REGENERATIVE AND ANTI-LOCK BRAKING SYSTEM IN ELECTRIC VEHICLES

A Thesis Submitted in Partial Fulfilment

of the Requirements for the Degree of

Master of Technology

in

Electronics and Instrumentation Engineering

by

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May 2014

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

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ODISHA, INDIA - 769008

CERTIFICATE

This is to certify that the thesis entitled **"REGENERATIVE AND ANTI-LOCK BRAKING SYSTEM IN ELECTRIC VEHICLES"** submitted by **Mr. SAGAR MALIYE** bearing roll no. **212EC3148** in partial fulfilment of the requirements for the award of Master of Technology in Electronics and Communication Engineering with specialization in **"Electronics and Instrumentation Engineering"** during session 2012-14 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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National Institute of Technology,
Rourkela

Date: 21st May, 2014
Place: Rourkela

Dedicated to my Family,
my Respected Teachers
and my Friends

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Next, I want to express my respects to Prof. A.K. Swain, Prof. U.C. Pati, Prof. T. K. Dan, Prof. D.P. Acharya, Prof. S.K. Patra, Prof. S. Meher and Prof. Poonam Singh for teaching me and helping me how to learn. They have always been very helpful and resourceful in all difficult situations and for that I am grateful to them.

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ABSTRACT

Many accidents are caused when a vehicle is braked hard, causing the wheels to lock up. At such times, the driver has no control over the steering of the vehicle and as a result cannot change the direction of the car. Anti-Lock Braking System prevents wheels from being locked up during braking by using a non continuous form of braking known as Pulse Width Modulation (PWM) braking. This gives the driver the control of the vehicle at all times and even while braking. Because of such type of braking, the wheels can better grip the road surface and the stopping distances also reduce significantly especially on tricky road surfaces like icy or wet roads.

The kinetic energy of the wheel is generally lost during braking in the form of heat due to friction between the brake pads. This energy can be recovered using a technique called as Regenerative Braking. In this technique, the excess energy is stored temporarily in capacitor banks before it gets converted to heat energy and is wasted. This system prolongs the battery life by recharging the battery using the stored energy. Hence the mileage of the electric vehicle also increases as it can travel more distance in a single battery charge. These two methods together help make an electric vehicle energy efficient as well as safer and easier to use thus preventing and reducing the number of accidents.

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1 INTRODUCTION

1.1 Importance of Electric Vehicles

An electric vehicle can be described as a vehicle which runs using an onboard electric generator like electric battery or a hydrogen fuel cell as its primary source of energy. An electric vehicle uses electric motors (either ac or dc) to move. In an age where fossil fuels like petrol, diesel are diminishing as well as getting costlier, Electric Vehicles hold a lot of importance today. Electric vehicles offer us an alternative to the vehicles driven using fossil fuels, which pollute the environment and also are getting costlier. Electric vehicles provide a smoother operation, stronger acceleration and are quieter as compared to conventional vehicles with Internal Combustion Engine (ICE).

1.2 General Structure of an Electric Vehicle

An Electric vehicle can be operated by using only an electric source like battery or it can also have a structure of a combustion engine parallel to the electric motor. Such a type of vehicle is known as Hybrid Electric Vehicle. HEVs give us an option of switching between the conventional IC engine and the electric motor setup. Either the battery or the gasoline engine runs the transmission and operates the motors of the vehicle. An electric vehicle can have either ac or dc motors. For ac motors, an inverter changes dc voltage of the battery to ac voltage before giving it to the motor. The gear structure of an electric vehicle remains same as a conventional vehicle to provide both variable speed and variable torque to the vehicle. The battery is the power source for the electric vehicle and after using the vehicle, the battery is then charged at the end of the day. Charge in the battery determines the travelling distance and hence the mileage of the electric vehicle. The battery may take a few hours to charge but gives sufficient energy for our general day to day travelling needs. An ICE vehicle can also be converted into an electric vehicle. This involves changing the engine from ICE to an electric motor to run the vehicle. Though the initial conversion cost may be incurred, it is beneficial and cost effective to the user and better for the environment.

1.3 Brake Systems in an Electric Vehicle

Brake Systems in electric vehicles can be of different types. In some vehicles, conventional friction brakes are used. In such systems, continuous braking is applied which produces friction and stops the wheels from rotating, thereby slowing down the vehicle. In such brake systems, the brake pads heat up and this leads to energy wastage in the form of heat. Another type of brake system is the Anti-Lock Brake System. Here, continuous braking is not applied. Instead, a non-continuous braking pattern is applied which slows or stops the vehicle as needed. Such a system is more efficient than the conventional braking system and gives a superior performance. Another type of braking system is the regenerative braking system. In such a system, the motor itself or any other circuit works to apply the brakes by controlling the current in the motor circuit. If an ac motor is used, then during braking it works as a generator and gives back energy to the battery and slows down the vehicle at the same time. Any other circuit can also be used to divert the motor current during braking so that the vehicle slows down. Such types of systems also recharge the battery and help in braking. But such brake systems cannot be used solely as they can slow down the vehicle but generally do not bring it to a complete stop. Hence such systems are used in conjunction with conventional friction brakes or Anti-Lock Braking System.

1.4 Anti-Lock Braking System

Anti-Lock Braking System (ABS) is one of the braking systems used in electric vehicles which can replace the conventional friction braking system by using a non-continuous braking pattern by taking into consideration factors like vehicle speed, deceleration, road conditions etc. ABS gives a superior braking performance as compared to conventional friction braking and also saves energy. In ABS, the problem of wheel lock up due to hard braking does not occur and hence the name anti-lock. The problem of directional lock up too is resolved in ABS. ABS gives directional control of the vehicle at all times to the driver even while braking. ABS operates in the low slip region so that the wheels have more traction with the road surface and hence wheel lock up does not occur. In advanced systems, multiple sensors detect the wheel speed individually and microcontrollers can know if a wheel is about to lock up. Accordingly the braking pattern is changed. The braking pattern in ABS is a non-continuous pwm wave due to which braking occurs efficiently and heat is not generated as much as in the conventional brakes.

1.5 Regeneration in Electric Vehicles

A battery provides energy to the electric motor to run. While braking, the kinetic energy of the motor is converted into heat energy due to friction in the brake pads and is subsequently lost. Regenerative Braking is an energy recovery system which tries to recover this energy before it is converted into heat. This energy can be stored temporarily or can be used immediately. Regenerative Braking is done by using the motor as a generator. While braking, the motor gives back energy to the battery and thus charges it. Alternatively, the current going to the electric motor while braking can be diverted and stored. This charge can then be given back to the battery when needed. Such temporary storage can be accomplished by using a flywheel setup or a capacitor bank.

1.6 Features of Electric Vehicles

The advantages of Electric Vehicles are-

1. It has zero emissions and is environmentally friendly.
2. It is much more silent than other vehicles.
3. It provides quicker acceleration.
4. Cost of the electric vehicle can be recovered in a few years through savings in fuel consumption.
5. It is more efficient in converting electrical energy to propulsion than conventional internal combustion engine (ICE) vehicles.
6. Regenerative braking can be implemented here which recovers energy and hence makes increases the range of the vehicle.
7. It reduces our dependence on the ever depleting fossil fuels like petrol and diesel.

The disadvantages of Electric vehicle are-

1. The maximum range of electric vehicles is between 150 to 200 kilometres while gasoline vehicles have a larger range of up to 300 kms.
2. Charging time required for charging the battery of electric vehicle is more and is typically in the range of a few hours.
3. The price of an electric vehicle is higher as compared to an ICE vehicle.
4. Battery packs of electric vehicle are bulky and take up considerable vehicle space.

1.7 Motivation

An electric vehicle provides a clear alternative to the internal combustion engine vehicles which run on fossil fuels like petrol and diesel. The fuels are depleting fast and alternative energy resources must be used as the consumption of fossil fuels goes on increasing every year due to usage of more vehicle but the production of these fuels is not keeping pace with the increasing demand. An electric vehicle provides many benefits as mentioned above and is environmentally friendly. Because of such benefits of electric vehicles, it is important that an electric vehicle be given the latest systems in braking, as it is an important part in the use of any vehicle. Braking systems like ABS and regenerative braking which will make the electric vehicle safer and easier to use as well as make it energy efficient should be implemented in the vehicles. If such systems are incorporated in electric vehicles and their advantages are seen by all, then the use and sale of electric vehicles all over the world will increase, especially in India which has a huge market for vehicles and is suffering from the ill effects of pollution due to vehicles in major cities. Increase in the number of electric vehicles will be beneficial to the society and to the environment. Also, wide use of Anti-lock Braking System will lead to fewer accidents on the streets and will save many lives by preventing many accidents.

1.8 Objective

The objective of the project is –

1. To build a circuit for Anti-Lock Braking System which will prevent the skidding of wheels during hard braking and keep the control of the vehicle at all times with the driver in Electric Vehicles by keeping the slip ratio in the control region.
2. To include a Regenerative Braking sub-system which will recover lost energy in the circuit and give it back to the battery.
3. To analyse the performance of the entire system to check its utility and confirm that Anti-lock Braking System along with regeneration makes an electric vehicle easier and safer to use as well as makes it more energy efficient.

1.9 Thesis Organisation

This thesis is divided into 5 chapters. The first chapter is the Introductory Chapter which gives us an overview of Electric Vehicles and their systems. It also includes the advantages and disadvantages of Electric vehicles and states the objective and motivation behind the project work.

The Second Chapter is Literature review. It includes description of eight papers and the contents of these papers which have been useful during the course of the project work.

The Third Chapter is Regenerative Anti-Lock Braking System (RABS). This chapter includes the details of working of Regenerative Braking and Anti-Lock Braking Systems. Also the history and origins of these braking systems have been mentioned in the chapter.

The Fourth Chapter is Implementation and Results. This chapter describes the circuits which have been used in the project work. The description of the circuits, their simulation, hardware construction and results for both simulation and hardware have been shown in graph and explained.

The Fifth Chapter is Conclusion and overall conclusion of the thesis is presented in this chapter. Also the scope for future work is also given in the chapter.

CHAPTER 2

Literature Review

2 LITERATURE REVIEW

1. Khatun P, Mellor P H, Bingham C M; “Application of Fuzzy Control Algorithms for Electric Vehicle Antilock Braking/Traction Control Systems”.

In paper [1], author P Khatun has described the preliminary research and implementation of an experimental test bench set up for an electric vehicle Antilock Braking System (ABS)/Traction Control System. Here a low cost test bench is used to develop fuzzy control algorithms. In the test bench, a brushless permanent magnet motor is used which is driven by a power inverter and is controlled by a DSP controller. The PM motor is connected to a three phase induction motor which is used to simulate actual road load. Simulation studies are employed to derive an initial rule base that is then tested on an experimental setup representing the dynamics of a braking system. Fuzzy logic membership functions are described for parameters like slip and observed load torque. On basis of the fuzzy rules set, the output torque demand function is derived. By using these fuzzy rules, the slip ratio is limited to 0.1 for dry surfaces. According to the fuzzy rules, the algorithm identifies unstable regions in the graph of torque-slip and reduces the slip. Eventually the slip stabilizes around 0.25 and the control region extends up to 0.35 for a dry road surface. The results indicate that ABS substantially improves performance and has potential for optimal control of wheels under difficult driving conditions.

2. Dixon J, Ortuzar M; “Regenerative Braking for an Electric Vehicle using Ultracapacitors and Buck-Boost Converter”.

This paper [2] describes a method to recover energy during braking by using a system of Buck-Boost converter and an Ultracapacitor bank. The buck-boost converter is made using IGBTs and the entire system has been tested on a Chevrolet electric truck. Using a control strategy, the maximum current going to the battery, minimum and maximum voltages of the Ultracapacitor bank are set. The control strategy uses a reference table and has inputs like the state of charge of the battery, vehicle speed, load current etc. A strategy is also given which uses sensors to determine the wheel decelerations so that the converter can be used optimally to recover maximum energy. Results are shown using graphs of battery current, voltage and the capacitor bank voltage. The graphs indicate the proper working of the buck-boost converter. This designed system allows higher acceleration and proper decelerations with minimal loss of energy and minimal degradation of the battery pack.

3. Xiufang Y, Xin Z; "Study of control logic for Automobile Anti-lock Braking System".

In this paper [3], to find the ideal logic principle for antilock braking, Simulink is used to create the state flow model for the ABS electronic control unit. The state flow diagram for a four channel ABS system is also charted out. The control logic uses logic threshold control method. It uses parameters like reference slip ratio and angular speed threshold to calculate the optimum braking pressure to be applied. The acceleration of the wheel is measured and plotted. When the acceleration is negative, i.e. deceleration is taking place, the logic keeps on monitoring the value till it is of lower value. When it increases, the logic detects when the wheel is about to lock up. This unstable region is detected and the braking pressure is now adjusted so that this unstable region is not encountered again and the wheel is decelerated without the wheel being locked up. A method of alternate boost pressure and decompress is employed so that the vehicle can stay in the stable region for as long as possible and the optimum braking pressure can be applied.

4. Xu C, Sha L, Cheng K; “Simulation of Integrated Controller of the Anti-Lock Braking System”.

In this paper [4], the simulation of a braking system is done by using an integrated controller consisting of a PID controller and a finite state machine. The parameters given to the system are wheel speed, vehicle speed, slip and braking distance. According to these parameters, the braking pressure is controlled. The drawback is that only a single wheel model is used to simulate the braking conditions. The results are compared when the slip ratio is the control parameter and when the integrated controller is used. The use of integrated controller gives a much better control over the slip ratio and the braking pressure can be stabilised to a stable value with much less time than without the controller and the braking distance too reduces significantly.

