

# **A Comprehensive Study on Battery Management System and Dynamic Analysis of Lithium Polymer Battery**

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5<sup>th</sup> May, 2016

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# **A Comprehensive Study on Battery Management System and Dynamic Analysis of Lithium Polymer Battery**

*Thesis submitted to the  
National Institute of Technology Rourkela  
in partial fulfillment of the requirements  
of the degree of*

***Bachelor of Technology  
in  
Electrical Engineering  
By***

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May 5, 2016

***Certificate***

This is to certify that the work presented in this thesis entitled “***A Comprehensive Study on Battery Management System and Dynamic Analysis of Lithium Polymer Battery***” by ***Agnivesh Satapathy*** (bearing Roll no. 112EE0097), ***Meghashree Das*** (bearing Roll no. 112EE0226) and ***Abhilash Majhi Samanta*** (bearing Roll no. 112EE0241) is a record of original research carried out by them under my supervision and guidance in partial fulfillment of the requirements for the degree of ***Bachelor of Technology in Electrical Engineering***. Neither this thesis nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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Date:

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# Declaration of Originality

We, hereby, declare that this thesis entitled “*A Comprehensive Study on Battery Management system and Dynamic Analysis of Lithium Polymer Battery*” represents our original work carried out by undergraduate students of NIT Rourkela and, to the best of our knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom we have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the thesis. Works of other authors, cited in this thesis, have been duly acknowledged under the section "Bibliography". We have also submitted our original research records to the scrutiny committee for evaluation of our thesis.

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# Abstract

The battery management system (BMS) is the most vital components of an electric vehicle. The main objective of the BMS is to ensure safe and consistent battery operation. To ensure proper functioning of the battery, state measuring and conditioning, cell balancing and control of charge are features that have been realized in BMS. The performance of different types of batteries is different under different environmental and working conditions. These irregularities in the performance of a battery are the primary challenge to the implementing of these functions in the BMS. State estimation of a battery, i.e. state of charge (SOC) and state of health (SOH), is a crucial function for a BMS. Li-Polymer battery has high discharge rate per unit mass and hence are very suitable for applications in electric automotive industry. This project addresses the modelling of a typical Li-Polymer battery and its dynamic characteristics. These battery models emulate the characteristics of real life Li-Po batteries, and help predict their behavior under different external as well as internal conditions. A dynamic model of lithium-polymer battery is designed using MATLAB/Simulink® in order to study the output characteristics of a lithium polymer battery unit. Dynamic simulations are done, which includes the effects of charging/discharging and operating temperature on battery terminal voltage output. The simulation results when compared to relevant studies, validated the model developed in the project.

**Keywords:** *battery management system; lithium-polymer battery; dynamic model; state of charge; state of health; effect of temperature*

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# **1 Introduction**

## **1.1 Overview**

An electric vehicle consists of these integral electrical components: electric motors, a motor controller, a traction battery and a battery management system, a plug-in charger, a wiring system, a regenerative braking system. The battery management system is one of the most vital components, when using Li-polymer batteries. At present, there are three types of batteries available: the lead-acid, nickel-metal hydride and lithium batteries. Lithium batteries have numerous advantages over its counterparts, and their performance is impeccable if they are operated using an efficient BMS. The Lithium battery requires minimal maintenance during its lifecycle, which is a big advantage since no scheduled cycling is required, and there is no memory effect in the battery. In addition to that, the Lithium battery is appropriate for electric vehicles because it has the least self-discharge rate high energy density and high operating voltage levels. However, Li-Po batteries, also have certain drawbacks. Lithium ions are brittle and hence to maintain the safe operation of these batteries, they require a built-in protective device in each pack. This device, BMS, limits the peak voltage of each battery unit during charging, thereby preventing the cell voltage to drop below a threshold during discharging. The BMS also controls the maximum charging and discharging currents and monitors the cell temperature. However, one of the major drawbacks of Li-Po batteries is that the batteries have a safe zone of operation beyond which the cell might get permanently damaged. It is clear that the goal of the BMS is to keep the battery operating within the safety zone; this could be done using safety devices such as circuit protection systems and thermal management systems.

To estimate the performance of battery under various conditions without any tedious and expensive prototyping and measurement for each prototype, a battery model is needed to be designed which reflects the real life characteristics of a Li-Po battery and can be used to evaluate their behavior under different conditions of charge/discharge and temperature variations. These models can be used to improve and optimize the battery system.

## **1.2 Literature Review**

### **1.2.1 Review on BMS:**

Simple BMSs could be designed using ICs and microcontrollers for low-power uses such as laptops. Electric vehicles, however, operate at very high voltage and current. Hence it is challenging to design BMS for such large number of battery cells. Monitoring and protecting the battery system, charge equalization and estimation of SOC and communicating with the vehicle

control unit, are few major functions implemented in the following BMS model designed by Qingyuan Electric Vehicle Inc.

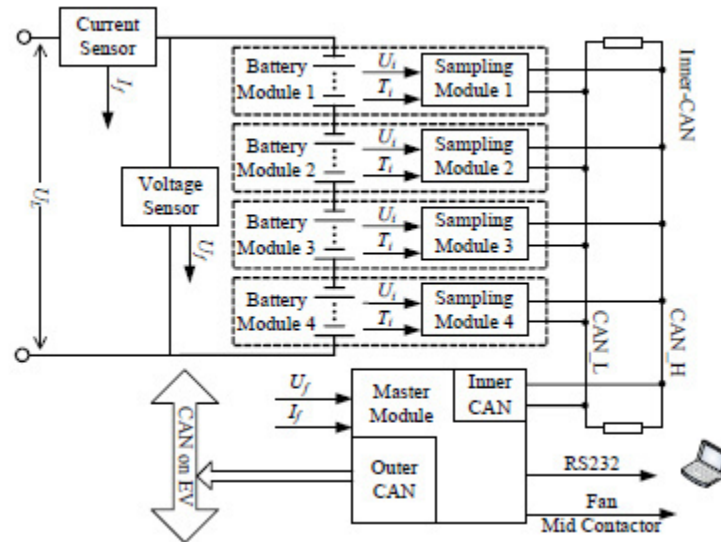


Figure 2-4 Structure of the BMS based on CAN-bus [16]

Reference [1] proposed a generalized BMS model whose major advantages over currently available BMS is that it is fault tolerant and provides battery protection. Also it has a number of battery modules that monitors and equalizes a string of battery cells.

Reference [2] proposed a digital Lithium battery charging and protection system using a DSP. However, use of DSP in the model instead of microcontroller increases the price of the BMS excessively. The following flowchart describes the operating principle of the model.

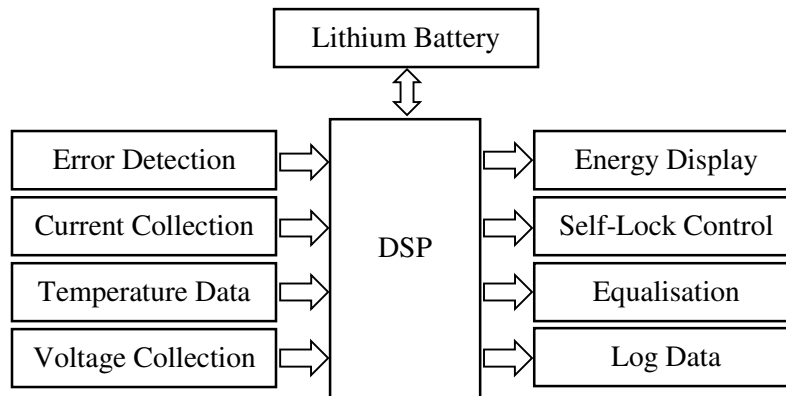


Figure 2-5 Principle of Battery Management System Based on DSP [18]

### 1.2.2 Review on Lithium Battery:

To get a better insight into the performance of Lithium batteries, various models are described in the later sections of the thesis. However, every suggested model has presented its own drawbacks. In some models, the transient behavior is neglected [8], while other works consider only fixed state

of charge [9]. Chen and Mora [7] proposed a model of the lithium battery that predicted the run time as well as the I-V characteristics accurately. This was done by considering both transient behavior and variable OC voltage and internal resistance. Even though this model doesn't consider the effects of temperature variations and capacity fading, these factors are very important to the performance of a lithium battery in terms of its battery life and safety. Following are few of the models suggested before.

### **Shepherd's Model**

Clarence M. Shepherd derived an equation that emulates the discharging processes of battery by calculating the potential during discharge and concluded that it is a function of discharge time, current density, and several other factors. He provided a complete description of the discharge characteristics of a cell. The model estimates cell charges, capacities, and the power developed by the cells, simultaneously calculating experimental errors.

However, the following assumptions were considered while mathematically analyzing the model:

- The cathode and/or anode had active porous materials present in them.
- The electrolyte resistance remained constant while discharging.
- The discharging current was considered constant.
- With the active material current density, the model had a linear polarization.

### **Tremblay Model**

Olivier Tremblay proposed a simple battery model with the help of simulation software. This model uses only SOC as a state variable to avoid forming algebraic loops to estimate other parameters. His model describes the battery chemistries accurately. The parameters of this model were taken from the discharge curve of the battery. The equivalent circuit of the battery however, had a simply controlled voltage source connected in series with a constant internal resistance. There were two limitations in this model.

- The minimum open circuit voltage was 0 V, whereas the maximum battery terminal voltage was not limited.
- The minimum battery capacity was 0 Ah, while the maximum capacity was not limited. Therefore, the maximum value of State of Charge could be greater than 100% in case the battery is overcharged.

### **1.2.3 Summary**

Battery modeling is very complex. A thorough knowledge of electrochemistry is needed. The two battery models mentioned above did not consider certain battery behaviors, such as self-discharging and capacity fading, which made the models less accurate. Neither of the models simulated actual battery performance because of their assumptions.

These assumptions are listed below:

- The internal resistance was assumed constant during the charge and discharge cycles; it did not vary with the amplitude of the current.
- The models assumed that the parameters could be deduced from the charging and discharging characteristics.
- The capacity of the battery was assumed constant regardless of the amplitude of the current.
- The models assumed that the battery would not self-discharge.
- The battery was assumed to have no memory effect.
- The temperature was assumed to have no effect on the behavior of the model

### **1.3 Problem Statement**

In this project, the battery and power system for an electric race car is needed. This power control system must satisfy the high current demands enabling optimum performance from the vehicle. Compatibility of all the components is a must and therefore, motor sizing should be done. For the protection and efficient performance of the battery unit, BMS should be installed. Meeting the guidelines of Formula SAE electric is the requirement that should be satisfied at all costs.

### **1.4 Objective**

Our objective is to do a thorough study of the operation and internal structure of all available BMSs in the market. We have to create a battery unit consisting of Lithium Polymer packs which includes proper cell balancing techniques and optimum performance while meeting the power demand. Hence we have to simulate the entire race in order to estimate the battery parameters as well as the motor specifications. The modelled battery unit must be compatible with the BMS of choice and the car. The SOC, terminal voltages and battery operation under various temperature are to be thoroughly studied.

### **1.5 Thesis Organisation**

The thesis is divided into 5 chapters. Apart from the introductory chapter, the other chapters are summarised below,

**Chapter 2** deals with the detailed study of Battery Management System. It describes the functions of a BMS, its internal structure and various topologies of BMS implementations. It reviews the currently available BMSs and also explains the concept and methods of cell balancing and other key features in a BMS.

**Chapter 3** explains the Lithium Polymer battery in details. It describes the characteristics of a Lithium battery and various models that can emulate real life behavior of Lithium Batteries. It suggests a model of the battery that includes the effects of capacity fading and temperature on the health of the battery. SOC estimations and related simulations are shown in the chapter in details.

