Analysis of an electric Equivalent Circuit Model of a Li-Ion battery to develop algorithms for battery states estimation.

Mohammad Haris Shamsi
Abstract

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Batteries have imparted momentum to the process of transition towards a green future. However, mass application of batteries is obstructed due to their explosive nature, a trait specific to Li-Ion batteries. To cater to an efficient battery utilization, an introduction of a battery management system would provide an ultimate solution. This thesis deals with different aspects crucial in designing a battery management system for high energy as well as high power applications.

To build a battery management system capable of predicting battery behavior, it is necessary to analyze the dynamic processes happening inside the battery. Hence, a battery equivalent circuit model is proposed in this thesis as well as proper analysis is done in MATLAB to project a generic structure applicable to all Li-Ion chemistries. The model accounts for all dynamic characteristics of a battery including non-linear open circuit voltage, discharge current and capacity. Effect of temperature is also modeled using a cooling system. The model is validated with test current profiles. Less than 0.1% error between measured and simulated voltage profiles indicates the effectiveness of the proposed model to predict the runtime behavior of the battery. Furthermore, the model is implemented with the energy as well as the power battery pack. State of charge calculations are performed using the proposed model and the coulomb counting method and the results indicate only a 4% variance. Therefore, the proposed model can be applied to develop a real-time battery management system for accurate battery states estimation.
Acknowledgements

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Abbreviations

BMS: Battery management System
SoC: State of Charge
Li-Ion: Lithium Ion
NiMH: Nickel Metal Hydride
NiCd: Nickel Cadmium
SoH: State of Health
DOD: Depth of Discharge
OCV: Open Circuit Voltage
IC: Integrated Circuit
DIY: Do It Yourself
ASIC: Application Specific Integrated Circuit
ADC: Analog to Digital converters
HEV: Hybrid Electric Vehicle
isoSPI: Isolated Serial Peripheral Interface
RF: Radio Frequency
GPIO: General Purpose Input/Output
SPI: Serial Peripheral Interface
USD: US Dollars
GUI: Graphical User Interface
PDT: Pulse Discharge Test
CDT: Continuous Discharge Test
EIS: Electrochemical Impedance Spectroscopy
1. Introduction

Irresponsible use of natural resources by the human race has led to irreversible effects on the environment to such a large extent that an equivalent of two more Earths are needed for the flourishing of the growing population. The unrestricted use of fossil fuels has led to an alarming increase in the world’s average temperature, mainly because of rising levels of CO\textsubscript{2} in the atmosphere [1]. This increase in temperature is leading to several adverse effects, which if left unattended would imply the extinction of human race [2].

In the wake of such dangers, alternatives to the use of fossil fuels like renewable energy sources are being promoted at a very large scale. Novel technologies to extract energy from wind, sun, etc. are a need of the hour. Collaboration at international levels is being pushed and has been, indeed, very successful in enhancing the development of such new technologies.

Alongside, the automotive sector is undergoing a complete transition towards electric vehicles. Electric vehicles have gained importance as low or zero emission means of transportation and even offer means of regenerative braking.

As such, energy storage technologies like flywheels, batteries etc. have gained importance for implementation with renewable energy sources and electric vehicles. However, their usage has not been so effective mainly because of the complexities associated with the management of these technologies [2].

1.1 Background

Energy storage in batteries is expected to play an important role in sustainable solutions for the future mainly due to the efficient energy utilization and zero–emission when in use. Different kinds of battery technologies have emerged in the past few years. From low power applications like portable electronics to high power applications like electric vehicles, large numbers of batteries have flooded the market [3]. As a consequence, the choice of the battery technology and its effective utilization is of paramount importance. From today’s perspective, Li-Ion batteries are in dominance in the majority of battery applications. High energy and power densities of these batteries are two of the major reasons for their dominance. Depending upon the application, an appropriate number of batteries are connected in series or parallel to achieve the desired specifications.

In spite of the associated advantages and flexibilities, Li-Ion chemistries are very sensitive to abusive operation schedules like overcharge and deep discharge. Such abuse results in damage to the battery, shortening of lifetime and sometimes even hazardous situations if left unattended. Dealing with these issues requires a proper Battery Management System (BMS). A BMS would
ensure efficient operation of each cell inside the battery pack and would keep individual cell parameters within safe operating limits. Moreover, a BMS also updates the current status of the overall battery pack in order to keep track of the available energy or state of charge (SoC) inside the pack. However, because the internal parameters of the cells inside the battery pack vary with age, accurate estimation of battery runtime becomes quite a challenging task [4]. The cells inside a battery pack are not charge synchronized, which means each and every cell has a different capacity. This phenomenon results in a reduction of the overall capacity of a series connected battery pack as the defective cell limits the operation. A BMS also ensures that charge is properly distributed across all the cells.

To analyze all these challenges associated with Lithium-Ion (Li-Ion) battery technology, a battery model that takes into account all of these uncertainties is required.

1.2 Challenges Associated with a BMS

Battery management systems have flourished from simple analog design to complicated integrated chips with improved user interfaces. However, the complicated design has made these management systems costlier, making them a big factor in the overall pricing of systems utilizing them. The high cost owes to the choice of algorithms implemented inside for charging and discharging of the batteries. Also, as the system to which these batteries supply power becomes even more sophisticated, the BMS will be required to handle more functionality.

The dynamic behavior of batteries makes the algorithms obsolete. For instance, an algorithm implemented for measuring the SoC of a battery pack might not give a correct reading because of calibration issues, which may lead to the battery being overcharged or over discharged. This would ultimately result in the degradation of individual cells in the battery pack.

1.3 Thesis Motivation and Objectives

The thesis work is a joint collaboration project between Volvo Construction Equipment and Uppsala University. The resources used to accomplish this project are provided by both the organizations. The project is directly linked with the development of a BMS to be implemented in a product from Volvo Construction Equipment.

The goal of this thesis is to explore the main issues in the design and management of a Li-Ion battery. The thesis will cover aspects ranging from different Li-ion technologies to BMS requirements and architectures and techniques for
battery status estimation and charge equalization. Furthermore, this is complemented with the design of a battery model and algorithms to predict the battery performance accurately. The proposed model is intended to be implemented in a real time-BMS system.

The first objective of the thesis is to propose a battery modeling approach, which dynamically updates the model parameters, based on battery discharge currents and SOC variations. The model is realized by performing the following experiments:

- Continuous discharge tests with different discharge currents depending on the size and type of battery pack.
- Pulsed discharge tests with different discharge currents depending on the size and type of battery pack.

The second objective of this thesis is to analyze the battery model:

- To design the algorithms for implementation in a BMS.
- To demarcate between the behaviors of the two different kinds (one designed to supply high energy and the other to supply high power) of battery packs.

Furthermore, the designed battery model is integrated with real-time data provided by Volvo Construction Equipment.

1.4 Methodology

Figure 1 describes the function cycle in a BMS. The key to the efficient management of a battery is the design of algorithms to implement the basic functions in a BMS. These algorithms have to be accurate enough in order to properly estimate the battery states. In order to do so, the following methodology is used in this thesis work:

1. Exhaustive Inspection

The first part of the project work consists of exhaustive studies of different available batteries and BMS technologies, such as balancing algorithms and management. This includes testing different algorithms and electronics for the final BMS. Since the project includes so many different areas, a large amount of time is spent on planning how to realize the project.
2. Implementation

The second part of the project consists of an implementation phase of the found solution for a battery pack. In addition to the development of software and assembly of hardware, the cells for the project are found. The different parts of the project, both software and hardware are implemented piecewise to ensure the system is as flexible as possible. The cells, initially, are operated without any BMS, with the further addition of the desired algorithms.

3. Assembling

The final step is to combine the implemented BMS and the battery cells into a complete battery pack.
1.5 Thesis Outline

The thesis is outlined as follows:

Section 2 introduces the different Li-Ion technologies and aspects associated with different chemistries.

Section 3 includes a detailed description of aspects associated with a BMS. The battery state algorithms are discussed in brief.

Section 4 gives a brief idea of different kinds of battery models and a battery modeling approach is thereby described.

Section 5 deals with the combination of experimental results and the battery model. It includes the analysis and results of different elements concerning a BMS.

Section 6 states the conclusions from the model and includes a brief introduction to the future work.
2. An Introduction to Batteries

This section deals with aspects related to batteries in general. Furthermore, properties, associated with different types of batteries available in the market today, are discussed. Section 2.2 specifies some practical information, typically for Li-Ion batteries. It deals with safety issues, charge-discharge characteristics, and challenges associated with Li-Ion batteries.

2.1 Concepts Related to Batteries

2.1.1 Elements of a Battery

A battery is a device that converts the chemical energy contained in its active material directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction [3]. In the case of a rechargeable system, a battery is recharged by a reversal of the process. The electrochemical storage element inside a battery is termed “a cell”. One or more cells are assembled together to form a battery. The cells may be connected in series or parallel to achieve a desired voltage or current. A cell mainly comprises the following elements:

1. Anode (Negative Electrode)
   The electrochemical reaction, oxidation, occurs at this electrode. The reaction releases electrons that flow to the cathode via an external circuit. The material of the anode is selected based on its efficiency, high specific capacity, conductivity, stability, ease of fabrication and cost [3].

2. Cathode (Positive Electrode)
   The cathode accepts electrons from the anode and undergoes reduction. The selection of the cathode material is based on its voltage and chemical stability over time [3].

3. Electrolyte
   The electrolyte provides the medium for transfer of charge, as ions, inside the cell between cathode and anode. The electrolyte can be liquid, such as water or other solvents with dissolved salts, or it can be solid or gel type. The selection of electrolyte is done based on its high conductivity, non-reactivity with electrode materials, stability in properties at various temperatures, safety, and cost [3].

The best combination of anode and cathode materials is that will be lightest and will give a high cell voltage and capacity. Both the electrodes are electronically isolated, preventing internal short circuit conditions [6]. However,
they are surrounded by the electrolyte. In an actual cell design, separators are used to provide a mechanical isolation between the anode and cathode.

2.1.2 Cell Operation

During the discharge process, the anode undergoes oxidation, losing electrons, which travel to the cathode that accepts the electrons and undergoes reduction. The reverse cycle occurs during the charging process. The charge and discharge processes are shown in Figure 2.

![Figure 2 The charge and discharge process inside an electrochemical cell.](image)

Whenever a reaction occurs, there is a decrease in the free energy of the system [3]. The decrease in free energy is transformed into electrical energy. The type of active material contained in the cell determines the standard potential of a cell. It is calculated by the summation of anodic and cathodic potentials.

2.1.3 Battery Chemistries

This section includes a description of common battery chemistries that are available on the market today.