5. Piroddi L, Tanelli M; “Real time identification of tire- road friction conditions”.

This work [5] aims at the real-time estimation of the wheel slip value corresponding to the peak of the tire–road friction curve, in order to provide anti-lock braking systems (ABS) with reliable information on its value upon activation. Different techniques based on recursive least squares and the maximum likelihood approach are used for friction curve fitting and their merits and drawbacks thoroughly examined. Also, optical and pressure sensors are used for measuring the brake pad pressure and working. Their output is then filtered and made sure that there is phase coherence between all signals. The algorithm selects the wheel which has the relatively fastest speed among the four wheels, i.e. the wheel which has the lowest longitudinal slip. The estimated vehicle speed is then found out according to the algorithm. Also a comparison is made between the value of coefficient of friction μ obtained through estimation and its actual value.

6. Chuanwei Z, Zhifeng B; “Study on Regenerative Braking of Electric Vehicle”.

In this paper [6], a control scheme for a constant regenerative current is given based on the analysis of several regenerative braking schemes. The three main control strategies discussed are maximum regenerative efficiency control, maximum regenerative power control and the constant regenerative current control. Analysis is performed for two modes, the continuous current mode and the discrete current mode. Using the above analysis, a formula for regenerative efficiency of a control scheme is derived. The analysis of the braking system is done to find out two aspects, the electric loop efficiency and the regenerative energy efficiency. Using the results of the analysis, the paper concludes that the constant regenerative current control scheme is better than the maximum regenerative power control scheme and the maximum regenerative efficiency control scheme. Also, the paper concludes that the used method gives a higher regenerative braking efficiency and better control performance.

7. Xue X, Cheng K; “Selection of Electric Motor Drives for Electric Vehicles”.

In this paper [7], six types of drive systems for electric motor drives for electric vehicles are discussed. The six types are compared with respect to cost, cooling, fault tolerance, safety, efficiency, weight, maximum speed and reliability. The six systems discussed are- conventional type, transmission-less type, cascade type, in-wheel type with reduction gears, in-wheel direct drive type and four wheel direct drive type. The drives which are compared are the Brushed DC motor drives, Induction motor drives, Permanent Magnet Brushless DC Motor Drives and the switched reluctance motor drives. After analysis of each system and comparison, the paper concludes that the switched reluctance motor drive are the best choice for driving an electric vehicle even though the brushed dc motor drive is most widely used for an electric vehicle.

8. Zhang Z, Li W, Zheng L; “Regenerative Braking for Electric Vehicle based on Fuzzy Logic Control Strategy”.

In this paper [8], to recycle more energy during regenerative braking, a regenerative braking force calculation controller is designed based on fuzzy logic. Here, Sugeno's fuzzy logic controller is used which has 3 inputs and the output is the braking force. The three inputs are vehicle speed, driver’s braking requirements and the battery’s state of charge. Fuzzy membership functions are defined for the above inputs and outputs and the output is found out in the range of 0 to 1. Each input has a membership value of high, medium and low based on which the fuzzy rules are developed. The simulations which are carried out show a substantial improvement in energy efficiency of an electric vehicle.

CHAPTER 3

Regenerative Anti-Lock Braking System (RABS)

Anti-Lock Braking System

History

Operation

Regenerative Braking

History

Operation

Advantages

Disadvantages

3 REGENERATIVE ANTI-LOCK BRAKING SYSTEM (RABS)

3.1 Anti-Lock Braking System (ABS)

When a vehicle is travelling at a high speed, braking the vehicle causes the wheels to slow down. But the vehicle body itself is travelling at a high speed and has its own momentum which does not slow down as fast as the wheels. This causes the wheels to lock up. A locked up wheel has no traction with the road surface and hence the direction of the vehicle cannot be controlled or changed. Hence, Anti-lock braking is preferred over conventional braking. Anti-lock brake systems address two conditions related to brake application; vehicle directional control and wheel lockup. When brakes are applied, friction is generated between the brake pads and the disc attached to the wheels. This friction causes the wheels to slow down and finally come to a halt. But at the same time, a lot of heat is generated in the brake pads as the kinetic energy of the wheels is converted into heat energy. When hard braking occurs, a parameter known as slip ratio increases and when this value reaches 1, the wheels get locked up. Locked up wheels have no traction with the road surface and are just dragged along the road due to the momentum of the vehicle. Hence, any attempt to change the direction of the vehicle by changing the direction of the wheels is futile as the wheels are not rotating at all. Hence, it is vital to control the braking applied to the electric vehicle so that the wheels do not cease rotation and the vehicle directionality can be controlled at all times.

3.1.1 History

Anti-Lock Braking System (ABS) is being used for a long time and was first used in brake systems for aircrafts. Because of ABS, the pilots could apply the brakes fully without having to manually increase the braking force slowly so the wheels may not skid. A substantial improvement in braking quality and distance was observed. Hence in the later years this technology was applied to vehicles. Royal Enfield used this technology in their bikes. Their research showed that ABS is instrumental in preventing accidents occurring in two wheelers. The performance of bikes and cars also improved and stopping distances while braking were reduced to a great extent, especially in tricky road conditions like icy or wet roads where wheel lock ups are common. After extensive research on vehicular ABS by Bosch, Honda and BMW, ABS is nowadays fairly common technology in vehicles. In Electric vehicles too, this technology provides all the benefits as for any other vehicle.

3.1.2 Operation

ABS is a vehicular safety system that manipulates the braking force that is applied to the wheels so that the wheels keep on rotating constantly and do not cease rotation during braking. A rotating wheel has more tractive force than a locked up wheel hence ABS provides more grip to the vehicle and better control to the driver. Using ABS improves vehicle control and decreases the stopping distances on dry as well as slippery surfaces like icy and wet roads.

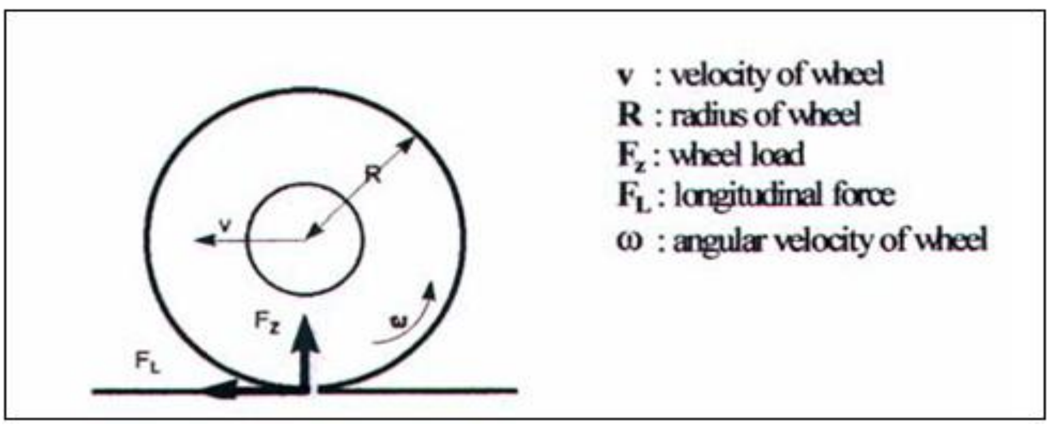

Figure 3.1 : Wheel Model

The tractive force (F_L) between a tire and the road surface (Figure 3.1) is proportional to the normal load (F_Z), the constant of proportionality being termed the adhesion coefficient (μ). The adhesion coefficient μ, is the ratio of tire brake force at the tire road interface and the normal load acting on the tire [11,12], i.e. $\mu = \frac{FL}{Fz}$.

The value of adhesion coefficient depends on tire characteristics like ageing, wear and tear, compound of rubber used etc as well as the road surface conditions i.e. whether the road surface is dry, icy or wet. Generally the adhesion coefficient can be considered as a function of slip ratio, s. The slip ratio is defined as the normalised relative difference in the wheel velocity and the vehicle velocity: $s = \frac{v - Rw}{v}$, where R is the radius of the wheel, w is the angular velocity of the wheel and v is the velocity of the vehicle.

During braking, when brakes are applied, the wheel speed changes first but the vehicle speed does not change as fast as the wheel speed due to the larger momentum of the vehicle. Hence the slip ratio goes on increasing. At a tipping point, wheels can no longer rotate and cease rotation. At that time the wheel velocity becomes zero while the vehicle velocity is still some finite value. At this moment, the slip value becomes 1 and the wheels lock up.

The typical μ-s characteristics are shown in figure 3.2. We can see that as the slip value increases initially, the coefficient of adhesion μ also increases. μ goes on increasing and reaches a certain high point which is called as $\mu_{max.}$ After this point, as the slip value increases the μ value goes on decreasing. The region in which the μ value goes on increasing along with slip value up to μ_{max} is known as the 'control region'. We see that for different type of road surfaces, the curves are similar shaped but the μ value goes on decreasing as the road surface changes from dry to wet and then icy. In the control region, as brakes are applied and the slip value starts to increase, the coefficient of adhesion μ also starts to increase. As a result, the traction between the road surface and wheel increases and the wheels get more grip on the road.

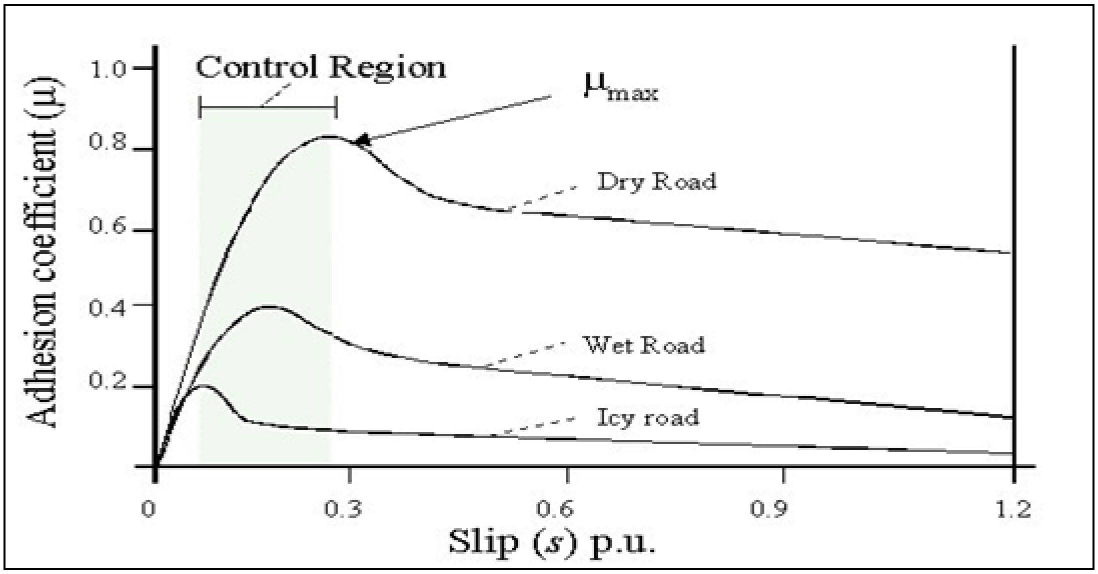

Figure 3.2 : Example μ-s characteristics for various road conditions

The objective of an Antilock Braking System (ABS) is to control the tractive force applied to the wheels during braking in order to limit the slip, *s*, between the road surface and the tires, and consequently only operate within the stable control region of the μ-slip characteristics as shown in Figure 2. Table 1 shows the typical values of slip at which the maximum adhesion coefficient is obtained, for various road conditions [1].

Road Condition	Max adhesion coefficient (μ_{max})	Optimum Slip (s)
Dry Road	0.85	0.35
Wet Road	0.4	0.2
Icy Road	0.2	0.1

Table 1: Max values of μ for various road surfaces

We try to keep the slip at its optimum value in the control region during braking so that the tractive force between wheel and road surface remains high and the driver gets to keep the control of the electric vehicle even during hard braking [9].