**Chapter 4** describes the Permanent Magnet DC motor. Its working principle, equivalent circuit and torque speed characteristics are discussed in details. It also deals with the motor sizing problem by simulating the real race conditions in MATLAB and validating the compatibility of the chosen PMDC motor and the battery unit as a source.

**Chapter 5** discusses the conclusions drawn from the project and future scope of work in this project.

## **2 Battery Management System**

### **2.1 Introduction:**

A battery management system is a controlling unit, which works as a connecting module between the battery and the vehicle drive train. It also improves the battery performance significantly, along with a greater optimization of vehicle operations such as cruising or braking or continuous acceleration etc. It also has a pivotal role of maintaining the battery in a healthy condition and calculating the safety parameters for vehicle operations. It as a whole gives a factual idea about the state of safety, performance and longevity of the battery. It is an essential part of every electrical vehicle because of its control aspect, it uses feedback control method to get the vehicle to an optimum operating point without violating the safety conditions.

The battery management system prevents the overcharging of the batteries, which leads to explosion because of overheating, and also limits the over discharge reducing the cell capacity. BMS also addresses many abnormal conditions like over voltage or over current. It should monitor the abnormal conditions, notify the user and if necessary take fault clearing procedure. Typically a comprehensive battery management system in an electrical vehicle should have functionalities such as:

- Data acquisition
- Cell balancing
- Safety precaution
- Ability to determine as well as predicting the state of the battery
- Ability to control battery charging and discharging
- Thermal management
- Data delivery to the user interface
- Ability to communicate between all battery components

Simpler versions of battery management systems are used commonly in laptops and mobile phones. The complexity of designing and developing a BMS for electrical vehicles is more as the batteries in the electrical vehicles usually provide high current at a high voltage, which certainly requires advanced sensing and monitoring methods. The use of microprocessors in the system, not only ensures the flexibility in analyzing data provided by the sensor but also the prompt response to an abnormal condition. Different battery management systems follow a different algorithm to ensure protection and performance.

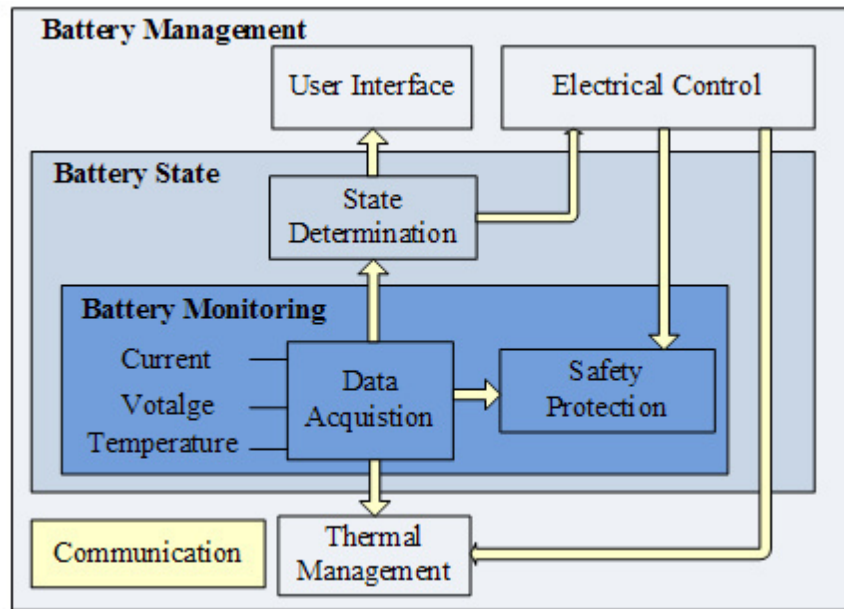


Fig 2.1: Block diagram of BMS

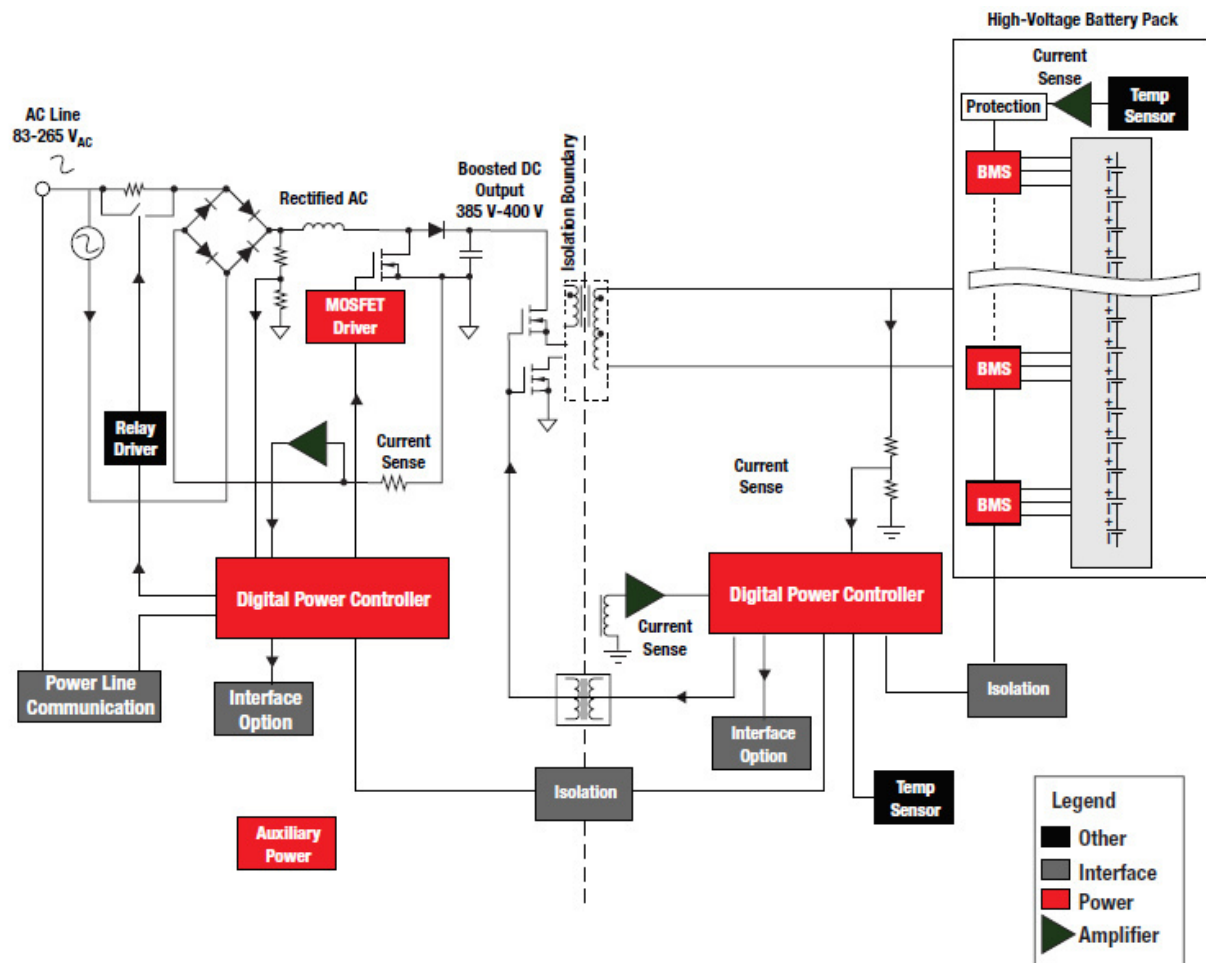


Fig. 2.2: Internal Structure of a BMS manufactured by Texas Instruments.



In the commercial level many BMS with different features are available, as for instance

**1. TI-EM1401-EVM:**

TI-EM1401-EV<sub>m</sub> is a chipset used in large format Li-ion batteries, which does the basic functionality of a BMS, that is, monitoring, balancing and communication among components. Each of these BMS can manage 6-14 cells (approx. 60V) for Li-ion batteries. This also comes with an independent protection for circuitry. Some of its features are:

- Active bidirectional cell balancing
- Multi-cell charge/discharge capability
- CAN BUS interface
- Isolated communication at a level of 5V
- Flexible design for 6-14 cells
- High accuracy in measuring the cell voltages

**2. Orion BMS:**

Orion BMS kit is the highest quality BMS available commercially for electrical vehicle and hybrid vehicles applications. Some of the features are:

- Capable of measuring 48/72/108 cells
- The centralized design which provides immunity to noise.
- Passive cell balancing
- State of charge calculation
- Discharge current limit and charging current limit calculation
- Cell voltage measurement from 0.5 V to 5 V
- Fully programmable dual CANBUS 2.0b interfaces
- OBD2 diagnostic protocol support

## **2.2 Functions of BMS:**

As discussed in the introduction part of Battery management system, the system performs a lot of functions from gathering data to analyzing it to implementing suitable pre-loaded algorithms to ensure safer functionality of the vehicle at an optimum operating point. Some of the important functions of BMS are:

- *Charging and Discharging Control:* The life period of a battery depends on the handling of it during the charging and the discharging periods. In most cases batteries get damaged due to improper charging than any other reasons. For Li-ion battery a constant current constant

voltage charging method is used for charging. In the constant current phase the charging device or the charger provides a constant current to the battery, because of which, the voltage of the battery increases till it reaches a constant voltage. After that the charger maintains this voltage as the battery current decreases in an exponential manner until the charging of the batteries is finished. While discharging, the discharge current should be controlled to ensure that the level of charge should not drop beyond a certain limit.

- *State of charge calculation:* State of the charge of a battery, calculated by the BMS, is used as a feedback signal in a control system or as a reference for the user to control the charging and discharging of the batteries. Primarily three methods are used to determine the state of charge of battery:
  - Direct measurement by using voltmeter
  - Coulomb counting
  - A combination of the above two techniques

In the coulomb counting method, battery current is integrated with respect to time to get the relative value its charge. In combination method when the actual charge approaches zero charge or full charge, the voltmeter is used to measure the battery voltage and calibrate state of charge.

- *State of Health (SOH) determination:* SOH gives a clear scenario of the battery performance compared to a fresh battery. Generally, cell inductance or cell capacitance are used to designate the health of the battery, as these parameters change with the age of the battery.
- *Cell balancing:* Cell balancing is a method, in which the charge of each cell in a series chain is equalized by compensating charge in the weaker cells to have an enhanced battery life. In a battery chain small difference in charge carrying capacity between two cells, present because of variable manufacturing or operating conditions, get magnified with subsequent charging discharging cycles. During these cycles weaker cells get overstressed and become weaker and weaker. In general, three cell balancing schemes are adopted. Each of those schemes has been discussed briefly below.
  - *Active cell balancing:* In this scheme, charge from a stronger cell is derived and supplied to a weaker cell.
  - *Passive cell balancing:* In this method, first the cells with the highest charge are identified by dissipative techniques and then the extra energy in that cell is removed through a bypass resistor till the charge or the voltage of that cell matches with other weaker cells.
  - *Charge shunting:* In the charge shunting method all the cell are first charged to the rated voltage of a good cell, then the current of the stronger cells are bypassed to the weaker cell till their voltages become equal.

