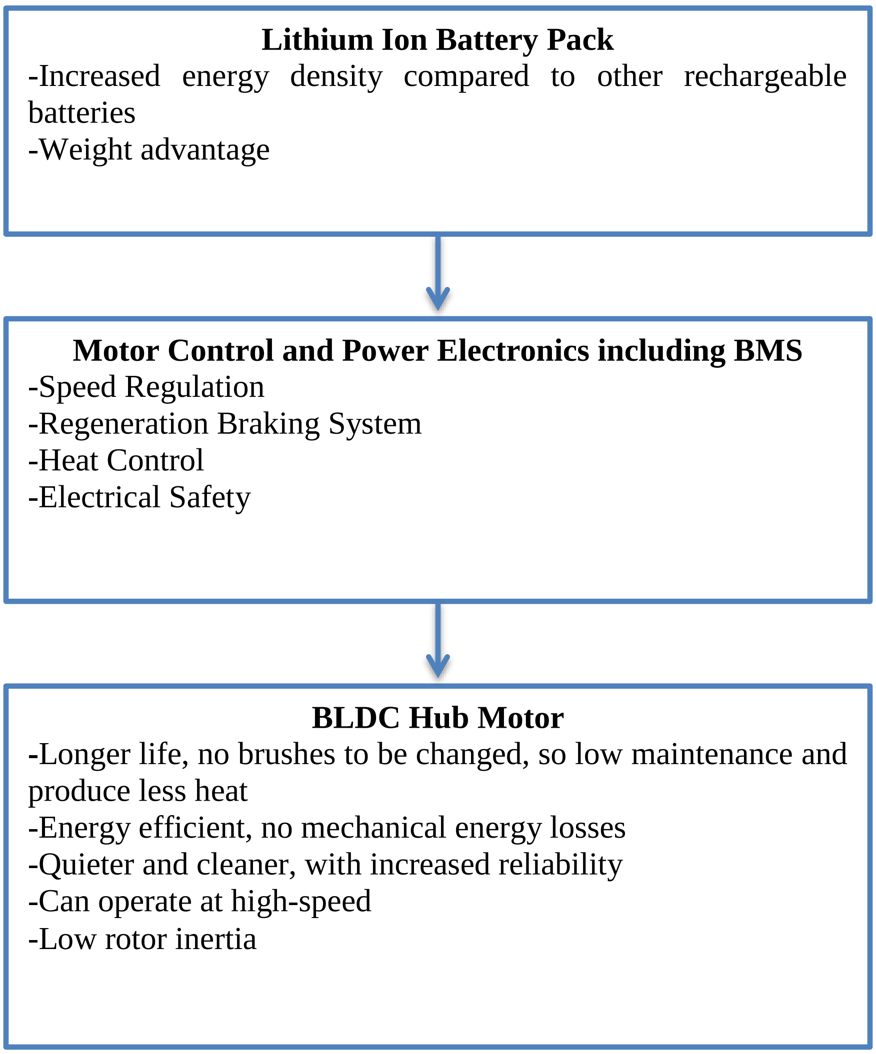

Fig. 12 System block diagram

3.1.1: Design Choices

We simulated the design in both Simulink and PSIM in order to optimally utilize the design features in both software modules. This allowed us to compare variables such as types of switches and hall sensors. However, the design circuit comprised of the same components as described below.

The electrical component of the project comprises of the following sub components:

- Three Phase Inverter Design
  - Could use IGBTs or MOSFETs. We chose MOSFETs owing to the high switching frequency available through their usage. We are operating at 20kHz. However, we implemented the inverter circuit using MOSFETs in PSIM and IGBTs in Simulink to observe the functionality of both.
- PWM Design/Switching Sequence
  - Depending on the hall sensors installed in our BLDC motor; unipolar, we resorted to using a sequence that gave 0s and 1s for the hardware. However, the PSIM simulation used bipolar hall sensors giving 0s, 1s and -1s, and the Simulink simulation used 1s and 0s.
- Speed Control
  - Speed was controlled using a PI controller. The values of which were determined using an inbuilt PI Gain Calculator in Simulink. We could not use the auto PI calculator because our circuit could not be linearized.
- Inrush Current Control
  - The initial current spikes were controlled through soft switching. Another method could employ a PI controller. However, given our circuit was nonlinear, it was not possible to determine the exact values; therefore, we used soft switching as we

will be implementing the same algorithm in the hardware.

- Regenerative Braking

Regenerative braking occurs as the body diodes of the switches provide a path for power flow in the reverse direction.

3.2: DESIGN METHODOLOGY AND TOOLS- ELECTRICAL

3.2.1: Simulations

Simulations were carried out simultaneously in Simulink and PowerSim as described in the previous section. The motivation was to compare results from both the softwares. The motor models in both softwares were different. PSIM has a BLDC model but the same model in Simulink was not compatible with other libraries; therefore, we had to use a synchronous machine in Simulink. The most commonly available configuration for a BLDC is a 3 phase, 120 deg, Y-connected machine. The package for this machine is available in both PowerSim and Simulink.

In PowerSim, a six switch inverter was implemented using MOSFETs. The motor package provides access to the 3 phases, the common node, hall sensor outputs and machine load torque. Hall sensors keep track of the rotor position so that commutation can be done in sensored control. Table 1 (pg. 33) was put together to decode hall sensor outputs and use them to excite corresponding phases to provide a stable output torque. This is what replaces brushes of a traditional DC motor. For a certain sequence of hall sensor outputs, the switches are configured such that one phase is connected to positive DC rail voltage, one phase to negative DC (or ground) and the third one is left open.

Motor Drive- PSIM:

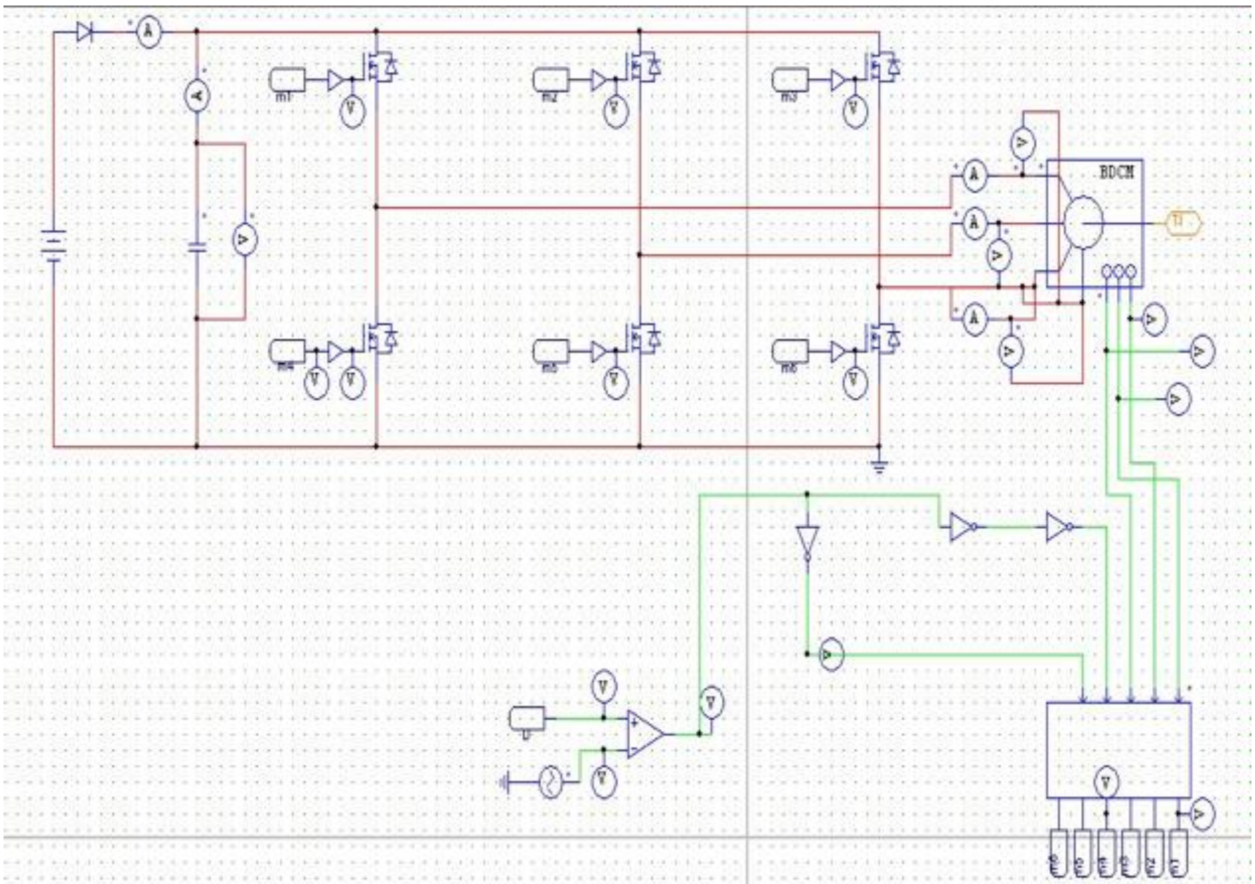

Fig.13 PSIM motor drive circuit

In Simulink, the same six switch inverter was designed with IGBTs. This was done because of some issues in MOSFET package compatibility. The available machine package was a Permanent Magnet Synchronous Machine (PMSM). The BLDC model not being compatible with most libraries and the likeliness of PMSM behaving like a BLDC when driven through the latter’s drive were the key factors in taking this decision. The PMSM package also provides access to hall sensor outputs, which are decoded to excite the corresponding windings using Table 2 (pg. 34).

Motor Drive- Simulink:

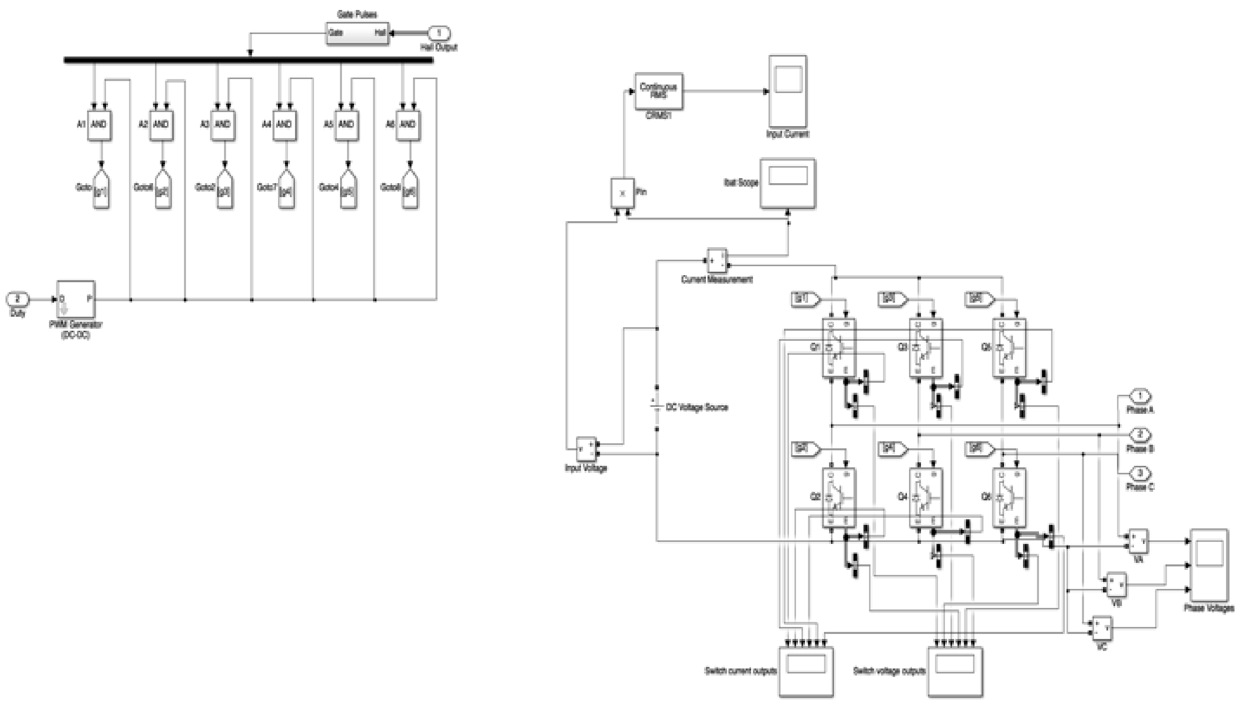

Fig.14 Simulink motor drive circuit

These circuits comprise of all the components including regenerative braking, three-phase inverter schematic, PWM provision and speed and current control.

3.2.1.1: Inverter Design and PWM Provision

The three phase inverter comprised of six switches each of which were turned on and off according to a sequence that enabled the rotation of the motor by giving the appropriate voltage across each phase.

The switching sequences were computed for both unipolar and bipolar hall sensors. The PWM was generated at a frequency of 20kHz. The PWM was generated according to a given duty cycle, that depended on the current speed's deviation from the required speed. This PWM was then logically operated with the switching sequence for each switch via AND gates. The resultant signal was fed to the gates of the transistors. Generation of the duty cycle is explained in detail alongside speed control**.**

PSIM Sequence (For bipolar hall sensors)

Cycle	**H1**	**H2**	**H3**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
1	1	-1	0	OFF	sw	OFF	OFF	sw	ON
2	0	-1	1	sw	OFF	OFF	sw	OFF	ON
3	-1	0	1	sw	OFF	OFF	sw	ON	OFF
4	-1	1	0	OFF	OFF	sw	OFF	ON	sw
5	0	1	-1	OFF	OFF	sw	ON	OFF	sw
6	1	0	-1	OFF	sw	OFF	ON	sw	OFF

Table 1: PSIM hall sensor sequence

Simulink Sequence (We used this for our hardware implementation because the hall sensors installed in the motor were unipolar)

State	H1	H2	H3	S1	S2	S3	S4	S5	S6
0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	1	1	0
2	0	1	0	0	1	1	0	0	0
3	0	1	1	0	0	1	1	0	0
4	1	0	0	1	0	0	0	0	1
5	1	0	1	0	0	0	0	1	1
6	1	1	0	1	1	0	0	0	0
7	1	1	1	0	0	0	0	0	0

Table 2: Simulink hall sensor sequence

The transistor gate voltages and currents, and the phase voltages and currents were obtained as a result of the PWM generated according to the sequence stated above. This is given in section ***2.4***.

3.2.1.2: Speed Control

A control loop identifies the error in the motor's speed with respect to a set reference and changes the duty cycle accordingly. This duty cycle is then fed to the PWM generator that gives a signal to the gates of the switches, resulting in the required phase voltage and currents that excite the coils of the motor to initiate and maintain a state of rotation in the forward direction. A control loop identifies the error in the motor's speed with respect to a set reference and changes the duty cycle accordingly. This duty cycle is then fed to the PWM generator that gives a PWM signal to the gates of the Mosfets or the bases of the IGBTs, resulting in the required phase voltage and currents that excite the coils of the motor to initiate and maintain a state of rotation in the forward direction. For a given sequence, one high side switch is fed with PWM and the appropriate low side switch is fed with an inverted PWM so that the positive DC rail voltage is supplied to a phase for DTs (On time of a PWM wave). The phase is shorted for (1-D)Ts (Off time of a PWM wave). This forms a buck converter with the motor windings as the inductance. This gives a smaller voltage on the output, thus varying the input power and hence the speed of the motor. A variable duty cycle PWM generator was created in PowerSim by comparing a triangular wave to a DC voltage level using an operational amplifier. In Simulink the control loop error was fed to a PID controller, which generated a corresponding duty cycle, mapped between 0 and 1; that was delivered to a PWM generator. This PWM was fed to the gates of the switches.