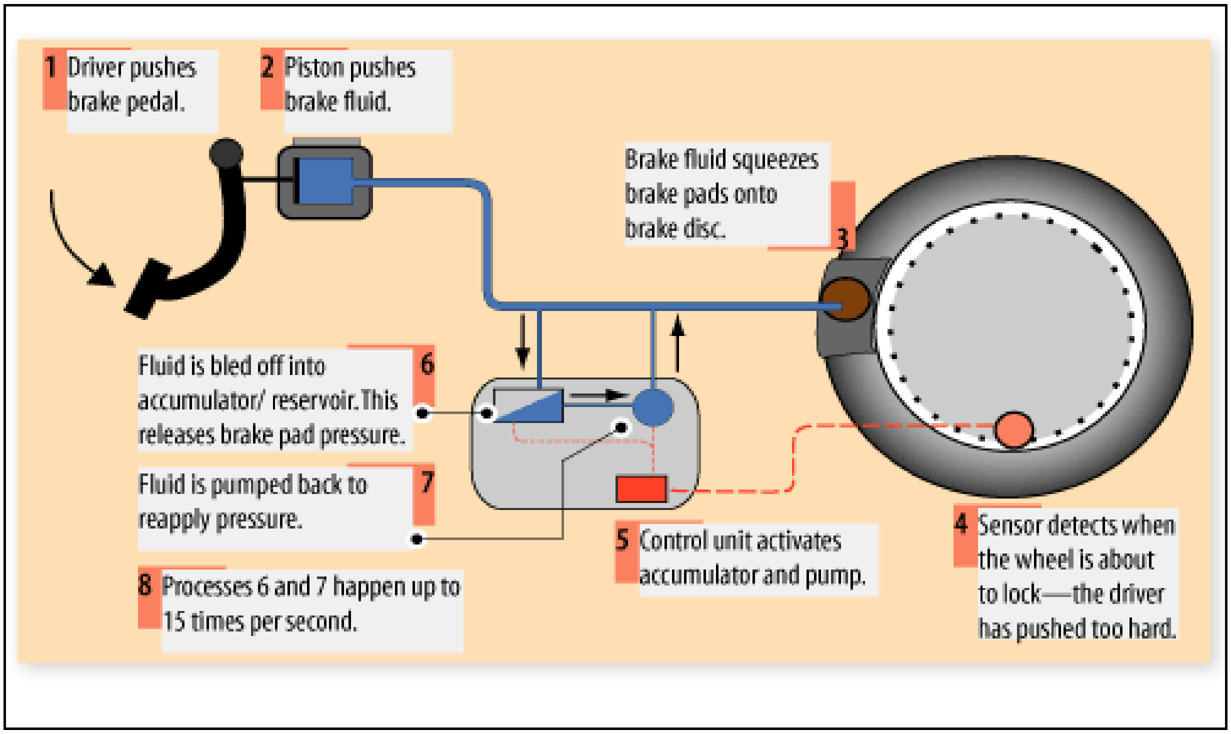

Figure 3.3 : Anti-lock Braking System control strategy

Some ABS systems use speed sensors on either all four wheels or the pair of front and rear wheels. When the sensors detect the deceleration in the wheel is abnormally high, the microcontroller understands that the wheel is about to lock up. The microcontroller immediately changes the braking pattern to either that wheel individually or to all wheels so that the wheel lock up is avoided. The above figure shows the control strategy for ABS. In some ABS systems, an Electronic Control Unit (ECU) is dedicated for optimum braking purposes [14]. The ECU takes into consideration the wheel speed and the change in wheel velocity during braking and then gives the optimum braking pattern to the wheels which rules out the possibility of wheel lock up [10]. For e.g., the pressure on the brakes will be kept less on a slippery road so that the wheels don't get locked up. The ECU is a useful tool to have during hard braking situations. When brakes are pressed hard to prevent an accident or in any other panic situation, the ECU monitors the sudden change in speed and adjusts the braking pattern accordingly to prevent wheel lock up which would have happened almost immediately in normal conditions after hard pressing of the brakes.

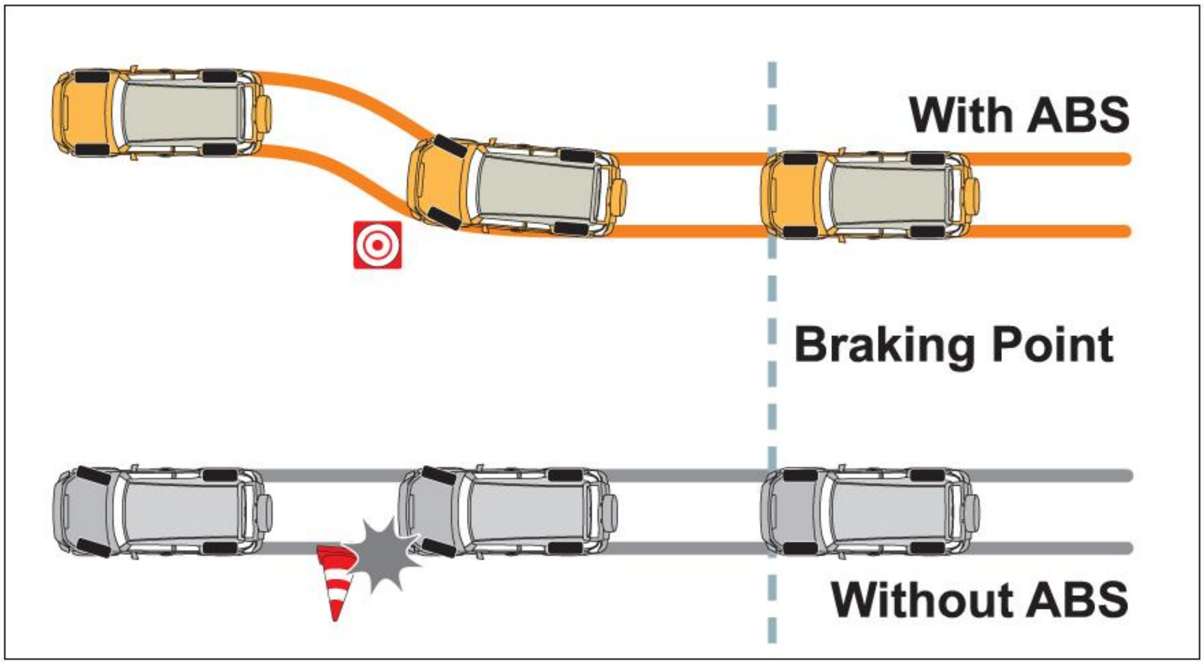

Figure 3.4 : Effect of using Anti-lock Braking System

Hybrid Electric vehicles which Anti-lock Braking System may have an hydraulic braking system. Here, the braking is done by using pressure of a hydraulic fluid like oil to press the brake pads onto the disc brakes. According to the control strategy, the sensors continuously monitor the wheel speed. During braking, if the wheel deceleration is more than a certain value, the controller knows that the wheel is about to lock up [13,15]. So the control unit drains some of the hydraulic fluid into another accumulator so that the correct amount of braking pressure may be applied to avoid wheel lock up. When the deceleration value decreases and it is safe to apply more braking power to stop the vehicle, the control unit transfers the fluid kept in the accumulator to the main chamber. This system using a control unit is fast and the process of removing the hydraulic fluid to adjust the brake pressure and then giving it back into the chamber when more pressure can be safely applied can be done as many as 15 times per second. The wheel speeds are continuously monitored and for small and medium braking, not much intervention of the control unit is required although the braking is under observation from the sensors at all times. The above mentioned process is vital to the system when the brakes are pressed hard i.e. in a panic situation or to avoid an accident, and using it the braking process is done fast, accurately and safely.

3.2 Regenerative Braking

Regenerative Braking is an energy recovery mechanism which saves energy which would have been otherwise wasted as heat due to friction while braking, and stores it in a capacitor bank or a flywheel setup temporarily. This energy is then given back to the battery thereby charging it. In Regenerative braking, an electric vehicles uses the motor as a generator when the brakes are applied, to transfer kinetic energy from the wheels which is wasted during braking into an energy storage device like capacitor bank. The energy wasted as heat can be up to 30% of the total energy and even if some portion of this energy is saved then it can be utilized to run the electric vehicle further.

3.2.1 History

Regenerative Braking was first used in the nineteenth century when a smart car using this technique was patented. In the smart car, an auxiliary spring is provided which stores excess energy from the motor as well as from the momentum of the vehicle. This stored energy in the spring can be used to assist in the running of the car or run the car for small distances if the motor gets disabled. This system of regenerative braking was modified and used in racing sports, where it is called as ‘kinetic energy recovery system’. This is used to provide higher acceleration to the cars over short distances by giving the recovered energy back to the motors. Regenerative Braking is also used in railways to recover energy during braking at stations and give it back to the main power line so that it can be utilised by other trains.

3.2.2 Operation

In regenerative braking, when a car needs to be braked, the motor is rotated in the reverse direction, or if the motor is an ac motor, it is then operated in the third quadrant of operation. The effect is that the motor now acts as a generator and provides energy back to the battery. In some cases, this energy may be stored in some alternative storage systems temporarily, like capacitor bank, flywheel, spring systems etc.

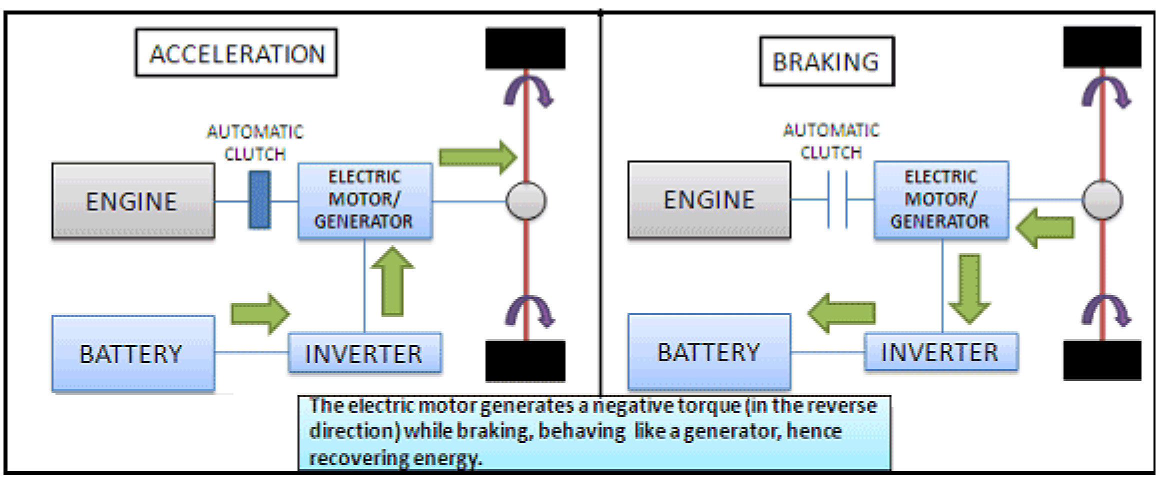

Figure 3.5 : Working of Regenerative Braking

Regenerative Braking is used in conjunction with friction brakes. In some cases, at slow speeds, the regenerative braking alone may not be sufficient to bring the vehicle to a complete halt. If the regenerative torque cannot be made high enough to match the braking torque, then the friction brakes make up the difference. Also, if the regenerative brakes fail, then the friction brakes act as a backup braking system. Regenerative braking can be used in both pure electric as well as hybrid electric vehicles [17]. In hybrid vehicles, the gas consumption is reduced because of it. The regenerative braking along with friction brakes can be used in two ways. First, the available braking power from regenerative braking can be calculated and the rest can be supplied by the friction brakes. In such a case, a microcontroller calculates such values in real time using the system parameters. The parameters involved are battery state of charge, vehicle velocity, motor capacity etc. Secondly, without using a controller, both regenerative brakes and the friction brake

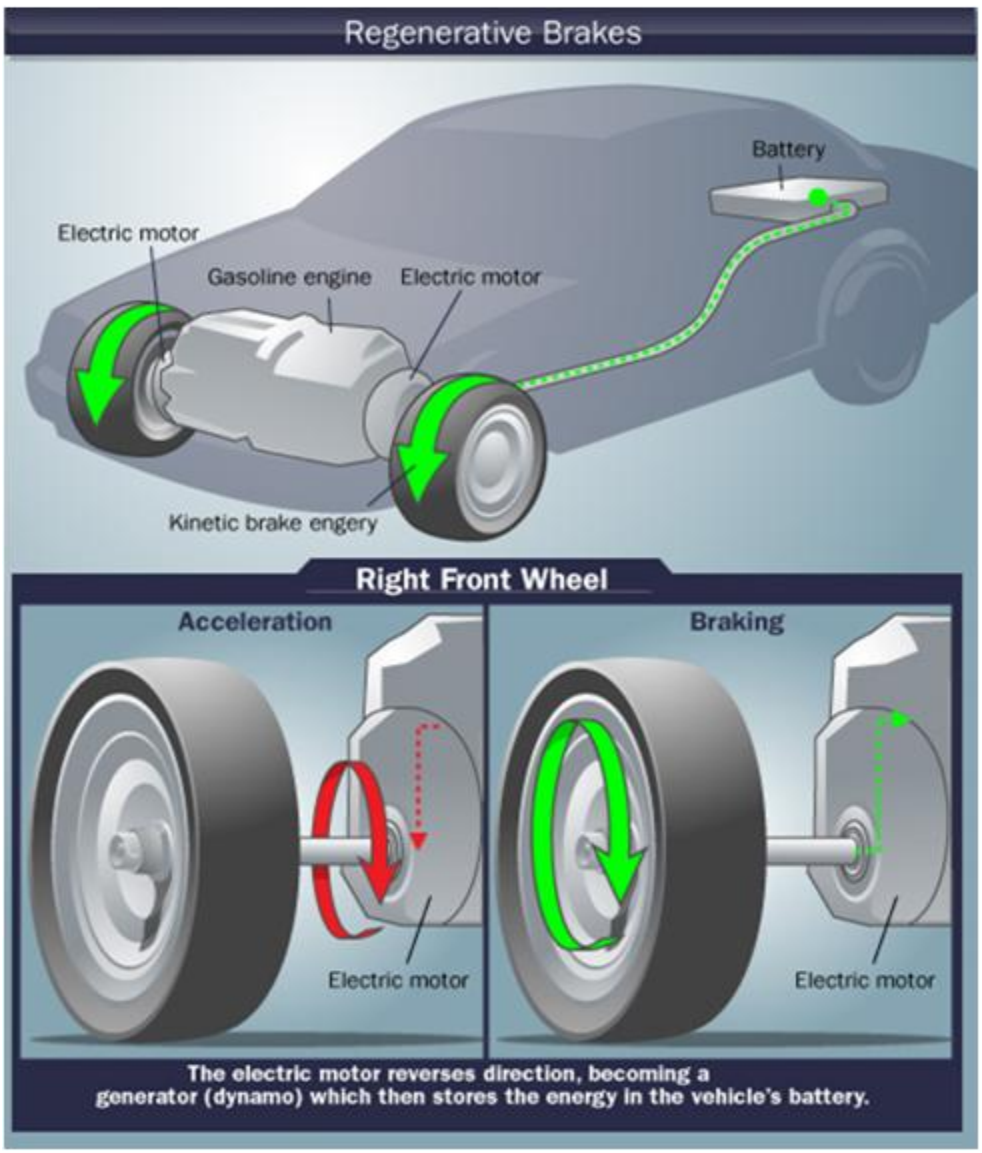

Figure 3.6 : Regenerative Braking in a Hybrid Electric Vehicle

can be applied in tandem. Regenerative braking is applied to only those wheels which are driven by the motor [16]. Hence, either only front axle or rear axle can have it. The other set of wheels can have frictional brake systems. Friction brakes systems need not be conventional brakes, and systems like Anti-lock Brake System can be used along with the regenerative brakes.