1. **Lead-Acid**
   The first practical lead-acid battery was built in 1860, although research was started a little earlier [3]. Elements that form a lead-acid battery are Lead, Lead Oxide and diluted Sulfuric Acid. These batteries have now reached a mature stage and the cost has reduced drastically. Some of the major disadvantages are self-discharge, high weight, low specific power, and energy. Moreover, these batteries have smaller cycle life compared to other batteries.
2. Nickel
Nickel based batteries have proved to be commercially viable in the past few decades [8]. These batteries have remained as a sole choice in many applications, mainly due to high energy density, long cycle life, and rapid recharge capabilities. Among the various chemistries, Nickel Metal Hydride (NiMH) and Nickel-Cadmium (Ni-Cd) are the most popular ones. The positive electrode consists of Nickel Hydroxide and the negative electrode consists of Metal Hydride in the case of NiMH or Cadmium Hydroxide in the case of Ni-Cd. These batteries lie in between Lead-Acid and Li-Ion batteries with respect to specific energy and specific power values [3]. Ni-Cd chemistry suffers from the presence of poisonous cadmium and hence, has been banned from industrial employment in several countries [9].

3. Lithium-Ion
Li-Ion battery has rapidly become the standard power source in a broad array of markets and battery performance, which has seen a tremendous improvement as Li-Ion batteries are applied to an increasingly diverse range of products. These batteries employ lithium storage compounds as positive and negative electrodes. As a battery is cycled, lithium ions (Li+) exchange between positive and negative electrodes. The positive electrode material is typically a metal oxide with a layered structure while the negative electrode comprises a layered structure of graphitic carbon. Li-Ion batteries are classified according to the type of positive electrode, which is discussed in Section 2.2.1. On one side, these batteries seem to be the most promising choice for many applications, because of low maintenance, long cycle life, high specific power and energy, low self-discharge and high efficiency. On the other side, these batteries have to be operated very carefully because of negligible tolerance to abusive charge and discharge cycles [10].

A comparison of the common batteries is shown in Figure 3. The shares of worldwide sales for Ni-Cd, Ni-MH, and Li-Ion portable batteries are 23%, 14% and 63% [12]. Li-Ion batteries seem to be the preferred choice for many applications because of high volumetric as well as gravimetric energy density.
2.2 Li-Ion Battery Concepts and Specifications

The following section describes the different Li-Ion chemistries and also states some practical aspects related to Li-Ion batteries.

2.2.1 Li-Ion Battery Chemistries

Various Li-Ion chemistries have emerged in the past few years with significant improvements in values of specific power and specific energy. The different types of Li-Ion batteries are the following:

1. Lithium Cobalt Oxide

Lithium cobalt oxide (LCO) cells are mainly designed to be used in notebook PCs where a high rate of discharge is not a requirement. Characterized by high specific energy with values between 175-
240Wh/kg [3], these cells provide high electrical performance but suffer from poor thermal stability. This chemistry is still the most common among Li-Ion batteries.

2. Lithium Manganese Oxide
The batteries made out of lithium manganese oxide (LMO) as the positive electrode are inexpensive, particularly because of the absence of cobalt. These batteries are designed to be used as power cells and thus have low specific energy lying in the range of 100-150Wh/kg [5]. This chemistry is typically safer than LCO. However, instability at higher temperatures still persists.

3. Lithium Nickel Manganese Cobalt Oxide
Lithium nickel manganese cobalt oxide (Li-NMC) chemistry offers the advantage of modulation of characteristics of a battery to be used as energy or power cells. While being implemented as energy cells, such chemistries offer the same range of energy densities as LCO. When implemented as power cells, specific energy is reduced to values in the range of 100-150Wh/kg while specific power reaches a maximum with battery handling continuous pulses of over 30C. Depending on the composition, these batteries find application in automotive sector or as a replacement for LCO chemistry in portable equipment [13].

4. Lithium Nickel Cobalt Aluminium Oxide
Lithium nickel cobalt aluminium oxide (Li-NCA) batteries are characterized by their highest specific capacity compared to other chemistries available. Li-NCA batteries share similarities with Li-NMC by offering high specific energy, reasonably good specific power, and long cycle life. High cost and marginal safety are the negatives associated with these battery chemistries [5].

5. Lithium Iron Phosphate
Lithium Iron Phosphate (LiFePO4) chemistries offer good electrical performance with low internal resistance. The key benefits associated with these batteries are high current rating, long cycle life, good thermal stability, enhanced safety and tolerance if abused. However, as a trade-off, these batteries offer lower voltage/cell which in turn reduces the specific energy to the lowest amongst the Li-ion batteries [3].

Figure 4 shows the comparison between all the Li-Ion chemistries based on the essential parameters. The values in the chart along the six edges are relative (expressed in %) and have been taken from [5]. As is evident from the chart, no single chemistry appears to be perfect for any application. This relates to the fact that all the chemistries are application specific and the implementation varies from one application to the next.
2.2.2 Li-Ion Battery Operation

The basic operation of Li-Ion is the same as described in Section 2.1.2. Figure 5 gives a more detailed insight into the inside movement of Li+ ions between the negative and positive electrodes, during charging.

The positive electrode, as explained in Section 2.2.1, is a Li-intercalation compound while the negative electrode is graphitic carbon, which holds Lithium in its layers. Li-Ion batteries are also known as rock chair batteries because Li ions are inserted and removed from the respective structures of the electrodes [11]. While charging, Li Ions are removed from the layered oxide compound of the positive electrode and intercalated into the graphite layers. The process is reversed on discharge.
2.2.3 Li-Ion Cell Formats

Cylindrical, prismatic and pouch cell formats are nowadays common as available Li-Ion cell formats. Wound cylindrical or prismatic cell formats are typical in small cells (< 4Ah). These cells inherently retain their shape against expansion because of thermal stresses while with pouch cells, proper pressure needs to be applied to restrict their expansion. Pouch cells are also termed as Li-Ion Polymer cells. Originally, these cells consisted of a polymer or gel electrolyte but the cells marketed today as polymer Li-Ion cells are regular Li-Ion cells in a flexible aluminized polymer package [3]. Table 1 highlights the main properties of different cell designs.

**Table 1 Comparison of Li-Ion cell formats**

<table>
<thead>
<tr>
<th></th>
<th>Cylindrical</th>
<th>Prismatic</th>
<th>Pouch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosure</td>
<td>Encased in metal or hard plastic cylinder</td>
<td>Enclosed in semi-hard plastic case</td>
<td>Soft bag containment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Connections</th>
<th>Welded nickel or copper plates</th>
<th>Threaded hole for bolt</th>
<th>Tabs that are clamped, soldered or welded</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expansion of the assembly when fully charged</strong></td>
<td>Inherent shape of the assembly</td>
<td>Requires retaining plates at the ends of battery</td>
<td>Requires retaining plates at the ends of pack assembly</td>
</tr>
<tr>
<td><strong>Appropriateness for custom projects</strong></td>
<td>Best for retrofits, small shape can be fit into all available space</td>
<td>Minimal design effort Dimenssions adjustable to fit into available space</td>
<td>Quite poor, High design effort</td>
</tr>
</tbody>
</table>

### 2.2.4 Charge and Discharge Characteristics

The charge and discharge voltage profiles of a Li-Ion cell are displayed in Figure 6. As evident from the discharge voltage curve, a Li-Ion cell offers a flat voltage profile in the mid-plateau, which is a basic requirement for many applications. The initial drop in voltage is due to the internal resistance of the cell. The cell is allowed to discharge only until the voltage across the cell becomes equal to the cut-off voltage, which is considered as the safe operating limit and is specified by the manufacturer.

![Charge and Discharge Voltage Profiles](image)

**Figure 6** Charge and discharge voltage profiles of a Li-Ion cell.

Li-Ion cells are charged using constant current-constant voltage logic. Initially, the cells are provided with a charging current (≤max rated charge current, specified by the manufacturer) while the voltage across the terminals of
the cell increases to maximum cell voltage. The current starts decreasing as the cell voltage reaches the maximum value and the supply is cut off when the current drops down to a cut-off value as specified by the manufacturer.

2.2.5 C-Rate and Capacity

The charge and discharge currents for a cell are specified in multiples of the C rate. A discharge rate of 1C implies the battery will discharge in about one hour when C amount of Amperes are extracted from the cell continuously [6]. Manufacturers provide a range of C rates feasible for the safe operation of cells. The area of application of the battery is decided based on the C to ensure that the battery will be able to handle the charge and discharge levels.

In physical terms, a capacity associated with a Li-ion cell is the amount of active material on the electrodes. Moreover, the capacity of a battery is analogous to the C rate and decreases by a few percent for higher C rates. It is calculated as a product of the C rate and the number of hours, the battery delivers the C (Amperes) amount of current, as depicted by (1). The decrease in capacity occurs due to the profound effect of internal resistance at high C rates [7]. Manufacturers always specify a minimum voltage limit until which current can be extracted from a battery. At low current rates, the cell’s internal resistance has minimal effect on the time required to reach the specified cut-off voltage limit. However, at high C rates, the time to reach the cut-off voltage decreases, which reduces the overall capacity of a battery [7].

\[
Capacity = C \text{ rate} \, (\text{Amperes}) \times Time \, (\text{hours})
\]  

(1)

2.2.6 State of Charge and Depth of Discharge

SoC is a term used to express the charge available inside a battery or cell at a certain point in time. Expressed in terms of percentage, 100% when the battery or cell is fully charged and 0% when the battery or cell is fully discharged, SoC also functions as a fuel gauge, especially in electric vehicles. Cells forming a battery pack have their individual SoCs and the battery pack has a SoC of its own.

The depth of discharge (DOD) signifies the amount of charge taken out from a cell. It is expressed in Ah and is equal to zero for a fully charged cell. The value of DOD increases with the amount of charge taken out from the cell. DOD attains a value equal to the cell capacity when the cell has been fully discharged.
SoC and DOD represent the charge movement inside or outside the cell. However, the values are not the inverse of each other. For instance, a SoC value of 0% represents a completely drained battery. However, at the same instant, the DOD value is not equal to the cell’s capacity due to the fact that there is always some unused and inaccessible capacity remaining in the battery.

2.2.7 Internal Resistance
Every individual Li-Ion cell possesses a certain amount of internal resistance, typically in the order of a few milliohms (mΩ) [7]. The resistance associated with a cell falls into the category of dynamic resistance. This implies that the value of the resistance changes with variation in certain factors. Some of the factors include SoC, temperature, discharge current and usage. With SoC, the value of the resistance is high at both extremes while with temperature, the value of the resistance jumps to a high value at lower temperatures [4]. At higher discharge levels, the resistance value attains a high value. With increased usage, the internal resistance of a cell increases [7]. The resistance of Li-Ion cells fabricated for use in high power applications is less in comparison to cells fabricated for use as energy cells.

2.3 Challenges with Li-Ion Batteries
The following section describes some practical phenomena associated with Li-Ion batteries.