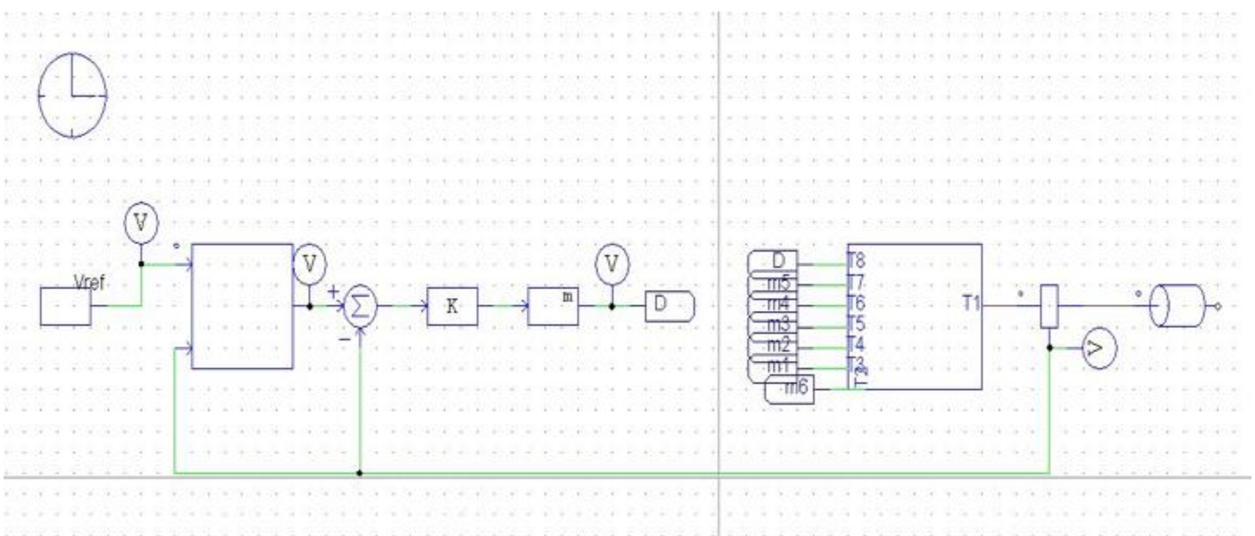

Fig.15 Speed Control Schematic – PSIM

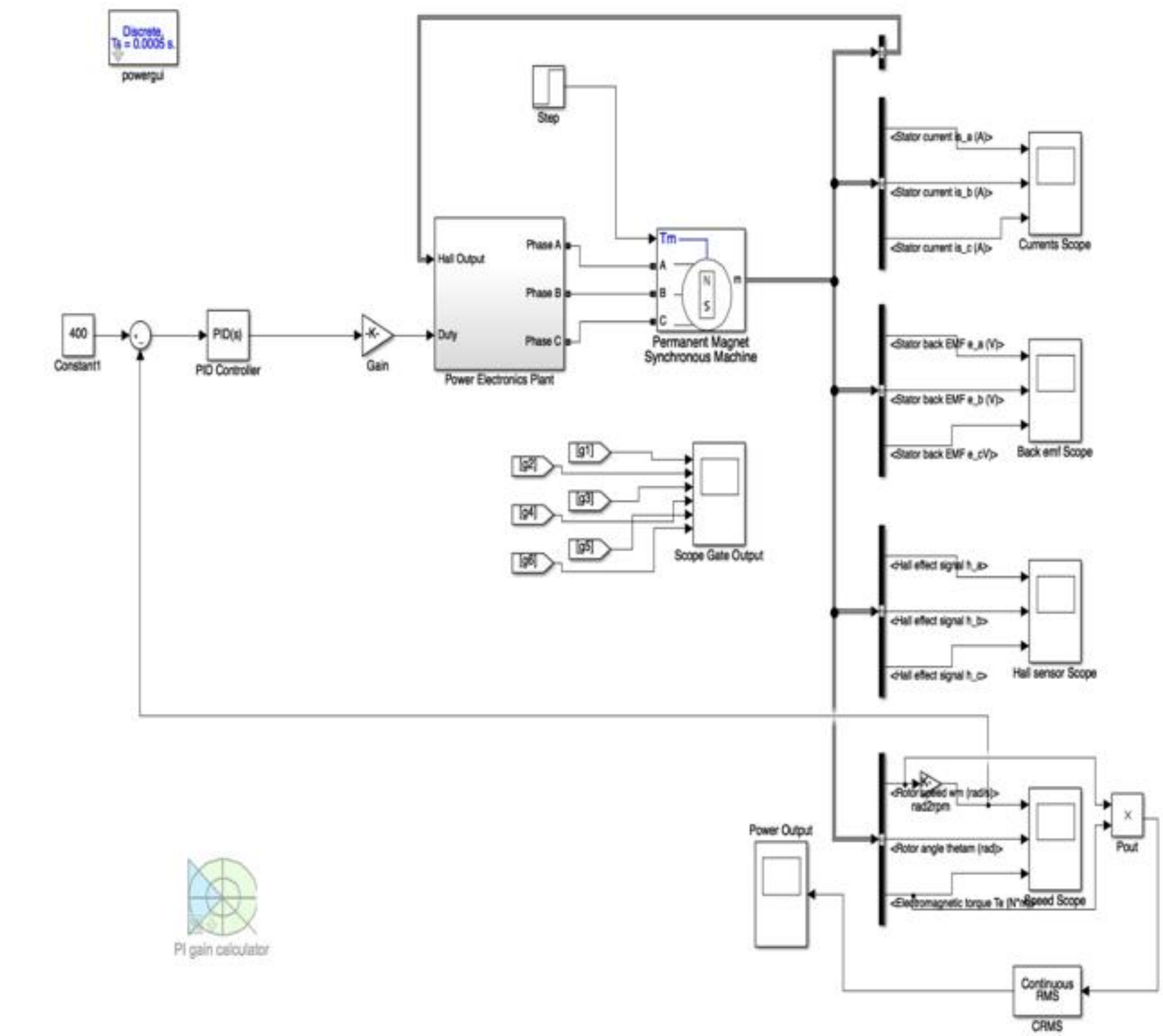

Fig.16 Speed Control Schematic- Simulink

3.2.1.3: Inrush Current Control

During acceleration, the motor draws huge current. This current usually exceeds the amount that the source can provide. Moreover, it also increases the stress on the electronic components. This inrush current was controlled via soft switching. The duty cycle is not increased immediately; rather it is increased slowly till it reaches the desired value.

Soft switching was handled through code, both in PowerSim and Simulink because it is simple and can be readily modified according to the machine parameters and operational constraints. Whenever the duty cycle is changed, a small piece of code increases (or decreases) it gradually, in steps, rather than changing abruptly. This results in a slower response but can practically protect switches from over current in both motor and generator operation

3.2.1.4: Regenerative Braking

A power flow in the opposite direction (from motor to battery) is observed when the motor's input speed is reduced. It acts as a generator during deceleration and the torque is reversed

Design

· A capacitor is added in parallel with the DC voltage source to model a battery. Reverse current from the motor cannot flow into the DC source. This current charges the capacitor

· Positive current in the capacitor indicates regenerative braking

This is a standard feature on most electric and hybrid electric drivetrains. In principle, the energy wasted during braking is harnessed, charging the battery, which helps reducing the overall energy consumption. During regenerative braking, the machine acts as a generator and supplies real power rather than consuming it. In our proposed motor control, no additional changes need to be done to implement regenerative braking. When PWM duty cycle is decreased, the motor does not suddenly slow down because of inertia. The same topology described in Speed Control now makes a boost converter using the motor winding as the inductance and now produces a higher voltage at the DC rail node, which makes a current flow towards the source. This can be used to charge a battery or a capacitor.

3.2.2: Hardware

The hardware setup was designed using power mosfets. The design was similar to those used in simulations apart from the IPM module we used in hardware instead of discrete mosfets. We used IRAM 136-3023B, 30A, and 150V module. This module comes with optimized power management, which helped us in further enhancing the efficiency of our drive circuit.

Speed control, Inrush current control, and regenerative braking were all implemented in hardware in the same way as done in simulations. Input for speed control was taken from a potentiometer.

We used Arduino as our preferred mico-controller because it allowed editing the code conveniently through its user –friendly interface, with no compromise in functionality.

A 48V lithium ion battery powered the hardware circuit. The battery came with battery management system (BMS), which monitored the battery health. The circuit was well protected by installing fuses and emergency switches.

The circuit had three buck converters to provide 15V, 12V, and 5V to the circuit. A horn was also installed and was fused separately. Fig. 18 shows a high level picture of the hardware circuit.

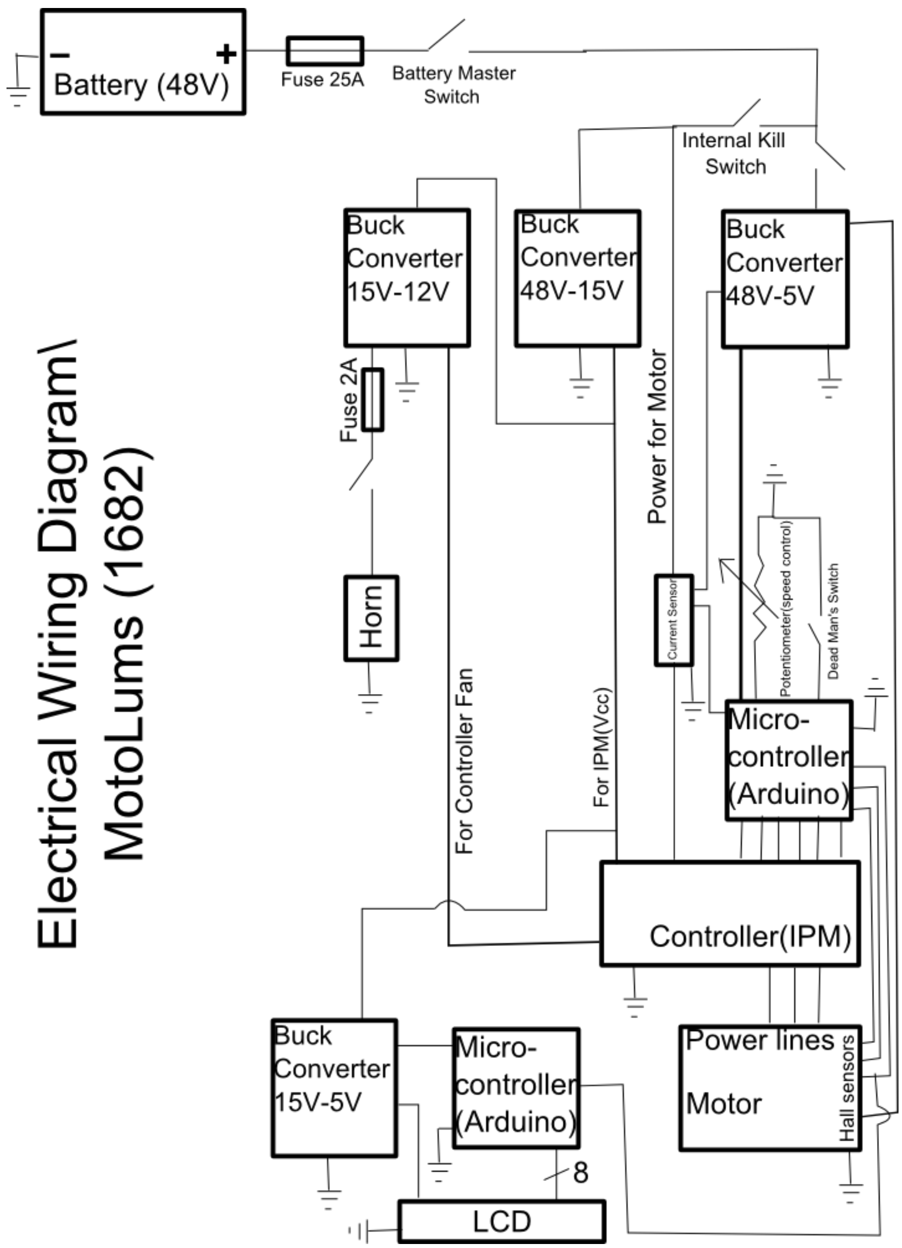

Fig. 17 Electrical diagram of the hardware circuit

3.3: MECHANICAL DESIGN

3.3.1: Frame

The frame had to be very lightweight because the vehicle would be entering and competing in Shell Eco Marathon Asia 2017. The structure, for the sake of simplicity and our mechanical limitations was designed as a body on frame rather than a monocoque. The frame was designed in Solid Edge ST8 and some basic simulations were done to make sure it would withstand the weight of driver. After that, it was fabricated with PVC pipes to get an idea of the dimensions, which turned out to need some changes. After appropriate changes, it was fabricated with aluminum pipe (1 inch outer diameter, 1 cm wall thickness). The competition guidelines were followed while doing so. All this work was done in summer 2016. The frame weighs just under 5 kg.