When a motor is used for regenerative braking, it is reversed in direction of operation. The shaft rotates in the same direction. But as a motor it consumes electricity to generate rotation of the wheels while as a generator, it uses the kinetic energy of the rotating wheels to generate electricity to give back to the battery.

3.2.3 Advantages

The advantages of Regenerative Braking are-

i. Energy which is wasted in frictional braking is recovered here.

ii. As load on frictional braking reduces, brake pads last longer.

iii. Energy is given back to battery which increases battery life and vehicle mileage.

3.2.4 Disadvantages

The disadvantages of Regenerative Braking are-

i. It cannot be used a standalone braking system and friction brakes too are required.

ii. Regenerative brakes are not that effective at lower speeds

iii. Regenerative braking can be used only on wheels which are driven by motor i.e. only the front axle or the rear axle.

CHAPTER 4

Implementation and Results

Experimental Test Circuit

PWM Circuit

Regeneration Circuit

PWM Circuit Waveforms

Simulation of Regenerative Circuit

Test Circuit in Hardware

4 IMPLEMENTATION AND RESULTS

4.1 Experimental test circuit

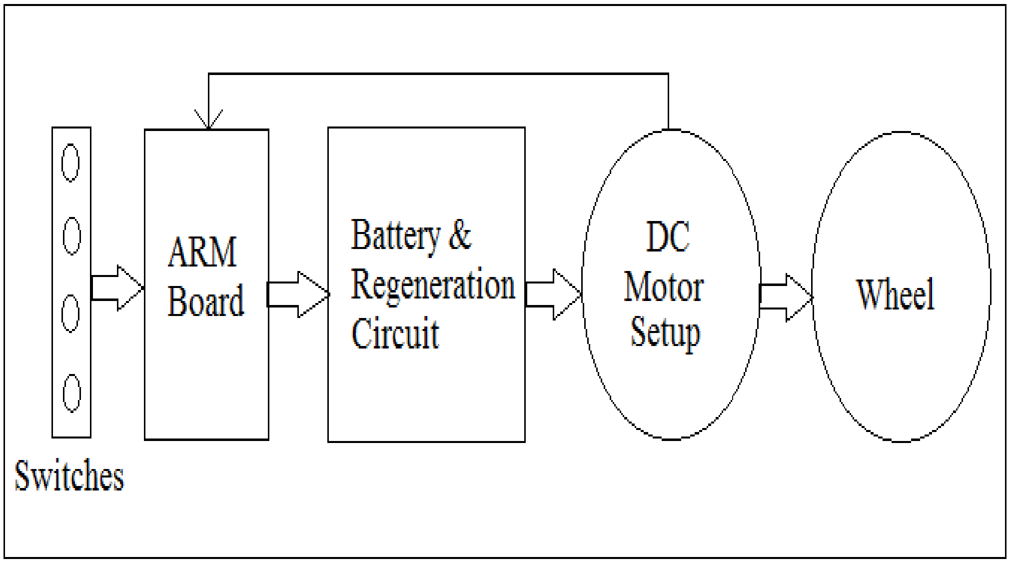

Figure 4.1 : Experimental Test Circuit

Anti-Lock Braking and Regeneration is tested practically using the experimental test circuit. This circuit has an ARM cortex microcontroller kit. ARM Cortex is a high speed microcontroller with 5 ports each of 16 bits, multiple advanced timers, serial and parallel communication protocols etc. This kit is used to receive and send signals to the circuit. A lead-acid battery pack is also present which provides energy to the circuit. The motor is a gearless DC motor with high rpm and is run through a motor driver IC. The motor driver IC provides higher current for driving the motor. For the purpose of testing, only a small wheel is connected to the motor. The wheel may be considered as a light load. The motor is connected to the wheel via a shaft. The wheel setup has a braking mechanism which is controlled using signals from the microcontroller. The Regeneration circuit has a battery pack and a capacitor bank which are connected to each other through an IGBT Buck-Boost converter. In the buck-boost converter, the IGBTs are operated as fast switches to allow or stop the flow of current through the capacitor Bank.

4.2 PWM Circuit

The PWM (Pulse Width Modulation) circuit is a part of the experimental test circuit. This circuit refers to the switches at the port side of the microcontroller and the pwm braking signals given through the output port pins to the braking mechanism in the experimental test circuit. There are 3 switches provided for variable speed function of the motor and these are used to emulate the accelerator pedal of a vehicle. The switches are connected to the pins of Port A which has been configured as an input port. The switches are used to generate low, medium and high speeds of the motor so as to emulate low, medium and hard pressing of the accelerator. Each successive switch increases the speed of the motor. For running the DC motor, a pwm wave is given on the Port E output pin which goes to the motor driver IC. Each switch is given a particular duty cycle value which can be changed by changing the value in the program burned in the arm microcontroller. General duty cycle values taken for the three switches are 25%, 50%, and 75%. The duty cycle of the pwm wave decides the average voltage of the dc motor thereby controlling its speed. Only one braking switch is provided in the circuit which is used to show hard braking of the vehicle.

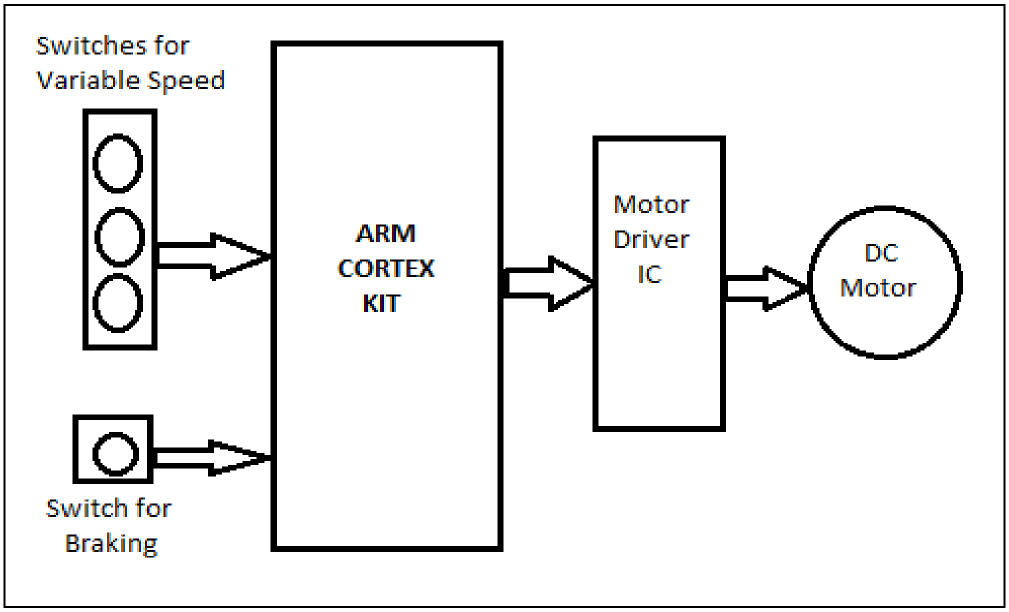

Figure 4.2 : PWM Circuit

Generally the wheels get locked up and the vehicle skids when it is braked hard from high speed and is brought to full stop. Hence this condition is used here. On pressing this switch, the microcontroller applies pwm braking to the motor until the motor is completely stopped i.e. the electric vehicle is completely brought to a halt. In PWM braking, the braking signal is not held continuously high as is the case in conventional braking. Instead, a controlled and varying duty cycle square wave is given as the braking signal. During the on time of the wave, the braking signal is high and the wheels are braked. During the off time of the wave, the braking signal goes low and the brakes are released. At that time the wheels can rotate and also any change in direction of the wheels can be done which is not the case in conventional friction braking. During the on time of the next cycle of the pwm signal, the brakes are again applied and the process continues. This applying and releasing of brakes takes places at fast speeds and the wheel can be braked and released up to 15 times per second, i.e. at a frequency of 15 Hertz.This allows the tires to better grip the surface, thus keeping the slip value low and at the same time maintain a small stopping distance. This type of braking avoids the problems caused during conventional friction braking without compromising vehicle safety and braking effectiveness. PWM braking ensures that the motor is stopped swiftly and without locking of the wheel due to hard braking and also without compromising the ability to change direction while braking. To show the variable speeds and the braking pattern signal, a DC Motor is used. The waveforms are observed on the CRO.

4.3 Regeneration Circuit

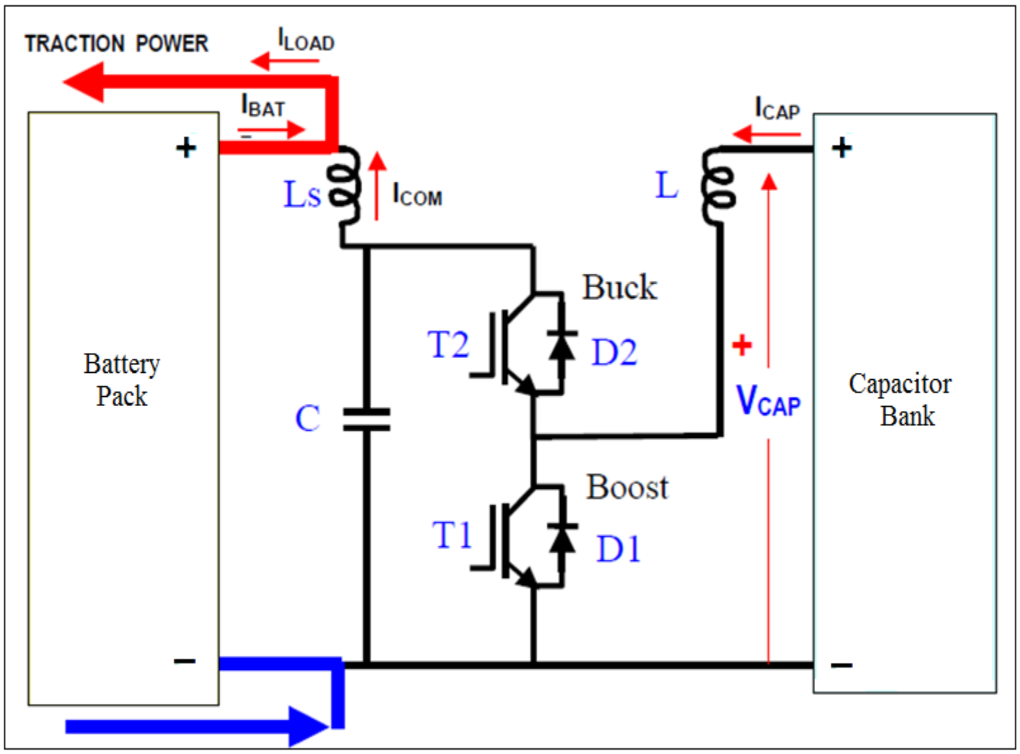

Figure 4.3 : Regeneration Circuit

The Regeneration Circuit [2,18] consists of a Battery pack which provides the energy to the circuit. The battery pack used here is a Lead-Acid Battery with nominal voltage of 12 Volts and a capacity of 1.3Ah. A Capacitor Bank is present which stores the energy temporarily which is generally wasted during braking in the form of heat energy. In the capacitor bank, capacitors are connected in parallel so that the total capacitance of the bank increases. The total energy stored in the capacitor bank [19] depends on the capacitance as well as the voltage of the capacitor bank. The Battery pack and the Capacitor bank are connected through the IGBT Buck-Boost Converter. The inductor L is taken of value 10mH while inductor Ls has a value of 1 μH. The single capacitor used in the circuit is of 470 μF while the combined capacitance of the capacitor bank is 7.6 mF. The voltage rating of all capacitances is 35 Volts.

The two operations which take place in the regeneration circuit are the Buck operation and the Boost operation [20]. The Buck operation takes place during deceleration of the vehicle i.e. when the vehicle is braked. In the circuit, this is done by pressing the braking switch. The Boost operation takes places during the acceleration of the vehicle i.e. when the electric vehicle goes to a higher speed from a lower speed. Here, this is achieved by pressing the successive speed switches provided.

In Buck operation, the converter diverts the current going to the motor from the battery to the capacitor bank. That operation is accomplished with a controlled Pulse Width Modulation (PWM) signal on IGBT T2. When T2 is turned ON, the energy goes to the capacitor bank from the battery pack through T2 and the inductor L stores some of this energy. When T2 is turned OFF, inductor L tries to continue the current and the remaining energy stored in L is transferred inside the capacitor bank through the path completed by diode D1. For Buck operation, the duty cycle of pwm signal given to IGBT T2 is generally 75%.