2.3.1 Capacity Loss
The capacity of a Li-Ion battery is not fixed, but rather it varies over the lifetime. The capacity decreases linearly with the number of charge and discharge cycles [15]. Although a portion of the capacity loss is associated with the loss of active material inside the cell, the rest of it is not actually lost, but simply remains unused. This unused amount is a direct result of the increase in the value of internal resistance over the battery lifetime. The cell goes undercharged and under discharged because of the increasing cell resistance. While the cut-off voltages for charging and discharging remain fixed, cells are charged and discharged less and less, resulting in an apparent loss of capacity. The portion of the capacity unused due to increased internal resistance can be recovered by increasing the cut-off voltage in the case of charging and decreasing the cut-off voltage in the case of discharging [7].
2.3.2 Temperature Effects

A Li-Ion battery may catch fire if the temperature is not constrained within the safe limits as specified by the manufacturer. Especially, for power cells, high discharge currents lead to a significant increase of the cell temperature, resulting in thermal runaway [4]. Storage of cells in too hot or too cold environments will result in loss of capacity and an eventual decrease in battery life.

A battery that delivers 100% of rated capacity at 27°C will only deliver 50% at -18°C [5]. This decrease is attributed to the increased internal resistance because of low temperatures. Charging at low temperatures, ranging around -40°C, is practically not feasible. Although the performance is improved at elevated temperatures, cycle life gets reduced. A battery operating at 30°C has its cycle life reduced by 20% and at 40°C, the reduction is approximately 40% [5].

2.3.3 Cell Imbalance

Cell imbalance results from variations of the SoC across individual cells connected in series to form a battery pack. Because of this imbalance, the overall capacity of the battery pack is reduced to that of the weakest cell. The effect of imbalance is shown in Figure 7.

Consider a 3-cell battery pack. The cells to the left represent the state before the start of discharge. After discharging the battery pack, cell 3 is drained out first and the BMS stops the pack current. As depicted, cell 1 and cell 2 have a few percent of their capacity remaining.

In extreme cases, this imbalance issue might even render a battery pack useless.

Figure 7: Individual cell capacities before and after discharge.
2.4 Li-Ion Cells used in the experiments

The Li-Ion cells used in performing the discharge and charge experiments are described below. To establish the demarcation between energy and power cells, experiments are performed with cells from both categories. The data sheets are included in Appendix A.

2.4.1 Energy Cell: Panasonic NCR18650B

The energy cells NCR18650B from Panasonic are cylindrical in shape with a length of 65 mm and diameter of 18 mm, as shown in Figure 8. These cells offer a nominal capacity of 3250 mAh and a nominal voltage of 3.63 V. These cells have Li-NCA chemistry and thereby, have high specific energy. The maximum magnitude of discharge current is limited to 2C as specified by the manufacturer. The maximum charging current and voltage are 1.625 A and 4.2 V. The batteries are charged using constant current constant voltage (CCCV) logic with the cut off current being 65 mA. These cells have an internal resistance of around 40 mΩ. A battery stack is formed by a series connection of 7 cells, resulting in a total nominal voltage of 25.4 V. Each cell weighs approximately 48.5 g [Appendix A.1].

![Image of Panasonic NCR18650B Li-Ion energy cells used in the experiment.](image)

2.4.2 Power Cell: A123 Systems AHP14

The power cells AHP14 from A123 systems are prismatic pouch cells with cell dimensions as (7.5 x 160 x 225) mm, as shown in Figure 9. These cells offer a nominal capacity of 14 Ah and a nominal voltage of 3.3 V. These cells have LiFePO4 chemistry and hence, offer a high specific power while delivering a low nominal voltage. The maximum pulse discharge current is 500 A. These cells have a very low internal resistance, which averages around 3 mΩ. The batteries are charged using constant current constant voltage (CCCV)
logic with the cut off current being 100 mA. The maximum charging current and voltage are 10 A and 3.6 V. A battery stack is formed by a series connection of 8 cells, resulting in a total nominal voltage of 26.4 V. Each cell weighs approximately 510 g [Appendix A.2].

Figure 9 A123 Systems AHP14 Li-Ion power cell used in the experiment.
3. Battery Management System for Li-Ion Batteries

3.1 General Definition of a BMS

Li-Ion battery operation could be destructive for each individual cell if not managed efficiently. Hence, an integrated system, which ensures the cells in a battery pack are operated within their safe operating limits, is required. A battery management system forms an integral part of a Li-Ion battery pack. Compared to other battery chemistries, BMS is particularly important for Li-Ion batteries because of their intolerance to abuse and unbalancing issues in a series string of large Li-Ion battery packs.

There is no specific definition associated with a BMS. The functions performed by a BMS are typically application specific. The following section describes the functions of a BMS, in general. Along with some generic text, some practical information is also included giving an idea of an actual implementation of a BMS.

3.1.1 Main Functions of a BMS

The main function of a BMS is grouped in a span of four areas as specified below [7].

1. Measurement
   One of the most important tasks of a BMS is the measurement of physical parameters of each cell inside a battery pack, which includes cell voltages, cell temperature, and pack current. Some of the important aspects related to each of these measurements are:
   i. Voltage Measurement
      A BMS record individual cell voltages or it may measure cell tap voltages and then calculate individual values by subtracting the values of two taps. The information is then passed on to a processor after analog to digital conversion.
      A practical concern related to these measurements would be the rate at which these voltages are recorded. The rate is usually application specific. One reading every 10 seconds is an acceptable rate for backup power applications while for variable-current application profiles, the rate should be one reading every second [7].
      Another practical concern would be regarding the accuracy of voltage measurements, which depends on, whether; the voltages are used for
battery state estimation. For instance, for charge-discharge detection, an accuracy of 100 mV will suffice. For balancing, voltage measurements with a 50 mV accuracy will be appropriate. However, for estimation of SoC in applications like hybrid electric vehicles (HEVs), an accuracy of 1 mV is required because of the fact that the battery pack voltage always remains in the mid-region of voltage discharge curve, which has a slope of 1 mV/s. For accurate detection of SoC, high accuracy is a must.

ii. Current Measurement
Current measurement is implemented to ensure the battery pack current is always within the safe operating area. Current recorded is used in the measurement of the cell’s internal resistance, which is further utilized to incorporate the internal resistance voltage drop compensation in the cell’s terminal voltage. Current shunts and Hall effect sensors are the most common current measuring devices. Current shunts are usually high precision resistors with a low resistance value. The voltage drop, which is proportional to current, across the shunt resistor, is used to calculate the value of current. These shunts do not suffer from any offset errors. However, the value of resistance depends on temperature, which might introduce some errors in current measurements [7]. Proper shielding is required against electrical interferences as the small signals might get distorted. Accuracy obtained from shunt resistors is close to 0.1%
Hall effect sensors employ modules shaped like a ring, through which the cable carrying the current is routed. Measurements are not affected by temperature and stay accurate over time [7]. However, these sensors suffer from an offset at zero current, which introduces a requirement of frequent calibration. In applications like HEVs, frequent calibration at zero currents is done to remove the offset. Unlike the current shunt, these sensors are integrated with individual amplifiers and thus electrical isolation is not a concern.

iii. Temperature Measurement
Temperature remains a critical issue for Li-Ion battery operation mainly due to strict charging and discharging temperature limits. Cells have an irregular temperature profile across the battery pack which may lead to localized heating. Temperature sensors are, usually, employed for each cell or for the whole battery pack. A midway distribution of temperature sensors could be few specific spots that would be the hottest or the coldest.

2. Management
Management by a BMS includes the utilization of the measured parameters to restrict the battery usage within the safe operating area, to maximize the pack’s capacity and to bring the battery pack within safe operating limits. Following points state the main focus points under management:
i. Isolation of the battery pack
A BMS employs different types of limiting values for the measured parameters of a battery pack. Battery current reduction or interruption is done based on these limiting values. For instance, there are four different limits for current, shown in Figure 10, specified by a battery manufacturer.

![Figure 10 Operating limits for Panasonic NCR18650B cells [7].](image)

The limiting values in Figure 10 are for Panasonic NCR18650B Li-Ion cell. A BMS might force the same value for the four current limits. However, more sophisticated BMS will have different settings for each of those values. For instance, a BMS includes algorithms that can differentiate between continuous and peak discharge currents and determine the appropriate time to start reducing the current by integrating the excess current during a peak.

The same logic is applied whenever the cell voltage or the battery pack temperature goes beyond the specified limits. The battery current will be shut down in the event of any limit violation. Current interruption can be achieved in two ways. A BMS may send signals to the outside system to reduce the battery current or stop using it. A BMS could also employ a protector, like a solid-state switch, that would obstruct the battery current itself.

ii. Balancing
As discussed in Section 2.3.3, an imbalance in a series string of a Li-Ion battery pack can damage one or more cells inside the pack. Hence, a BMS employs algorithms to ensure that all the cells have the same voltage and hence, the same SoC. The algorithms for balancing are discussed in the Section 3.2.3. Balancing can be either passive or active. Passive balancing implies that the extra energy is extracted from
the highly charged cells and is dissipated in an external resistor. Active balancing involves the distribution of energy among the cells [17]. A BMS alters the way in which the cells inside a pack realize the pack current. A BMS might remove some charge from the most charged cells, forming a room for the charging current while at the same time, the least charged cells receive more current. A BMS may bypass the charging current across the most charged cells. Moreover, feeding extra current to least charged cells would be beneficial too but that would involve complex electronics.

iii. Thermal Stresses
A BMS controls the temperature of a battery pack through heating or cooling. Having a prior knowledge of the temperature, the BMS operates a mechanism to keep the pack above its minimum temperature limit or below its maximum temperature limit. The BMS could operate a fan, in case the pack needs to be cooled down or operate the entire passive balancing loads to increase the pack temperature.

3. Evaluation
From the measured data, a BMS is able to perform a set of calculations for battery states estimation, for instance, SoC, state of health (SoH), internal resistance and capacity. The parameters evaluated offer indirect estimates and hence, are prone to large discrepancies.

i. State of Charge
There is no direct way of measuring the SoC for a Li-Ion battery. Each and every method for SoC estimation suffers from its own limitations. Some of the methods are voltage translation, coulomb counting etc. These methods will be discussed in Section 3.2.1.

ii. State of Health
The SoH is a measure of remaining cycle life of a battery. With the increasing number of cycles, the internal resistance increases, while at the same time, the capacity decreases. SoH gives an estimation of the remaining cycle life by the utilization of these parameters.

iii. Internal Resistance
As stated earlier, the values for cell resistance are too dynamic and depend on SoC, temperature, current direction and usage. A BMS needs the cell resistance value to perform the internal resistance voltage drop compensation for accurate estimation of SoC and also for estimation of SoH. Because of the dynamic nature, a BMS cannot rely on the measured value for a long time and measurement needs to be taken at regular intervals.

iv. Capacity
SoC estimation is directly linked with the calculation of cell’s capacity. A decrease in the actual capacity is used for SoH estimation. Measuring a cell’s capacity requires the cell to be discharged or
charged completely. As with the values of internal resistance, a BMS cannot rely on the measured value of capacity for too long as the capacity differs with each cycle.