Fig. 18 A model of the prototype vehicle structure

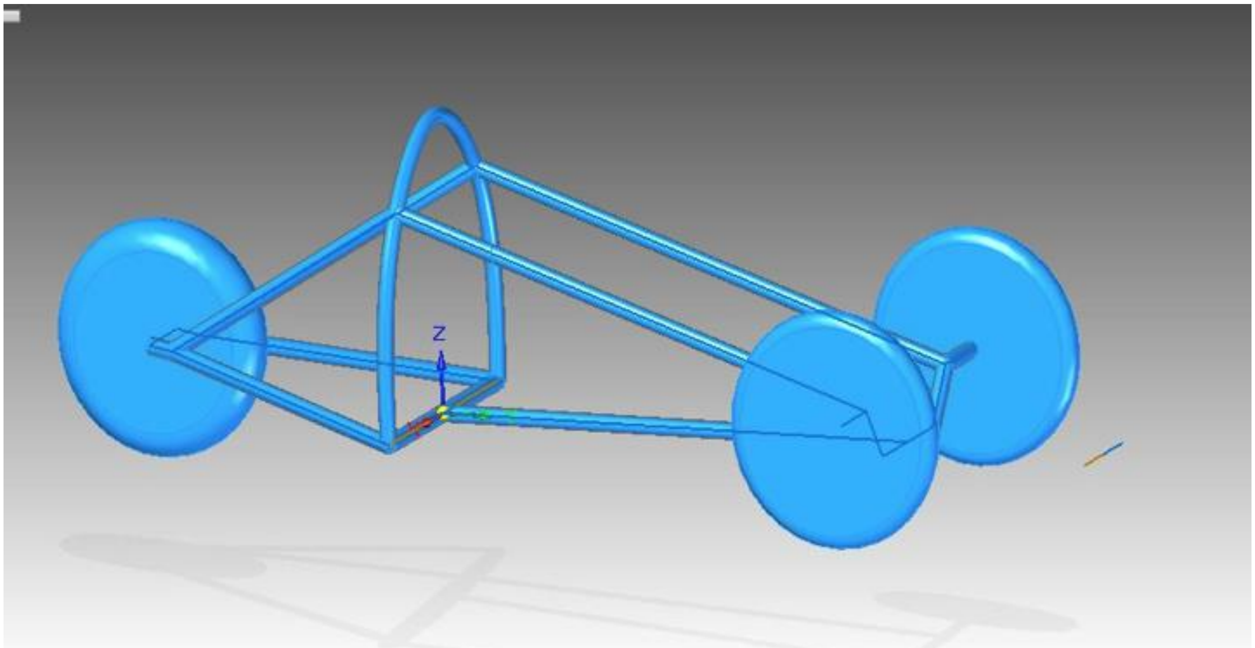

Fig. 19 A 3-D model of the vehicle

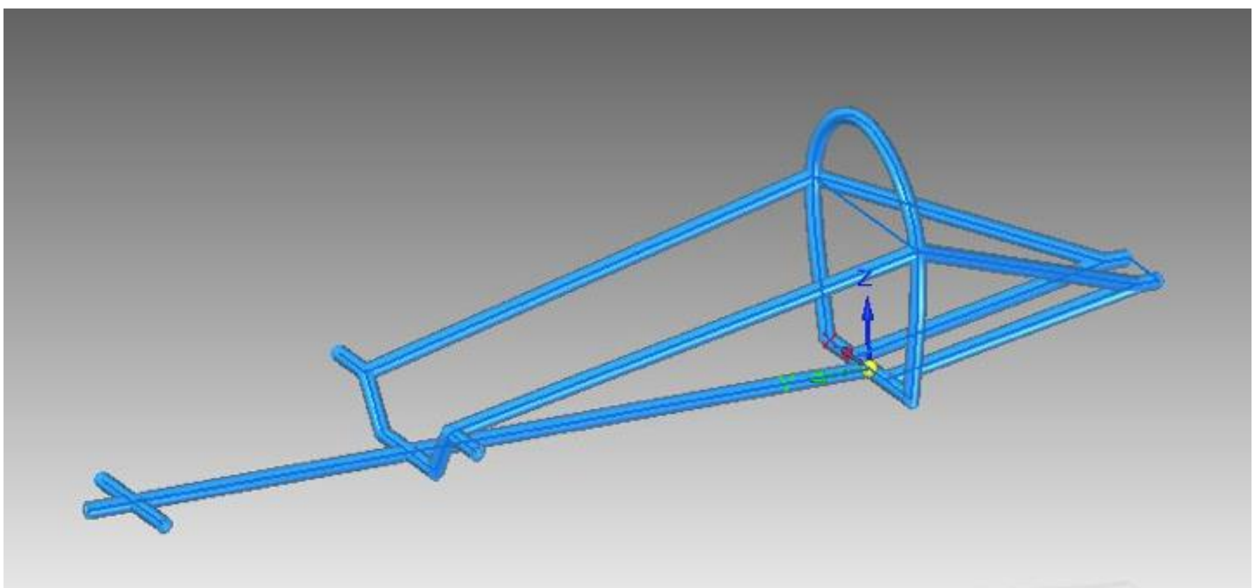

Fig. 20 Side view of the 3-D model for the frame of the vehicle

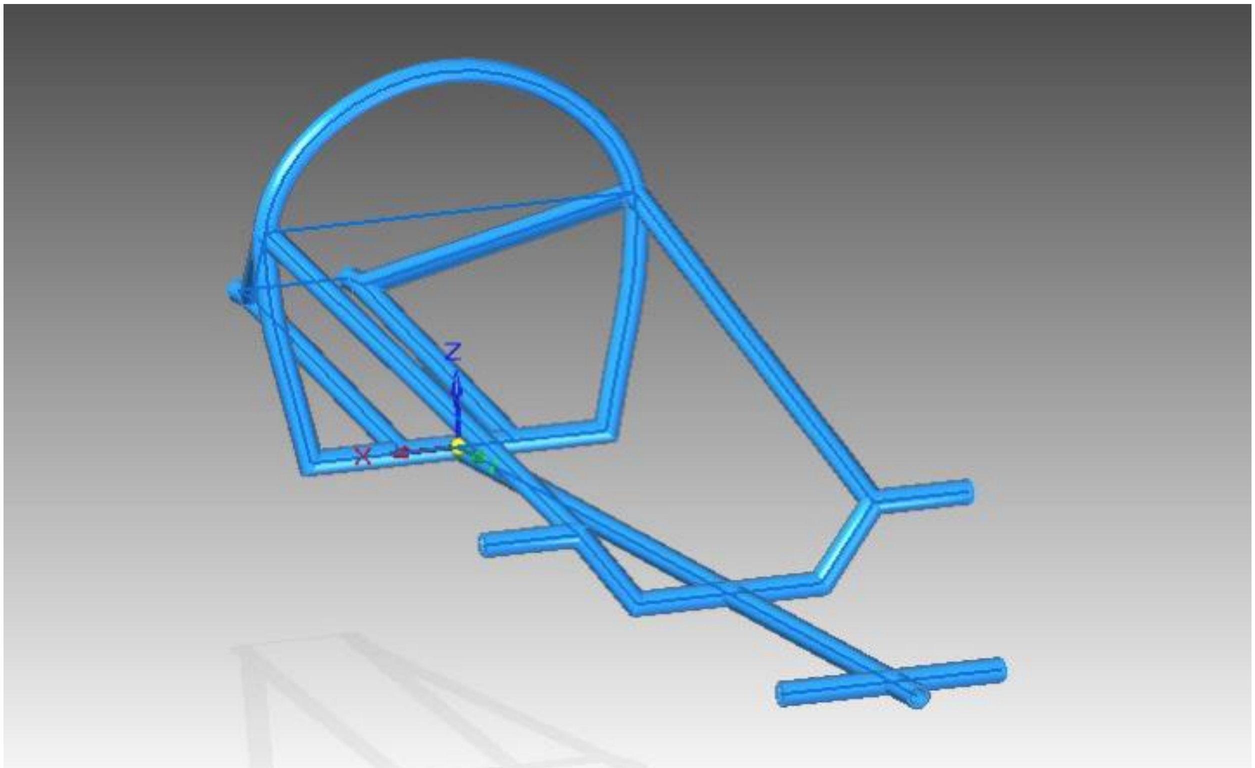

Fig. 21 Front view of the 3-D model for the frame of the vehicle

Fig. 22 Actual frame of the vehicle

3.3.2: Body

The body was designed in PTC Creo. Although no aerodynamic profiling was done due to our own limitations, a general aerodynamic shape was kept in mind while designing it. Cross sections at specified distances were sketched for all 3 planes which were then printed out to the exact dimensions on paper. These prints were used as guides to cut wooden panels, which were then fitted together to make the basic structure for a wooden pattern.

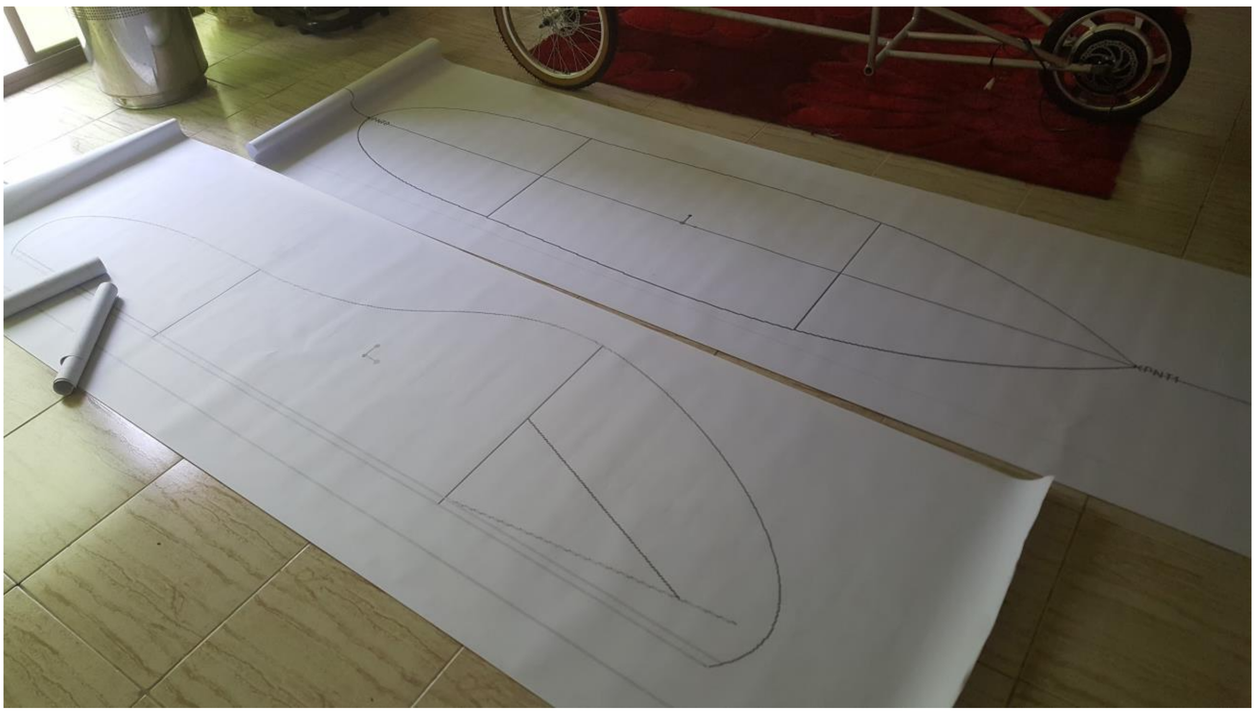

Fig. 23 Cross Section prints according to exact dimensions

Fig. 24 Wooden pattern without thermo pore filling

The empty spaces were filled with thermopore which was then contoured to give the whole structure a smooth outline. The final surface was prepared using a mixture of wall putty and plaster of paris, followed by extensive sanding and then painting.

Fig. 25 Final shape after filling with thermo pore

This pattern was then used to make a negative mold with fiberglass. To start with, mold release wax and PVA (Polyvinyl Actetate) were applied to the surface so the final product could be released. After that, a coat of polyester resin was applied to the pattern, then fiberglass cloth (Chopped Strand Mat, 400 GSM) was laid on top of that. This was repeated twice to give it some strength so the mold could withstand its own weight when lifted. Unfortunately, the first time we did it, the resin/hardener mixture was not correct and after a day, it turned it into a semi-solid jelly. We had to remove it, prepare the pattern again, and then repeat the fiberglass process again. This took quite a lot of time and effort. We could not release the fiberglass mold from the pattern although enough releasing agents were applied initially. This made it inevitable to cut the mold and take it off, which was joined after being taken off.

Fig. 26 Fiberglass negative mold

The final body was made using the negative mold. First, a thin coat of epoxy resin was applied and then a layer of carbon fiber cloth (200 GSM, 2x2 twill) was laid, followed by another epoxy coat and another carbon fiber layer. This could have been left to cure as is, but the body needed to be light so we used vacuum bagging, a technique which takes out extra resin. A nylon peel ply was laid on top of final carbon fiber layer, followed by a layer of polyester bleeder sheet. The whole system was sealed in a vacuum bagging film using a butyl rubber sealant tape and then a vacuum pump was attached, creating negative pressure, which conforms the carbon fiber to the mold and squeezes out any extra resin. The polyester bleeder absorbs this extra resin and the nylon peel ply ensures that the final carbon fiber product releases from bleeder and vacuum bagging film.

Fig. 27 Vacuum bagging process

Fig. 28 Carbon fiber body

The base of the vehicle was similarly made using carbon fiber.

3.3.3: Tires and Steering

The vehicle has 2 front and one rear tire. The rear tire came pre fitted with the hub motor. Bicycle rims (16 inch) were used for front wheels. The tires we used in the competition are made by Michelin and are available through Shell. Initially, we had fitted locally available tires, same size as Michelin so it was easy to change them later. Disc brakes were installed and proper fittings were made from steel.

The steering hubs were designed in PTC Creo but the whole assembly wasn't, rather we followed a simple design used in go karts. This configuration does not require a rack and pinion, thus saving weight. We could only use it because the turning radius had to be less than 8 meters and for that, calculations showed that the wheel turning angle had to be 13 degrees at most, though the wheels can turn much more than that. This too was done in summer.

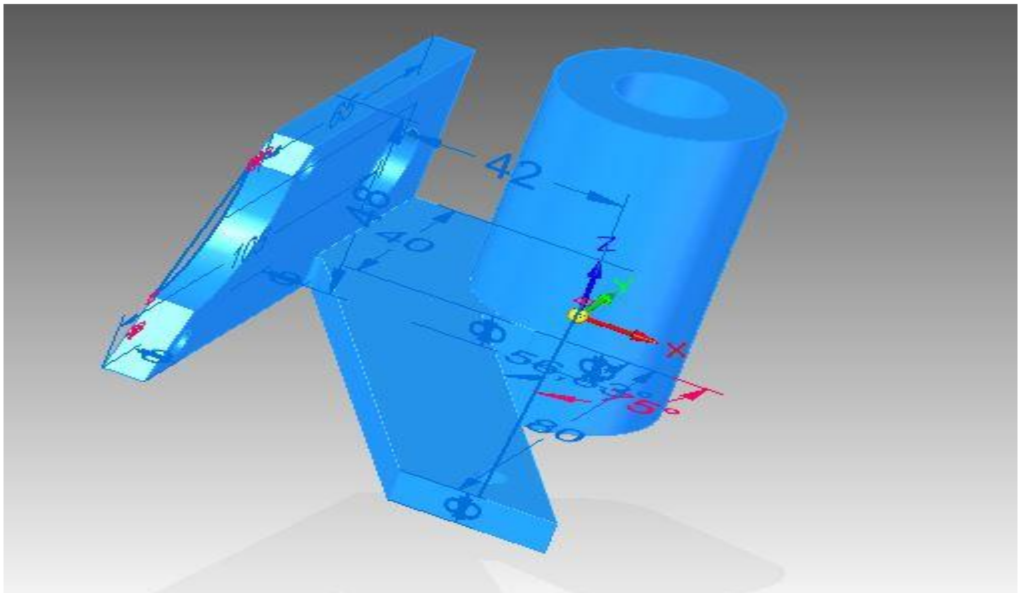

Fig. 29 3-D model for the steering hubs

Fig. 30 Steering system of actual vehicle

3.3.4: Seat

The initial plan was to make the seat using carbon fiber. The exact same process as the body was followed, only this time the pattern was made from acrylic sheets because it was easier to test fit them according to driver's measurements. Then a fiberglass negative mold was made, followed by vacuum bagging a carbon fiber - fiberglass hybrid because we ran out of carbon fiber.

Fig. 31 Seat during vacuum bagging

Chapter 4

DESIGN, SIMULATION AND IMPLEMENTATION RESULTS

4.1: SIMULATION AND IMPLEMENTATION RESULTS

4.1.1: Hall Sensor Results

The hall sensor outputs are 120 degrees out of phase as expected. These help determine the position of the hub motor.

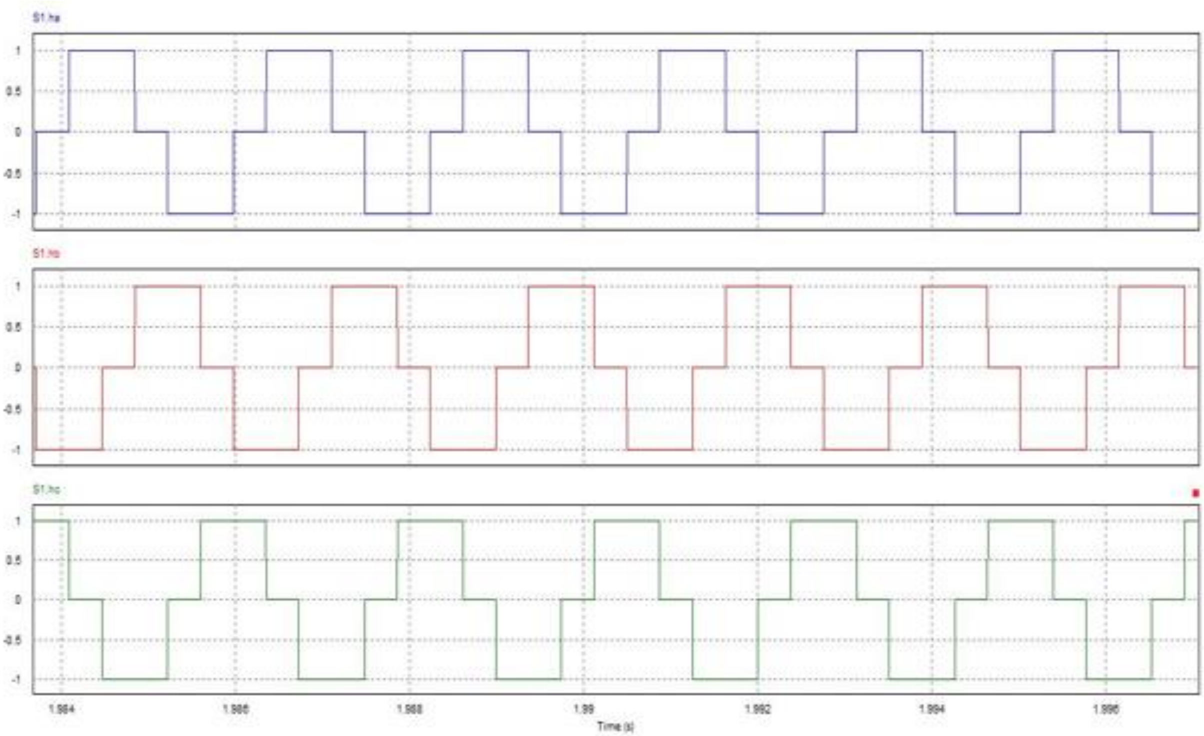

Fig. 32 PSIM (Voltage in volts Vs. Time in seconds) Output for bipolar sensors.