During the Boost operation (acceleration), IGBT T1 is switched on and off at a controlled duty cycle, to transfer the required amount of energy to the battery pack from the capacitor. During acceleration, more power is required to provide more current to the motor and this extra current is given to the battery from the capacitor bank. When T1 is switched ON, energy from the capacitor bank is stored in the inductor L and the path is completed through IGBT T1. When T1 is turned OFF, the energy stored in inductor L is transferred into capacitor C through the diode D2 and then into the battery pack. The inductor Ls is placed to soften the current pulses going into the battery pack. The battery gets this extra current from the capacitor bank, but to increase the existing voltage of the battery, many boost cycles are required as capacity of the battery is high and Lead-Acid batteries generally charge slower. For Boost operation, the duty cycle given to the IGBT T1 is about 25%. During this operation, the capacitor bank does not empty out its entire charge. This depends on the amount of current which can flow till the IGBT T1 is operated. If any charge is still left in the capacitor bank, it is stored as it is and is used during the next Boost cycle to return the energy back to the battery. In practical applications, if super capacitors are used, then the performance of the circuit is amplified due to the superior performance of super capacitors. Super capacitors are able to charge and discharge much faster than regular capacitors. Also their charge capacity is up to 20 times that of regular capacitor. The cost of super capacitors or ultra capacitors is higher but because of their superior performance, they can be used in such circuits for regenerative braking.

4.4 PWM circuit waveforms

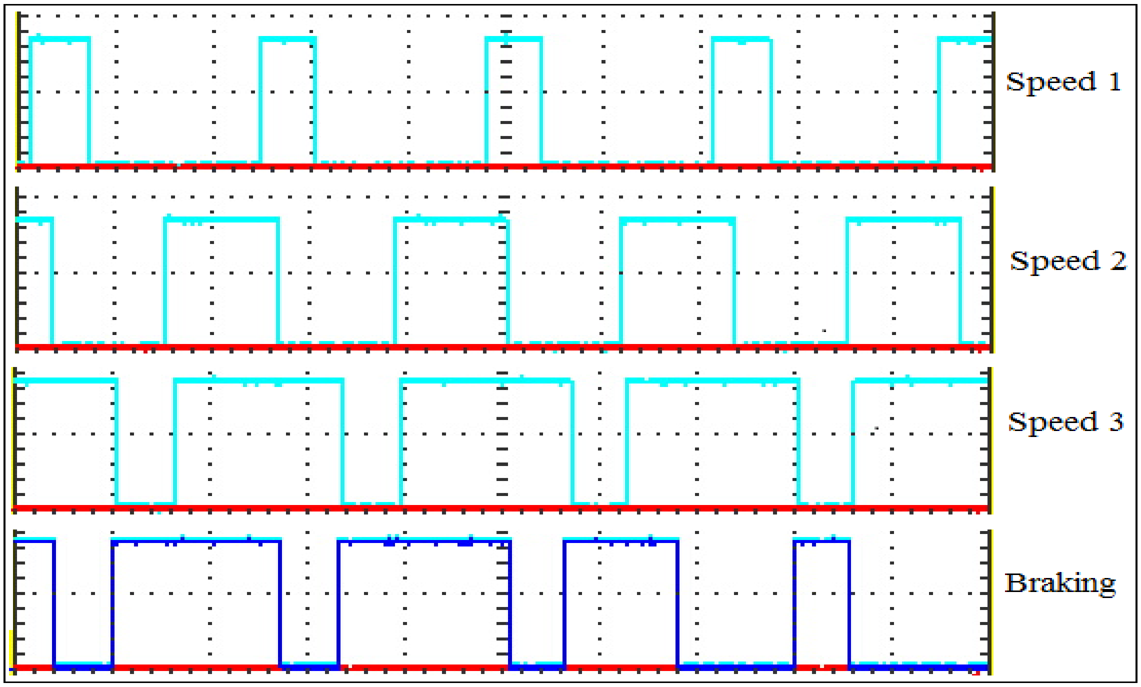

Figure 4.4 : PWM Waveforms

In the waveforms we can see the graphs for the 3 different speeds and the braking pattern graph. The corresponding duty cycle values for the 3 speed switches are set at 25%, 50% and 75%. When the braking switch is pressed, the duty cycle of the pwm wave given to the motor goes on decreasing continuously i.e. the braking pattern signal goes on increasing from lower duty cycle to a higher duty cycle in successive cycles. As a result, in a few cycles, the motor is brought to a complete halt by using this non-continuous braking pattern signal. In the waveforms, we can see that the voltage given to the motor goes on decreasing i.e. the speed goes on reducing till it becomes zero. Since, this type of pwm braking pattern is applied by using microcontrollers and other electronic devices, it can be applied at a faster frequency than what can be done manually. Typically, the pwm braking pattern cycle can be applied at a rate of about 15 hertz, i.e. the wheel experiences 15 cycles of pwm braking pattern in 1 second. Hence, there is no increase in stopping time or distance even when a continuous friction brake is not applied. Conversely, due to a non-continuous braking pattern, the brakes give a better performance in slippery roads which are covered in ice or water. The braking distance is also reduced and also directional control of the vehicle is always available with the driver even while braking.

4.5 Simulation of Regenerative Circuit

Simulation of regeneration circuit is done in Simulink (Matlab). The values of all components are set as described above. In the simulation, graphs are displayed in CRO scope for Battery Voltage, Battery Current, Capacitor Bank Voltage and Current, and PWM signal given to drive IGBT. Output is shown for 3 cycles of pwm wave which is given to the IGBT.

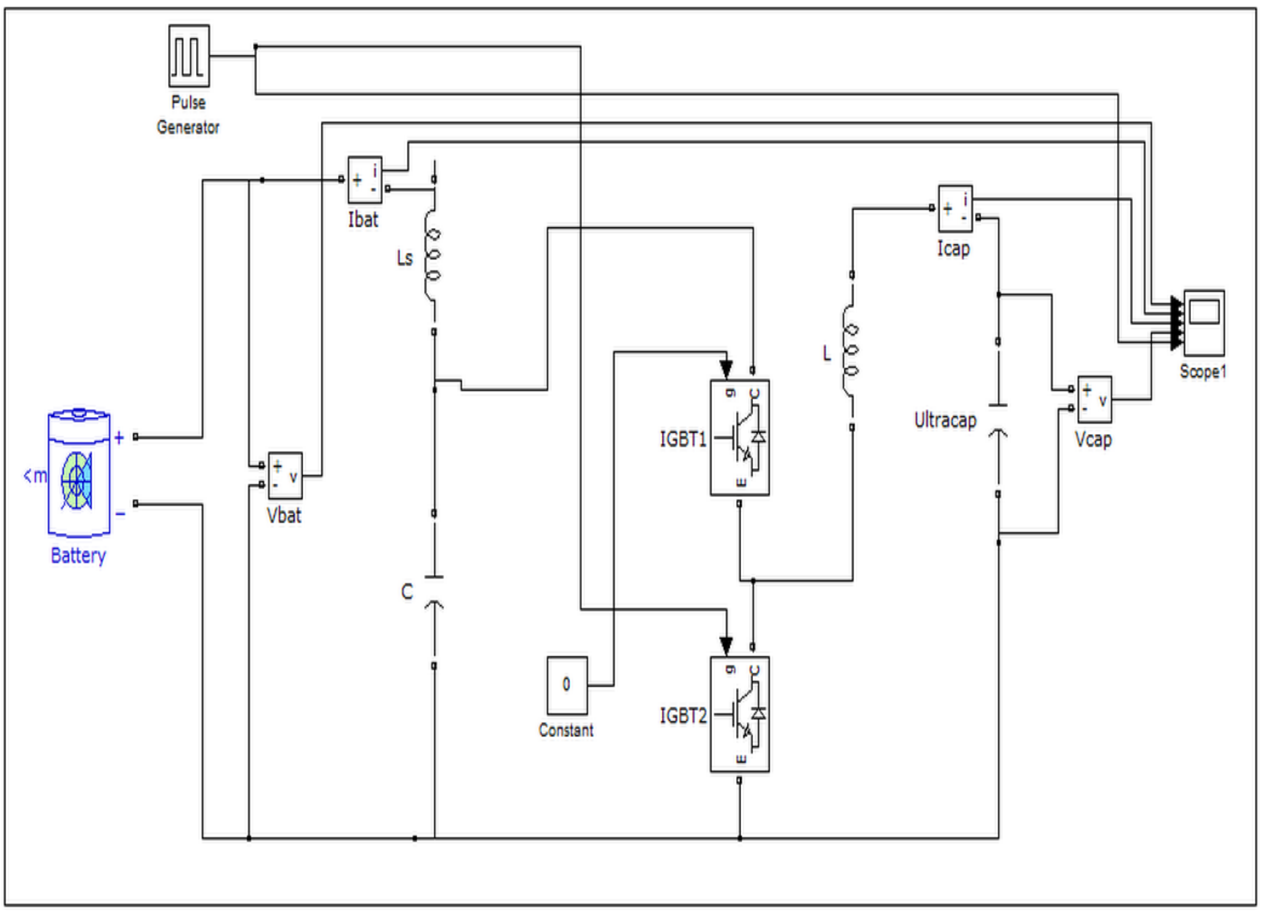

Figure 4.5 : Block Diagram in Simulink

During the Buck operation, we see that the capacitor bank voltage goes on increasing during successive cycles. The initial charge present in the capacitor bank is zero hence the voltage across the capacitor bank is also initially zero. The voltage across it then goes on increasing from zero to 11 volts at the end of the third cycle. The pwm wave given to drive the IGBTs is set at 60% duty cycle. We observe that the battery voltage is fairly constant around the 12 Volt mark with slight fluctuations. The current from battery side is drawn towards the capacitor bank only during the on time of the pulse given to IGBT and is otherwise zero. The current through the capacitor bank increases during the on time of pwm wave and decreases a little during the off time.

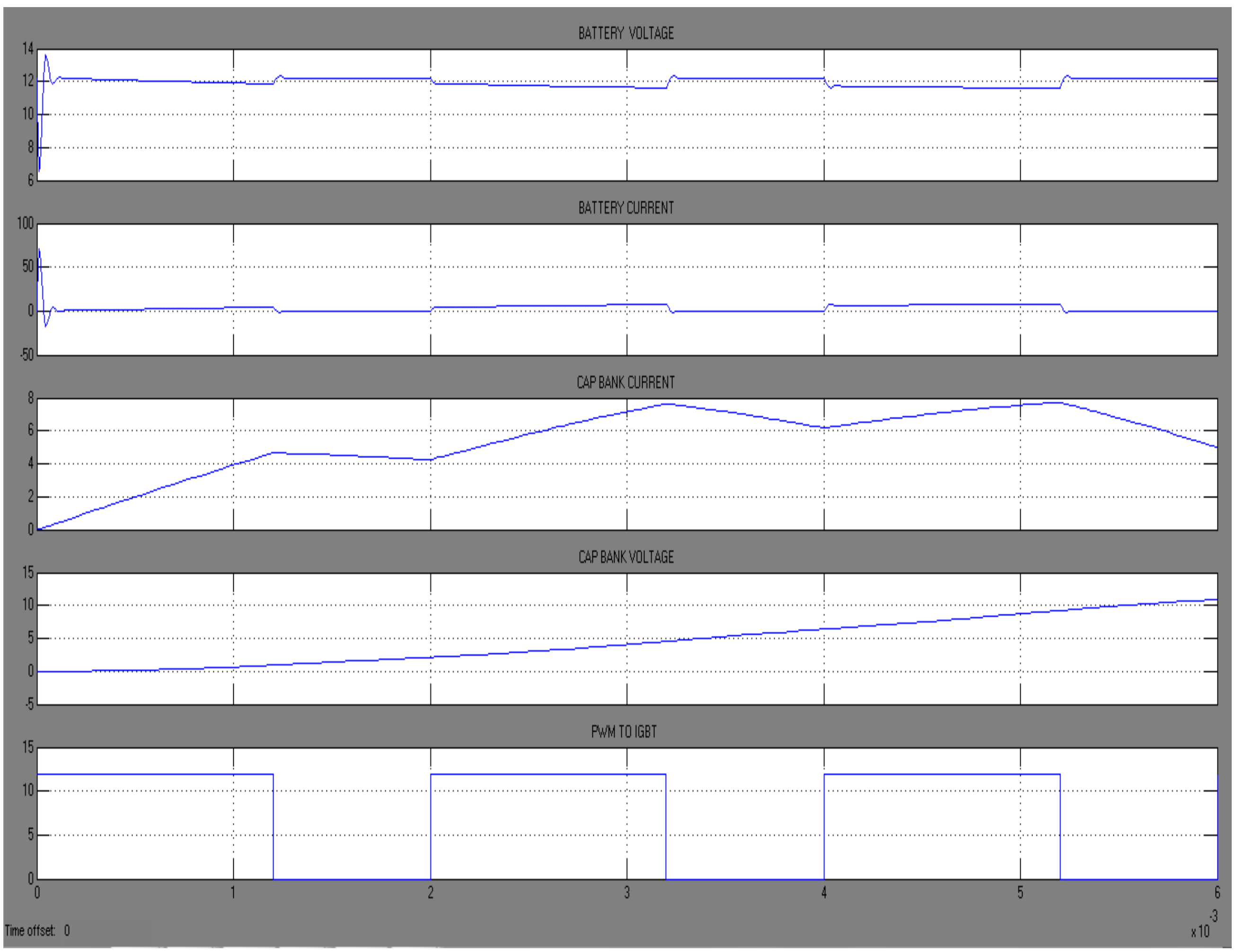

Figure 4.6 : Buck Operation Waveforms

During the off time, the charge stored in the inductor L is given to the capacitor bank and no extra current is taken from the battery side. This path is completed through diode D1. This charge inside the capacitor bank is stored there temporarily till the time the boost cycle occurs. During the Boost operation, we see that the capacitor bank voltage goes on decreasing during successive cycles. The initial charge present in the capacitor bank is whatever charge was stored in it during the previous cycle of buck operation. The voltage goes on decreasing from its initial voltage value till the boost operation is on. We can see in the graph of the boost cycle that the capacitor bank voltage goes on decreasing from 10 volts to 5.5 volts at the end of third cycle.