4. Communications
A BMS might communicate with the external systems for current interruption or reduction in the event of abusive operation. Also, the status of the battery pack and the BMS needs to be communicated to the outside systems. For instance, in an electric vehicle, battery pack status has to be communicated to the user. A BMS might also receive some inputs from the external sensors for system configuration.

To perform these functions, a dedicated analog or digital signal might be implemented to drive the external solid-state devices. Also a data link, like a serial port, is required for communication with the digital data.

3.1.2 BMS Topologies
BMSs are categorized based on the integration with the battery pack. A BMS board might be placed on each cell or can be structured as a single unit. Every topology has its own benefits and drawbacks. The selection of a specific topology is based on the costs involved, system sophistication, installation and maintenance aspects and finally the level of accuracy desired [20]. Following are the two main types of topologies:

1. Concentrated BMS
A concentrated BMS has one board assembly controlling the entire battery pack. There are different ways of connecting a BMS in a centralized topology. In low voltage applications, all the cells are connected to a single circuitry that implements all the BMS functions. As these boards can handle only a few cells in series and hence, are stacked up to monitor more cells by dividing the entire battery pack into modules. One such board acts as a master controller for the others in the stack. A separate master controller could also be included to handle computations, while the other boards do the necessary measurements.

The centralized topology possesses the advantage of low cost, ease of installation and isolation from electrical noise. However, the measurements are not precise and the system cannot be expanded beyond a certain number of cells. The topology is shown in Figure 11.

2. Distributed BMS
As the name suggests, in this topology, the electronic circuitry is placed on the individual cells. The measurements from each board are communicated to
a BMS controller, which handles the battery states estimation. This kind of topology offers high reliability and is suited for applications, which require higher degrees of sophistication. With this topology, it is easier to include new cells in the system.

As the circuitry is placed close to the cells, the performance might be affected by the electrical noise.

![Diagram of BMS topologies]

*Figure 11 Concentrated (left) and distributed (right) BMS topologies*

A diagram representing the two topologies is presented in Figure 11. There is no perfect choice of a topology. The choice is purely application specific and depends on a lot of factors.

### 3.2 Algorithms for Battery States Estimation

Different algorithms for battery runtime parameters like SoC and SoH are described as under.
3.2.1 State of Charge

Battery SoC estimation has always been the critical issue with a BMS. A lot of research has been done in the past few decades but a perfect estimation tool has not been found yet. The different methods available for SoC estimation are:

1. Coulomb counting method
   This is one of the basic methods for SoC estimation. As the name suggests, this method calculates the SoC by integrating the SoC flowing in and out of the battery. The values of the obtained SoC are relative and hence, a starting point is required for absolute estimation. This method can be represented by (2)

   \[ SoC = SoC_0 - \frac{\eta \int I dt}{C} \]  

   Where \( SoC_0 \) represents the initial state of charge at the time \( t_0 \), \( C \) represents the actual capacity in Ah, \( \eta \) is the coulombic efficiency considered to be unity and \( I \) represents currently flowing in or out of the battery. As far as the SoC precision is concerned, this method suffers from drawbacks such as offset in the measurement sensor resulting in SoC drift. Moreover, the coulomb efficiency varies with operating states of batteries such as SoC, temperature, current, etc. [19].

   To remove such errors, various methods related to enhanced coulomb counting, as in [22], have been developed. These methods include corrections for charging and operating efficiencies. Furthermore, these also take into account the capacity fade mechanism of Li-Ion batteries. In such methods, the maximum releasable capacity is re-calibrated during each cycle of operation for more precise SoC estimation.

2. Open circuit voltage method
   This method aims to develop a one to one correspondence between SoC and open circuit voltage (OCV) of a cell. This method leads to an accurate estimation of SoC. The disadvantage being the long resting time required by batteries to reach the balance potential, i.e. the open circuit voltage. Also, this method is less likely to be implemented in practical applications because of the high level of accuracy (1 mV) required to estimate SoC in the mid region of the voltage curve. Careful consideration is needed, as there exists a hysteresis phenomenon in Li-Ion cells [23] because of which the charge OCV and discharge OCV possess different values.
The OCV method has been supplemented with some advanced research, such as [24]. These advanced techniques utilize linear quadratic estimation techniques to modify the conventional OCV-SoC relationship that is independent of the battery conditions. Figure 12 depicts efficient regions of implementation of coulomb counting and voltage translation algorithms.

3. Battery model-based SoC estimation method

The biggest advantage of this method is the online estimation of OCV, which gives an estimation of SoC. The common battery models include equivalent circuit model [25], mathematical [27] and electrochemical models [26]. Battery modeling based on ECM will be discussed in Section 4 in more detail. ECM models incorporate the dynamic nature of batteries using electrical components. These models use parameter estimation tools to estimate the values of electrical components, which in turn help in accurate estimation of OCV and SoC.

The electrochemical models are established based on mass transfer inside the cell and parameter identification is quite complex with huge computations. On the other hand, mathematical models suffer from high inaccuracy [34].

3.2.2 State of Health

The SoH is a crucial feature of a BMS from a user’s perspective. The algorithms behind the evaluation of SoH make use of the battery capacity as well.
as the resistance. The capacity degrades with an increase in the number of charge-discharge cycles while the internal resistance increases.

In most of the SoH estimation algorithms, as in [22], accurate estimation of SoC is done by updating the value of capacity after every charge-discharge cycle. This updated value is used to observe the deterioration of the capacity of the battery, which is an indication of SoH. Equation (3) is used to express SoH in percent.

\[
SoH = \frac{C_m}{C_{rated}} \times 100\%
\]

(3)

Where \(C_m\) represents the maximum releasable capacity in Ah and \(C_{rated}\) represents the rated capacity in Ah specified by the manufacturer.

3.2.3 Charge Balancing across Cells

The uniformity of charge is evaluated by means of voltage, cell capacity, SoC and internal resistance [19]. The balancing algorithms, implemented in a Li-Ion BMS, are based on different regions of the discharge voltage curve. The algorithms are classified into three types [7] as follows:

1. **Voltage based**
   This algorithm works on the notion that cells with the same voltage have the same SoC. It can only be implemented during the charging process. However, the terminal voltage of a cell is different from the open circuit voltage because of the internal resistance voltage drop and also the internal resistance varies from cell to cell. Hence, even if all the cells have the same terminal voltage, the values for OCVs are going to be different, which would lead to the wrong notion of SoC. Determination of OCV values and with high accuracy would lead to proper results when using this algorithm.

2. **Final Voltage based**
   This algorithm utilizes the steep change in voltage values towards the end of the charge. The charge characteristics of a Li-Ion cell reveal that the voltage increases by about 100 mV when approaching 100% SoC. All the cells in the pack experience the same shift in their voltages. This will denote that all the cells are approaching 100% SoC. An advantage of this algorithm is that voltages measured need not be highly accurate as the algorithm does not operate in the mid region of voltage curve.
However, this algorithm suffers from the same disadvantage of varying internal resistances from cell to cell. During charging, the balancing circuit could remove charge from cells with high resistance instead of high SoC, because of high value for terminal voltage [17].

3. SoC History

This algorithm is based on the determination of depth of discharge from the values of SoC using (4).

\[
DOD = \text{Capacity (Ah)} \times (1 - \frac{\text{SoC} (\%)}{100})
\] (4)

The BMS calculates the change in DoD values of all cells compared to the least charged one and calculates the time required for balancing, having a prior knowledge of the balancing current. To bring all the cells to the same DOD values, the balancing current is applied to all the cells except the least charged one during charging or discharging. This method has the same disadvantages as that of the previous two methods. The balancing is affected by the discrepancies in SoC estimation from cell voltage.

The balancing algorithms stated above, more or less, are concentrated to work towards the end of charge. However, some applications like HEVs require that the SoC should always be limited to 50%. In such cases, battery packs should be completely charged once in a while to perform top balancing. Balancing in the mid-voltage region would require a high precision BMS because of the flat discharge voltage profile [17].

A practical equalization circuit can be categorized as dissipative or passive and non-dissipative or active circuits [18]. Passive circuits employ discharge resistors to remove out the extra charge from the most charged cell while active circuits distribute the extra charge across the less charged cells. Active circuits do not waste the extra energy, unlike the passive circuits. However, the development of active circuits needs extra components, which increase the overall cost of the BMS and at the same time, the standby power loss in these circuits might even exceed the power wasted as heat in the passive circuits [21][39]. For instance, in an arbitrary case of an HEV having a 10 Ah battery [7], the power wasted as heat using passive circuits (costing around USD 10) is equivalent to 0.08 W when cells are balanced once a week for 10 minutes at 100% SoC. While for the same conditions, power wasted in the standby mode in an active circuit (costing around USD 100) is 0.44 W, which renders the basic need of these circuits completely useless. Some manufacturers, like Texas Instruments, have already introduced integrated chips implementing active balancing. However, their use in the BMS available in the market today is not significant.
A new approach, still not into commercially available, involves the redistribution of energy. During discharging, extra energy is taken from the cell with the highest capacity and thereby, avoiding the limitations imposed by the cell with the lowest capacity. The circuits employ DC-DC converters, which boost the voltage of cells with a high capacity to the pack voltage and hence, increase the amount of energy taken from them. This method ensures that all the cells remain at same SoC levels all the time. Because of the immature nature of this technology, cost analysis reveals that it is better to add new cells rather than use DC-DC converters [7] for redistribution.

3.3 BMS Comparison: off the shelf vs. custom-made

This section describes the actual components employed inside a BMS. There are BMSs available from different manufacturers in the market today. The functionalities differ from manufacturer to manufacturer. An insight into the costs is also included in Section 3.3.1. As the market is distributed and there are not one or two players who dominate the market, three manufacturers have been chosen based on the variety of products provided, the functionalities of the BMS and the cost.

The BMSs, available in the market, are classified by the functionality as protectors, balancers, monitors and meters and by the method of implementation as analog and digital.

<table>
<thead>
<tr>
<th>Implementation method/functionality</th>
<th>Reports individual voltages</th>
<th>Balances the cells in a battery</th>
<th>Requests to shut off the battery current</th>
<th>Includes a switch to isolate the load and battery</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Digital BMS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can identify the type and intensity of fault.</td>
<td>Protectors</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Balancers</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monitors</td>
<td>✓</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Meters</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Analog BMS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Can detect a fault but cannot identify the type and intensity.</td>
<td>Protectors</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balancers</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td></td>
<td>Monitors</td>
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<td></td>
<td>Meters</td>
<td>✓</td>
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</tbody>
</table>
Table 2 presents the difference between all the categories [37]. The companies chosen for the analysis are Lithium Balance (based in Denmark), Elithion (based in the US) and CleanPower Auto (based in the US).

3.3.1 Off the shelf BMS

As the Li-Ion technology has not matured yet and new Li-Ion chemistries are being introduced, different manufacturers provide different BMSs depending on the type of application.