- *Log book function:* The battery management system not only monitors and gathers the data to analyze them, but also holds data (both experimentally acquired and standard values of different parameters at normal working condition). The SOH of a battery is measured and compared to that of a fresh battery, because of which the BMS must have some reference data within it.
- *Communication:* Like many micro-processor based controlling system, the battery management system uses bi directional data links to get different parameter data from the sensors, to store this information and to deliver diagnosis based upon these parameters by offering central signals through communication. The selection of communication protocols depends on the battery applications. To ensure smoother operation of the vehicle, the BMSs, used in the electrical vehicles or in the hybrid vehicles, interconnect with upper vehicle controller as well as with a motor controller. The two main communication etiquettes are:
  - Data buses (for instance RS232, RS485 etc.)
  - Controller Area Network (CAN) bus (industry standard for on-board vehicle communication)

## 2.3 Topology:

The structure of a battery management system depends on the requirements of the vehicle performance. Each BMS topology or structure has some pros and cons of its own, because of which the choice of BMS topology solely depends on the implementation. Every structure has been divided into three basic layers according to their functionalities.

- *Battery monitoring:* This block of the BMS consists of sensors to gather data about different parameters. The real time data is acquired and are analyzed for conserving system security and optimizing performance.
- *Battery state:* This block of the Battery management system decides the charging time and discharge strategy through cell balancing methods.
- *Battery management:* This layer of BMS makes sure that there is proper thermal management among the batteries, continuous passage of information to the user interface and synchronized communication between the different components of the BMS.

There are three basic topologies in any battery management system. They are:

- *Distributed Topology:*  
In this topology, voltage monitors and discharge balancers, which can turn off the charging device and can report its status, along with digital communication devices are connected in parallel with each cell. These sub-controllers (sI, sII, sIII, ... in the figure) are connected to a master controller. Simplicity and reliability are the major advantages of this topology.

The biggest disadvantage of this topology is that it involves a lot of slave controllers and the difficulty in installing the boards on each cell.

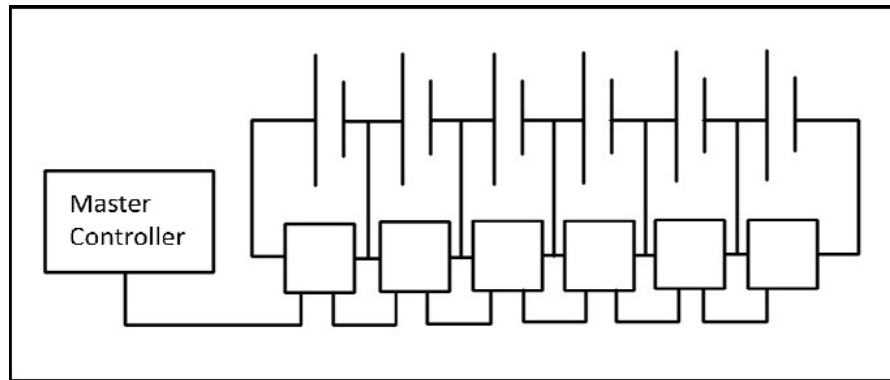


Fig. 2.3: Distributed topology of BMS

- *Modular Topology:*

In the modular structure, a few cells are controlled by a single slave controller and each of these slave controllers communicates with the master controller. No printed tiny circuit boards are not needed in this type of arrangement. But in electrical vehicles the interaction between master-slave controllers becomes a bit tough.

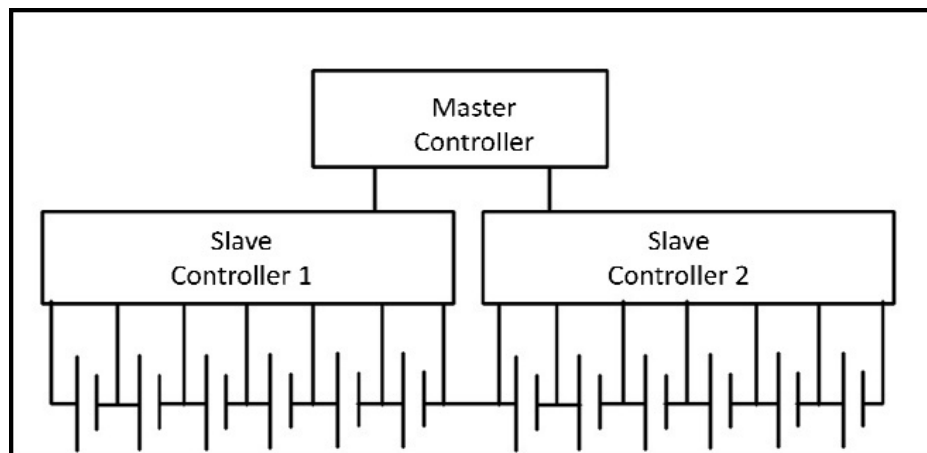


Fig. 2.4: Modular topology of BMS

- *Centralized Topology:*

Here, each and every cell in the battery pack is directly connected to a centralized master controller. The controller maintains the safety and increases the efficiency of each cell via battery balancing, while carrying out other important functions. This design is preferred because it only requires a single mounting point and there is no complex inter vehicle

communication. But with an increase in controlled units, the heat generated by the master controller increases exponentially. Wiring between the master controller and battery cells becomes difficult as all the cells are distributed at the various location the vehicle.

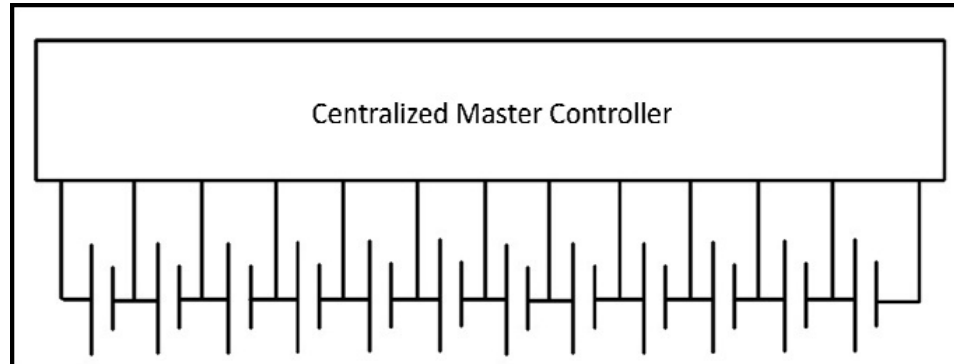


Fig. 2.5: Centralized topology of BMS

## 3 Battery

### 3.1 Lithium Polymer Battery

Lithium is the metal with maximum energy density per unit mass. Given its light weight and high electrochemical potential, it is preferred as anode in rechargeable batteries. Because of the instability of Lithium metal during charging, Lithium derivatives are fast replacing it. Lithium polymer and Lithium ion batteries provide much safer operation at a slight less energy density. However, proper safeguards have to be in place during the charging and discharging process. With virtually no maintenance, no memory effect and least self-discharge rate among all batteries, Lithium batteries are the obvious choices when it comes to powering an electric vehicle. Li-ion and Li-Po batteries need to be operated within a specific voltage range and the currents while charging and discharging must be monitored at each time instant to ensure safe operation within the permissible temperature range. This task is done by the battery management system.

The performance of the Li batteries is estimated by its terminal voltage and operating temperature. The peak voltage should not be allowed to exceed the permissible limit while charging and at the same time it should always be maintained above the threshold value during discharging. This ensures optimum performance of the battery and longevity of the battery life. The operating temperature of the battery should be controlled at all times. Battery is prone to damage when subjected to either higher temperature ( $> 45^{\circ}\text{C}$ ) or extremely low temperatures ( $< 0^{\circ}\text{C}$ ). Fig. 3.1 and 3.2 shows the permissible voltage and current limits while fig. 3.3 describes the effect of temperature on the battery life or the number of cycles. It is evident that the life of the battery is maximum when operated in the temperature range of  $15\text{-}25^{\circ}\text{C}$ . Any deviation from this range decreases the battery life drastically.



Fig. 3.1: Voltage vs Temperature – Safe operating zone



Fig. 3.2: Current vs Temperature – Current limits at different temperatures

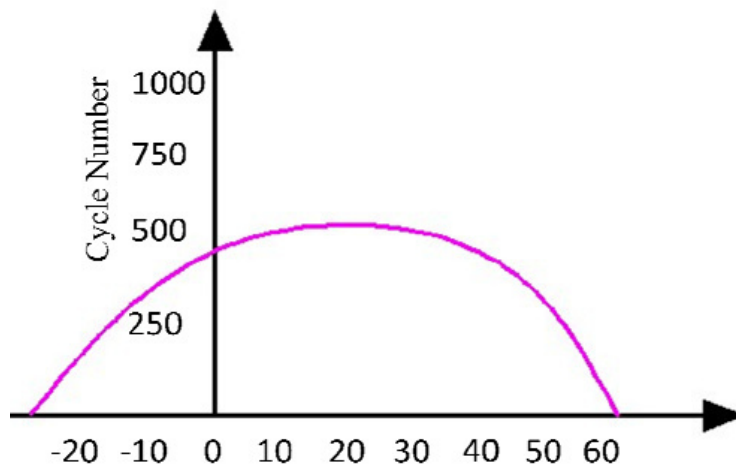


Fig. 3.3: Battery Life cycles vs Temperature graph

## 3.2 Battery Models

As discussed in the literature review, there are several battery models proposed under various assumptions and the equations of the model and their characteristic curves are described in this section of the chapter.

### 1. Shepherd Model

Governing equation is given by,

$$E = E_s - K * \frac{Q}{Q - it} * i - Ri + A \exp(-BQ^{-1}it)$$

Where,

E is the battery voltage;

$E_s$  is the constant potential;

K is the coefficient of polarization;

Q is the amount of active material;

i is the current density

t is the time

A and B are constants estimated from curve fitting.

### 2. Tremblay Model

This model makes a modification to the previous model by using a voltage controlled source in series with the internal resistance.

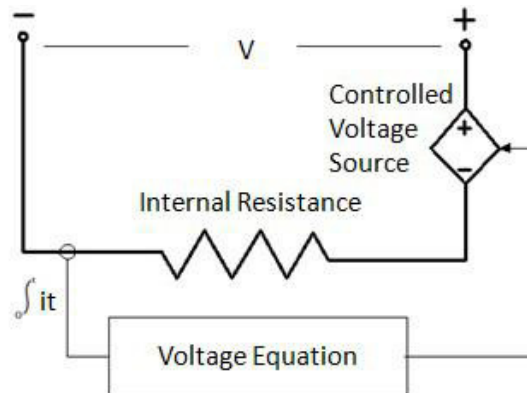


Fig. 3.4: Modification in Tremblay model.

Mathematically this change is described by the following equations,

$$V = E - Ri$$

Where,

V= Battery voltage;

E = No load voltage;

R is the internal resistance;

i is the battery current.