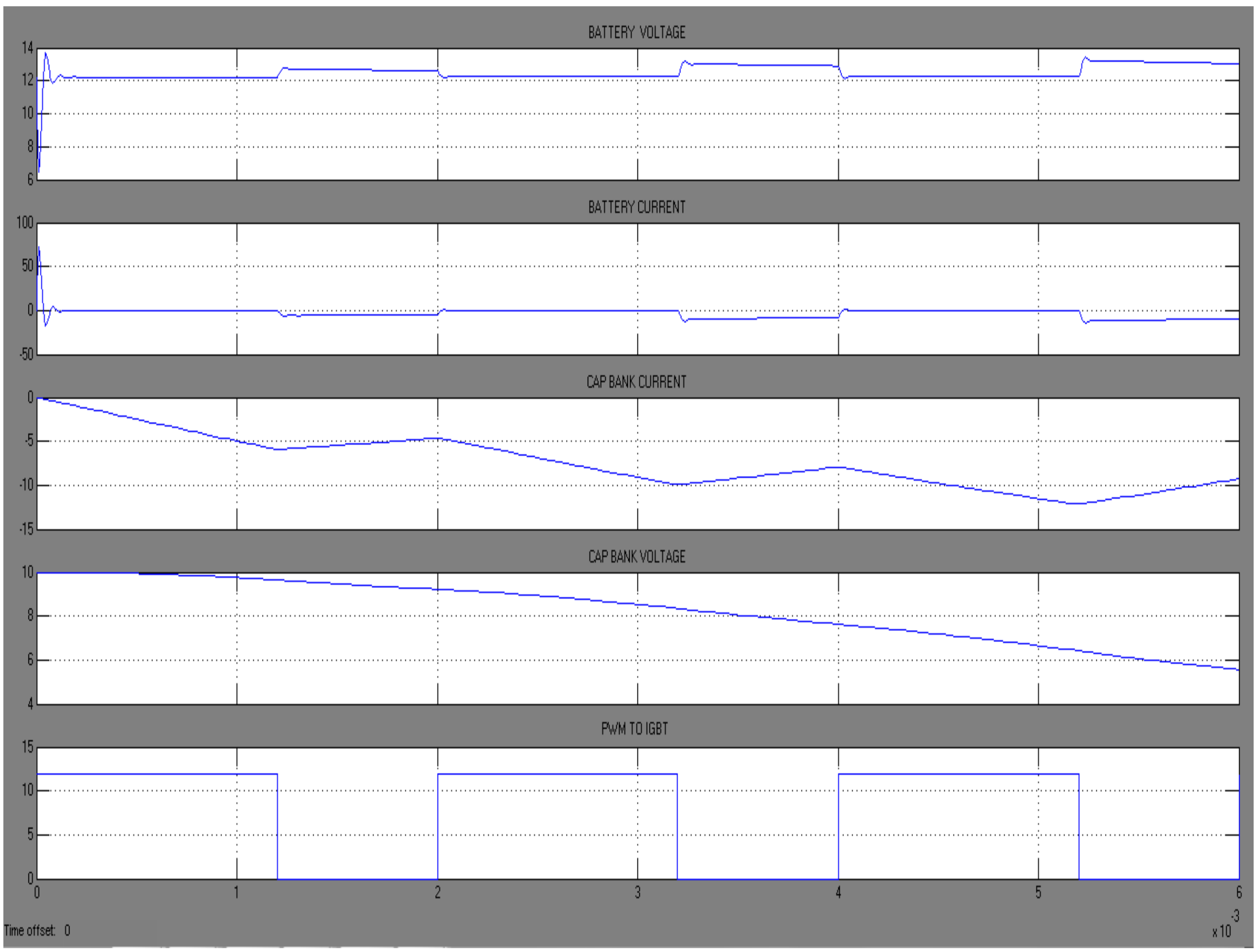

Figure 4.7 : Boost Operation Waveforms

Like buck cycle, here too the duty cycle of the pwm wave used to drive the IGBT T1 is kept at 60%. We see that the capacitor bank gives out more current during the on time of the cycle and the current reduces from the bank during the off time. This is because the charge that is stored in the inductor L during the on time is now transferred towards the battery. During the on time of the pwm wave, no current reaches the battery and hence the battery current is zero. During the off time, the inductor provides current to the battery and hence the battery current shows a negative value. Due to this current intake, the battery voltage also goes on increasing and hence at the end of the third cycle we see that the battery voltage increasing from being 12 volts initially to around 13.2 volts. There is still charge left in the capacitor bank and hence the voltage of the bank is 5.5 volts. This charge remains in the capacitor bank as it is until the next boost operation takes place and at that time the charge is transferred to the battery as described.

4.6 Experimental Test Circuit in Hardware

While testing the regeneration circuit in hardware, a few changes are made from the circuit used in simulations. The two IGBTs used in buck-boost converter are replaced by power MOSFET ICs. The power MOSFETs have 3 terminals, namely drain, source and gate which are equivalent to the IGBT terminals of collector, emitter and base. The threshold voltage for a power MOSFET is 2 volts. The frequency of the pwm signal to the mosfets is increased from 2 mS in simulation up to 200 mS in hardware. This pwm signal is generated by using advanced timers in the ARM cortex microcontroller. According to the desired pwm wave to be generated, the code is written and burned in the microcontroller.

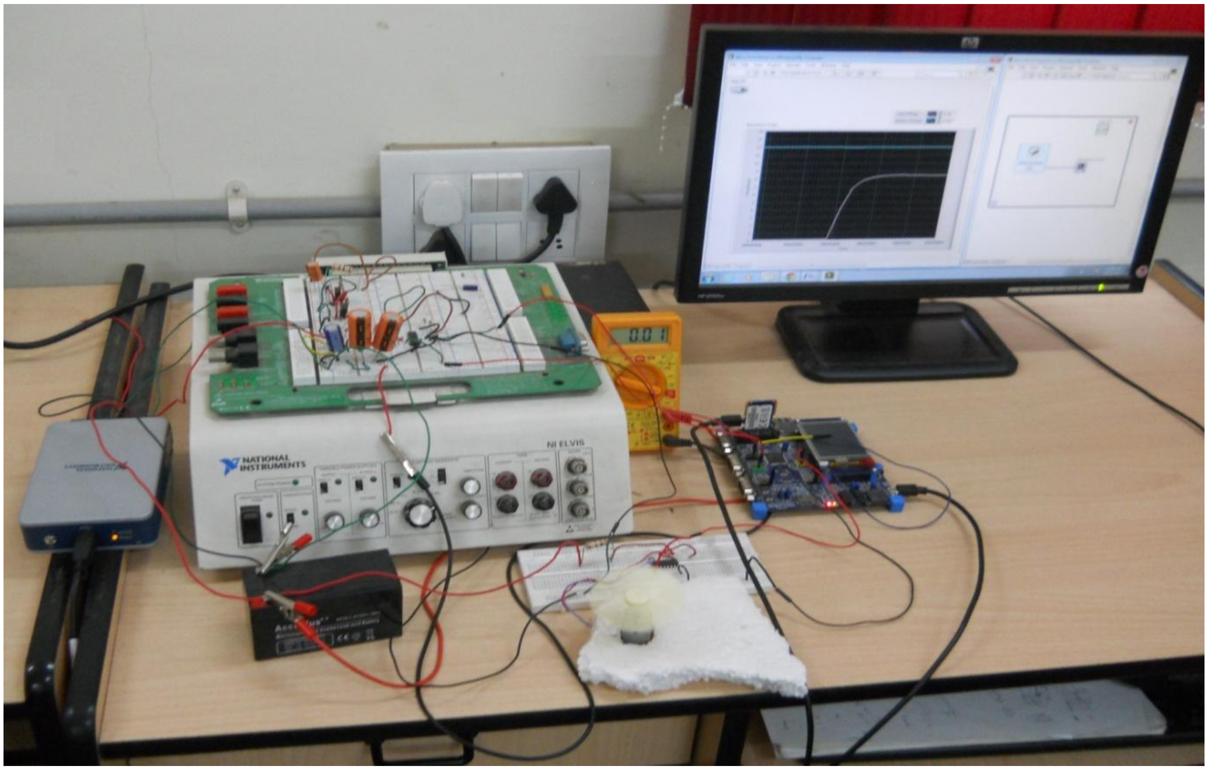

Figure 4.8 : Experimental Setup in hardware

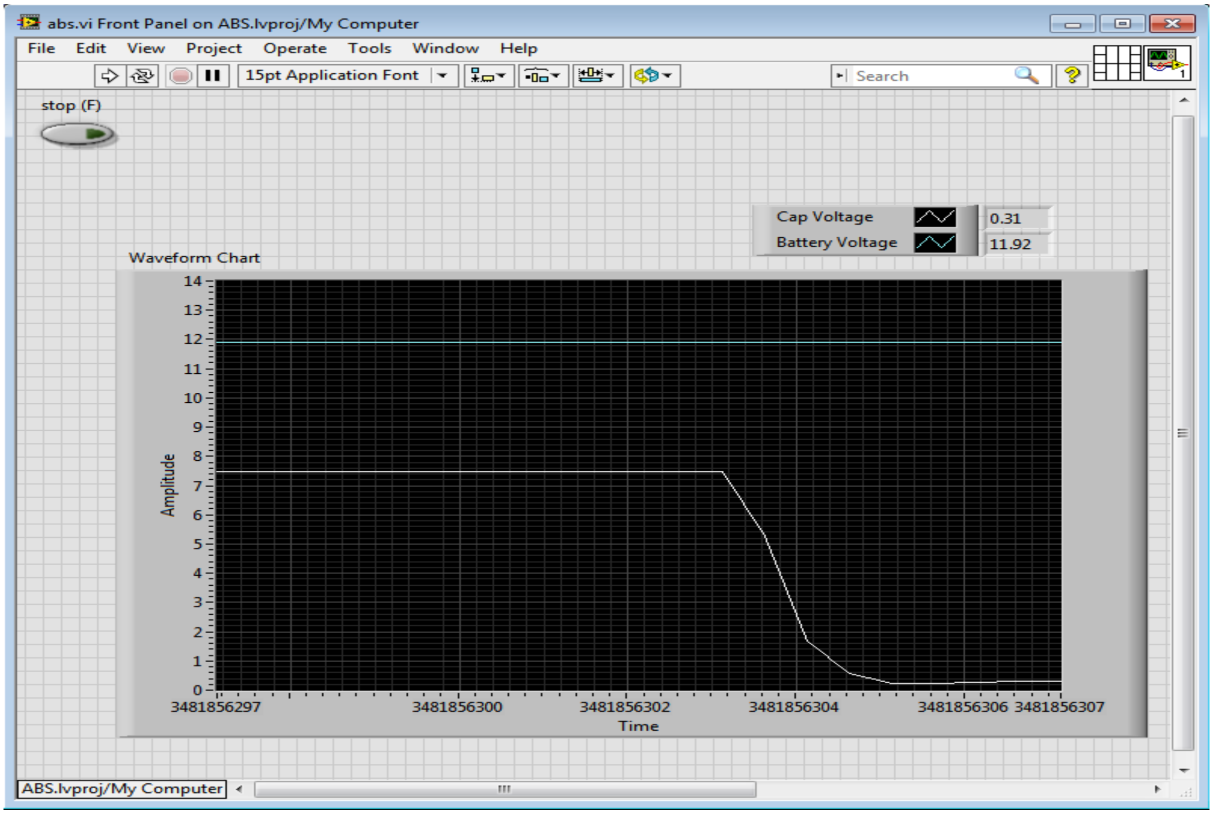

Figure 4.9 : Front Panel in Labview

The hardware setup is connected to the computer via a data acquisition card. The results are displayed in Labview software which shows the waveforms graphs as well as the numeric value of voltages in the circuit. The ARM Cortex microcontroller is also connected to the computer through USB connections and it works on 0 to 3.3 volt logic. The mosfets used in the circuit need higher voltage to drive them. Hence an Op-amp working as a non-inverting amplifier is used which amplifies the voltage to the 10 to 12 volts range. The pwm signals generated for the two power mosfets are first given to quad op-amp IC LM 324 and from there they are given to the power mosfets after being amplified. Each Buck or Boost operation is limited to 3 cycles as the deceleration or acceleration of the motor gets completed in that time and after that the motor either is at halt or runs at a steady pace. The microcontroller has 4 switches at its input port, 3 for