The Danish company, Lithium Balance, offers two types of BMS: one of which includes centralized protectors and the other type is master/slave balancer. Centralized protectors, designated as i-BMS are designed for low to medium voltages (max 72 V) and can be used with cells of any format. These BMS can handle up to 250 A of current and are compatible with the chargers available in the market. Master/Slave balancers, designated as s-BMS, are designed for large battery packs, up to 1000 V [40]. These balancers are scalable with each slave controlling up to 8 cells in series and with the master, controlling up to 8 slaves.

Elithion, a U.S. based company, designs distributed BMS for all Li-Ion cell formats. The BMS includes an individual board for each cell, powered by the cell itself and measures cell voltage and temperature and provides a balancing current. A BMS controller controls the individual cell boards and also implements basic BMS functions like SoC, capacity, and resistance and SoH calculations. It can, even, control the heating and cooling of the pack using external systems [37].

CleanPower Auto, another company based in the US, offers digital BMS balancers. These BMS provide an excellent balance between functionality and simplicity. Ideal for do it yourself (DIY) hobbyists making their own EV, these BMSs can handle voltages up to 350 V and can be used in distributed as well as centralized topologies [38]. With a mere cost of USD 100, these BMSs employ Hall effect sensors and can measure up to 1000 A. Integration of an LCD display adds an extra cost of USD 70. The display shows the SoC, battery voltage, current, and temperature [38].

3.3.2 Custom BMS

In most of the applications, off the shelf BMS available in the market do not exactly fit into the function description required by the battery pack due to application specific nature of the BMS. This calls for the need to design a custom circuitry that could be implemented as per the requirements. Building a BMS from scratch requires the selection of the BMS application specific
integrated circuits, designated as ASICs. BMS ASICs for small battery packs are readily available. However, when it comes to large battery packs, there are certain limitations to the application specific integrated circuits (ASICs) available. These ASICs are designed for small battery currents and handle a few cells in series. Most of such ASICs are scalable to be implemented in large Li-Ion battery packs but the integration comes with certain drawbacks. Small multiple BMS ASICs have a fixed identity and these couldn’t be addressed directly. A multiplexer is required to read each individual integrated circuit (IC). Also, these ICs don’t have the provisions to read the battery current from the master controller, which will obstruct their advanced functioning.

There are companies offering BMS ASICs intended for large Li-Ion battery packs. Companies like Texas Instruments and Linear Technology, offer different ranges of such ASICs, which are designed to be scalable [7]. One of such ASICs, from Linear Technology, is implemented in this thesis work and will be discussed in more detail in the Section 3.4. These ASICs are grouped into two categories: Analog and Digital, the difference between which has been discussed earlier. The ASICs need to be complemented with temperature and current sensors and processors that would handle the flow of information to and from the ASICs.

3.4 Implementation of ASIC from Linear Technology

The BMS ASIC used to monitor the cells in this project, is acquired from Linear Technology. Multiple cell monitor, part number LTC6804, measures up to 12 cells in series with a total measurement error of 1.2 mV [41]. It implements voltage measurements using two 16-bit analog to digital Converters (ADCs), operating simultaneously. It has provisions for passive cell balancing using external resistors. Designed especially for HEVs, up to 16 ICs can be connected in series, leading to a total number of 192 cells in series. The cell measurement range is 0 V to 5 V, suitable for every Li-Ion chemistry.

Each LTC6804 has an isolated serial peripheral interface (isoSPI) for high-speed, radio frequency (RF) immune, local area communications. Multiple ICs can be connected in a daisy chain (part number LTC6804-1) or parallel port configuration (part number LTC6804-2). In sleep mode, the current consumption is only 4 µA. The working temperature range of the LTC6804 IC is -40°C to 85°C.

This IC can implement under/over voltage monitoring. After measuring each individual cell, the value is compared to the thresholds stored in the memory. If any value moves outside the limits, a bit in the memory is stored as a flag. LTC6804 provides five auxiliary ADC inputs in the form of general-purpose
input/output (GPIOs) pins, which can be used for any analog signal from sensors generating a compatible voltage. As such, current can be measured using a Hall effect sensor or a current shunt. The use of auxiliary ADC inputs has the possibility of being digitized within the same conversion sequence as the cell voltages, thus synchronizing cell voltage and current measurements. The absolute maximum ratings and the pin configuration of LTC6804 are included in Appendix B.

The BMS design, used in this thesis work, utilizes the LTC6804-1 ASIC in the form of a demo board from the same company. Linear Technology manufactures such demo boards to test the functioning of the manufactured ICs. These boards are only meant for evaluation purposes.

3.5 Demo Board comprising of LTC6804-1 (Part Number DC1894B)

Demonstration circuit board DC1894B is a daisy-chainable isoSPI battery stack monitor featuring the LTC®6804-1 [42]. These boards can be linked through a 2-wire isolated serial interface to monitor any number of cells in a stack. Multiple DC1894B can be daisy-chained using RJ45 terminated Ethernet patch cables. The data measured can be sent over to a computer using a DC590B interface board. DC590B, from Linear Technology, is a USB-based controller with the generic serial peripheral interface (SPI) and inter-integrated circuit ports [43]. It is designed to mate with Linear Technology’s family of demonstration circuit boards. The schematic of the demo board is attached in the Appendix B.

This board employs external resistors of value 33 Ω for passive balancing with p-MOSFETs as switches, which can be controlled using the graphic user interface.

3.5.1 Hardware Setup

The demonstration circuit board includes 16 screw terminal connections. The cells are wired from screw terminal 4 to screw terminal 16, which makes up a total of 12 cells in series. The most negative point of the battery pack is connected to screw terminal 4 while the most positive are connected to screw terminal 16. The board needs to be supplied with at least 11 V, in order to properly bias the LTC6804-1 IC. When the board is using less than 12 cells, the cells can be divided into two groups with half of the cells connected to the lower measurement channels and the rest connected to the upper measurement channels, or the cells could fill up the lower channels first and then move on to the upper channels with all the unused channels at the top.
In this thesis work, 7 Panasonic NCR18650B cells are connected in series to form an energy battery pack while 8 A123 systems AHP14 cells are connected in series to form a power battery pack. In both the cases, the cells are wired in ascending order with all the unused measurement channels at the top. The circuit board is shown in Figure 13.

For instance, in the case of Panasonic cells, the cells are wired from screw terminal 1 (the most negative), then 2, 3 and so on, in ascending order until screw terminal 8 (most positive). The rest of the terminals are left unwired. Also, the topmost screw terminal 12 has to be connected to the most positive screw terminal of the battery pack. Hence, the screw terminals 8 and 12 are shorted together.

Connection with DC590B interface board utilizes a 14-pin ribbon, as depicted in Figure 14. The 14-pin ribbon is connected to the SPI BOTTOM connector on the bottom SPI board. For connecting several boards in series, an RJ45 cable is used from the bottom DC1894B isoSPI B RJ connector to the next DC1894B isoSPI A RJ connector. There are 4 jumpers on the demonstration circuit board, which need to be set before it starts functioning. The position of jumpers is specified in Table 3 and the jumpers are depicted in Figure 13.

Figure 13 Demonstration circuit Board from Linear Technology.
### Table 3 Jumper setting

<table>
<thead>
<tr>
<th>Jumpers</th>
<th>0 Position</th>
<th>1 Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP4- Discharge Timer</td>
<td>Timer Disabled</td>
<td>Timer Enabled</td>
</tr>
<tr>
<td></td>
<td><strong>Bottom Board</strong></td>
<td><strong>Upper Board</strong></td>
</tr>
<tr>
<td>JP1- Chip Select</td>
<td>SPI 14-Pin</td>
<td>isoSPI RJ45</td>
</tr>
<tr>
<td>JP2- Clock</td>
<td>SPI 14-Pin</td>
<td>isoSPI RJ45</td>
</tr>
<tr>
<td>JP3- Isolated Mode</td>
<td>Normal SPI</td>
<td>2-wire isoSPI</td>
</tr>
</tbody>
</table>

![Figure 14 Demonstration Circuit board connections.](image)

### 3.5.2 Software Setup

To access the demonstration circuit board from a computer, Linear Technology provides a QuikEval™ software, which can be downloaded from the company’s website [44]. The QuikEval software will recognize a connected demonstration circuit board. However, a graphical user interface (GUI) for DC1894B needs to be downloaded from the company’s website [42] and installed to have full access to the demo board. QuikEval software is not used to communicate with the board. All the communications are done through the GUI, as demonstrated in Figure 15.

The communication with the board can be checked using the READ CONFIG button in the GUI. Over/under voltage limits can be applied globally to each and every cell in the system or customized for the cells connected to an individual board, accessible through the left-hand tabs in multiple board systems.
Cell voltages can be read using the STARTCELL button in the GUI. The voltages are displayed in groups of 3 each. The software is also able to continuously read cells and store the measured voltages in .csv format, which can then be accessed using Microsoft EXCEL. The cells can be individually discharged, for passive balancing, by enabling the DCC box placed beneath the voltage display box of each cell. The cell voltages can’t be read using the STARTCELL button when the cells are being discharged. However, the measurements can be taken using STARTCELLDCC button but the measured voltages would include the contact resistance voltage drops.

Figure 15 Graphical user interface for the demo board.
4. Battery Modelling

This section includes the discussion for the need of a battery model and also a brief classification of different types of battery models present in the literature until today, with an in-depth analysis of battery modeling through equivalent circuit models.

As discussed in Section 3, battery states are not directly measurable by sensors and hence, these values are usually inferred using model-based estimation algorithms [16]. Accurate battery modeling techniques are, therefore, of utmost importance [29]. Such techniques can enhance the convenience, reliability and utility of Li-Ion battery packs in real-life applications. However, the complexity of these models still remains a critical issue, particularly, due to the large computational effort required. Hence, a tradeoff between accuracy and complexity need to be achieved, in order to utilize these models in microprocessors for accurate results in real-time [28]. As aptly put in [30], a high fidelity computer simulation needs to be developed. Laboratory test results should be able to predict battery performance in real-life and thus, modeling and simulation should act complementary to each other.

4.1 Types of Battery Models

A variety of battery models exist, which can predict battery performance with varying degrees of accuracy. The models differ by the nature of complexities as well as by the tests required for the implementation of the model [31]. The following section describes the classification of models in a detailed manner.

4.1.1 Electrochemical Models

Electrochemical models [34] cover the physical design aspects of a battery. They are suitable for understanding the distributed electrochemical reactions in the electrodes and the electrolyte. Such models relate the dependence of the microscopic parameters (e.g. active cell material, concentration distribution) to macroscopic characteristics (e.g. voltage and current) of the battery. Such models include every bit of detail of the inside mechanism of a battery, making them highly accurate. The parameters are related by coupled time-varying partial differential equations [32] - the solution to which may require days of simulation time. Also, the significant number of unknown parameters imparts over-fitting issues leading to poor model robustness (under extrapolation). Electrochemical models require a detailed knowledge of internal battery composition, which is often patent protected.
However, the complex numerical algorithms require a huge computational effort, which negates the accuracy merits of these models and renders them useless in battery management systems.