The characteristic discharging curve for a Lithium battery is as follows,

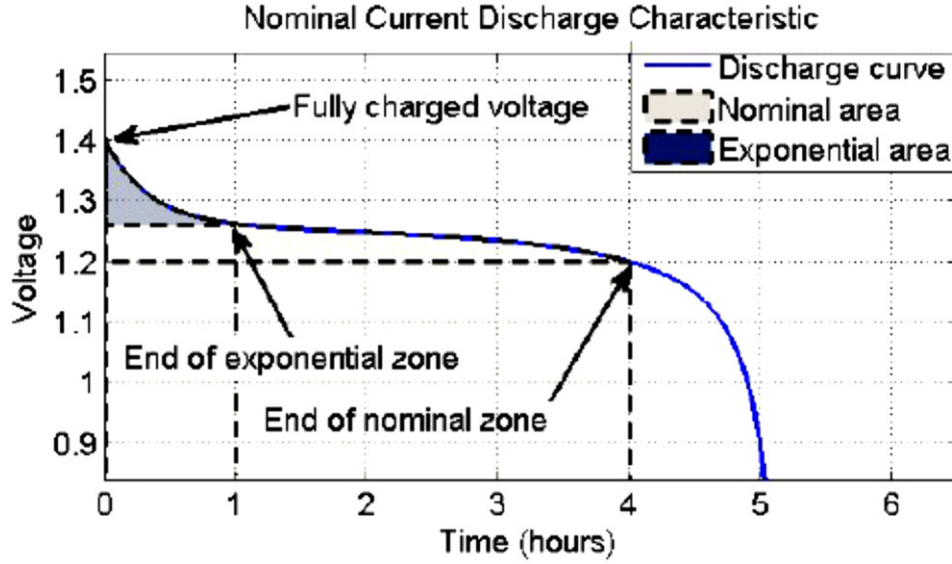


Fig. 3.5: Battery Discharging Curve

However, these models have a lot of limitations and there is a need of model that emulates the real life behavior of a Lithium battery and such a model of the battery is described below. This model considers the effect of temperature on the battery operations as well as the effects of capacity fading. The battery parameters are thus, described by the following equations,

a. OC Voltage of a battery

Terminal voltage of a lithium battery under no load is highly dependent on SOC and is given by,

$$V_{OC} = -1.031 * \exp(-35 * SOC) + 3.685 + 0.2156 * SOC - 0.1178 * SOC^2 + 0.321 * SOC^3$$

$$SOC = SOC_{ini} - \int (i_{bat} / C_{usable}) dt$$

b. Effect of capacity fading

Capacity fading is the irreversible loss in the usable capacitance of a battery overtime under operating conditions. Capacity fading has a linear correlation with time but increases drastically on exposure to higher operating temperature. Therefore, the capacitance of a battery at any given instance is given by,

$$C_{usable} = C_{initial} * CCF$$

Where, CCF: Capacity Correction Factor

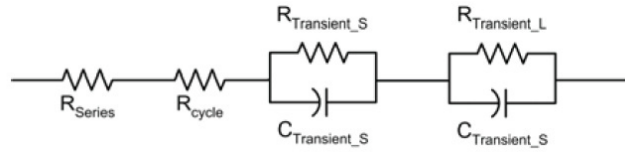
c. Estimation of internal impedance

Fig. 3.6: Equivalent circuit for the internal impedance of the battery model

Where,

$R_{series}$ : responsible for instantaneous voltage drop across the battery terminals

$R_{cycle}$ : resistance due to repeating charging discharging cycles

$R_{transient,S}$ ,  $R_{transient,L}$ ,  $C_{transient,S}$ ,  $C_{transient,L}$  are due to battery SOC and can be given by following formula []

$$R_{series} = 0.1562 * \exp(-24.37 * SOC) + 0.07446$$

$$R_{transient,S} = 0.3208 * \exp(-29.14 * SOC) + 0.04669$$

$$C_{transient,S} = 752.9 * \exp(-13.51 * SOC) + 703.6$$

$$R_{transient,L} = 6.603 * \exp(-155.2 * SOC) + 0.04984$$

$$C_{transient,L} = -6056 * \exp(-27.12 * SOC) + 4475$$

$$R_{cycle} = k_3 * N^{0.5}$$

### 3.3 Dynamic Simulation of Li-Polymer Battery

#### 3.3.1 Simulink Model of the Li-Polymer Battery

After consulting the data sheet and the vendors' data for the lithium polymer batteries, the following model is designed. Input is taken as a vector of current and temperature values at each instant and fed into a steady discharge model.

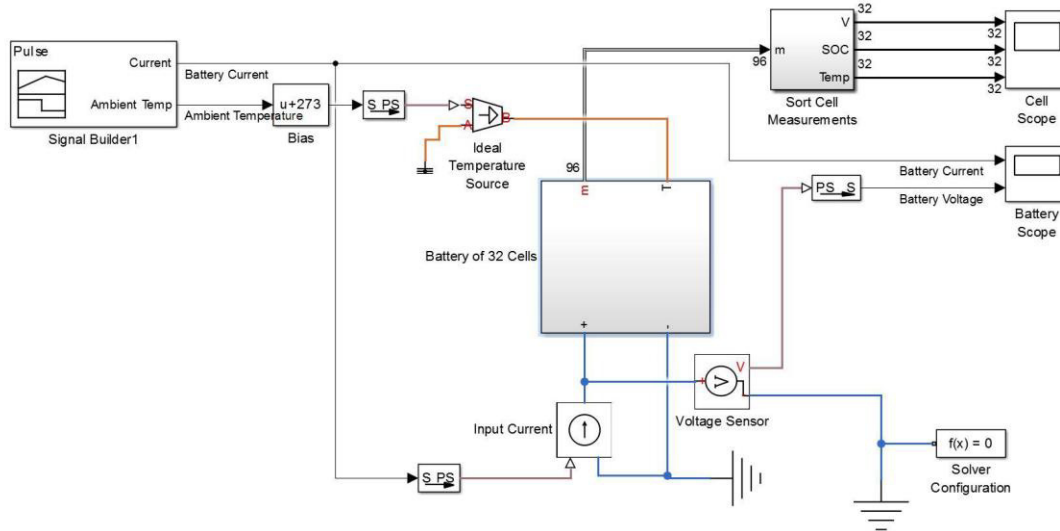


Fig. 3.7: Simulink Model for Dynamic Simulation of Lithium Polymer Battery Pack of 32 Cells

The above figure describes the simulation of battery pack of 32 cells when subjected to discharge current and temperature signals. The measurements from each cell is sorted out to plot cell voltages, state of charge and temperature of variation of each cell individually.

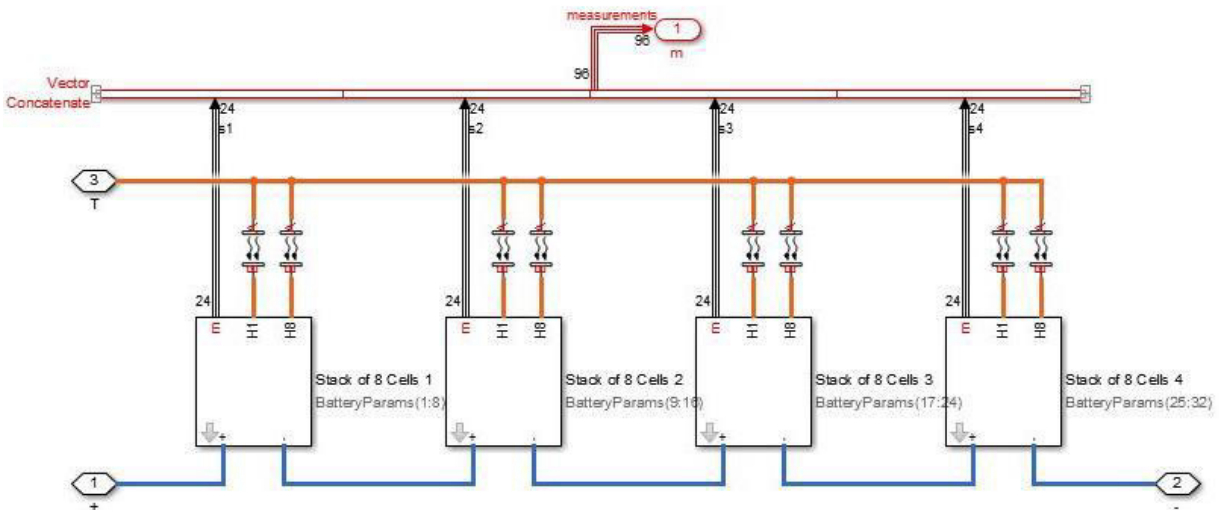


Fig. 3.8: Arrangement of 4 battery packs (8cells in each)

The second level shows the subsystem of four battery packs of 8 cells each. The heat signal is fed into the cell and the measure value are stored in a Vector Concentrator or Mux.

### 3.3.2 Simulation Results and Discussions

The model is simulated under ideal signal input and random signal inputs. The two vectors are shown below.

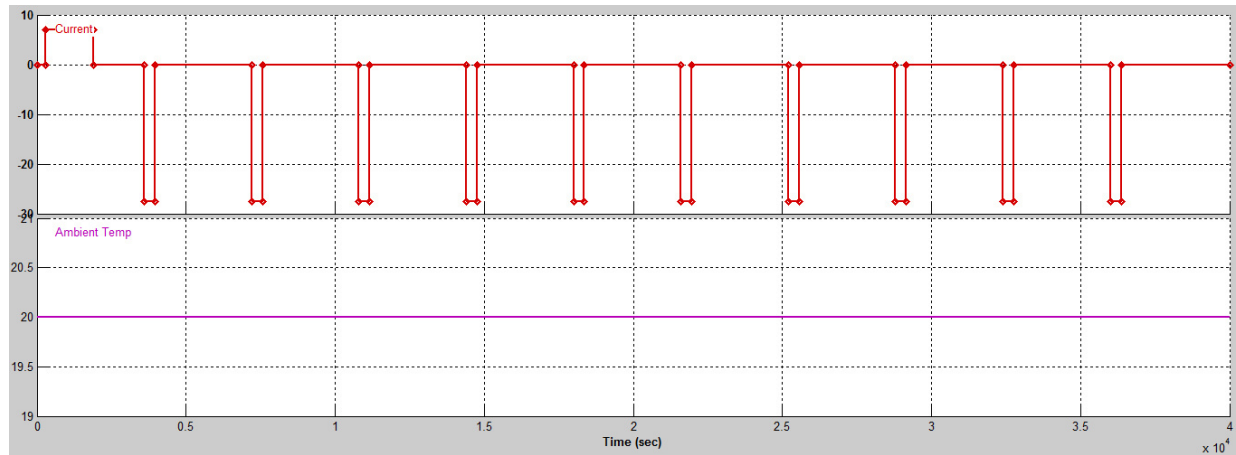


Fig. 3.9: Ideal Inputs – Current and Temperature

As observed in the waveform, when the negative pulse is provided energy is drawn from the battery and the battery voltage decreases. The trigger current pulse is periodic, so the voltage decreases in steps and uniformly. But during real world operations, current drawn from the battery is non-uniform and hence the changes in battery voltage is also non-uniform.