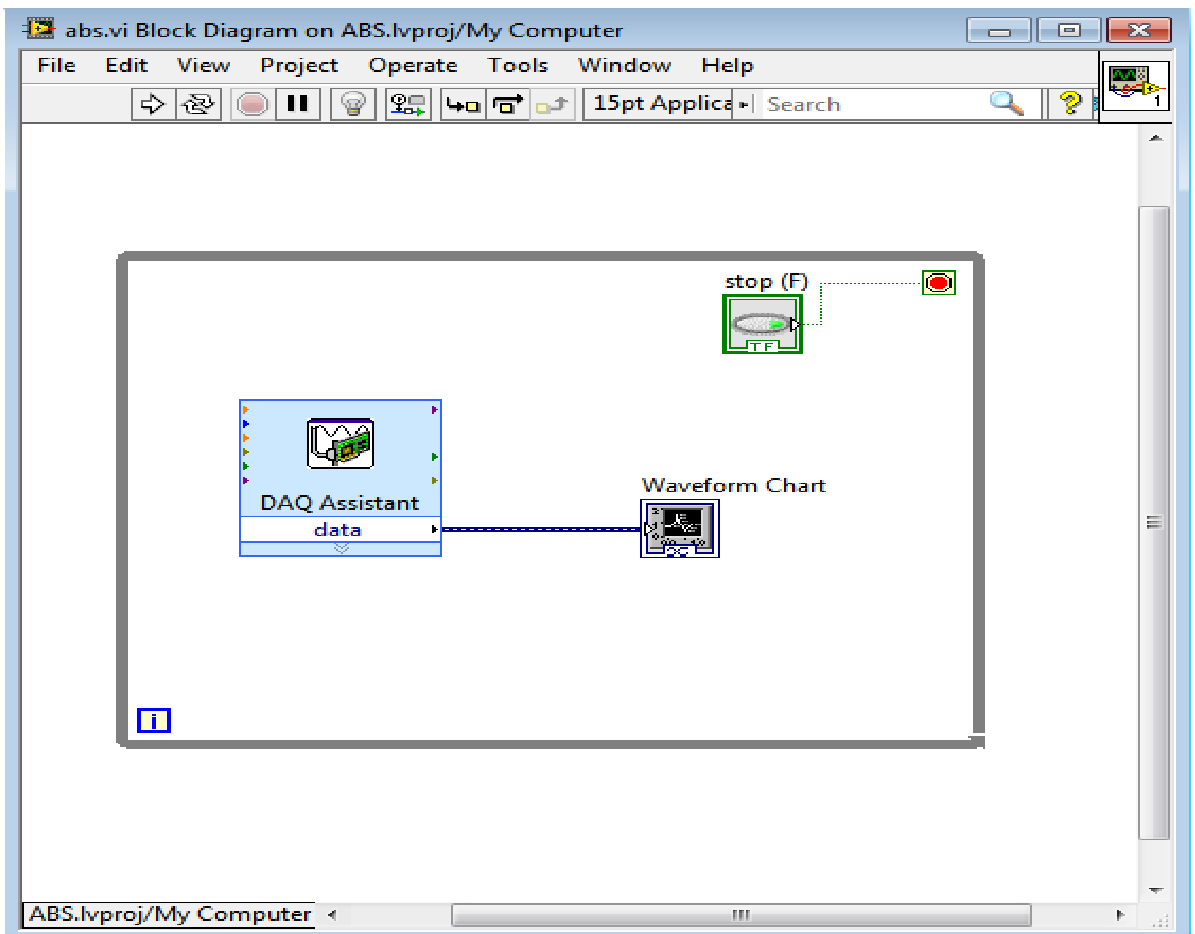

Figure 4.10 : Block Diagram in Labview

variable speeds and 1 for braking. When the motor is cruising at any steady speed and the braking switch is pressed, the braking pattern is generated and given to the DC motor. As a result, the DC Motor starts to slow down. Simultaneously, a pwm pattern is given to drive the mosfet T2 and the Buck operation is also started along with the deceleration of the motor. By the time the motor stops completely, the capacitor bank stores a certain amount of charge in it. After being at halt, pressing any of the speed switches starts the motor. After the motor starts running, when the third switch is pressed i.e. when accelerator is pressed hard, the Boost operation is started by sending a pwm wave to the mosfets T1. The charge which is present in the capacitor bank gets stored initially in the inductor L during the on time of the pwm driving signal, and

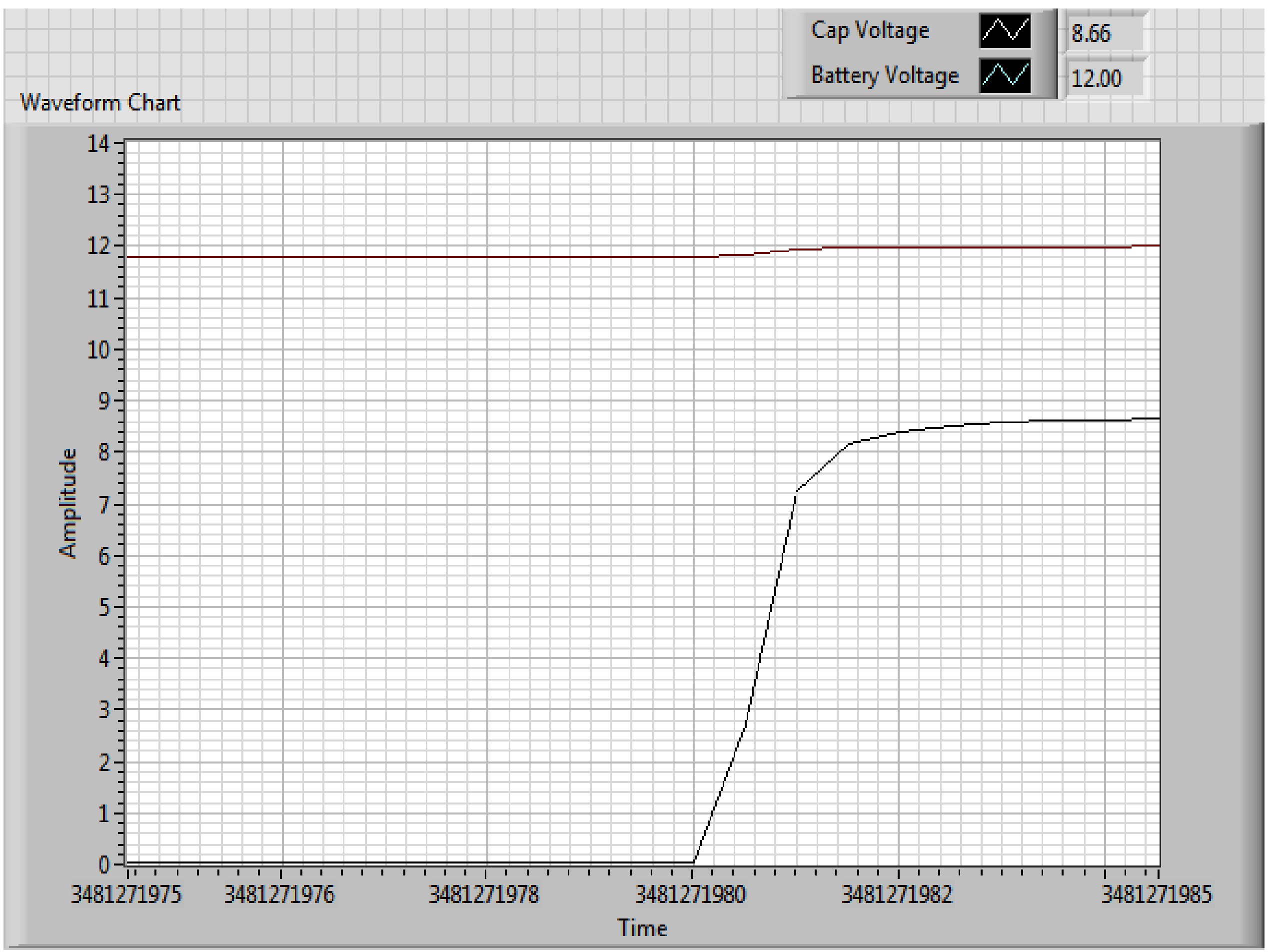

Figure 4.11 : Buck waveforms in Labview

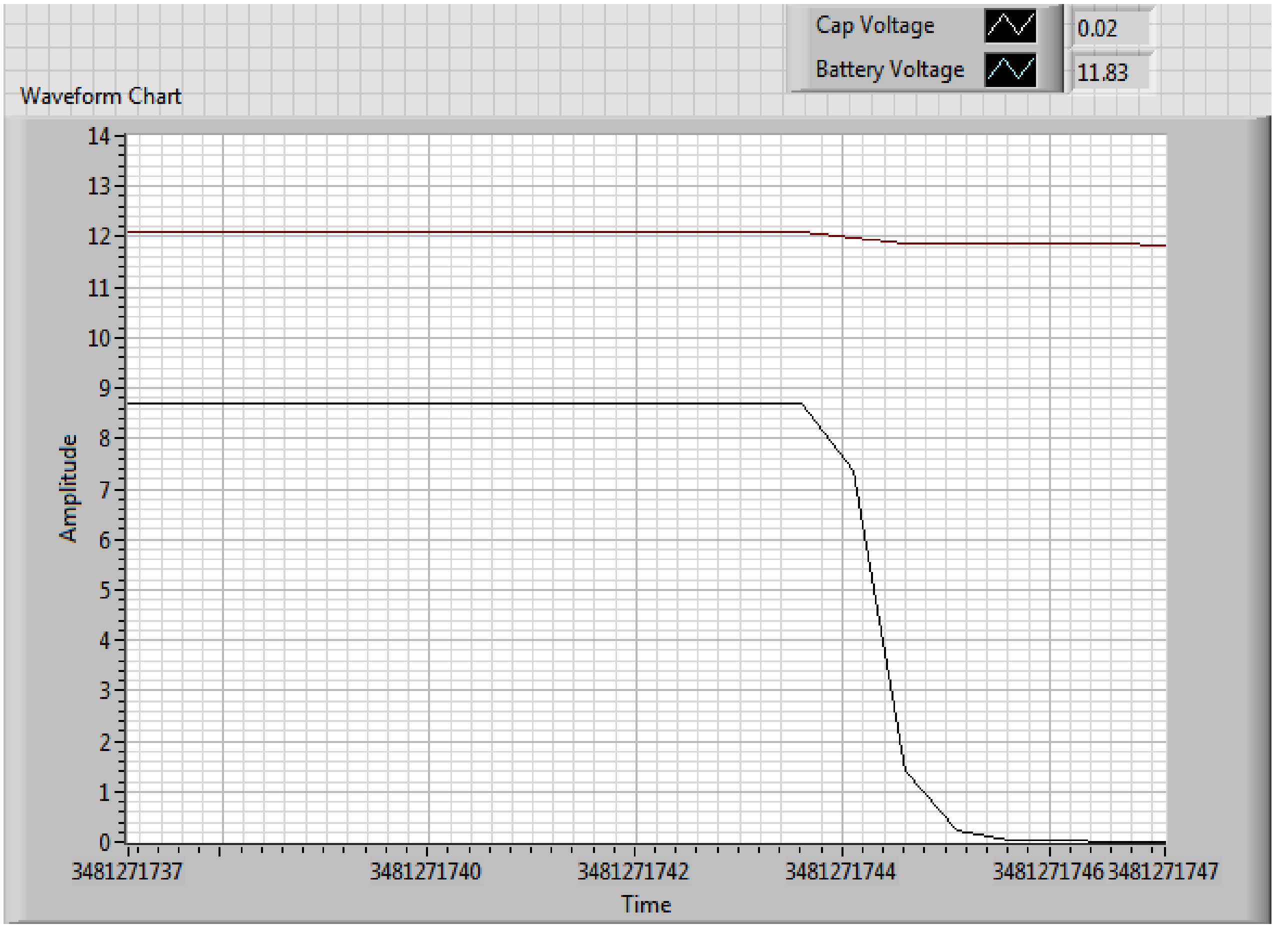

Figure 4.12 : Boost waveforms in Labview

during the off time, the charge is given to the battery. Although current flows back into the battery, unlike the simulation results where the change in battery voltage is instantaneous, here the there is not much change in the battery voltage as the lead-acid battery has comparatively slow charging and requires more instantaneous current to show a change in voltage than what is provided by the capacitor bank.

The capacitor bank gets charged to around 8.7 Volts after the Buck operation takes place. This value will vary if the duration and the duty cycle of the pwm wave used to drive the power mosfets is varied. The capacitance of the capacitor bank is of the value of 7.6 milliFarads due to multiple capacitors lined up in parallel.

The energy stored in the capacitor bank is given by-

$E = \frac{1}{2} \times C \times V^2$ .... Eq (4.1)

where E is the total energy stored in the capacitor bank, C is the total capacitance of the capacitor bank and V is the voltage across the capacitor bank.

Therefore, $E = \frac{1}{2} \times 7.6m \times 8.7^2$ = 0.287 Joules

The charge stored in the capacitor bank is given by-

$Q = C \times V$ = $7.6m \times 8.7$ = 66.1 milliCoulomb .... Eq (4.2)

While charging the battery back, a current of about 70 milliAmperes is observed during the Boost cycle. Hence the time for which the battery is charged can be calculated as-

$t = Q \div I$ = $66.1m \div 70m$ = 0.95 seconds .... Eq (4.3)

From this, the power can be calculated as-

$P = E \div t$ = $0.287 \div 0.95$ = 0.302 Watts .... Eq (4.4)

The charge, which is stored in the capacitor bank temporarily, is transferred back to the battery during the Boost cycle. Multiple cycles of boost operation will have sufficient charging effect on the battery so that the battery life is extended and the electric vehicle can run for longer distances and durations. For interfacing the analog voltage values in the circuit and for displaying them in Labview, we use a data acquisition card NI 9219. This DAQ card can process values from +60 to -60 volts. This card converts the analog values to digital and through USB connection gives it to the computer, where the DAQ assistant in Labview converts these values back to analog and displays them in real time. The waveform chart, which is used to display the voltages, shows the instantaneous values in both graphical form and numeric form in real time so that the values can be analyzed with ease.

CHAPTER 5

Conclusion

Conclusion

Future Work

5 CONCLUSION

5.1 Conclusion

Thus, Anti-Lock Braking provides better control of the vehicle to the driver and does not let the wheels lock up during braking there by reducing the chance of an accident occurring. The stopping distance using ABS is reduced in icy or wet road conditions than with conventional friction braking. Due to less heat being generated during braking, the brake pads too last much longer. ABS takes into consideration various factors before giving the braking pattern and hence the electric vehicle can safely stay within the stable slip region with no chance for a wheel being locked up. Even during the braking process, the driver is fully in control of the vehicle and can turn the direction of the vehicle at any instant.