4.1.2 Mathematical Models
Mathematical models are based on empirical relationships to predict the runtime characteristics of a battery. One of the examples of a mathematical model involves the use of stochastic methods [33], which deal with the uncertainties involved in charge recovery mechanisms during pulse discharge of batteries. These methods, however, do not offer any current-voltage relationship information, required for circuit optimization. Some analytical models make use of simple equations like Peukert’s law [34], capable of predicting the nonlinear relationship between battery capacity and the rate of discharge but do not take the recovery effect into consideration.

Mathematical models are relatively easy to compute compared to electrochemical and equivalent circuit models. However, these models only work for specific kinds of applications and typically offer very low accuracy, in the range of 5%-20% [32].

4.1.3 Equivalent Circuit Models
Equivalent circuit models (ECM) employ active (e.g. capacitors) and passive (e.g. resistors) electrical components to measure the battery performance. These models are a tradeoff between the accuracy and the computational effort, which implies that these models have higher accuracy than mathematical models and lower computational effort than electrochemical models. An ECM can be constructed by performing experiments of charge and discharge in a laboratory. ECMs have been widely accepted in the BMS of electric vehicle offering high dynamic simulation with high accuracy [35].

In this modeling approach, battery performance can be estimated directly from measuring and monitoring the conditions of cell operation. The associated equivalent circuit is used as a tool to predict battery behavior.

4.2 Components of an ECM
As depicted in Figure 16, an ECM consists of different electrical components. A voltage source, representing the open circuit voltage, parallel RC networks, representing the delay in voltage response and a resistor, representing the internal resistance of the cell are the major components of the ECM. Figure 16 shows an equivalent circuit model, implemented in this research work.
Previous modeling approaches, compared in [28], have developed ECMs with varying degrees of accuracy. Some have implemented ECMs with only one RC branch [30] while there are ECMs with two or more RC branches [29] offering improved accuracy. However, evaluation studies, such as [28], have proved that adding more complexity beyond two RC branches does not justify the increased accuracy with additional computational effort. Some models even include dedicated components to model the effect of hysteresis in Li-Ion batteries [36].

4.2.1 Dynamic RC Branches

The parallel RC networks in the ECM are used to incorporate the dynamic nature of the cell. These parameters are used to model the transient response. R1 and R2 are the faradaic contributions to the resistances, which include the charge transfer resistance. C1 and C2, termed as surface capacitors, represent the surface effects of battery and the internal chemical kinetics of the cell. As marked in Figure 17, the time constant of the delayed voltage response is modelled using the two RC branches.

All the parameters vary with variation of SoC, temperature and discharge current. In this thesis work, SoC and discharge current are considered in the analysis of the parameters. Effects due to change in temperature are not included and the cells are assumed to function at ambient temperatures. However, the cell operation is analyzed in the presence of an external cooling system.
4.2.2 Internal Resistance

The internal resistance of a cell is modeled using a resistor, whose value depends on temperature, SoC and discharge current. The instantaneous voltage drop, at the beginning of a discharge, arises because of the presence of this resistance.

4.2.3 Open Circuit Voltage

The OCV of the battery is modeled using a voltage controlled voltage source. The value of the OCV depends on SoC and varies non-linearly with SoC. It is measured as a steady state voltage at different SoC levels. The value of OCV depends on the cell temperature too, but according to several experimental studies, as in [25], the variation is not that evident and can be neglected to reduce the computational effort.

4.2.4 Battery Terminal Voltage

The voltage supplied by the battery to an external load is termed as battery terminal voltage. The value of this voltage differs quite significantly from the open circuit voltage and is obtained after deducting the voltage drop across the internal resistance and the two RC branches, as shown in Figure 18.
4.3 Experimental Tests

For the parameter estimation, it is necessary to account for the steady state as well as the transient response of each and every cell in the battery pack. Experimental tests are designed to conveniently obtain the experimental curves [30]. Two main type of tests are performed on each battery:

1. Pulse Discharge Test
   Pulse discharge test (PDT) includes the discharging of the battery pack by providing the current in the form of constant pulses. There is a rest time included between the application of two subsequent pulses. The rest time is decided based on the settling of open circuit voltage to steady state. Discharge pulses are supplied to the pack to reduce the SoC by 15% with each pulse. The duration of each pulse is calculated using the SoC dependency equation on the discharge current.

   The main aim of these tests is to extract the model parameters, Rs, R1, R2, C1, and C2. PDTs are performed at varying pulse current levels to identify the effect of discharge current on the model parameters. These tests are also used to determine the OCV-SoC curves.

   Discharge current values are decided based on the maximum current rating of the cell specified in the data sheet. Hence, for Panasonic 18650B cells, the current is varied between 0.3C and 2C and for A123 AP14 cells; the current is varied between 0.3C and 8C.
2. Continuous Discharge Test

Continuous discharge test (CDT) involves the discharging of a battery pack at constant continuous current levels. The current levels remain the same as for the PDTs.

These tests are used to identify the effect of different discharge currents on the capacity of the battery pack and of each cell.

4.4 Model Parameter Extraction

All the parameters proposed in the model are functions of SoC, current and temperature. However, only the dependency of SoC and current is analyzed because of the aforementioned reasons. Previous researches have used Electrochemical Impedance Spectroscopy (EIS) for extracting the parameter values. However, this technique cannot be utilized in practical applications, where the operation is much more dynamic and unpredictable.

Another much simpler theory [30] behind parameter extraction involves ohm’s law, which relates the proportionality between the instantaneous voltage and current. However, the technique works well only if the time step used is smaller than the time constant of the associated reaction so that the change in state can be considered minimal.

A much more advanced technique includes the application of curve fitting tools [31] in MATLAB to identify the values of Rs, R1, R2, C1, and C2. The value of Rs is determined using the instantaneous change in the value of the voltage at the end of a discharge pulse.

The technique proposed in this thesis is similar to the one as presented in [25]. This technique uses the parameter estimation tool in Simulink Design Optimization, which is discussed in more detail in Section 4.5. The difference lies in the fact that the model as in [25] does not take into account the effect of varying levels of discharge currents. However, the model as proposed in this thesis includes this effect.

4.5 Modeling in MATLAB

The ECM, as proposed in the beginning of Section 4.2, is modeled in Simulink. An exact equivalent of this model is also designed in Simscape to ease the process of parameter identification. The basic theory behind the modeling in MATLAB involves the following aspects:
1. **Rs Calculation**
   With reference to Figure 17, at the end of any discharge, there is an instantaneous voltage drop. This immediate drop is due the presence of Rs in the cell. The values of Rs can be calculated from discharge curves at different current levels and at different SoC levels, based on (5).

\[
Rs = \frac{V2 - V1}{I}
\]  

(5)

Where I represents the discharge current and V2-V1 represents the voltage difference as marked in Figure 17. The variation of Rs values will be discussed in Section 5.4.

2. **R1 R2 C1 C2 Identification**
   The equations, used in the design of the proposed model are:

\[
C1 \frac{dV2}{dt} + \frac{V2}{R1} = I
\]  

(6)

\[
C2 \frac{dV3}{dt} + \frac{V3}{R2} = I
\]  

(7)

Where I represents the cell current, V2 and V3 represent the voltages of the two RC networks, R1, C1 and R2, C2.

These equations represent the model developed using MATLAB. The solution to this equation can be derived analytically as these are first order RC circuits or using the parameter optimization tool, which enables quick and accurate results.

Simulink Design optimization employs iterative techniques to estimate the parameters. The discharge profile created from the model is compared to the experimental discharge profile and the parameters are updated at each step. The iteration ends when the simulated voltage at each step matches the experimental voltage. The process is repeated using different discharge profiles. The process will produce 2-D lookup tables, in which the parameters vary with SoC and current.

4.6 **Cell Test Setup**

Panasonic NCR18650B Energy and A123 Systems AHP14 Power Li-Ion cells are used in the discharge experiments. The cells are discharged at varied levels
of current, as mentioned in Section 4.3. The cells are connected in series to form a pack. The experimental setup consists of:

4.6.1 Charging System
The charging system consists of a DC power supply. The device allowed the battery pack to be charged under constant current-constant voltage regime. For Panasonic NCR18650B li-Ion cells, a constant current of 1.610 A is used to charge the cells. The voltage is carefully monitored to ensure the safe operating limit of 4.25 V. The power supply is cut off as soon as one of the cells in the pack reach the maximum voltage or the supply current reduces to 65 mA.

The A123 Systems AHP14 power cells are charged using a similar routine but with a constant current of 7.2 A and a constant voltage of 3.6 V. The power supply is cut off as soon as one of the cells in the pack reach the maximum voltage or the supply current reduces to 100 mA.

4.6.2 Discharging System
The discharging system included resistors with a resistance of 6 Ω each. Different values of overall resistance are achieved using a series or parallel combination of the individual ones.

4.6.3 Measurement System
The data acquisition board from Linear Technology is used to measure and store the cell voltages in a computer. The DAQ board uses a microprocessor, developed by LinearTech, LTC6804, which is specially designed for battery management applications. The voltages measured by this board have a 16-bit resolution, equivalent to 1 mV and are logged every half a second [44]. Current is measured using digital multimeters with high accuracy. Temperature is monitored using mini thermometers, having a range of -50°C to +60°C and a resolution of 1°C. Three of these thermometers are placed at different points of the pack, one at the highest potential, one at the lowest potential and one in the middle.

4.6.4 Cooling System
The effect of cooling is also monitored using a lab designed cooling box. The box employs two 12 V DC motors to stabilize the cell temperatures for Panasonic NCR18650B cells. A similar cooling system is utilized to stabilize the temperatures during the discharge of A123 Systems AHP14 cells.
5. Analysis and Results

This section describes in detail the observations from the experiments performed in the laboratory. The charge and discharge curves and the subsequent conclusions from those curves are discussed, in brief. Section 5.4 describes the parameter extraction from the experiments and the related variations with SoC.

5.1 Discharge Curves

The battery pack is discharged at different C-rates to obtain the voltage discharge curve for each C-rate. As mentioned in Section 2.2, Li-Ion batteries offer a relatively flat voltage profile all throughout the discharge process. All the cells are individually monitored in order to see the variation in voltages across each cell in the battery pack. This monitoring is done to ensure the harmonization of cells in the complete battery pack, which forms the core of a distributed BMS.

Along with the monitoring of each cell, the whole battery pack is monitored to see the effect of imbalance among the cells. The discharge curves are obtained for continuous as well as pulsating discharge currents to observe the intrinsic process inside the battery. Before each discharge process, the cells are charged at 0.5C. Only the discharge curves for one value of discharge current are discussed, rest of the curves is included in Appendix C.

5.1.1 Single Cell Voltage Variations

5.1.1.1 Panasonic NCR18650B Energy Cells

1. Continuous Discharge at 0.907C

   As demonstrated in Figure 19, all the cells are balanced before the start of the discharge process at 0.907C (all have the same voltage). Top balancing is done at the end of each charge cycle to ensure each and every cell has the same SoC.