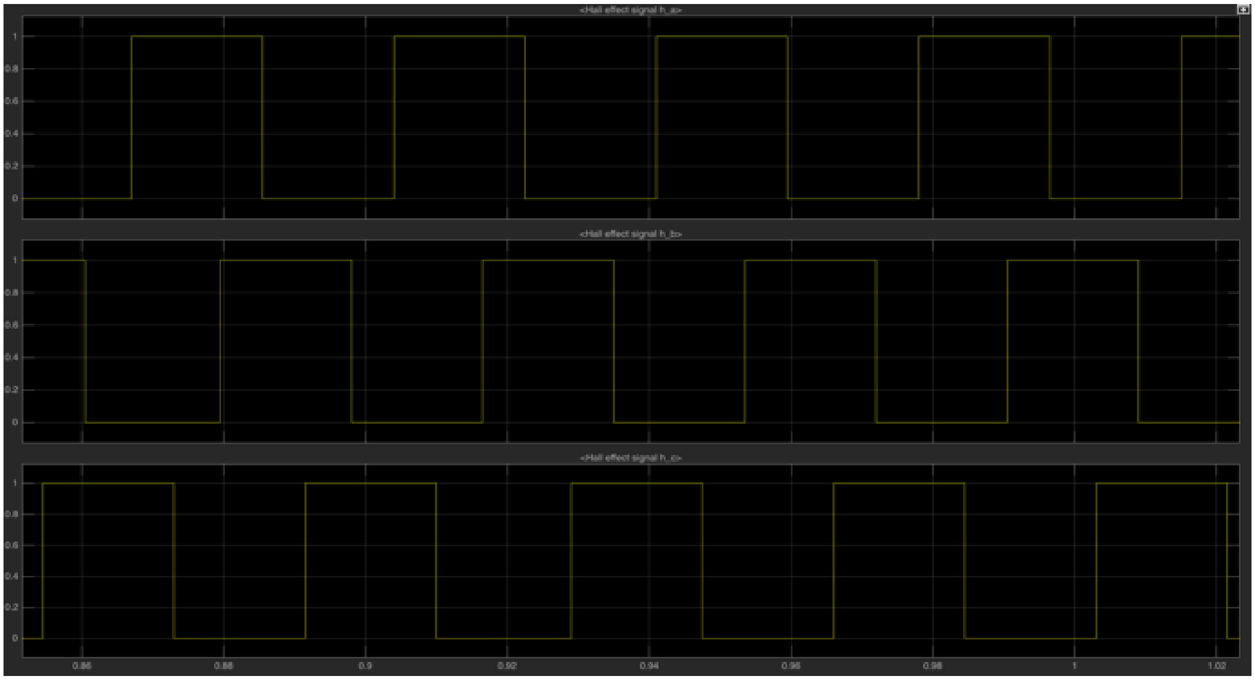

Fig. 33 Simulink (Voltage in volts Vs. Time in seconds) Output for unipolar sensors.

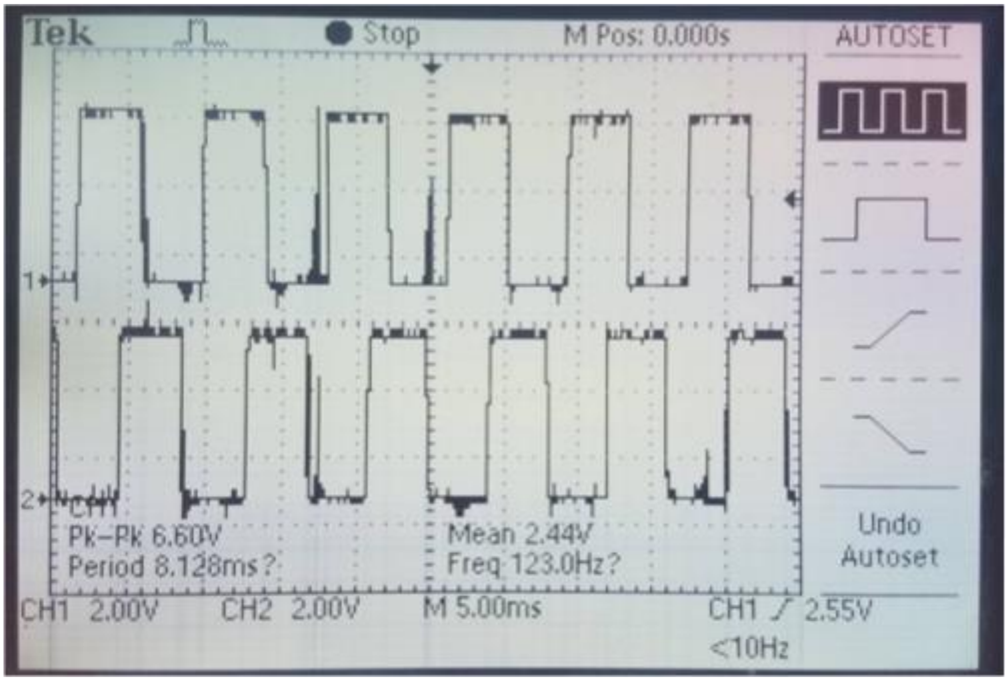

Fig. 34 Hall sensor output in hardware (Voltage in volts Vs. Time in milli-seconds)

4.1.2: Transistor Gate Voltages

On time is determined by the duty cycle. The PWM is logically operated with the switching sequence via AND gates. This can be observed in the voltage graphs below.

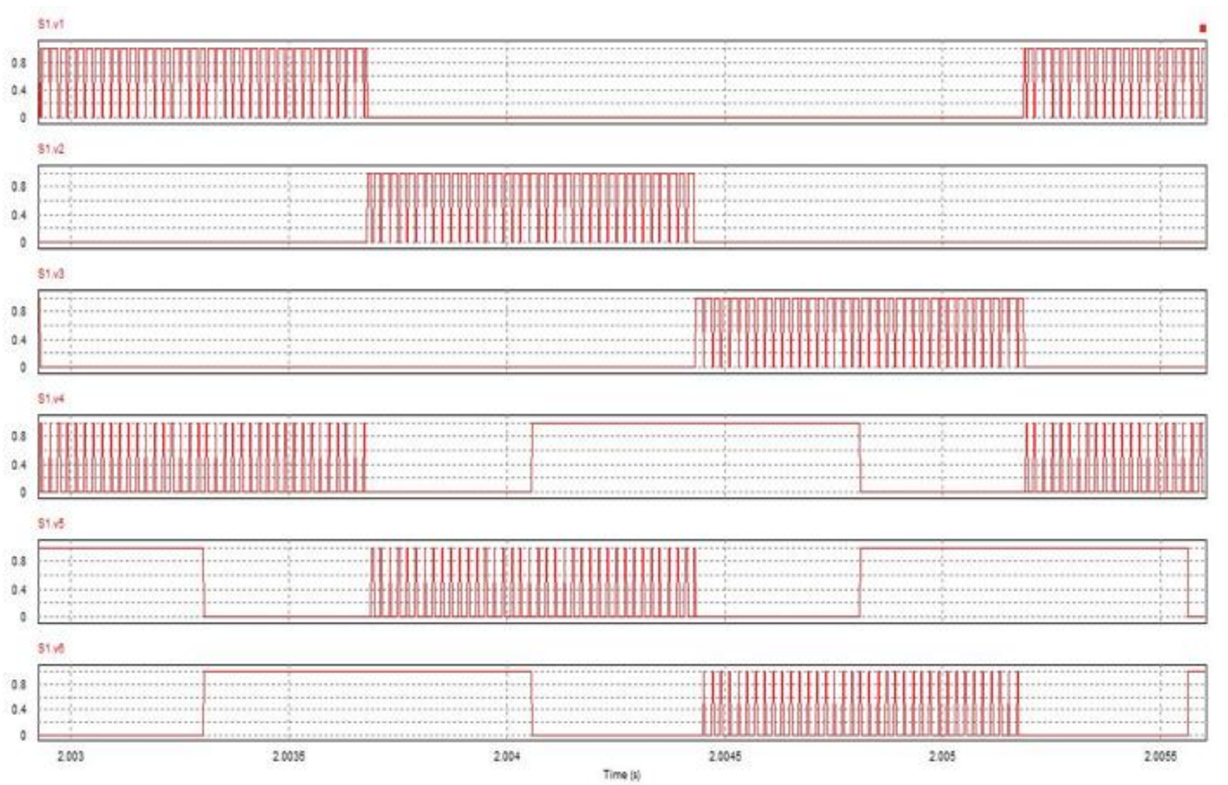

Fig. 35 PSIM (Voltage in volts Vs. Time in seconds)

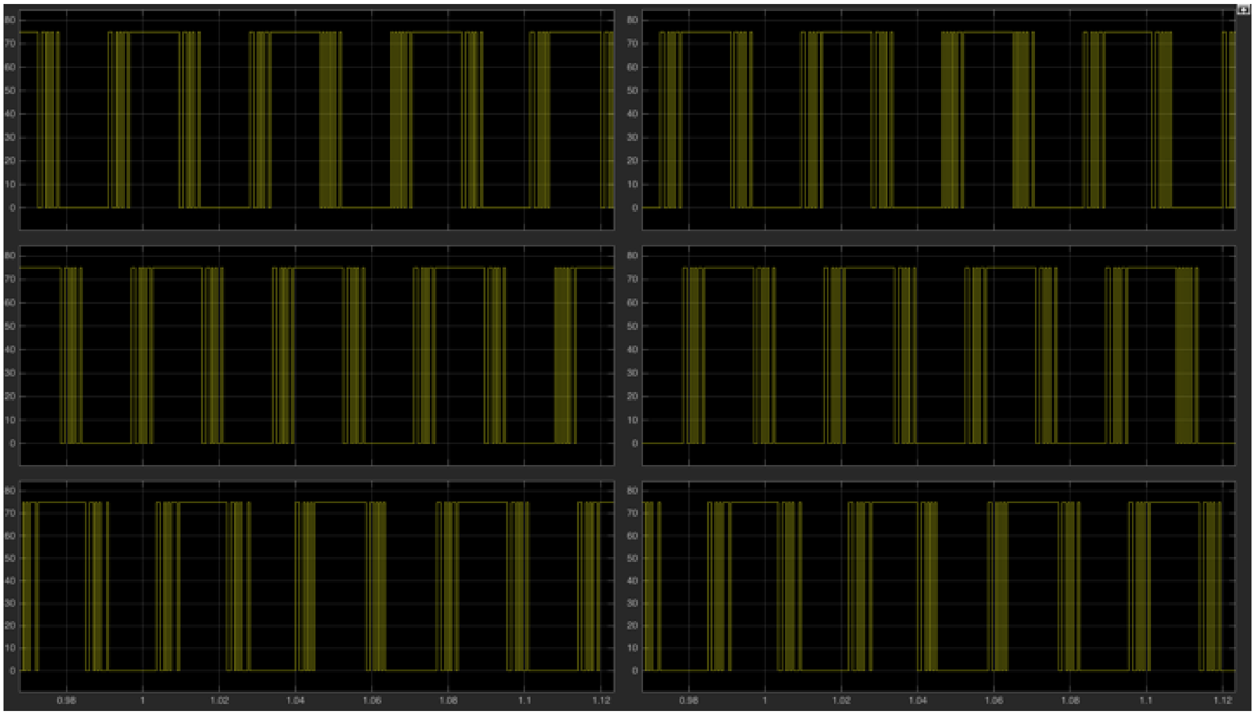

Fig. 36 Simulink (Voltage in volts Vs. Time in seconds)

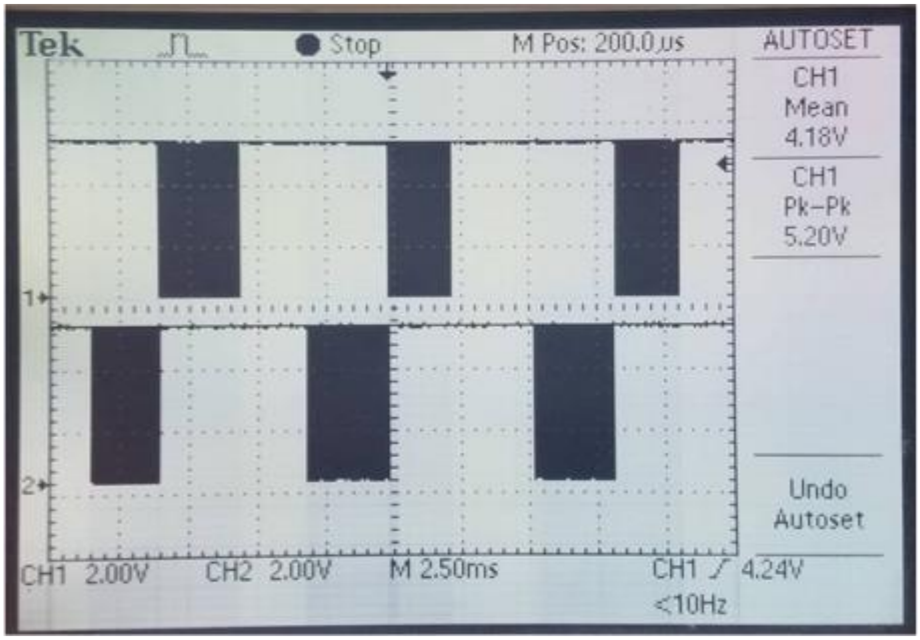

Fig. 37 Gate voltages in hardware (Voltage in volts Vs. Time in milli-seconds)

4.1.3: Transistor Gate Currents

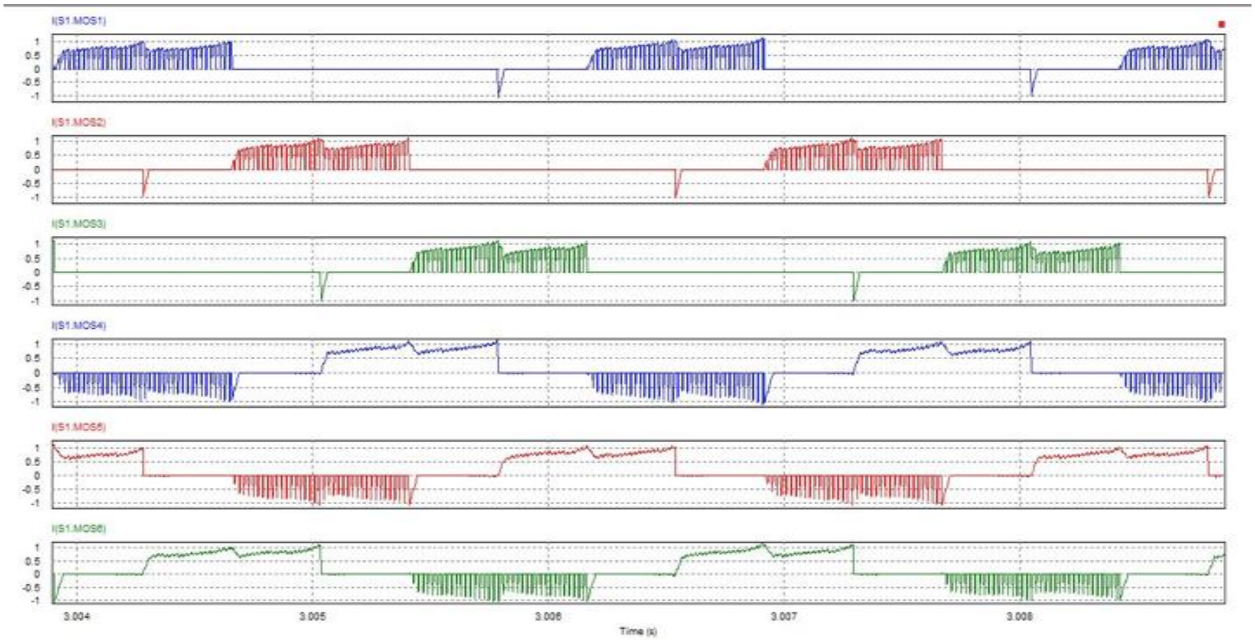

Fig. 38 PSIM (Current in amps Vs. Time in seconds)

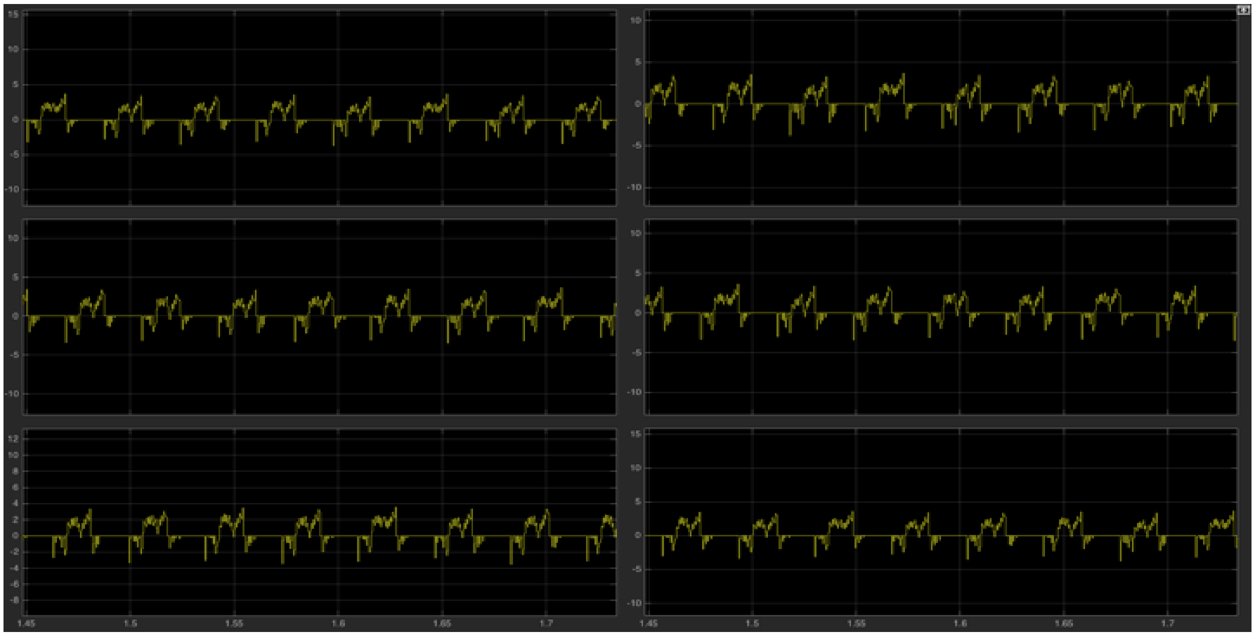

Fig. 39 Simulink (Current in amps Vs. Time in seconds)

4.1.4: Phase Voltages

Phase voltages are 120 degrees out of phase and trapezoidal in nature. It determines varies from +V to –V depending on the battery voltage. At any given instance only one phase is being operated.