#### IDEAL RESPONSE

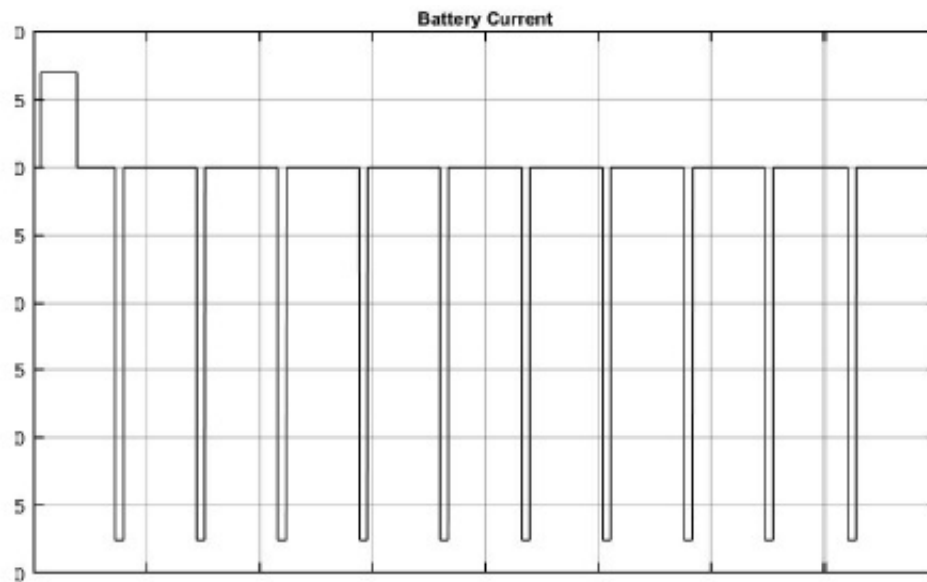


Fig. 3.10: Battery discharge current vs time for ideal input signal

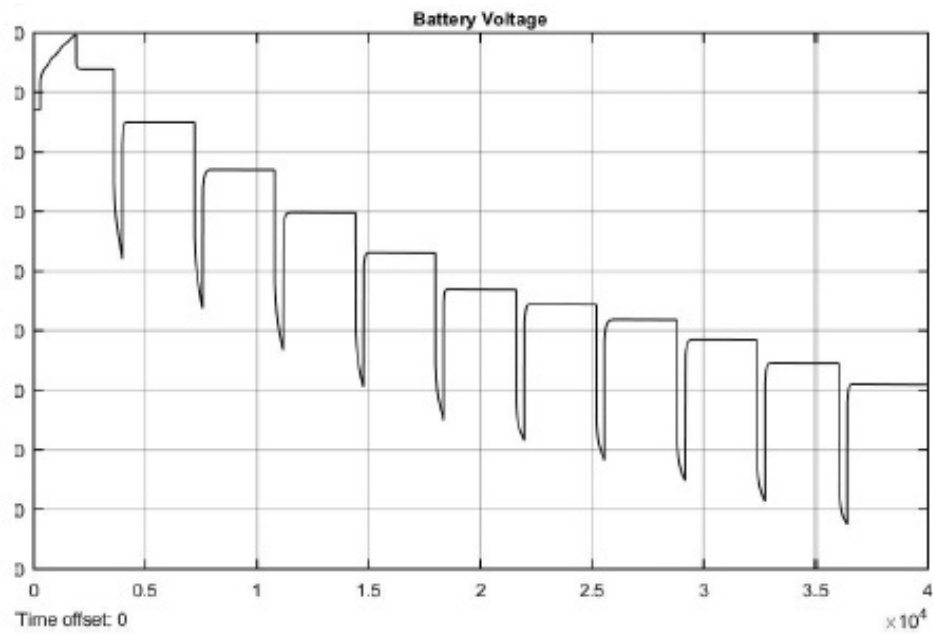


Fig. 3.11: Battery voltage vs time for ideal input signal

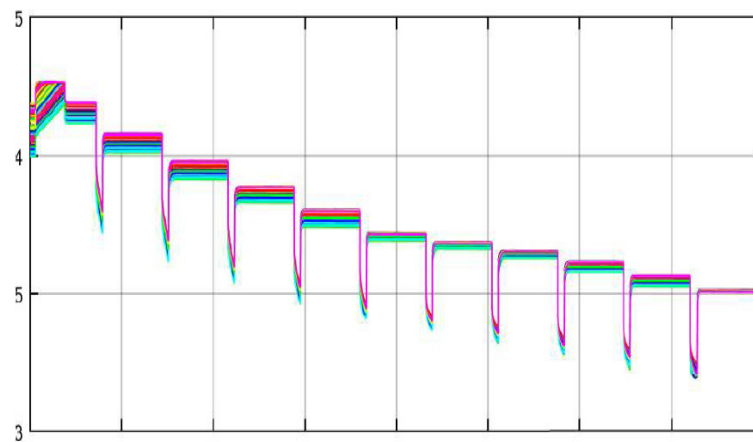


Fig. 3.12: Voltage drop across each cell

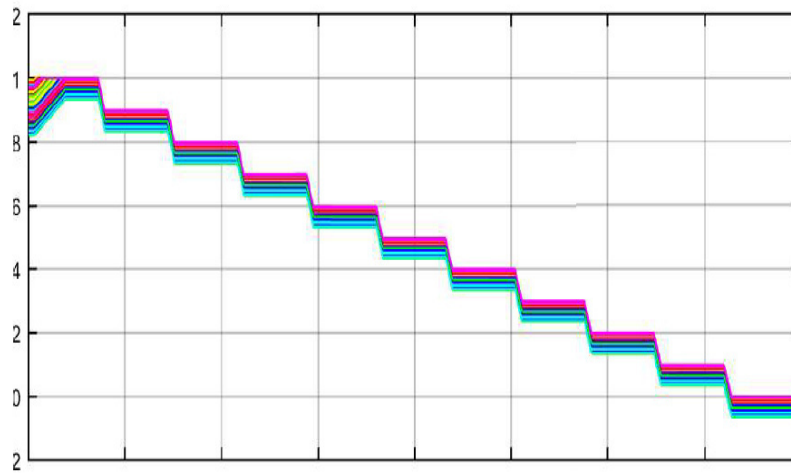


Fig. 3.13: SOC of each cell

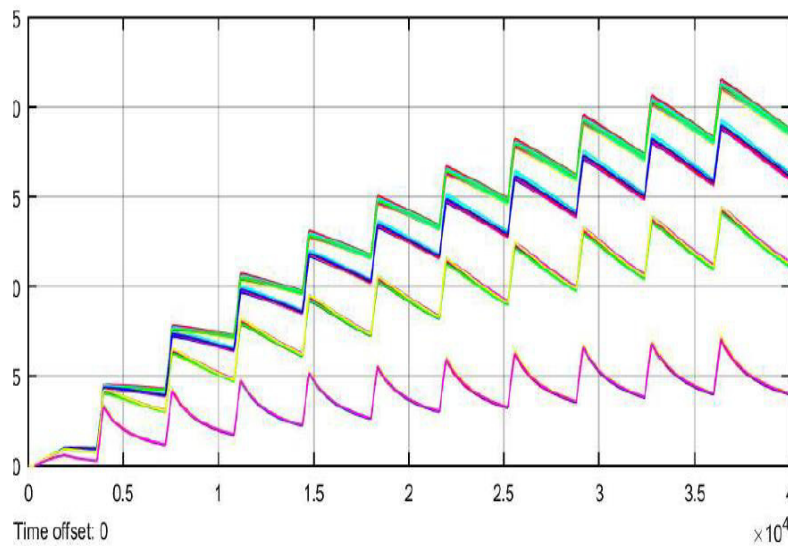


Fig. 3.14: Ideal Temperature variation of each cell

So the following input signals for the current and temperature is given as a random signal.

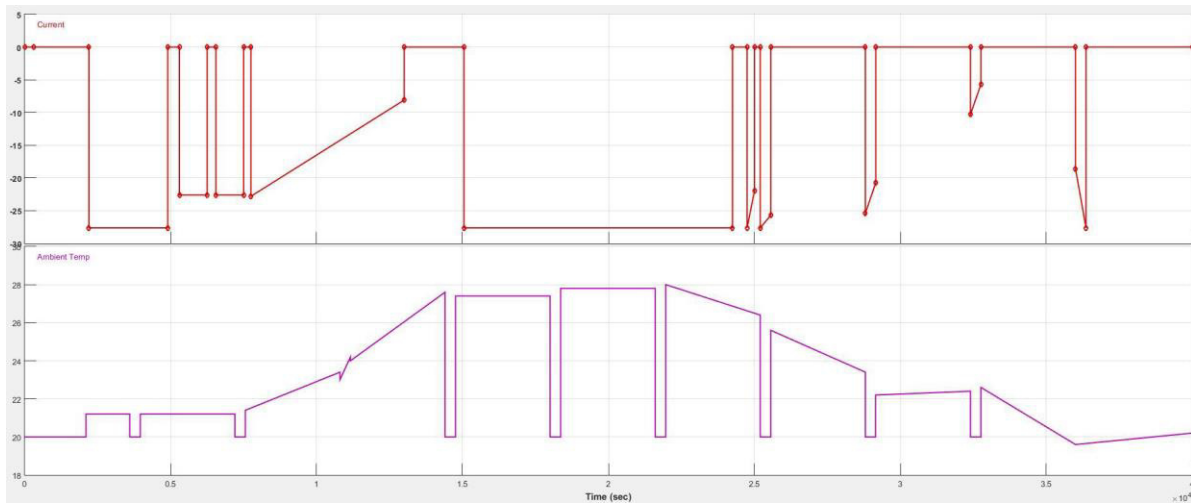


Fig. 3.15: Random input signal – Current and Temperature

The random current and temperature data are simulated and the following waveforms were observed. When the current demand, discharge from the batteries decreases. It is observed that the battery voltage rises. This is because of regeneration action of the simulation model. The discharge current, individual cell voltage and cell temperature is shown below.