   Evident from Figure 19, at the beginning of discharge, all the cells start at the same voltage. The initial voltage drop arises due to the internal resistance of cells. The cells work in harmony and remain at the same SoC levels all throughout the discharge process with a difference of only 0.02V between the highest and lowest cell voltages. However, as the discharge process comes to
an end, the difference between the highest and lowest cell voltages becomes 0.3 V, which implies a large difference in SoC of the order of 0-10%.

![Figure 19 Continuous discharge voltage profile of the energy cells at 0.907C.](image)

This leads to the conclusion that the SoC level of the battery is limited by the SoC level of the weakest cell, which in this case is cell 7 in the battery pack. Cell 7 is the first to reach the cut-off voltage of 2.5 V, after which this cell cannot be discharged further and as a result, the battery current needs to be shut off. All the other cells still have some capacity remaining, considered as unused or wasted capacity. A battery management system takes into consideration this phenomenon by bypassing the current through the weakest cells, and thus allowing the remaining cells to be discharged to their full capacity. The discharge current is depicted in Figure 20.

The pack current is expressed in the proportion of C-rates, corresponding to the nominal cell capacity. In the case of Panasonic cells, the nominal capacity as specified in the datasheet is 3250 mAh and the C value is 3250 mA [Appendix A.1]. The current, as in Figure 20, is 3 A. Therefore,

\[
\text{Pack Current (as a proportion of } C) = \frac{3}{3.250} = 0.907
\]
2. Pulse Discharge at 0.907C

The curves obtained for the pulse discharge of battery are shown in Figure 21. Again, individual cells are monitored to check the uniformity. These tests are used to extract the intrinsic parameters of the cell. The cell, which reaches the cut-off voltage, first is considered for parameter extraction, as the operation of other cells depends on the weakest one.

As is clear from Figure 21, Cell 7 still remains the weakest link. The different discharge pulses are followed by periods of rest to allow the OCVs to settle down. The proposed equivalent circuit model distinctly explains the response of the battery to these pulses. The instantaneous drop at the beginning of each pulse is a direct consequence of internal resistance, followed by the smooth decay of voltage with time. The smooth decay is represented by the time constant of RC networks in the proposed model. The instantaneous voltage rise, at the end of each pulse, results also because of the cell’s internal resistance. One striking observation from the pulse discharge curve is the change in the value of internal resistance at the end of discharge. The instantaneous voltage rise, at the end of 7th pulse, follows an abrupt increase in internal resistance as the voltages rise by approximately 0.8V for each cell. This clearly indicates the dependence of internal resistance on the values of SoC.

The change of intrinsic parameters with varying SoC levels can be incorporated if the BMS knows the parameter values well in advance to provide compensation for the internal resistance drop. This method will be sufficient for an accurate online estimation of SoC. The pulse current is depicted in Figure 22.
**Figure 21** Pulse discharge voltage profile of the energy cells at 0.907C.

**Figure 22** Energy battery pack pulse current.
5.1.1.2 A123 Systems AHP14 Power Cells

1. Continuous Discharge at 0.90C

Evident from Figure 23, at the beginning of discharge, all the cells start at the same voltage. The initial voltage drop arises due to the internal resistance of cells. The cell voltages drift apart from the balanced voltage value by approximately the same value (0.02 V) as for Panasonic NCR18650B energy cells. The cell voltages drift apart by 0.3 V at the end of the discharge leading to differences in SoC of the order of 10%. Cell 07 reaches the cutoff voltage first, and thus acts as a limiting factor in the pack operation.

The pack current is expressed in the proportion of C-rates, corresponding to the nominal cell capacity. In the case of A123 Systems cells, the nominal capacity as specified in the datasheet is 14 Ah and the C value is 14 A. The current, as in Figure 24, is 12.5 A. Therefore,

$$ Pack \ Current (as \ a \ proportion \ of \ C) = \frac{12.5}{14} = 0.90 $$

![Figure 23 Continuous discharge voltage profile of the power cells at 0.90C.](image-url)
2. Pulse Discharge at 0.90C

The pulse discharge curve, Figure 25, for power cells follows the same pattern as that for energy cells. One noticeable difference in the pulse discharge curves is that the change in OCV after each pulse is of the order of 20 mV for power cells and 100 mV for energy cells. The voltage decay for the working range of the power cells is of the order of few millivolts. Hence, a more precise BMS is required for the power cells if OCV-SoC algorithm is used for SoC estimation. The pulse current is depicted in Figure 26.
5.1.2 Battery Pack Voltage Variations

5.1.2.1 Panasonic NCR18650B Energy Cells
The continuous and pulse discharge voltage curves of the energy battery pack are shown in Figure 27 and Figure 28. All the cells are connected in series to achieve a total voltage of 29.2 V and a capacity of 3.25 Ah.

Figure 26 Power battery pulse current.

Figure 27 Continuous discharge voltage profile of the energy battery pack at 0.907C.
Due to the voltage and subsequent capacity variations across the cells, it is important to consider the intrinsic cell parameter variations in the formulation of a battery pack model. The nature of such an imbalance arises because of thermodynamic origins such as variations in the active material content or the kinetic origins represented by the amount of current extracted from the pack [30]. This requires that the relationship between OCV and SoC should be mapped for each and every cell, which would enhance the computational effort of ECM. However, studies as in [30] have found out that it is wise to make the weakest cell approximation for ECM rather than to evaluate each and every cell individually.

5.1.2.2 A123 Systems AHP14 Power Cells
The continuous and pulse discharge voltage curves of the power battery pack are shown in Figure 29 and Figure 30. All the cells are connected in series to achieve a total voltage of 28.6 V and a capacity of 14 Ah. As evident from the curves, the voltage profiles remain relatively more flat for power battery pack in comparison to the voltage profiles for energy battery pack.

*Figure 28 Pulse voltage profile of the energy battery pack at 0.907C.*
5.2 Charge Curve

5.2.1 Panasonic NCR 18650B Energy Cells

The charge voltage profile and the charging current for the battery pack are shown in Figure 31 and Figure 32. The pack is charged using a constant current constant voltage regime.
A constant current of 0.5C (or 1.610A) is applied to the battery pack until the voltage reaches 29.4V. The current then starts decreasing while the voltage is held constant. The supply is finally cut off when the current drops down to 0.065A.

Figure 31 Charge voltage profile of the energy battery pack at 0.5C.

Figure 32 Energy battery pack charging current profile at 0.5C.
5.2.2 A123 Systems AHP14 Power Cells

The voltage and current charge curves for the battery pack are shown in Figure 33 and Figure 34. The pack is charged using a constant current constant voltage regime.

![Figure 33 Charge voltage profile of the power battery pack at 0.5C.](image)

A very remarkable difference between the charging voltage profiles of energy and power battery packs is that the constant voltage regime works for only 0.30 h forming just a small proportion of the total charging time for power cells, whereas the constant voltage regime forms a major proportion of the charging time for energy cells, accounting for about 1.25 h. This phenomenon can be attributed to the fact that power cells are designed to deliver high power densities and thus, are designed to work in the mid-region of the discharge voltage profile. The charge diffusion is completed in the mid-region of the charging voltage profile, which explains the less time required in the constant voltage regime.

For energy cells, the charge diffusion process occurs mainly in the constant voltage regime. These cells are designed to deliver high energy densities and the cells are designed to work over the whole discharge profile.
5.3 Rate-Capacity Effect

The effect of different discharge currents on the capacity of the battery pack is described in this section.

5.3.1 Panasonic NCR18650B Energy Battery Pack

Figure 35 shows the comparison of voltage discharge curves at different currents. The continuous discharge currents are depicted in Figure 36. The capacity of the battery pack is estimated at each discharge current by calculating the area under the Figure 36 using the trapezoidal rule. The calculated capacities are tabulated in Table 4.

Table 4 Effect of discharge currents on the capacity of the energy battery pack.

<table>
<thead>
<tr>
<th>Discharge Currents (Amperes)</th>
<th>Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31C</td>
<td>3.171</td>
</tr>
<tr>
<td>0.633C</td>
<td>3.140</td>
</tr>
<tr>
<td>0.907C</td>
<td>2.949</td>
</tr>
<tr>
<td>1.808C</td>
<td>2.926</td>
</tr>
</tbody>
</table>
It can be inferred from Table 4 that capacity deterioration occurs with higher rates of discharge. The capacity is reduced by 7.7% when discharge rate is increased from 0.31C to 1.808C. As the algorithms implemented for SoC calculations in a real-time BMS depend on the value of capacity, a capacity correction is required for an accurate estimation of SoC.

The capacity correction can be implemented in a real-time BMS using a model that can change the value of the capacity based on the discharge current value.
The model proposed in this thesis work takes into account the capacity correction by using a lookup table with predefined values for variation of capacity with the current.

5.3.2 A123 Systems AHP14 Power Battery Pack

Figure 37 shows the comparison of voltage discharge curves at different currents. The continuous discharge currents are depicted in Figure 38. Table 5 depicts the calculated values of the capacity of the power battery pack.

*Table 5 Effect of discharge currents on the capacity of the power battery pack.*

<table>
<thead>
<tr>
<th>Discharge Currents (Amperes)</th>
<th>Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.47C</td>
<td>13.00</td>
</tr>
<tr>
<td>0.90C</td>
<td>12.94</td>
</tr>
<tr>
<td>3.30C</td>
<td>12.85</td>
</tr>
<tr>
<td>5.30C</td>
<td>12.72</td>
</tr>
<tr>
<td>7.30C</td>
<td>11.76</td>
</tr>
</tbody>
</table>

The capacity variations increase for the power battery pack (approximately 16%) compared to the energy battery pack (approximately 7.7%). This is due to the high level of discharge current extracted from the former. At 0.90C, the capacity fade is 0.97% for the energy battery pack and 0.46% for the power battery pack.

*Figure 37 Comparison of continuous discharge voltage profiles of the power battery pack at varying discharge levels.*
5.4 Parameter Extraction

As discussed in Section 4, an ECM is developed in MATLAB for extraction of model parameters. The model is fed with initial guesses for the 6 parameters, OCV, Rs, R1, R2, C1 and C2, and the experimental voltage discharge curves. A parameter optimization task is set using the Simulink control and optimization tools; through which simulated and measured voltage curves are compared at each step to obtain the model parameters.

As the pulse discharge curves are inserted into the estimation task, the parameters are obtained at the beginning and end of each pulse. The pulses, used in the experiment, discharge the battery pack in seven steps, reducing the SoC level at each step by 15%. The variation of parameters with the variation of SoC, hence, can be easily observed.

Also, the pulse discharge tests are performed at various current levels through which the parameter variation with discharge current can be observed.

5.4.1 Parameter Variation with SoC

5.4.1.1 OCV-SoC Variation
The OCV-SoC dependency of energy and power cells is depicted in Figure 39. As demonstrated in Figure 39, OCV is high for high levels of SoC while it reduces with a reduction in SoC levels. This dependence is very crucial for
accurate SoC estimation using ECMs. With the IR compensation added to the terminal voltage, estimation of correct values of OCV is utilized in the online estimation of SoC using the voltage translation algorithm.