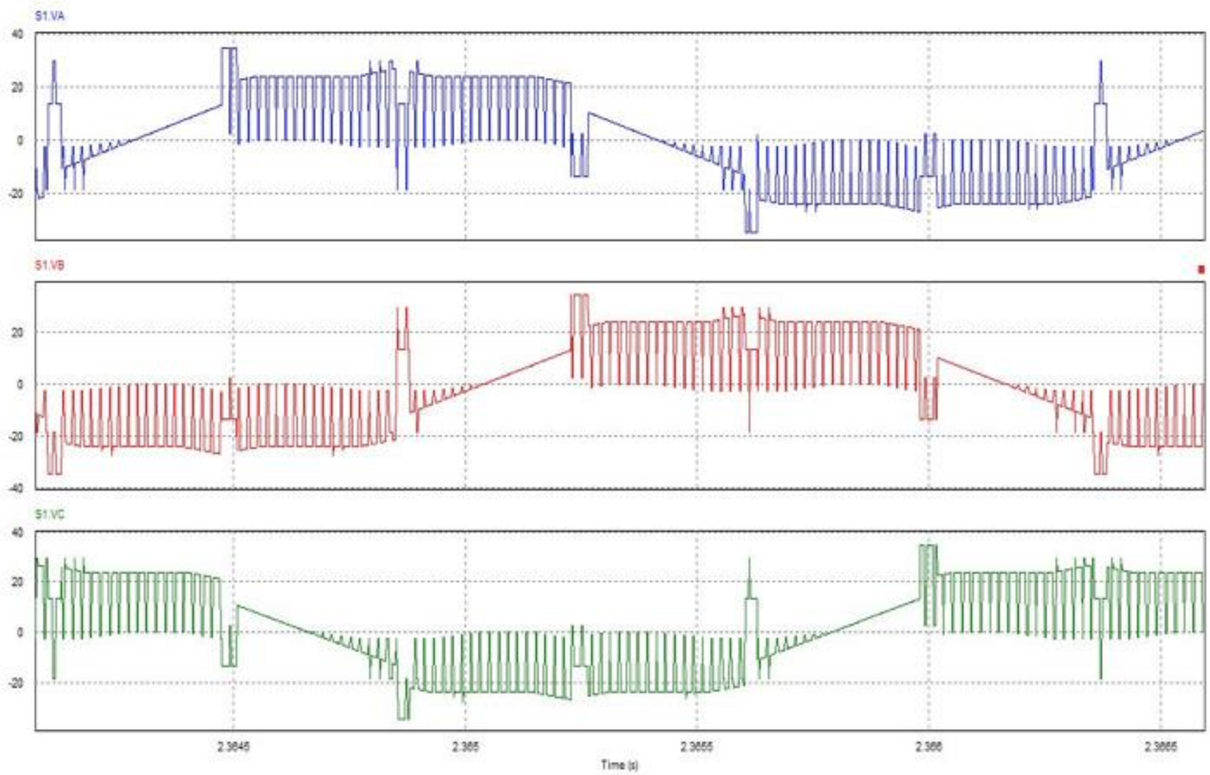

Fig. 40 PSIM (Voltage in volts Vs. Time in seconds)

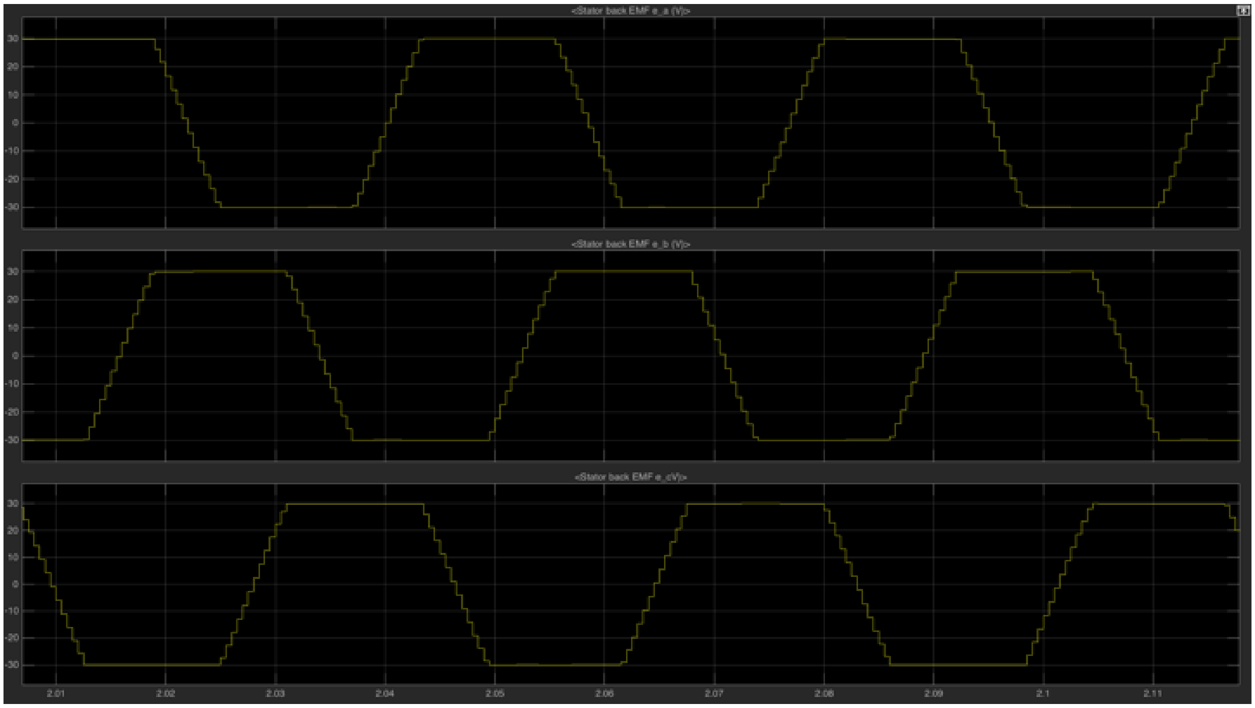

Fig. 41 Simulink (Voltage in volts Vs. Time in seconds)

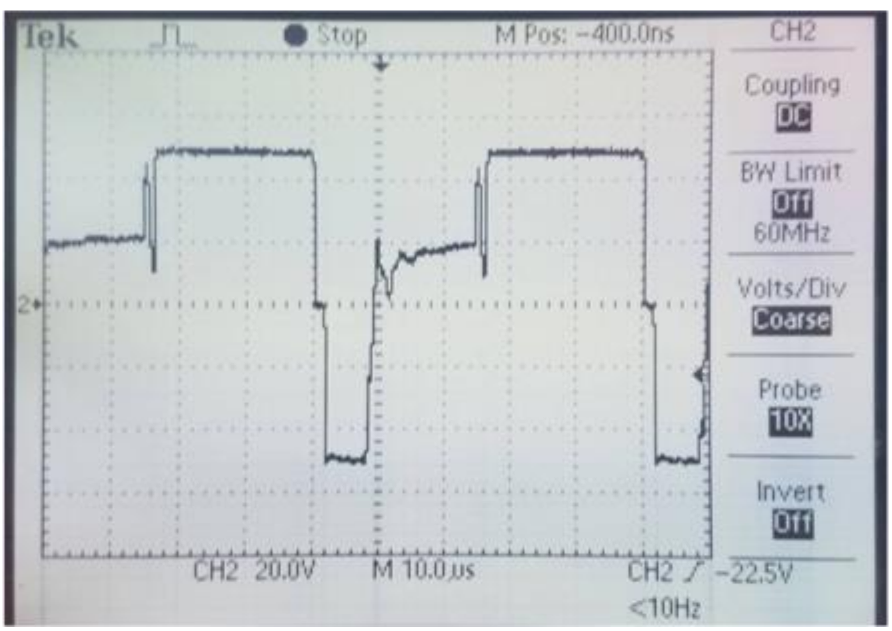

Fig. 42 Hardware phase voltages (Voltage in volts Vs. Time in micro-seconds)

4.1.5: Phase Currents

The current is also 120 degrees out of phase as expected.

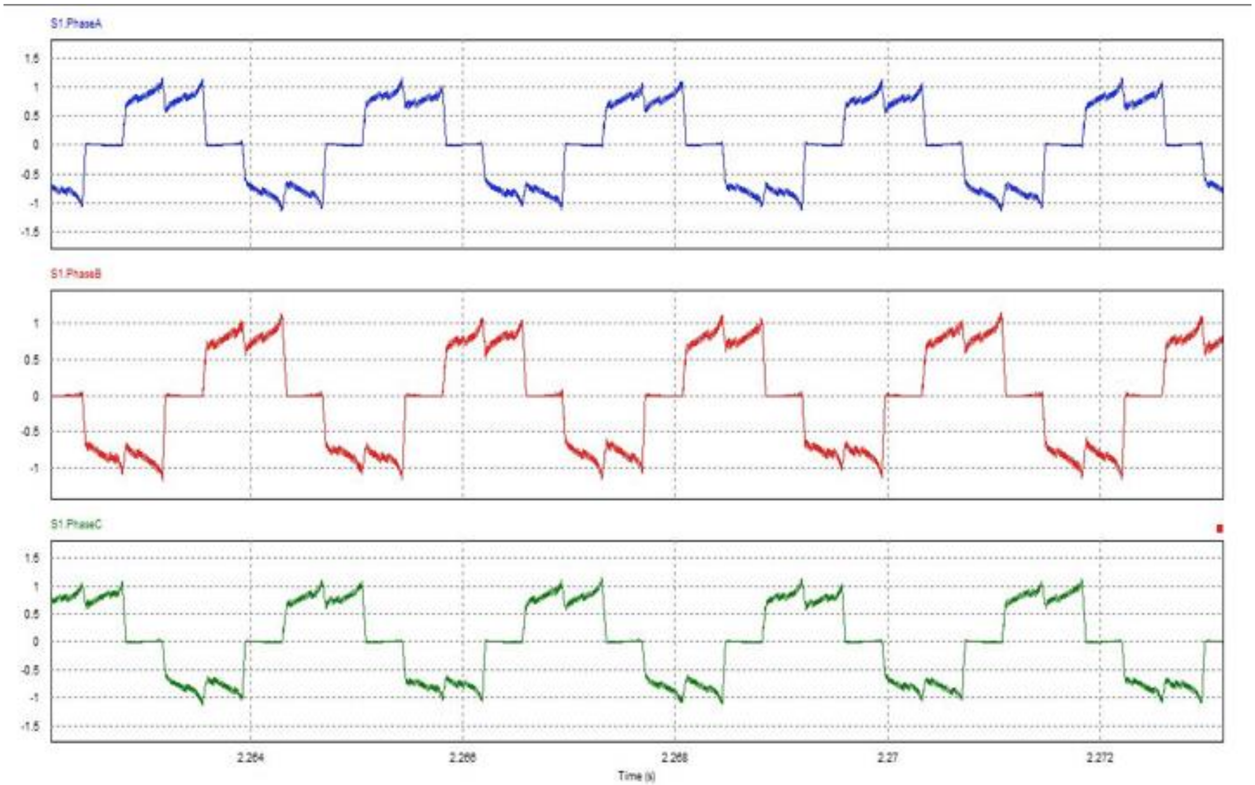

Fig. 43 PSIM (Current in amps Vs. Time in seconds)

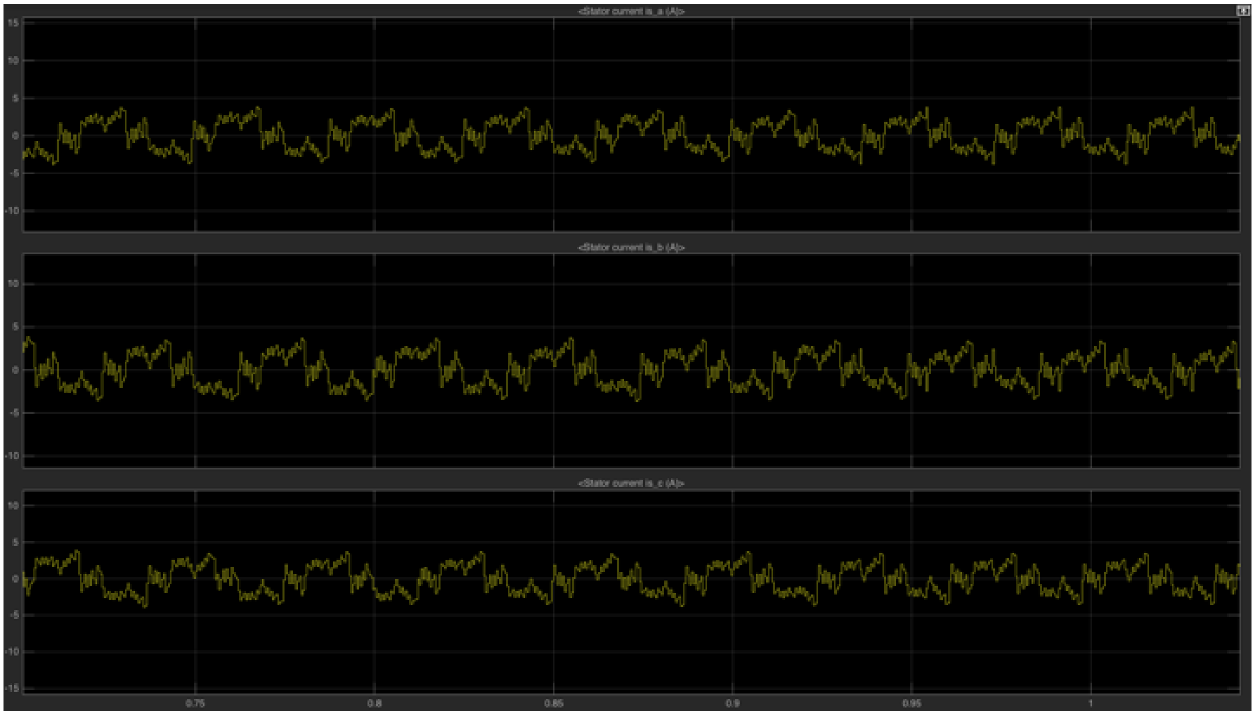

Fig. 44 Simulink (Current in amps Vs. Time in seconds)

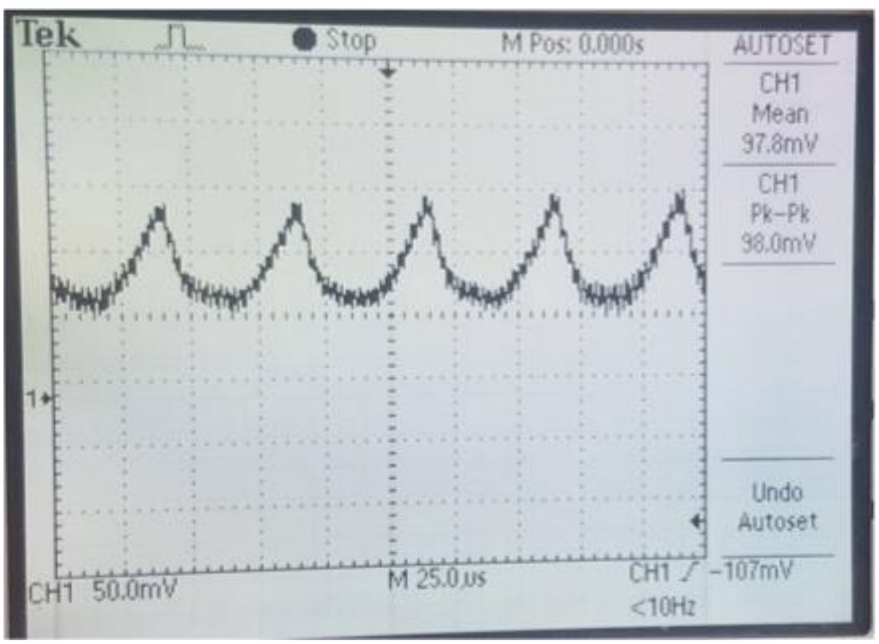

Fig. 45 Supply Current (Current in amps Vs. Time in micro-seconds)