### NON IDEAL RESPONSE

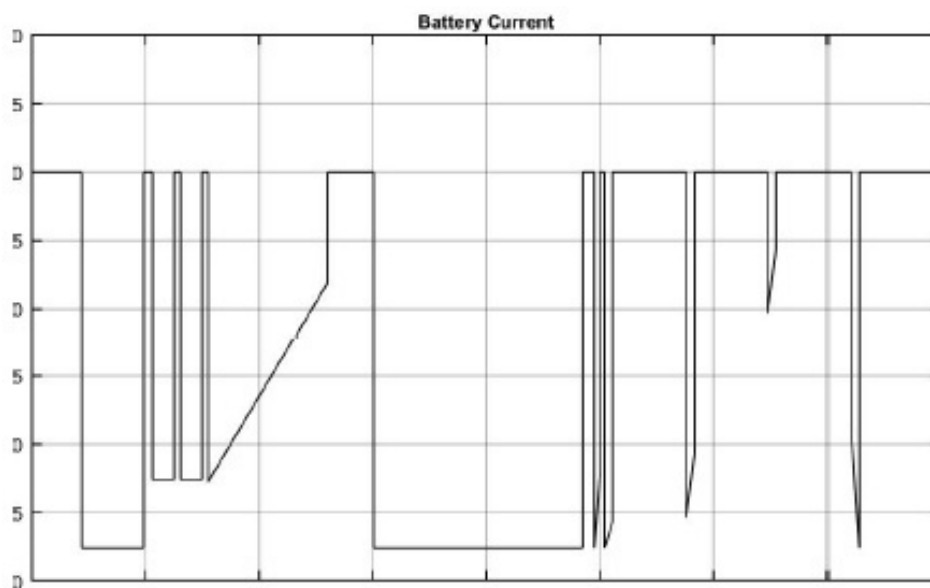


Fig. 3.16: Battery discharge current vs time for random input signal

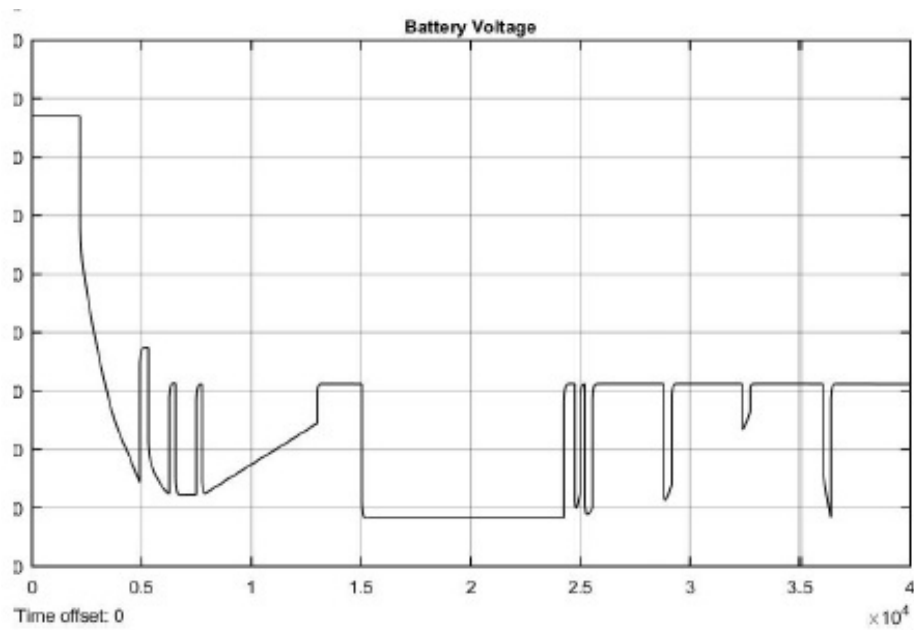


Fig. 3.17: Battery voltage vs time for random input signal

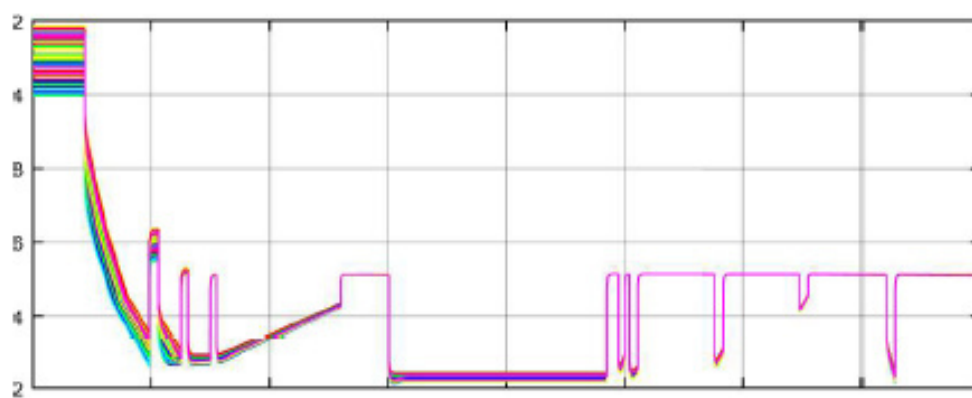


Fig. 3.18: Discharge Current vs time waveform for each cell

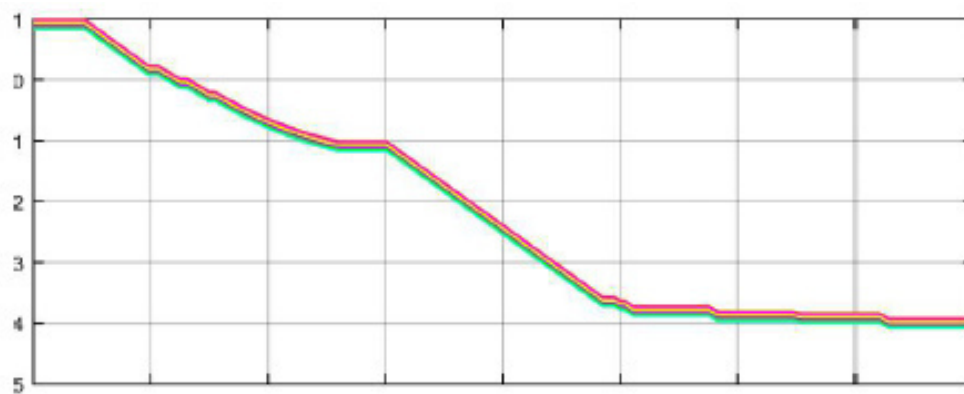


Fig. 3.19: SOC vs time waveform of each cell



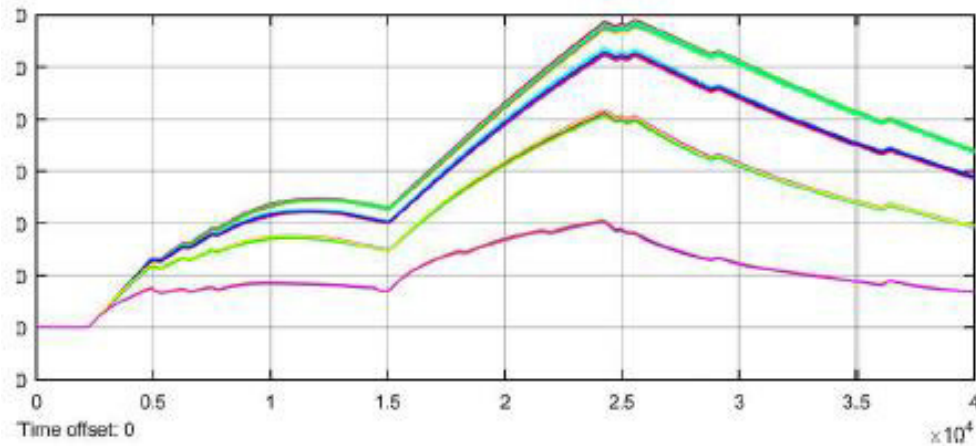


Fig. 3.20: Temperature vs Time waveform for each cell

### 3.4 Summary

The chapter described the key features of the element Lithium that makes it a preference in manufacturing battery. It discussed various models that emulates real life behavior of a lithium battery. Dynamic simulation of the proposed model is completed and from the ideal and non-ideal simulation following conclusion was drawn.

- The cell temperature of the battery packs in the middle of the setup is maximum. Whereas the battery packs on the sides don't heat up as much. This is due to better heat dissipation on the sides and edge of the battery packs.

## 4 PMDC Motor:

### 4.1 Introduction

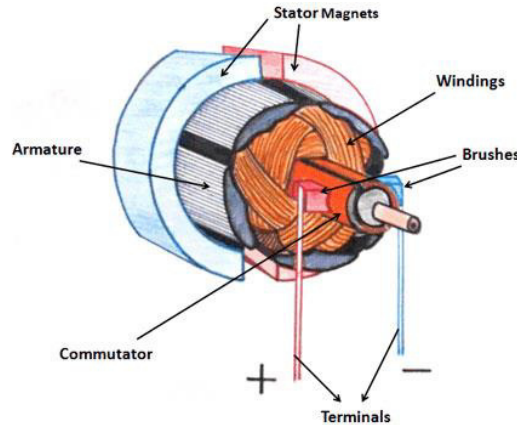


Fig.4.1: Labelled diagram of a PMDC Motor

Before we go into the details of permanent magnet dc motor, we have to understand the basic components and their operational features of a dc motor. The operation of any motor is based on Faraday's postulate that current running through a conductor generates a radial magnetic field. With current carrying loop the effective magnetic field lines are similar to that of a bar magnet. In the dc motors, the driving torque is produced due to the interaction a current carrying conductor with a magnetic field. The direction of the force acting on the conductor can be given as the cross product between the current element and magnetic field lines. It can be determined by Fleming's left hand rule.

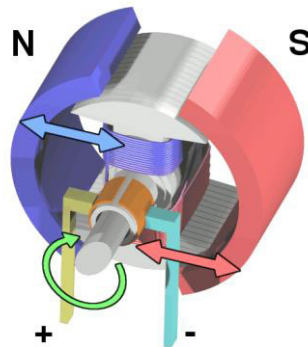


Fig.4.2: Working of a PMDC Motor

Although structurally dc motors are similar to the dc generators, but they are electrically opposite. In the dc motor, electrical power is supplied to the machine as input and mechanical power is obtained as output, where as in dc generator it's another way around. In a simple dc motor, there are two primary things: a set of magnets as the stator and an armature winding as the rotor. The electrical power is provided to the armature winding through a commutator, which converts the direct current to an alternating quantity which is helpful in producing a continuous one directional

torque. Most of the high rated dc motor use an extra winding to produce the stationary flux but in the case of PMDC motors, which are mostly used for low power applications, permanent magnets are used as the elements to provide the required magnetic field.

## 4.2 Advantages:

- Manufacturing cost is significantly reduced by the use of permanent magnets, for lower rated power application.
- Construction of the motor becomes less complex as there is no need of field winding.
- Unlike other dc motors with field excitation, PMDC is singly fed, because of which the overall efficiency is more.
- Another advantage we get due to the absence of field winding is that the motor is less bulky. Even for higher rated application, the use of neodymium with iron-boron alloy can be used, and these are even competitive with doubly fed field excited motors.

## 4.3 Specification and Motor Characteristics:

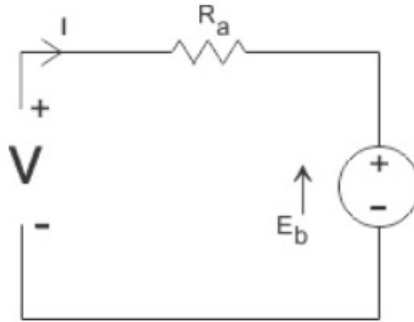


Fig. 4.3: Equivalent Circuit of a PMDC Motor

The equivalent circuit diagram for a permanent magnet dc motor is similar to that of a simple dc motor with separate field excitation. In the equivalent circuit model, the motor is presented as a circle with two carbon brushes. To these brushes, the external circuit is connected. On the supply terminal, the armature resistance is represented as “ $R_a$ ” and the voltage across the motor after the resistive voltage drop is taken as “ $E_b$ ”. The terminal voltage ( $V_t$ ) is the supplied voltage to the armature circuit. The current in the circuit is called the armature current ( $I_a$ ). So, if we apply KVL in the above diagram, we will have,

$$E_b = V_t - I_a R_a$$

For a dc machine in the motoring mode, the turns of armature winding cut the same field flux that gives rise the rotation in the first place. The cutting of the field flux by the armature turns induces an emf in the armature circuit, which is called as the back emf or the counter emf. As the induced emf opposes the flow of armature current, the word “back” or “counter” is used. It can also be called as the voltage behind armature circuit resistance. The average emf generated in one

conductor in the armature ( $E_a$ ) is given by the ratio of the total flux cut by the conductor and the total time required to cut that flux.

$$E_a = \frac{\Phi P}{60/N},$$

Where,

$\Phi$ =Flux produced by each pole,

P=No of poles

N=revolutions per minute

The net emf produced in the armature is equal to the back emf,

$$E_b = \frac{Z}{A} * E_a = \frac{\Phi NPZ}{60A},$$

Where,

Z= no of conductors in an armature

A=no of parallel paths.

The electrical power produced by the external circuit at the armature end is given by,

$$P_e = E_b * I_a$$

But electrical power can also be expressed as the product of electrical torque produced by the machine and the angular speed of rotation. That is,

$$P_e = T_e * \omega_e$$

In other words the electrical torque can be expressed as,

$$E_b = \frac{\Phi P Z I_a}{A}$$

The characteristics of the permanent magnet dc motor is exactly equal to the characteristic curves of the separately excited dc motor.

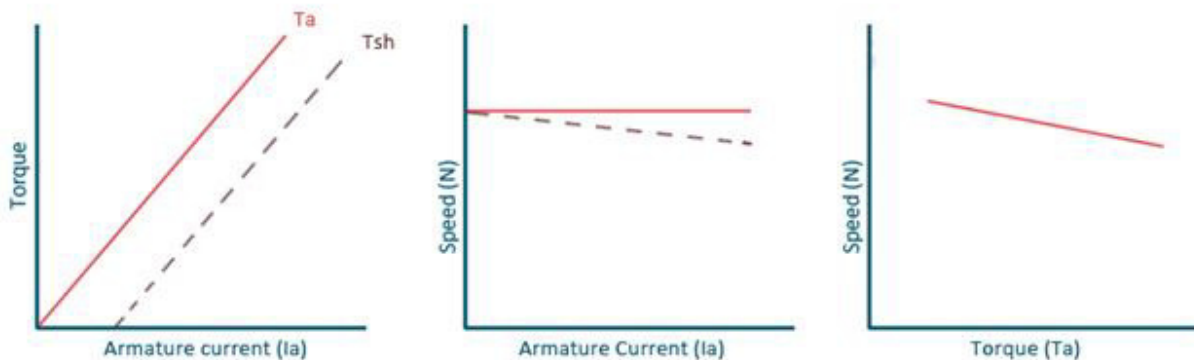


Fig 4.4: (a)  $I_a$ -  $T_e$  Characteristics, (b)  $I_a$ - N Characteristics, (c)  $T_e$  vs N Characteristics

In the proposed project, LYNCH-LEM200 D135 has been used. As it is an axial gap brushed dc motor, it is appropriate for traction applications such as motor cycles, go-karts and boats etc.