The Regenerative circuit stores and returns the energy back to the battery which would have been otherwise wasted. The buck-boost converter depends on signals from the microcontroller and operates in real time so that the energy can be stored at the exact moment of deceleration and can be returned back during the few seconds of acceleration. The capacitor bank too charges and discharges fast so that the energy flow can be fast and efficient without much loss. This makes a battery last longer as well as allows an electric vehicle to travel further on a single battery charge i.e. the mileage of the electric vehicle increases substantially. Regeneration along with Anti-Lock Braking System makes an electric vehicle energy efficient as well as safer and easier to use and proves to be a vital part in the proper functioning of an electric vehicle.

5.2 Scope for Future Work

The extension of the project work carried out here will be to test the circuits on a prototype vehicle. Slip can be more effectively measured when all the four wheels are present and braking is applied on only one of the axles. This will increase the accuracy of the braking pattern provided. Also, the capacitor bank can be replaced by Ultracapacitors when the system works on a higher voltage level. Ultracapacitors are costly but the can store 20 times the energy stored in conventional capacitors and have much less energy loss. The ultracapacitors when used in an actual electric vehicle which may be working around a 300Volt DC battery supply prove to be cost effective as well as capable of providing a superior performance.

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DISSEMINATION OF RESEARCH WORK

[1] **Sagar Maliye**, Sudeendra Kumar, Kamalakanta Mahapatra, "Regenerative and Anti-Lock Braking System in Electric Vehicles", Proc. of IEEE International Conference on Advanced Communication, Control and Computing Technologies (ICACCCT), Tamilnadu, India, May 2014 (Accepted).

APPENDIX A

Features of ARM Cortex M3 STM32C Microcontroller:

- Core: ARM 32-bit Cortex-M3 CPU
  - 72 MHz maximum frequency,1.25 DMIPS/MHz
  - Single-cycle multiplication and hardware division
- 256 Kb of Flash Memory and 64 Kb of SRAM
- Up to 80 fast I/O ports
  - 51/80 I/Os, all mappable on 16 external interrupt vectors
- Sleep, Stop and Standby modes available
- 2 × 12-bit, 1 µs A/D converters (16 channels)
  - Conversion range: 0 to 3.6 V
  - Sample and hold capability
  - Temperature sensor
- 2 × 12-bit D/A converters
- Supported peripherals: timers, ADCs, DAC, I2Ss, SPIs, I2Cs and USARTs
- Up to 10 timers
  - Four 16-bit timers, each with up to 4IC/OC/PWM or pulse counter
  - 1 × 16-bit motor control PWM timer with dead-time generation and emergency stop
  - 2 × 16-bit basic timers to drive the DAC
- 2 CAN, 2 I^2C, 5 USART, USB 2.0, Ethernet MAC interfaces available

APPENDIX B

FAIRCHILD SEMICONDUCTOR®

IRF530

Data Sheet **February 2002**

14A, 100V, 0.160 Ohm, N-Channel Power MOSFETs

These are N-Channel enhancement mode silicon gate power field effect transistors. They are advanced power MOSFETs designed, tested, and guaranteed to withstand a specified level of energy in the breakdown avalanche mode of operation. All of these power MOSFETs are designed for applications such as switching regulators, switching convertors, motor drivers, relay drivers, and drivers for high power bipolar switching transistors requiring high speed and low gate drive power. These types can be operated directly from integrated circuits.

Formerly developmental type TA17411.

Ordering Information

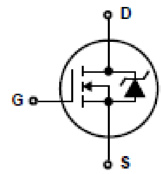
PART NUMBER	PACKAGE	BRAND
IRF530	TO-220AB	IRF530

NOTE: When ordering, use the entire part number.

Features

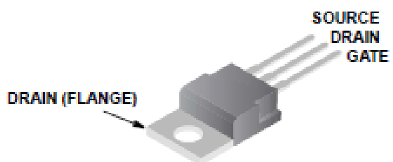
- 14A, 100V
- $r_{DS(ON)} = 0.160\Omega$
- Single Pulse Avalanche Energy Rated
- SOA is Power Dissipation Limited
- Nanosecond Switching Speeds
- Linear Transfer Characteristics
- High Input Impedance
- Related Literature
  - TB334 "Guidelines for Soldering Surface Mount Components to PC Boards"

Symbol



Packaging

JEDEC TO-220AB



APPENDIX C

LM124, LM224, LM324

Low power quad operational amplifiers

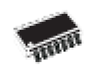
Features

- Wide gain bandwidth: 1.3 MHz
- Input common-mode voltage range includes ground
- Large voltage gain: 100 dB
- Very low supply current per amplifier: 375 µA
- Low input bias current: 20 nA
- Low input offset voltage: 5 mV max.
- Low input offset current: 2 nA
- Wide power supply range:
  - Single supply: +3 V to +30 V
- Dual supplies: ±1.5 V to ±15 V

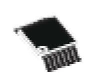
Description

The LM124, LM224 and LM324 consist of four independent, high gain, internally frequency-compensated operational amplifiers. They operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

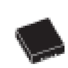
N
DIP14
(Plastic package)



D
SO-14
(Plastic micropackage)



P
TSSOP-14
(Thin shrink small outline package)



Q
QFN16 3x3
(Plastic micropackage)

1 Pin and schematic diagram

Figure 1. Pin connections (top view)

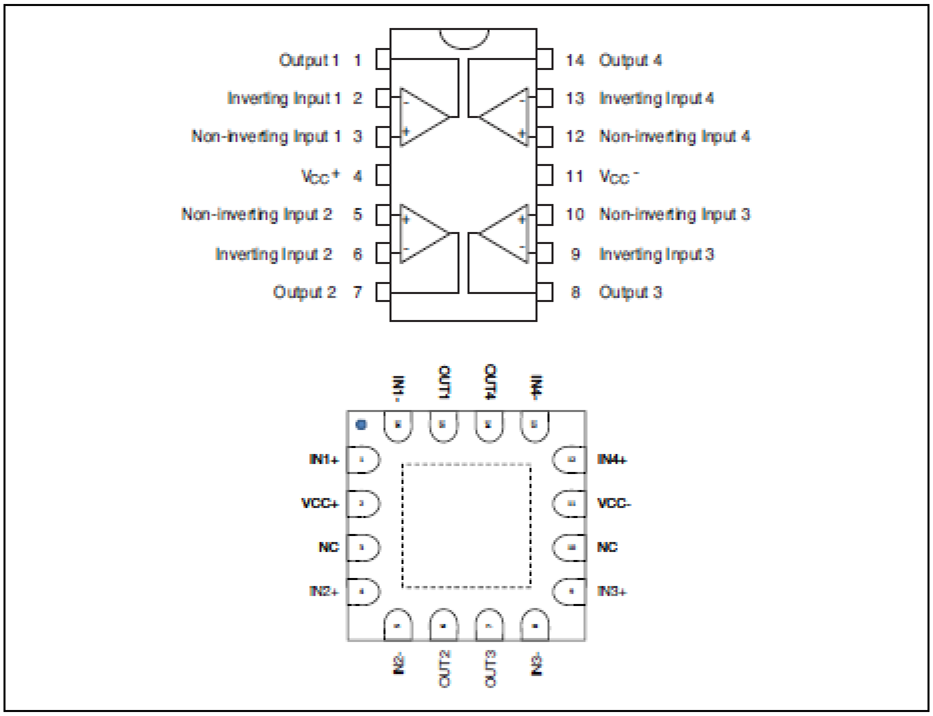
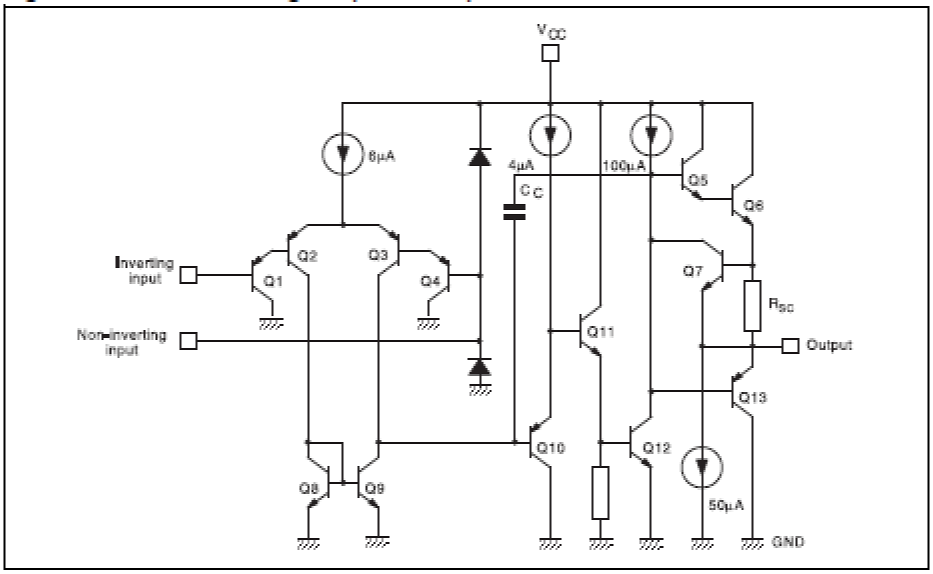


Figure 2. Schematic diagram (1/4 LM124)

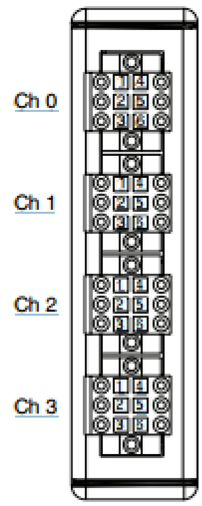


APPENDIX D

NI 9219

4-Channel, 24-Bit, Universal Analog Input Module

The NI 9219 has four 6-terminal spring-terminal connectors that provide connections for four analog input channels.



NI 9219 Signal Names

Terminal	Signal Name	Signal Description
1	T+	TEDS Data
2	T–	TEDS COM
3	EX+/HI*	Positive excitation or input signal
4	HI	Positive input signal
5	EX–/LO*	Negative excitation or input signal
6	LO	Negative input signal

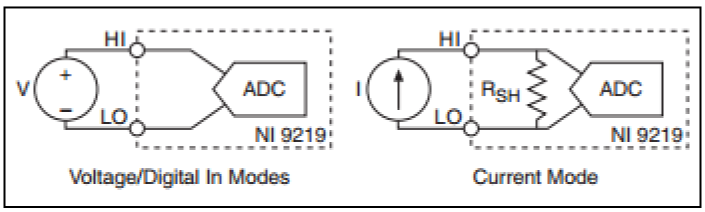
* Depending on the mode, terminals 3 and 5 are either the excitation signals or the input signals.

NI 9219 Terminal Assignments by Mode

Mode	Terminal					
	1	2	3	4	5	6
Voltage	T+	T–	—	HI	LO	—
Current	T+	T–	HI	—	LO	—
4-Wire Resistance	T+	T–	EX+	HI	EX–	LO
2-Wire Resistance	T+	T–	HI	—	LO	—
Thermocouple	T+	T–	—	HI	LO	—
4-Wire RTD	T+	T–	EX+	HI	EX–	LO
3-Wire RTD	T+	T–	EX+	—	EX–	LO
Quarter-Bridge	T+	T–	HI	—	LO	—
Half-Bridge	T+	T–	EX+	HI	EX–	—
Full-Bridge	T+	T–	EX+	HI	EX–	LO
Digital In	T+	T–	—	HI	LO	—
Open Contact	T+	T–	HI	—	LO	—

Voltage and Current Modes

In Voltage mode, the ADC measures voltage across the HI and LO terminals. In Current mode, the NI 9219 computes current from the voltage that the ADC measures across an internal shunt resistor.



Connections in Voltage, Current, and Digital In Modes

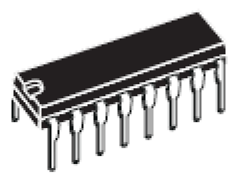
APPENDIX E

ULN 2003: Motor Driver IC

ULN2001A-ULN2002A
ULN2003A-ULN2004A

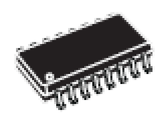
SEVEN DARLINGTON ARRAYS

- SEVEN DARLINGTONS PER PACKAGE
- OUTPUT CURRENT 500mA PER DRIVER (600mA PEAK)
- OUTPUT VOLTAGE 50V
- INTEGRATED SUPPRESSION DIODES FOR INDUCTIVE LOADS
- OUTPUTS CAN BE PARALLELED FOR HIGHER CURRENT
- TTL/CMOS/PMOS/DTL COMPATIBLE INPUTS
- INPUTS PINNED OPPOSITE OUTPUTS TO SIMPLIFY LAYOUT



DIP16

ORDERING NUMBERS: ULN2001A/2A/3A/4A



SO16

ORDERING NUMBERS: ULN2001D/2D/3D/4D

DESCRIPTION

The ULN2001A, ULN2002A, ULN2003 and ULN2004A are high voltage, high current darlington arrays each containing seven open collector darlington pairs with common emitters. Each channel rated at 500mA and can withstand peak currents of 600mA. Suppression diodes are included for inductive load driving and the inputs are pinned opposite the outputs to simplify board layout.

The four versions interface to all common logic families :

ULN2001A	General Purpose, DTL, TTL, PMOS, CMOS
ULN2002A	14-25V PMOS
ULN2003A	5V TTL, CMOS
ULN2004A	6–15V CMOS, PMOS

These versatile devices are useful for driving a wide range of loads including solenoids, relays DC motors, LED displays filament lamps, thermal printheads and high power buffers.

The ULN2001A/2002A/2003A and 2004A are supplied in 16 pin plastic DIP packages with a copper leadframe to reduce thermal resistance. They are available also in small outline package (SO-16) as ULN2001D/2002D/2003D/2004D.

PIN CONNECTION