4.1.6: Speed Control Results

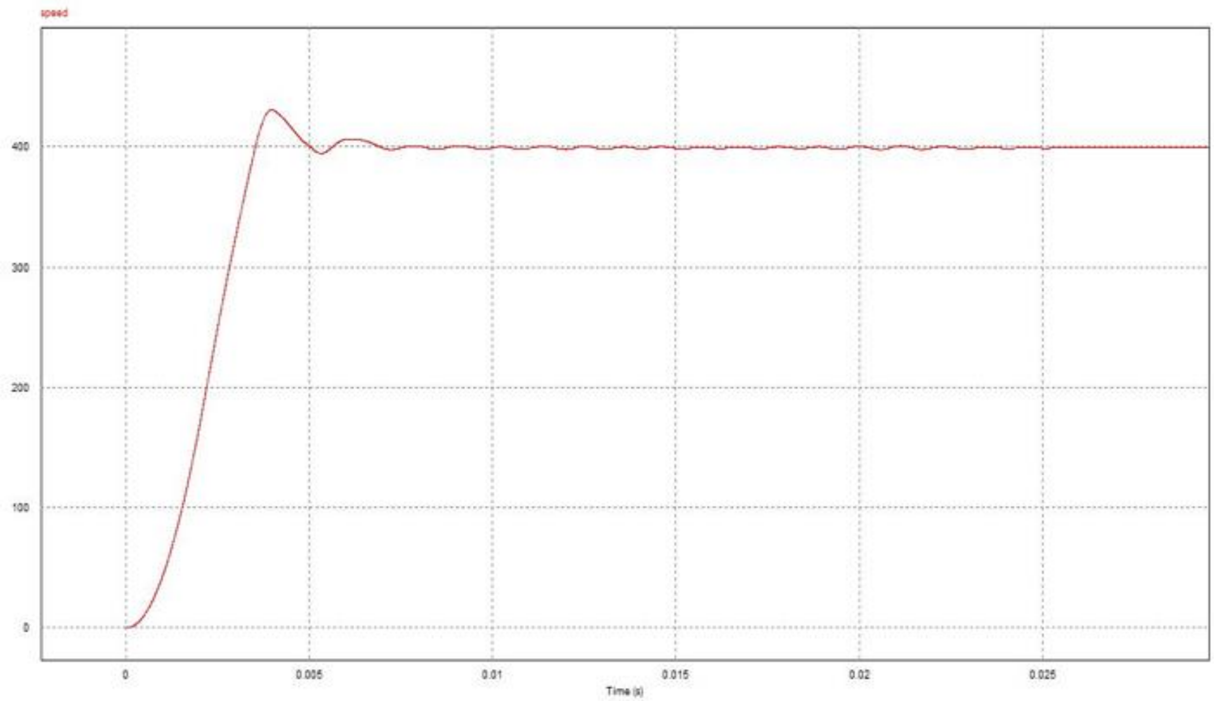

Fig. 46 PSIM - Vref=400rpm (Speed in revolutions per minute (rpm) Vs. Time in seconds)

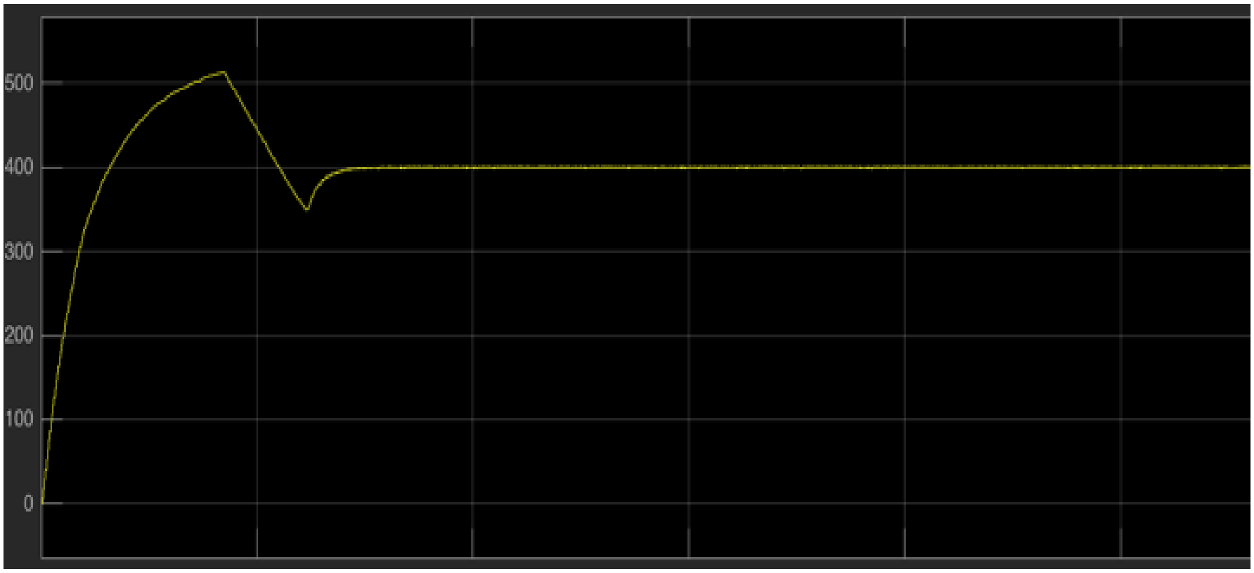

Fig. 47 Simulink - Vref=400rpm (Speed in rpm Vs. Time in seconds)

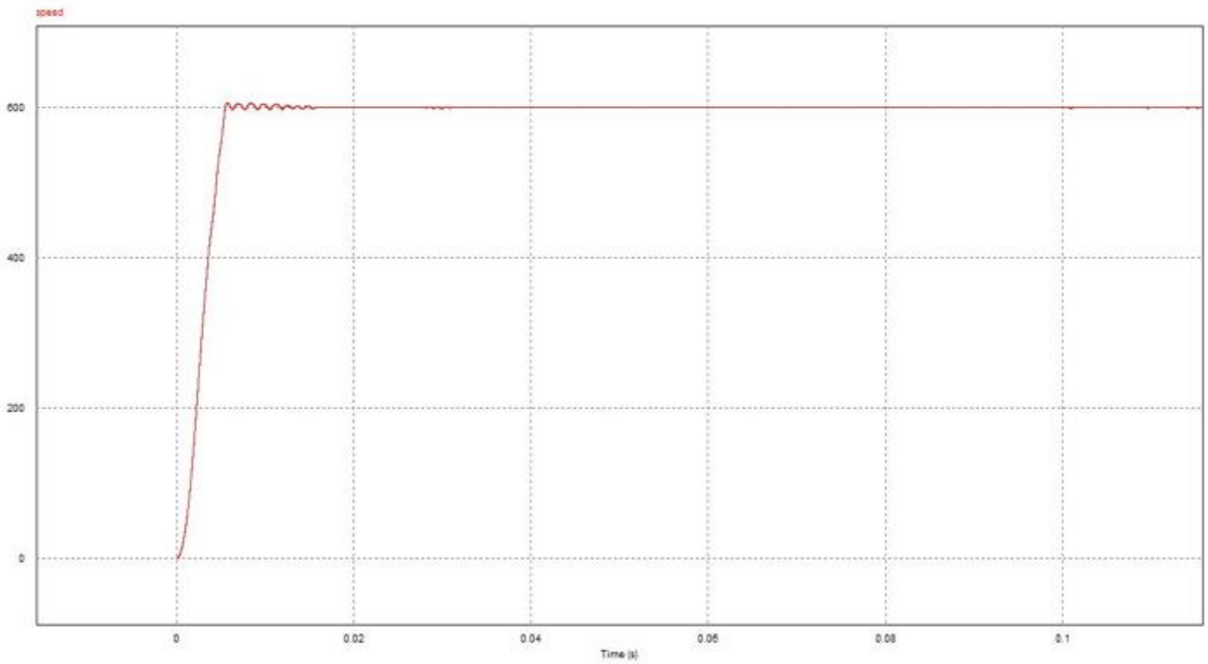

Fig. 48 PSIM - Vref=600rpm (Speed in rpm Vs. Time in seconds)

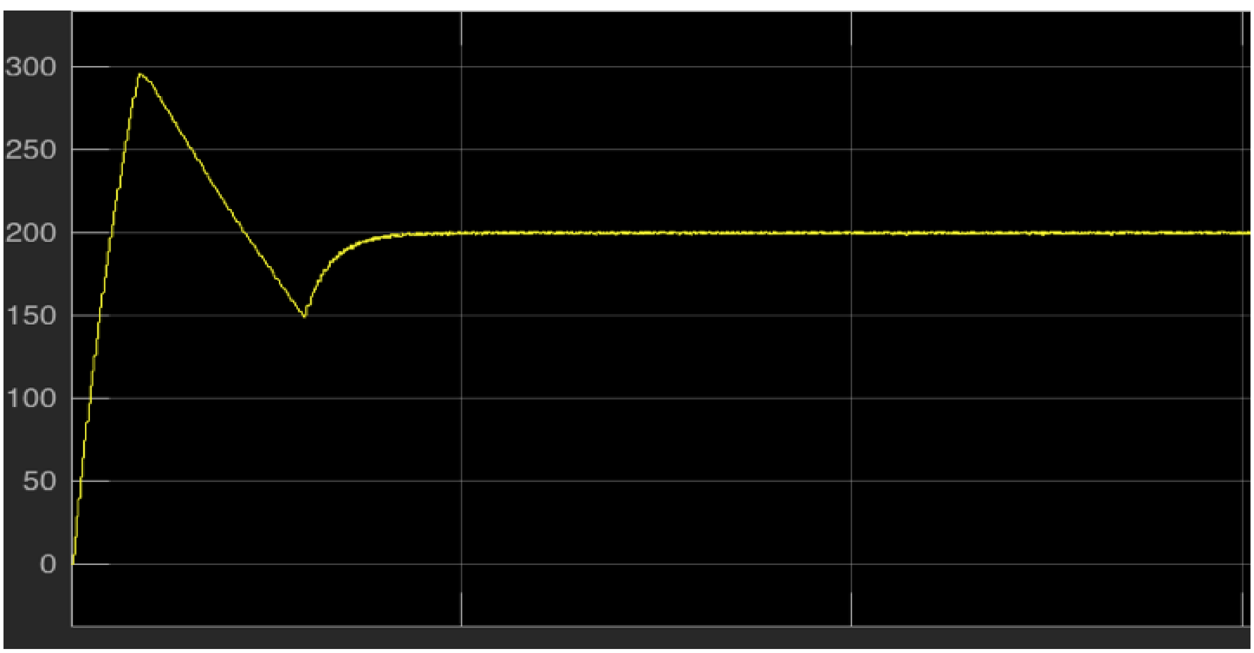

Fig. 49 Simulink - Vref=200rpm (Speed in rpm Vs. Time in seconds)

It was observed that the initial deviation especially in the case of Simulink resulted, as we could not specify the exact values for the proportional and integral elements governing the speed controller because our circuit was non-linear. However, the eventual stable speed helps identify that the desired result is being obtained.

In order to attain a certain desired speed, we have implemented a feedback control loop in both Simulink and PSIM. The feedback loop takes the system's output and input into consideration and enables the system or plant to adjust its performance to meet the specified desired speed. The duty cycle is adjusted so as to attain a greater or lower speed or maintain a certain speed. The switching sequence remains the same; however, the on/off time varies, changing the effective voltage. This in return translates to variation in the speed.

4.1.7: Inrush Current Control Results

We observed the behavior of the input current while simulating and noted that at time t=0, when the vehicle begins to accelerate from speed 0rpm initially, a huge inrush current can be seen. This is because torque is proportional to current and in this case during the initial acceleration we require a huge amount of torque, thus leading to the high inrush current.

However, as an effective engineering practice we tried to control this current as it has two major drawbacks:

- Source is unable to provide the huge amount of current
- Current surge increases the stress on the electronic components, which will eventually lead to the malfunctioning or over-heating of the components

Therefore, we decided to control the inrush current via soft switching. Unlike earlier, the duty cycle is now increased slowing till it reaches the desired reference speed through a feedback loop. Simulating in the two softwares helped us visualize the inrush current and look for a viable solution to the problem.

It can be observed that the initial current rose to 120A when soft switching was not employed. However, it dropped to 11A after the in rush current was controlled. Moreover, the speed curve obtained is also smoother than before.

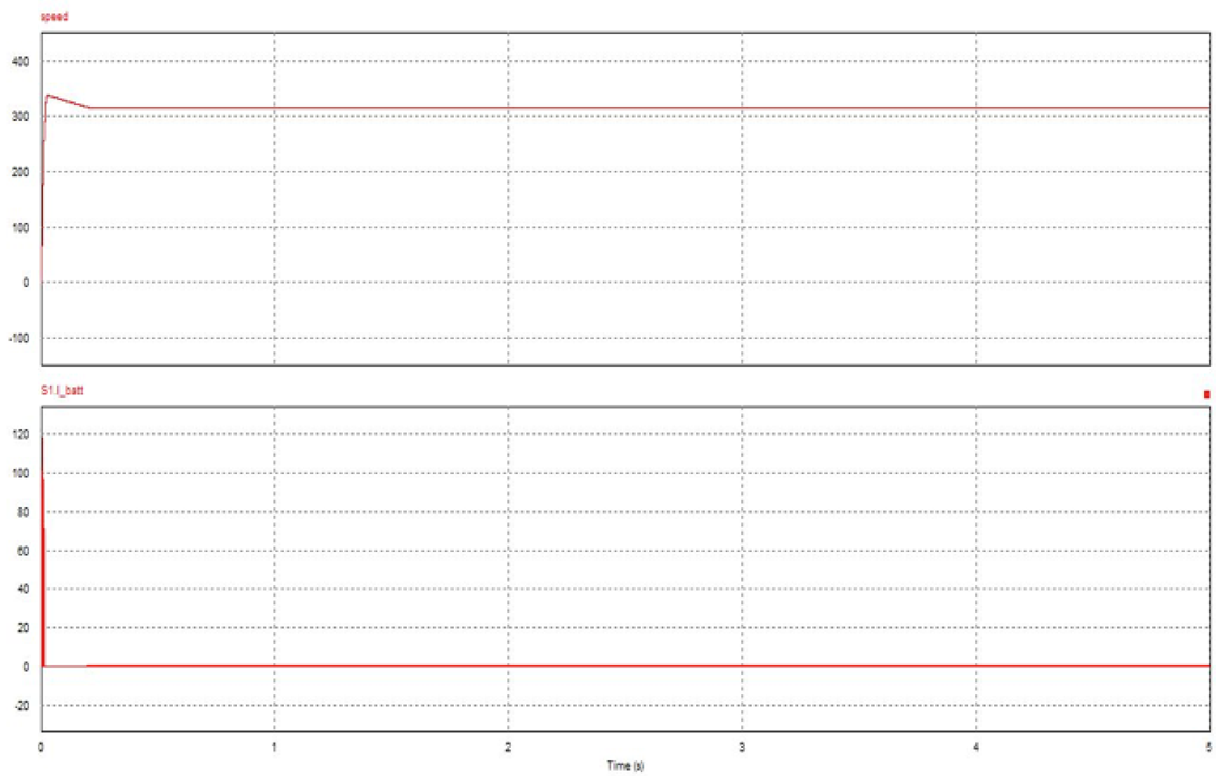

Fig. 50 PSIM - Top graph (Speed in rpm Vs. Time in seconds), Bottom graph (Current in amps Vs. Time in seconds)

Fig. 52 shows the current drawn from the battery after inrush current control is introduced.