Fig. 4.5: Lynch LEM-200 D135R motor

Main features of this motor include higher efficiency of 93%, longer brush life, light weight, simple electronic control, interchangeable shafts and speed proportional to voltage. Technical specifications of LYNCH-LEM200 D135R has been listed below.

- No load current=7.45A
- Torque constant( $K_T$ ) =  $0.207Nm/A$
- Speed constant=40 rpm/V
- Armature resistance( $R_a$ )=16.95mOhm
- Armature Inductance at 15Khz( $L_a$ )=16uH
- Armature inertia(J)= $0.0238Kg*m^2$
- Peak power=36KW
- Peak efficiency=93%
- Peak current=400A
- Rated power=18KW
- Rated speed=4400rpm
- Rated voltage=110V
- Rated current=200A
- Rated torque=42Nm

#### 4.4 Motor Sizing:

Motor sizing of any system depends on upon the load power and torque requirement. While selecting the parameters of the motor, the load curve and the moment of inertia become the two deciding factors. With the help of these two factors, ideal operating parameters can be determined.

A drive control system like the one in the proposed formula-one electric model vehicle, is always independent of the motor used, as long as they are brushed dc type.

To get a clear scenario of selection of motor various tests and curves are observed. It also depends on upon the energy source, which in this case is the battery packs and type of batteries used. Many torque curve techniques such as animatic torque curves, peak torque curves, and continuous torque curves, as well as many power curve techniques like acceleration curves, are also used for define the limits of the motor response. In the suggested electrical vehicle, hard acceleration method has been adopted to select proper values of different motor parameter. In the hard acceleration method, the aim is achieved through a MATLAB code describing a virtual machine. In the code in Appendix I, the vehicle has been made to accelerate on a track of length, 75m. The following results are obtained.

Output: Maxspeed = 25.800 5: GR for 5.27seconds @ 57.714mph

Maxspeed=57.7148mph

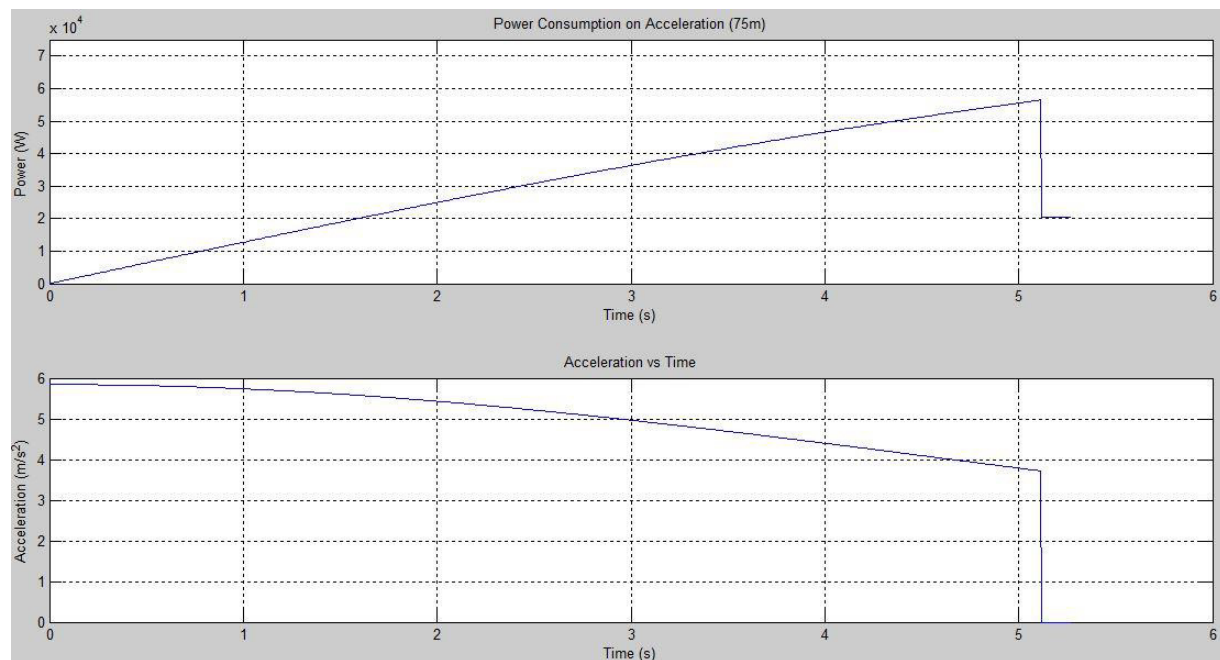


Fig. 4.6: Simulation for Acceleration Test

From the simulation, we learned that the 75m run should take 5.27 seconds at full throttle and we will need approximately 55Kw at top speed. This is more power than the battery could supply for very long but is acceptable for the time period of acceleration run.

We also need to know the autocross and the endurance power consumption profile.

To model the autocross and endurance events, the track is divided into three segments- straights, corners and slaloms. The simulation proceeds through these segments accelerating or braking but maintaining a speed close as possible to the fastest possible speed.

The track parameters are

- Distance of the segment
- Radius of the segment
- Type of the segment

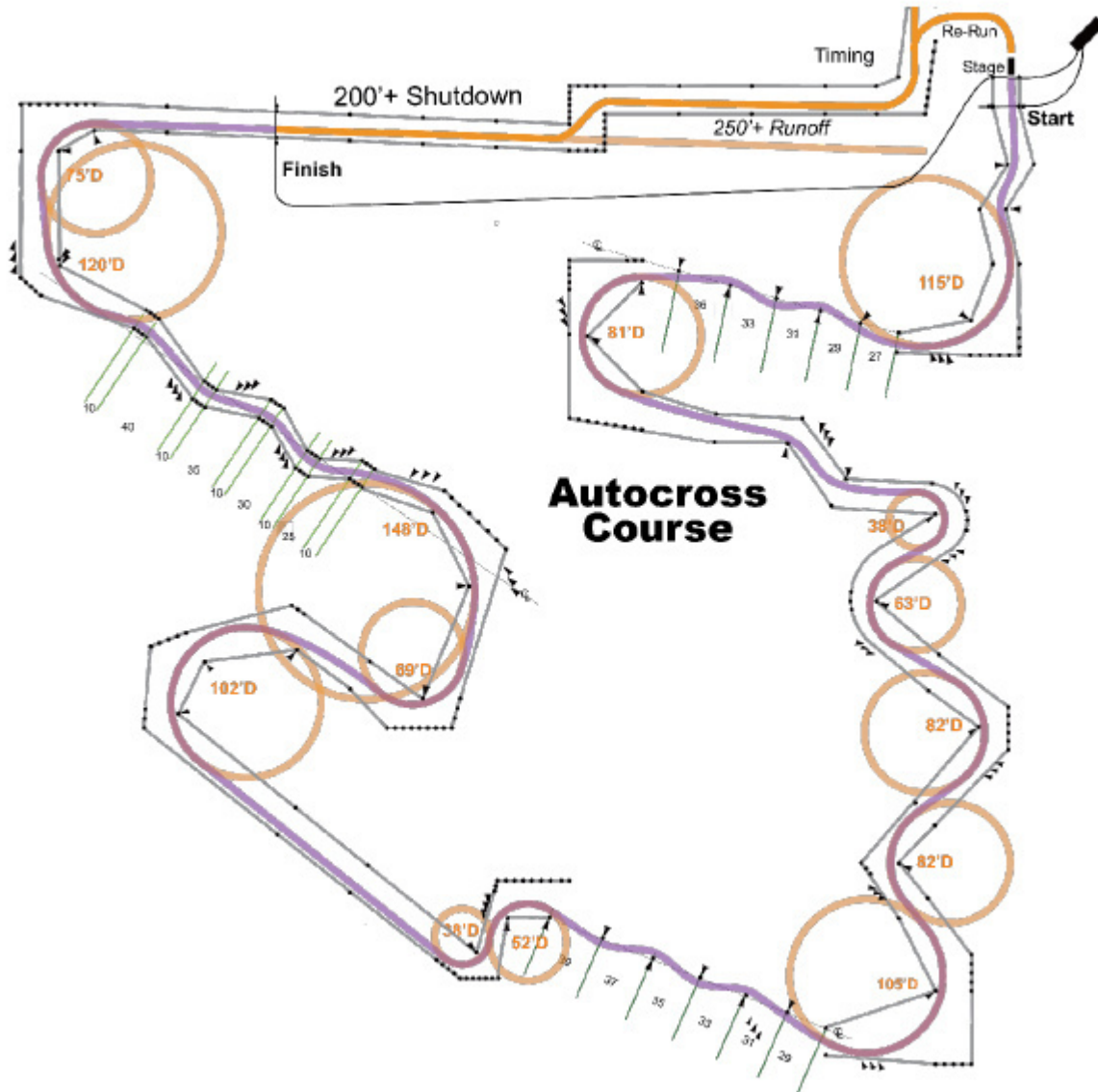


Fig. 4.7: The autocross course of Lincoln, Nebraska event of FSAE Electric

For the simulation we assumed a perfect driver who would accelerate and brake ideally and follow the perfect race line. The following formulas are used in the calculations of the track parameters.

1. Max velocity at corners,

$$V_{\max} = \sqrt{r\mu g}$$

Where,

$\mu$  = coefficient of friction

$r$  = radius

$g$  = acceleration due to gravity

2. Rolling resistance force,

$$F_{rr} = \mu_{rr} * M * g$$

Where  $M$  = mass of the vehicle

3. Drag force,

$$F_d = 0.5 * \rho_{\text{air}} * A_F * C_D * V$$

Where,

$\rho_{\text{air}}$  = air density

$A_F$  = front area

$C_D$  = drag coefficient

$V$  = velocity

4. Longitudinal force,

$$F_s = (V/V_{\max})^2 * \sin(\Theta_{\text{steering}}) * F_{\text{lateral}}/2$$

The result of the simulations are shown below,



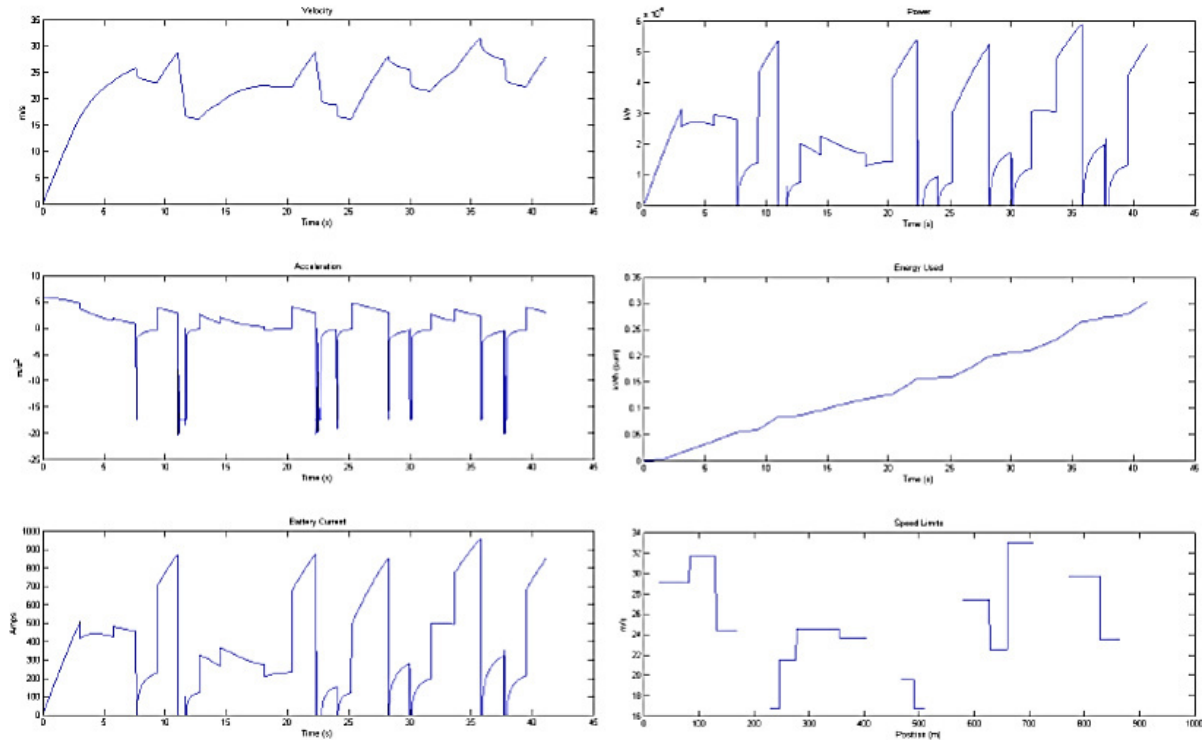


Fig. 4.8: Velocity (a), Power (b), Acceleration (c), Energy (d), Current (e), Speed Limits (f) vs Time

## 4.5 Summary

- The vehicle completes 1078m in 67.81sec. this single lap consumes 0.306kWh of energy at average rate of 14.63Kw. At this rate, the range of vehicle is estimated to be 22 km and total energy is 6.24kwh which exceeds the permissible limit of 5.5kWh. However, this is an ideal case with a perfect driver testing the limit of the vehicle components. A real driver will not be able to push the vehicle to heat limit.
- By simply reducing the maximum torque by 20% i.e. from 50Nm to 40Nm, the lap time goes up to 70.1s, With 0.265kWh at a rate of 12.257Kw. The total energy consumed now = 5.41kwh.
- Reducing torque by 20% is a drastic measure which may not be needed at all if a real driver is driving.

Therefore, we can conclude that the motor chosen can withstand the endurance test during the event and battery meets the energy requirements

## **5 Conclusion**

The project focused on a thorough study on BMS and detailed simulations i.e. both steady state and transient simulations, of the Lithium Polymer battery. The discharge characteristics of the battery model was compared to the real life behavior of a Lithium battery and the constants and parameter for designing the battery were calculated. Battery model was simulated for the effects of temperature on its performance and it was observed that units placed at the ends of the battery unit, underwent better cooling as compared to those in the center. The motor sizing simulations validated the choice of selected motor i.e. Lynch LEM 200 D135RAGS. Finally, the conclusion was drawn that the battery and the motor are compatible to the available BMS units and hence can be used in the Formula Electric Vehicle.

## **Future Scope of Work**

In order to make a complete model of the power system and drive control for the electric vehicle, the drive control system needs to be simulated. It takes input from the BMS and sensors from all over the vehicle and processes it to control the two motor but varying the torque accordingly. When the fabrication of the vehicle starts, proper protection and insulation of the electrical components must be kept in mind. The drive control unit must be programmed keeping in mind the demanding operations in a high performance electric vehicle. Compatibility of the control system with the BMS is essential.

# Appendix- I

MATLAB code for the simulation of Acceleration Test.

```
clear all
FArea = 1.1148;
ADensity = 1.2250;
DragCoefficient = 1.5;
Mph_per_M = 2.236936;
Wheel_r = 0.254;
Torque_p = 50;
MaximumRPM = 4850;
Mech_Eff = 0.95;
Mass = 320;
GR = 5;
Distance = 75;
Del_T = 0.01;
End_time = 100;
Acceleration = 0;
Velocity = 0;
Position = 0;
Maximum_Speed = ((MaximumRPM/GR/60) * (Wheel_r*2*pi))
i = 1;
while (i <= 100/Del_T)
    DragForce = (0.5)*ADensity*DragCoefficient*FArea*(Velocity.^2);
    Wheel_Force = 2 * Torque_p/Wheel_r * GR *Mech_Eff
    if (Velocity >= Maximum_Speed)
        Wheel_Force = DragForce;
        Velocity = Maximum_Speed;
        Acceleration = 0;
    else
        Acceleration = (Wheel_Force - DragForce)/Mass;
        Velocity = Velocity + (Acceleration * Del_T);
    end
    Accel(i) = Acceleration;
    Position = Position + (Velocity * Del_T);
    Power(i) = ((Wheel_Force * Velocity) / 0.9) / 0.95;
    if(Position > Distance)
        fprintf('%f GR: %f seconds at %f mph (Max = %f)\n', GR,
            i/100, Velocity * Mph_per_M, Maximum_Speed * Mph_per_M)
        break;
    end
    i = i + 1;
    Times(i) = i*Del_T;
end
subplot(2,1,1), plot(Times, Power)
title('Power Consumption on Acceleration (75m)')
xlabel('Time (s)')
ylabel('Power (W)')
axis([0 6 0 75000])
```

```
grid on
subplot(2,1,2), plot(Times, Accel)
axis([0 6 0 6])
title('Acceleration vs Time')
xlabel('Time (s)')
ylabel('Acceleration (m/s^2)')
grid on
```

# Appendix- II

## MATLAB code for track simulation for autocross event

```
clear all
clc;
%% Constants
ADensity = 1.2250;
Mph_per_M = 2.236936;
Gravity = 9.81;
FArea = 1.1148;
DragCoefficient = 1.5;
Wheel_r = 0.254;
Torque_p = 50;
MaximumRPM = 4850;
Mech_Eff = 0.95;
Mass = 320;
GR = 5;
Del_T = 0.01;
End_time = 100;
Braking_deceleration = 1.77 * Gravity;
FCoeff = 1.5;
RCoeff = 0.01;
MotorEff = .9;
Wheel_b = 1.524;
Track_W = 1.2192;
FLateral = 4855;
%% Track Definitions
% A-B
[Distance, Radius, Type, Segment] = autocross();
No_Segments = length(Segment);
Speed_L = inf;
Steer_angles = 0;
%% Build Speed_L
for i = 1 : No_Segments
    if (Type(i) == 2)
        Radius(i) = Radius(i);
        Distance(i) = Distance(i);
        Speed_L = [Speed_L SpeedLimitVector(Radius(i), Distance(i), FCoeff)];
        steeringAngle = asin(Wheel_b/(Radius(i) - Track_W/2));
        Steer_angles = [Steer_angles constants(Distance(i), steeringAngle)];
    else
        Distance(i) = Distance(i);
        Speed_L = [Speed_L SpeedLimitVector(inf, Distance(i), FCoeff)];
        Steer_angles = [Steer_angles constants(Distance(i), 0)];
    end
end
%% Simulate Lap
Position = 0;
Velocity = 0;
Acceleration = 0;
```

```

Time_S = 0;
E_Log = 0;
C_Log = 0;
P_Log = 0;
V_Log = 0;
A_Log = 0;
Po_Log = 0;
end
while(true)
P_temp = Position + (Velocity * Del_T);
V_temp = Velocity;
isBraking = 0;
V_target = inf;
while (V_temp > 0)
if (round(P_temp) + 1 > length(Speed_L))
isBraking = 0;
break;
else if (Speed_L(round(P_temp) + 1) < V_temp)
V_target = Velocity - (V_temp - Speed_L(round(P_temp) + 1));
isBraking = 1;
break;
end
if (V_target > Velocity - (V_temp - Speed_L(round(P_temp) + 1)))
V_target = Velocity - (V_temp - Speed_L(round(P_temp) + 1));
end
P_temp = P_temp + (V_temp * Del_T);
V_temp = V_temp - (Braking_deceleration * Del_T);
end
A_target = ((V_target - Velocity) * Del_T);
DragForce = (0.5)*ADensity*DragCoefficient*FArea*(Velocity.^2);
fractionSpeedLimit = (Velocity / Speed_L(min(round(Position)+1, numel(Steer_angles))));
LateralForce = FLateral * (fractionSpeedLimit^2);
F_Turn =abs(sin(Steer_angles(min(round(Position)+1, numel(Steer_angles)))))*(LateralForce/2));
F_rr = RCoeff * Gravity * Mass;
Wheel_Force_target = (V_target - Velocity) * Mass /Del_T + DragForce + F_Turn + F_rr;
A_Mul = sqrt(1-(fractionSpeedLimit^2));
Wheel_Force = min(2 * A_Mul*Torque_p/Wheel_r * GR * Mech_Eff, Wheel_Force_target);
if (isBraking == 1)
Wheel_Force = 0;
Brake_Force = Mass * Braking_deceleration;
Brake_Force = min(abs(Wheel_Force_target), Brake_Force);
Acceleration = - (Brake_Force + DragForce + F_Turn + F_rr)/Mass;
else
Acceleration = (Wheel_Force - DragForce - F_Turn -F_rr)/Mass;
end
Velocity = Velocity + Acceleration * Del_T;
Position = Position + Velocity * Del_T;
Time_S = Time_S + 1;
if (Position > length(Speed_L))
break;
end
P_Log(Time_S) = Position;
V_Log(Time_S) = Velocity;

```

```

A_Log(Time_S) = Acceleration;
Po_Log(Time_S) = Velocity * max (Wheel_Force, 0);
C_Log(Time_S) = ((Po_Log(Time_S) / 72) / 0.9) / 0.95;
E_Log(Time_S) = E_Log(max(Time_S - 1,1)) +(Po_Log(Time_S) / 0.9) / 1000 / 3600 * Del_T ;
end
x = Del_T: Del_T : length(V_Log) * Del_T;
figure(1)
subplot(3, 2, 1)
plot(x, V_Log)
title('Velocity');
xlabel('Time (s)');
ylabel('m/s')
subplot(3, 2, 2)
plot(x, Po_Log)
title('Power');
xlabel('Time (s)');
ylabel('kW')
subplot(3, 2, 3)
plot(x, A_Log)
title('Acceleration');
xlabel('Time (s)');
ylabel('m/s^2')
subplot(3, 2, 4)
plot(x, E_Log)
title('Energy Used');
xlabel('Time (s)');
ylabel('kWh (sum)')
subplot(3, 2, 5)
plot(x, C_Log)
title('Battery Current');
xlabel('Time (s)');
ylabel('Amps')
subplot(3, 2, 6)
x = 1: length(Speed_L);
plot(x, Speed_L)
title('Speed Limits');
xlabel('Position (m)');
ylabel('m/s')
fprintf('Friction Coeff: %f completed in %f seconds with %f kWh with average power: %f kW, average battery
current: %f Amps\n\n', FCoeff, length(V_Log) * Del_T, E_Log(Time_S-1), mean(Po_Log)/1000, mean(C_Log))

```

#### FUNCTIONS USED IN THE MAIN CODE:

##### const.m

```

function y = constants( length, value )
temp(1:round(length)) = value;
y = temp;
end

```

##### Speed\_L Vector.m

```

function [ y ] = Speed_L_Vector( radius, distance, friction)
Max_Seg_Speed = sqrt( friction * 9.81 * radius );
y = constants(distance, MaxSegmentSpeed);
end

```

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