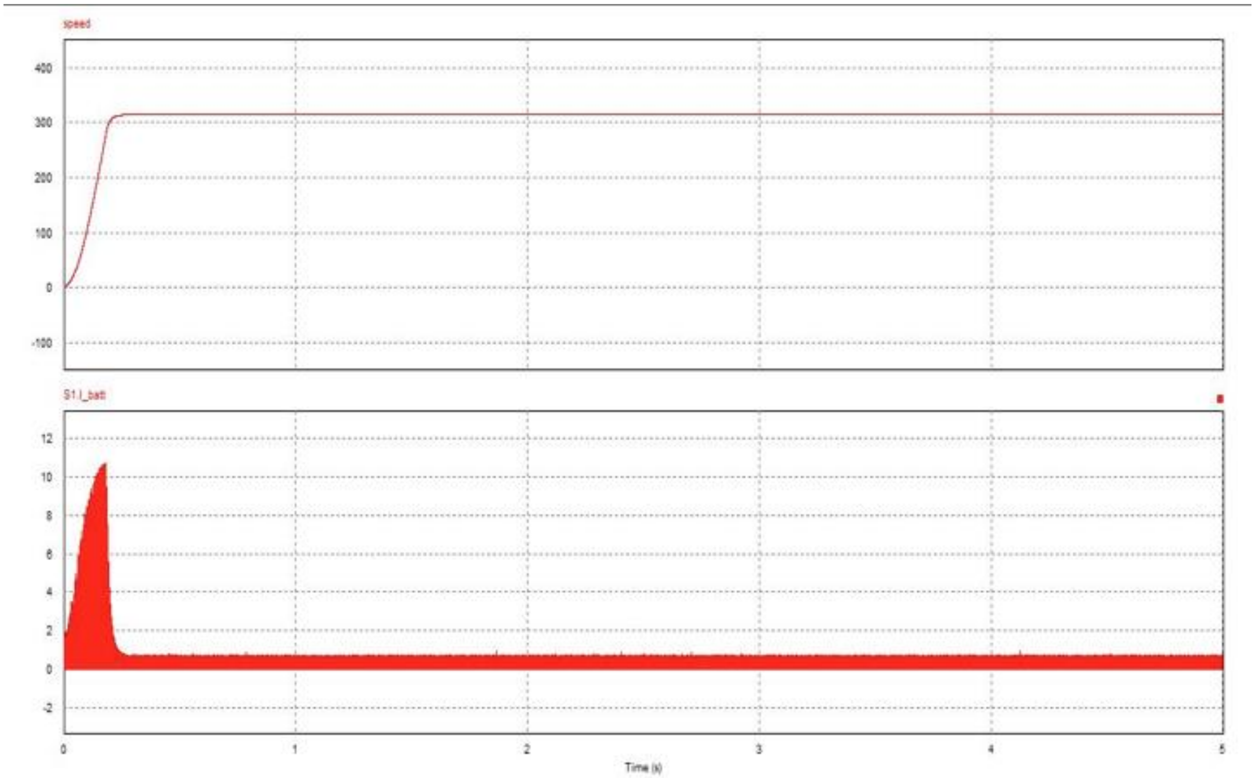

Fig. 51 PSIM- Top graph (Speed in rpm Vs. Time in seconds), Bottom graph (Current in amps Vs. Time in seconds)

The inrush current in case of Simulink did not exceed 11A for Vref = 400rpm and 15A for Vref = 600rpm. Hence, soft switching was not employed in this. This can be observed in the figure below. The left hand figure is for Vref = 400rpm and the right hand figure for Vref = 600rpm.

4.1.8: Regenerative Braking Results

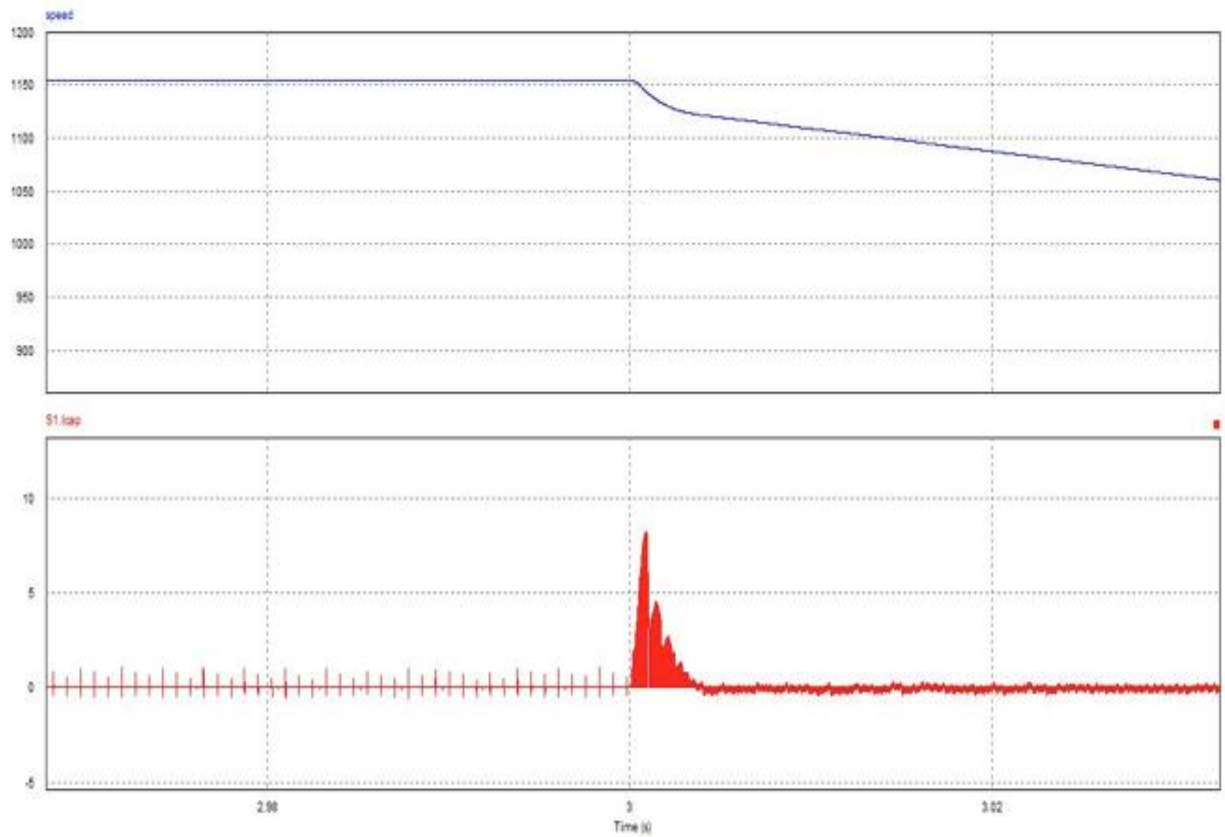

Fig. 52 PSIM- Top graph (Speed in rpm Vs. Time in seconds), Bottom graph (Current in amps Vs. Time in seconds)

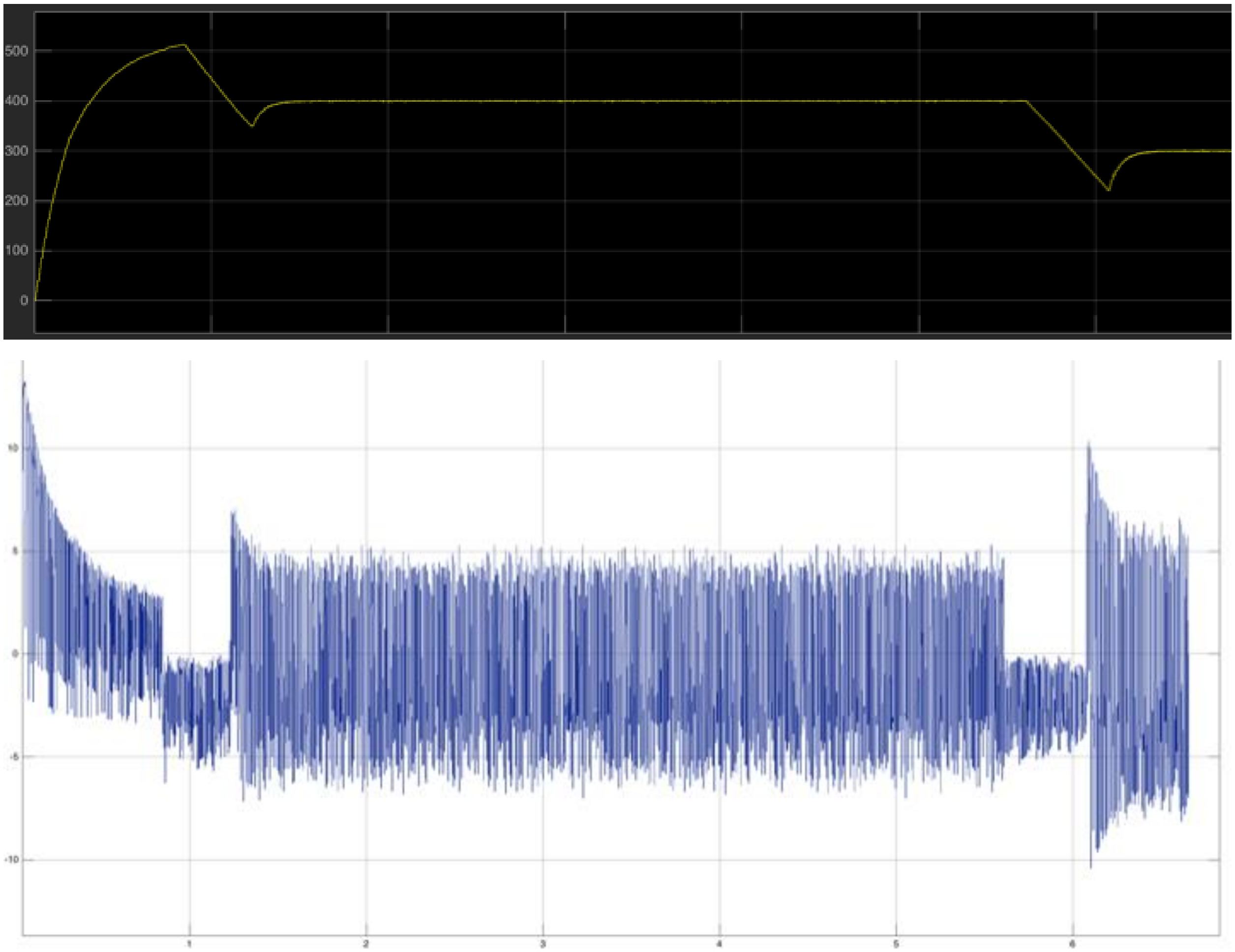

Fig. 53 Simulink - Top graph (Speed in rpm Vs. Time in seconds), Bottom graph (Current in amps Vs. Time in seconds)

As soon as the brakes are applied/speed is reduced, we observe a current surge and subsequent current flow in the negative direction, identifying how current now flows in the opposite direction, reversing the direction of power flow. This highlights how regenerative braking takes place and current now flows to the battery through the body diodes of the switches.

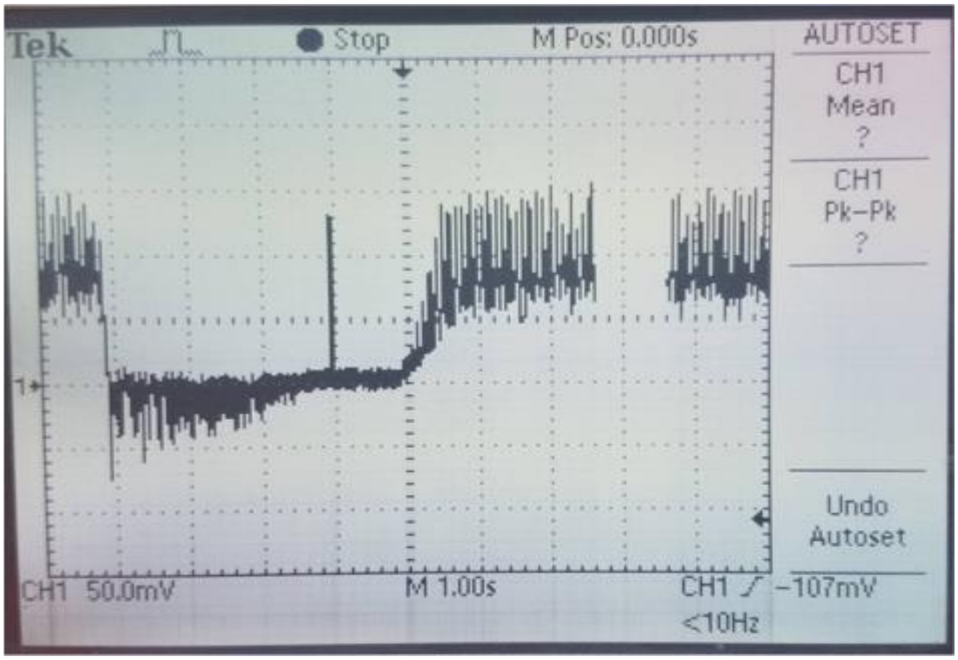

Fig. 54 Hardware – Regenerative braking with inrush current control (Current in amps Vs. Time in seconds)

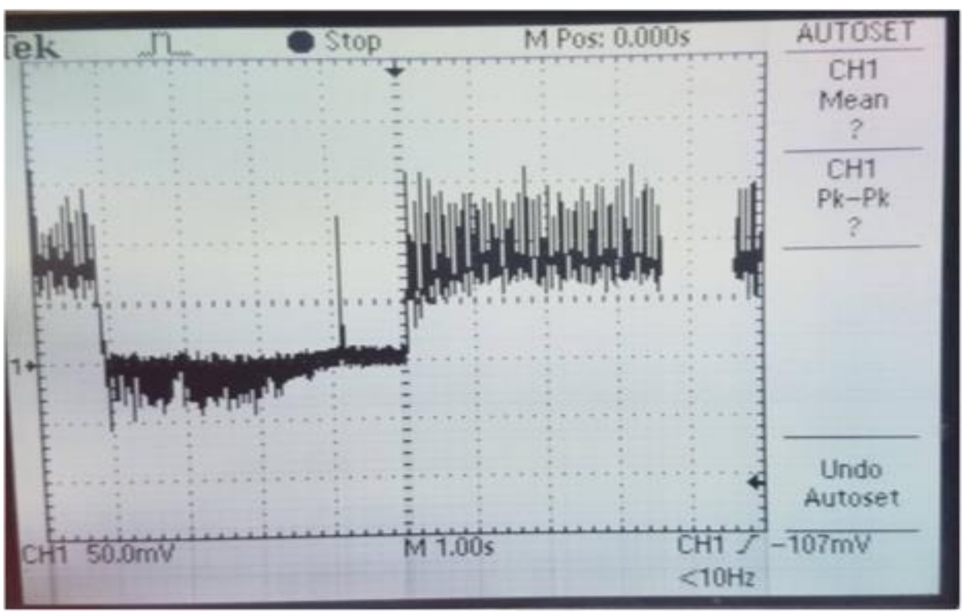

Fig. 55 Hardware – Regenerative braking without inrush current control (Current in amps Vs. Time in seconds)

Chapter 5

COST ANALYSIS

Hardware (Chassis materials)

Item	Comment	Unit Price	Quantity	Total
Aluminum Pipe (1inch diameter, 10mm wall)	kg	350	5.1	1785
Welding				2400
Steering assembly fitting+welding+labour				10000
Aluminum Pipe (1inch diameter, 10mm wall)	kg	400	1.38	552
Ball Bearing (for steering shaft)		50	2	100
Cable Tensioner		90	4	360
Brakes, tyres, wheels				5700
5 point seatbelt	155Yuan			2354
Bearing Housing (steering shaft)		400	1	400

Nut 5/32	rate per dozen	20	4	80
Screw 5/32 1" long	rate per dozen	25	2	50
Screw 5/32 3/4" long	rate per dozen	20	2	40
Hinge 2"		10	6	60
Screw 6mm 1.5" long		15	20	300
Screw 8mm 1.5" long		20	20	400
Nut 6mm		3	20	60
Nut 8mm		4	20	60
Washer for 6mm		4	48	242
Washer for 8mm		5	48	290
Screw+Nut 5/32	rate per dozen	20	2	40
Screw+Nut 5/32		60	1	60
Washer 1/8"		1/3	150	50
Washer 1/2"		10	10	100

Washer+Screws 5/32		1.2	100	120
Bolt (lock) 2.5"		20	3	60
L bracket 1.5"		10	3	30
Magnetic door Catcher		15	3	45
Hinge 3"		10	10	100
Screw 8mm 2.5" long + nut		10	10	100
Eye bolt 10mm + nut		80	3	240
Screw 2" with nut		5	4	20
Michelin Tyres	87eur total	3406	3	10220

Table 3. Chassis material cost

Hardware (Body materials)

Item	Comment	Unit Price	Quantity	Total
Carbon Fiber			USD 115 per 10m	120.46 25
Carbon Fiber shipping			USD 81.85	

Chop Strand Mat (CSM fiberglass) 450GSM	kg	218
Polyester Resin 1104	kg	170
Epoxy Resin	set (1kg resin + 0.5kg hardener)	1100
Cobalt Hardener		10
MEKP Hardener		280
Solvent (cleaner)	0.5kg/bottle	100
PVA	bottle	60
Mold release wax		260
Roller		200
Thermopore sheet 4x4 (2 inch thick)		400
Thermopore sheet 3x3 (1 inch thick)		150
Thermopore sheet 1.5x3 (1 inch thick)		95
Wood (Lasani) 4x8		1300

Wood shipping (pick-up rent)		
Plastic sheet white (2mmx6ftx4ft)		2100
Plastic sheet clear (2mmx3ftx4ft)		1000
Wall Putty 20kg pack		1750
Lacquer Spray can		130
Paint Spray Can (Blue)		150
Polyester Resin 1103		180
Polyester bleeder sheet 1inch thick		50
Wall Putty 5kg pack		450
Polyester Resin 1104		185
Rubber Trim	Rate per foot	20
Rubber Trim	Rate per foot	40
Aluminum sheet for bulkhead	rate per kg	500

Table 4. Body material cost

Electronics

Item	Comment	Unit Price	Quantity	Total
BLDC motor (with shipping)			USD 187.39	19629.1
Battery			USD 388	40643
Battery Shipping + customs			USD85+PKR7500	
Arduino Mega				900
Hot Melt Glue Gun				550
IRFP4568				350
FibreGlass PCB Board 12x12				400
1uF Cap. 100V				4
6.8uF Cap. 100V				4
4.7uF Cap. 100V				4
3.3uF Cap. 100V				4
10uF Cap. 100V				4

1uF Cap. 100V		5
470uF Cap. 100V		35
4.7uF Cap. 100V		5
3.3uF Cap. 100V		5
10uF Cap. 100V		5
DC-DC buck LM2596		120
Horn		150
T-block Connector KF45		8
Arduino Power plug/connector		10
FiberGlass PCB Board 12x6		200
6pin connector		50
4pin connector		40
2pin connector		25
Heat shrink	rate per yard	2
Hall sensor 44E		50

Hall sensor 95A		200
T-block Connector KF25		5
Fuse Holder		150
Fuse 25A,32A	2x25A,2x32A	25

Table 5. Electronics cost

Others

Item	Comment	Unit Price	Quantity	Total
Plastic Sheet (thin, double)	meter	100	1	100
Double tape	meter	10	10	100
Plastic Cup		10	10	100
Playdoh		35	1	35
Hard Plastic Film		190	1	190
Plastic Sheet (thick)	meter	80	2	160

Double Tape roll		120	1	120
Glue		60	1	60
Glue	kg	240	1	240
Glue	kg	190	1	190
Glue	kg	200	1	200
Plaster of Paris	kg	20	22	440
Latex Gloves (pack of 100)		550	1	550
Latex Gloves (pack of 100)		485	1	485
Saw blade		20	2	40
Plastic bowl		35	3	105
Brush 3"		50	15	75

			0
10L container for resin	130	1	130
Sandpaper 100grit	20	24	480
Grinder Sandpaper 36grit	80	4	320
Angle Grinder	2200	1	2200
Angle Grinder replacement sander 70grit	70	2	140
Angle Grinder cutting disk (thin)	35	2	70
Angle Grinder wool pad	200	2	400
Angle Grinder wool pad velcro adapter	50	1	50
Angle Grinder cutting disk (thick)	70	1	70
Threading Tap (moose)	100	1	100
Polythene sheet 20ftx7ft(double) 2.6kg	290	2.6	75

			4
Screws + Nuts	10	5	50
Peel Ply	300	10	3000
Butyl Tape	1075	3	3225
Peel Ply+Tape Shipping			300
Vacuum Bagging sheet	300	10	3000
Vacuum sheet shipping			500
Masking Tape 2"	60	1	60
Masking Tape 1"	80	1	80
Silicon Glue rod	25	2	50
Paint Brush 2"	90	3	270
Masking Tape 1"	60	1	60

Masking Tape 2"	60	1	60
Masking Tape 1"	30	1	30
Silicon Glue rod	20	19	380
Plastic Bowl	20	5	100
Plastic Sheet	290	1.93	560
Paint Brush 2"	50	10	500
5kg Resin Container	50	1	50
Paint Brush 2"	60	6	360
Silicon Gun	250	1	250
Silicon sealant tube	200	1	200
Electrical tape	25	2	50
Super glue (GMSA) 20g pack	60	1	60

Heater rod		100	1	100
Magic Depoxy large		110	1	110
Spray Paint matt black		130	1	130

Table 6. Miscellaneous cost

Crate

Item	Comment	Unit Price	Quantity	Total
Wood Plank 0.5x4" x10ft		430	4	1720
Plywood sheet 0.75" 4x8ft		1400	7	9800
Wood Plank 0.25x2" x10ft		230	20	4600
Wood Plank 1.5x3.5" x7ft		400	4	1600
Wood Plank 1.25x2.5" x10ft		250	3	750
Wood Plank 1x0.75" x8ft		75	4	300

Nails 3"				100
Nails 1.5"				150
Nails 1"	0.25kg			40
Lock		20	2	40
Crate transportation from lahore to taxilla			1	18000

Table 7. Crate cost

Total cost: PKR. 227013.14

Total	**227013.14**

Chapter 6

SOCIETAL RELEVANCE

Not only do electric vehicles play a significant role in reducing carbon emissions, averting the adverse effects of global warming and reducing air pollution, but the power electronics and design specifications utilized in their construction help increase energy efficiency. These factors are essential in fulfilling the growing needs of the energy sector and in the long run reducing the burden on the health sector of the country. Efficient electric vehicles would ensure that oil and gas imports are reduced, enabling Pakistan to invest in other sectors creating more jobs and boosting its economy. Adoption of the idea of integrating this green technology in the country would bring further attention to the renewable energy sector, aiming to build a self-sufficient country.

Pakistan has long been importing oil and gas from Iran, Saudi Arabia, Qatar and Turkmenistan to fulfill the growing needs of its energy sector. Burden on this sector has risen with the increase in industrialization and little has been done to make the country self-sufficient in terms of energy resources and production. Pakistan's crude oil imports rose from 74 thousand barrels per day in 1986 to 151 thousand barrels per day in 2012, and continue to rise [36]. According to Shahid Iqbal's report in Dawn, a report of the State Bank showed that the country paid a total of $6.69 billion for the import of petroleum products and crude oil during the July-Nov 2014-15. The amount was higher than the import bill of the same period previous year, which was around $6.43bn [37]. Therefore, there is a need to ensure that the use of oil and gas is minimized, especially in the transport sector, where the number of vehicles on road and the road length keeps on increasing every year, adding load to the existing oil and gas quantities. Shift to electric vehicles will ensure no use of oil and gas as fuels as the only requirement will be in the form of electricity that will be minimized by increasing the efficiency of the vehicle, which is the main aim of this project. Therefore, this will imply a net decrease in the need for oil and gas. There is a dire need to move to renewable resources, not only to prevent the adverse effects of global warming, but also to reduce the financial burden on the country. The capital that will be saved from the reduction in import of oil and gas may be used to invest further in the renewable energy sector, and in shifting current technology including vehicles away from non-renewable resources. This project aims to construct a battery electric vehicle that uses no internal combustion engine, thus no fuel that needs to be imported.

The persistent problem of load shedding of electricity, and petrol and CNG is a notable marker. This not only affects the economy of the country, reducing the production time per day in various industries and offices, but also the daily lives of people, from giving rise to commute issues to increasing the stress associated with the rising prices of fuel for their vehicles. With the gradual increase in electric vehicles on the roads of Pakistan, CNG and petrol load shedding may be avoided. However, charging of these vehicles would entail an increased pressure on electricity generation. This is a valid drawback; however, comparably lesser gas and oil quantities may be required to fulfill this need for electricity generation, and in the long run given that investments are made in the renewable energy sector, and further developments are made to increase the energy efficiency of the vehicles, this may be countered.

Vehicle parts can be manufactured in Pakistan, as for our battery electric vehicle, including the lightweight body made of carbon fiber, the aluminum body frame and the BLDC hub motors among many others. Even though the initial cost of construction will be high, in the long run this will lead to reduced imports for vehicle fuel consumption needs. With the mass production of these cars, and dedicated manufacturing units, the prices will lower, making them available to the masses, potentially avoiding the societal gap based on wealth. This area itself will provide employment opportunities for many. With the increase in youth population, 35.4% population under age 15 [38], unemployment seems to be a major issue in the country, which may be overcome by introducing a potential new industry.

Electrical cars are also necessary to limit or avert the unfavorable effects of global warming and reduce the ever-increasing air pollution that causes several health problems. The environmental impact of these cars is highlighted in the previous section. However, “highly inefficient energy use, accelerated growth in vehicle population and vehicle kilometers traveled, increasing industrial activity without adequate air emission treatment or control, open burning of solid waste including plastic, and use of ozone depleting substances (ODSs) are some of the major causes of deterioration of ambient air quality…The health impacts of air, water pollution and productivity losses from deforestation and soil erosion have been assessed at 1.71 billion dollars, or 3.3 percent of GNP, in the early 90s. The losses attributed to air pollution, in terms of health care costs, amount to 500 million dollars a year” [39]. Air pollution itself leads to various diseases such as lung cancer, chronic bronchitis and mental impairment, among many others. The amount associated with the treatment is very high as mentioned earlier, highlighting how the population of the country is affected in terms of health and expense.

It is imperative to note that even though the initial cost of electric vehicles may be higher than that for regular ICE vehicles, in the long run, energy efficiency will play a major role in breaking even and eventually benefiting the customer and the country at large, reducing the toll on its oil and gas imports, combating air pollution, and thus the costs associated with health care, resulting in a healthier population that will eventually be satisfied with the reduction in the cost for driving their vehicles. This project aims to present a prototype design, constructed with the resources available in Pakistan, in a way to optimize energy, exhibiting a green and cost-effective alternative to ICE vehicles.

Chapter 7

ENVIRONMENTAL IMPACT AND SUSTAINABILITY

There is an increase in the use of electrical vehicles all across the globe, with the advent of a determined approach towards minimizing the carbon footprint by decarbonizing road transport. After considering various transportation alternatives including hybrid electric vehicles that are occasionally yet increasingly being seen on several roads in Pakistan, we concluded that battery electric vehicles hold the greatest potential for averting or limiting climate change problems. Internal combustion engine based vehicles are not only contributing to the immediate increase in air pollution but are also leading to various adverse effects of global warming, along with depleting this planet's limited natural resources such as coal, oil and gas. Battery electric vehicles hardly create any carbon emissions, potentially surmounting the ozone layer depletion issue. They are electrically powered, leading to zero dependence on fuels from non-renewable energy resources.

With the shift of economic activity towards more energy intensive sectors, the carbon dioxide emissions have increased in Pakistan. The increase is not only attributed to the increase in vehicle population but also the general population of the country. The increased demand in food results in greater production, leading to deforestation, and greater use of fossil fuels. This in effect contributes to the increased concentration of greenhouse gases leading to air pollution and global warming. Thus, increased economic activity will lead to further increase in carbon dioxide emissions as identified by Arsalan Khan and Faisal Jami in their study, "Energy Related Carbon Diode Emissions in Pakistan: A Decomposition Analysis Using LMD" [40]. According to the Global Climate Risk Index 2016 by the Germanwatch, Pakistan is featured both in the long-term index and in the last four years' lists of countries most affected [41]. According to the World

Bank, in the period 1990 to 2005, carbon dioxide, methane and nitrous oxide emissions in the country increased by 97.4, 33.2 and 44.5 per cent, respectively, making air pollution a weighty environmental problem in Pakistan. Another study by the Pakistan Environmental Protection Agency (EPA) together with the Japan International Cooperation Agency (JICA) in Lahore, Faisalabad, Gujranwala, Rawalpindi and Islamabad showed that fine particulate matter levels were 6-7 times greater than WHO guidelines. Many factors have led to this poor air quality in many cities of Pakistan, increased vehicular emissions being the highlight. Experts estimate that between 60 to 70 per cent of the degradation of urban air quality can be attributed to vehicles. The number of motor vehicles registered in the country has increased from 4,303,296 to 5,366,460 between 1998 and 2007, an increase of 24.7 per cent. According to the International Association for Natural Gas Vehicles, in December 2009, Pakistan had 2.4 million vehicles running on CNG, the highest in the world. Moreover, it had 3,105 CNG refueling stations, also the highest in the world [42]. Moreover, lead compounds that are added to petrol to increase the efficiency of car engines also get released into the environment. The country has faced devastating effects of air pollution usually in the form of health issues, along with those of global warming, including severe recurrent floods due to the melting of glaciers, along with yearly spurs of heat waves and droughts. Therefore, there is an immediate need to limit or avert the climatic changes caused by global warming, as fossil fuel-based vehicles are doing no good to the cause.

The International Journal of Hydrogen Energy, in their article, “Fuel Cell and Battery Electric Vehicles Compared”, conclude that “all-electric vehicles will be required in combination with hybrids, plug-in hybrids and biofuels to achieve an 80% reduction in greenhouse gas emissions below 1990 levels, while simultaneously cutting dependence on imported oil and eliminating nearly all controllable urban air pollution from the light duty vehicle fleet. Hybrids and plug-ins that continue to use an internal combustion engine will not be adequate by themselves to achieve our societal objectives, even if they are powered with biofuels" [43]. Therefore, there is a necessity to increase the pace of switching to all-electric vehicles.

We studied the global warming emissions of battery electric cars from the manufacturing of their car parts and batteries to their disposal and reuse. The Union of Concerned Scientists has undertaken a two-year review of the climate emissions from vehicle production, operation, and disposal and concluded "battery electric cars generate *half* the emissions of the average comparable gasoline car, even when pollution from battery manufacturing is accounted for" [44].

However, along with working towards the idea of decarbonizing road transport by focusing on all-electric vehicles, it is important to increase energy efficiency by developing and implementing improvements to current automotive technologies. Joesph Romm, in his article, "The Car and Fuel of the Future", specifies, "in the near-term, by far the most cost-effective strategy for reducing emissions and fuel use is efficiency" [45]. Our project focuses on building a carbon-fiber body for the vehicle because it is lightweight along with having high stiffness, and high tensile strength. Carbon fiber does not corrode, degrade, rust or fatigue, giving it a much longer lifecycle. This means that it has to be produced once where a steel part would have to be replaced multiple times, reducing the emission charges on the material at the time of its production [46]. The chassis is made of aluminum, another lightweight material that can be recycled easily. A peer-reviewed study by the Department of Energy's Oak Ridge National Laboratory found that an aluminum-intensive vehicle could achieve up to a "20 percent reduction in total life cycle energy consumption and up to a 17 percent reduction in carbon dioxide emissions" [47]. Moreover, we are using specified Michelin tires that have a low rolling resistance. Reduced frictional losses and the lightweight body frame ensure that the energy efficiency of the vehicle is increased. Furthermore, we are using BLDC motors that include more torque per weight (the weight factor is countered by the lightweight materials being used), and more torque per watt leading to increased efficiency, because they do not have frictional and electrical losses due to brushes.

With the use of all-electric cars, capital that was previously being spent on importing oil and gas, can then be utilized to limit or reverse the effects of global warming and to formulate and implement environmental policies, including increased investments in the renewable energy sector, in return making electricity production mechanisms largely environmentally friendly. According to the Transportation Research Board of the National Academies of Sciences, Engineering, Medicine, “if substantial progress can be made in solving electric vehicle technology challenges and, critically, the power-sector can be decarbonized and expanded to supply a large proportion of road transport demand, around a 90 per cent reduction per kilometer emissions would be achievable across the fleet” [48].

With our design, we are making an effort to reduce the carbon footprint by increasing energy efficiency using a tested zero-emission battery-electric vehicle and incorporating innovative technological improvements.

Chapter 8

CONCLUSION AND FUTURE RECOMMENDATIONS

The proposed solution is a fully functional battery electric vehicle prototype designed under controlled parameters and operating on a sensored BLDC drive, with increased energy efficiency being achieved through its power electronics control mechanism and mechanical structure. The work was done to highlight how drive parameters can be optimized when constraints are employed. The proposed vehicle is designed, implemented and tested to confirm expected results, by highlighting the coherence between simulation and hardware implementation results. The drive with regenerative braking capability was operated at a frequency of 20kHz, with the speed being controlled in a simple and effective manner through PWM generation and duty cycle variance. Safety was taken into consideration by including an inrush current control mechanism based on soft switching. It was concluded that sensorless control is a more robust control technique. We aim to implement this technique in the future to provide a hardware-based comparison of the two control strategies. The proposed solution has direct application in countries that are facing the adverse effects of air pollution and climate change.

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