![Variation of OCV with SoC](image)

**Figure 39 Variation of OCV with SoC.**

The voltage is nearly constant in the mid-SoC regions, between 20% and 80% for the power cell, which requires high-resolution (up to 1 mV) ADCs for voltage measurements. Another important characteristic of this curve signifies the fact that the voltage change is steeper for the energy cell than for the power cell. The power cells are designed to work in the mid-SoC region while the energy cells are designed to work throughout the entire SoC range.

5.4.1.2 Internal Resistance Rs Vs. SoC Variation

According to the obtained result shown in Figure 40 and Figure 41, the value of internal resistance goes high at SoC levels close to zero. Also, the value of Rs nearly remains constant for other SoC levels. This behaviour is more evident for an energy cell than that for a power cell. The values of the internal resistance of the power cell is 100 times less than that of the energy cell.

This increase in internal resistance might be implemented in a BMS to detect the end of charge. Battery capacity is also limited by the value of this resistance. Since cells having high internal resistance will have high voltage drops at the end of discharge, a portion of the capacity remains unused as the BMS shuts off the pack current when the voltage falls below the cut-off limit. However, if the BMS knows in prior the value of this resistance, it can compensate for the remaining capacity by adding the value of internal resistance
drop to the measured voltage, thereby, increasing the energy taken out from the battery.

**Figure 40** Variation of internal resistance of the energy cell with SoC.

**Figure 41** Variation of internal resistance of the power cell with SoC.

5.4.1.3 $R_1, R_2, C_1,$ and $C_2$ Vs SoC variations
The variation of RC network parameters of the energy and the power cell with SoC is shown in Figure 42, Figure 43, Figure 44 and Figure 45.
The capacitance values C1 and C2 of the energy cell as well as the power cell do not follow any specific trend with SoC levels and vary abruptly because of the dynamic nature of the charge movement process inside the battery.

The resistance values R1 and R2 of the energy cell and the power cell follow the same trend as the internal resistance values. The values attain a high value at the end of discharge, i.e. 0% SoC (more evident for energy cell) due to the charge depletion at the respective electrodes. This charge depletion obstructs the further charge diffusion increasing the resistance at the end.
5.4.2 Parameter Variation with Discharge Current

As reflected in Figure 46, the internal resistance values of the energy cells remain almost within a constant range at different discharge currents for SoC levels in the range of 0.2 to 1.0. The values undergo a significant increase for
low values of SoC (below 0.2). The resistance increases with decreasing levels of discharge current values.

The variation of parameters OCV, C1, C2, R1 and R2 are not found to follow any trend with discharge current and the figures have been included in Appendix C3. The parameter values of the power cells follow the same trend as the energy cells and are depicted in Appendix D3.

5.5 Model Validation

5.5.1 Parameter Variation across Cells
To identify the parameter variation across cells, three cells are chosen from the battery pack based on the measured performance. The parameters are analyzed for the weakest cell (the cell to reach the cut-off voltage first at the end of discharge), the strongest cell (the cell with the highest voltage at the instant when the weakest cell reaches the cut-off voltage) and the cell that delivered a medium performance.

Figure 47 shows the difference in the simulated voltage profile of the weakest cell and the measured voltage profile of the strongest cell of the energy cell at 0.633C. The major variations occur in the values of OCV, shown in Figure 48, after each discharge pulse and the values of internal resistance at the end of discharge.
**Figure 47** Comparison of the simulated voltage profile of the weakest energy cell with the measured voltage profile of the strongest energy cell at 0.6333C discharge.

**Figure 48** Variation in OCV with the cell performance of the energy cell at 0.633C discharge.
Figure 49 shows the variations in the values of internal resistance based on cell performance of the energy cells at 0.633C. The discrepancies in the voltage profile of each cell arise mainly due to the variations in internal resistance. The variations increase at the start and end of the discharge. The values of R1 and R2 follow similar trend as Rs. However, C1 and C2 do not follow any trend with variations in cell performance. The figures are included in Appendix C4.

Similar analysis with power cells yielded similar trends of parameter variation across cells. The results and figures are included in Appendix D4.

![Figure 49 Variation in internal resistance with the cell performance of the energy cell at 0.633C discharge.](image)

5.5.2 Simulation of Test Profiles

A test current profile based on the data provided by Volvo Construction Equipment is created to check the relevance and functioning of the proposed model. The weakest cell is taken into consideration for both energy as well as power cells. The variation of SoC from cell to cell is also observed using the test profiles. Moreover, SoC estimation is done using the model as well as the coulomb counting method and the proximity of the calculated values is taken into consideration.

The comparison of the simulated and measured voltage profile of the energy cell is depicted in Figure 50. The test current profile (negative current values for discharge and positive current values for charge) is shown in Figure 51. For energy cells, the SoC discrepancies from cell to cell are within a range of 6% as depicted in Figure 52. The SoC level across each is found to vary more
with higher discharge currents. As far as the SoC estimation is concerned, the variation in SoC values estimated using the proposed model and the coulomb counting method is found out to be less than 4%.

Figure 50 Simulated and measured voltage of the test profile of the energy cell.

Figure 51 Current test profile of the energy cell.
A similar test profile is analysed using the model parameters of the power cell. The simulated and measured voltage profile is depicted in Figure 53. The test current profile and SoC calculations are presented alongside in Figure 53.

The simulated voltage profile exactly traces the measured voltage profile, except at the start of the test run. The error between the profiles is encountered to be less than 0.1% for the overall profile with an exception of 2.98% at the beginning of the cycle. The main reason of this discrepancy at the beginning is not known at the moment but the possible reasons could include dynamic variations in internal resistance, dynamic operating conditions, thermal stresses etc. For power cells, the SoC discrepancies from cell to cell are within a range of 8% as depicted in Figure 54. The discrepancies tend to increase after each high current discharge. As far as the SoC estimation is concerned, the variation in SoC values estimated using the proposed model and the coulomb counting method is found out to be less than 2%.
Figure 53 Simulated and measured voltage profile, test current profile and SoC calculations of the power cell.

The negative values of the test current imply that the battery pack is being discharged while the positive values imply that the battery pack is being charged.
Temperature is closely monitored by placing temperature sensors at different locations in the battery pack. The temperature increase at the cell surface is observed with and without a cooling system. The temperature rise is stabilized in the presence of a cooling system. The rise in temperature without the cooling system is between 22°C and 28°C at three different locations in the pack, which is reduced to less than 14°C with a cooling system.

The variation in voltage discharge curve at 0.907C, with and without a cooling system, is shown in Figure 55. The voltage decay is found to be less steep in the presence of a cooling system, which implies that the intrinsic parameters also depend on temperature. The temperature analysis is not included in the scope of this thesis and the pack is assumed to be working at ambient temperature.
Figure 55 Discharge voltage profile of the energy battery pack with and without a cooling system at 0.907C.
6. Conclusions and Future Work

An accurate, self-corrective and intensive electrical model for a Li-Ion battery has been proposed in this thesis. The model captures the dynamic characteristics of a battery. In actual runtime, this model can be implemented to measure the battery performance. Through this modeling approach, the parameters are dynamically updated based on SoC and discharge current variations. The model parameters are extracted using simulation-based approach. The parameters of the proposed model are found to vary with SoC and discharge current.

The important aspects to be considered in the design of a BMS are also investigated in this thesis work. The choice of a distributed or a concentrated BMS depends on the type of application as well as on the degree of sophistication required. The selection between active and passive balancing still remains a point of concern. However, from the examples presented, it is always wise to passive balance rather than adding extra circuitry for active balancing. The overall effect is the reduced capacity of the whole battery pack. Balancing the cells before the start of a discharge cycle forces the uniform operation of individual cells in a battery pack. However, the cell voltages grow apart as the discharge cycle moves to the end, mainly because of the different values of internal resistances.

An analysis of the discharge profiles has been accomplished in this thesis work. This analysis includes the effect of varying discharge currents on the capacity of the battery.

Accurate battery state estimation algorithms have also been discussed for real-time implementation in a BMS. These algorithms are inferred using the discharge profiles as well as the battery model. Integration of these two aspects leads to accurate state estimation when the battery is in operation.

Model validation has been performed using the extracted parameters for test current profiles for energy as well as power cells. The simulated profiles are found to match the measured profiles with some discrepancies at the beginning of the test run.

Future work to this project could include the effect of temperature variations on the model parameters. The model has not been investigated from a thermal point of view. Li-Ion batteries are very sensitive to temperature variations. Operating above the specified limits might lead to thermal runaway and a permanent damage to the cells in the battery pack.
References


[19] Languang Lu, Xuebing Han, Jianqiu Li, Jianfeng Hua, Minggao Ouyang, A review on the key issues for lithium-ion battery management in electric vehicles, Journal of Power Sources, Volume 226, 15 March 2013, Pages 272-288.
[23] Michael A. Roscher, Dirk Uwe Sauer, Dynamic electric behavior and open-circuit-voltage modeling of LiFePO4-based lithium ion secondary batteries, Journal of Power Sources, Volume 196, Issue 1, 1 January 2011, Pages 331-336.
Appendix A

A.1 Panasonic NCR18650B Cell Specification Sheet

For more information on how Panasonic can assist you with your battery power solution needs, visit us at www.panasonic.com/industrial/batteries-oem, e-mail secsales@us.panasonic.com, or call (469) 362-5600.
A.2 A123 Systems AHP14 Cell Specification Sheet

14Ah Prismatic Pouch Cell
Nanophosphate® Lithium-Ion

A123’s patented Nanophosphate technology provides this prismatic cell with outstanding cycle life and a very high power output. With a high usable energy range and industry-leading abuse tolerance, this cell delivers excellent performance even under the most rigorous testing. Packaging these lightweight cells is easy because of the compact design that’s ready for virtually any application.

Applications
- HEV Heavy Duty Commercial Vehicles
- HEV Passenger Vehicles
- Starter Battery

Product Specifications

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<tr>
<td>Storage Temperature</td>
<td>-40°C to 60°C</td>
</tr>
</tbody>
</table>

Abuse Test | Result
---|---
Nail Penetration | Pass—EUCAR 4
Overcharge | Pass—EUCAR 3
Over-discharge | Pass—EUCAR 3
Thermal Stability | Pass—EUCAR 4
External Short | Pass—EUCAR 3
Crush | Pass—EUCAR 3

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Appendix B

B.1 Ratings and Pin Configuration of LTC6804
B.2 Schematics of the Demo Board DC1894B
Appendix C

Discharge Voltage Profiles and Parameter Extraction Results of Energy Cells

C.1 Continuous Discharge Voltage Profiles

C.1.1 Continuous Discharge at 0.31C

Continuous discharge voltage profile of individual energy cells at 0.31C.
C.1.2 Continuous Discharge at 0.633C

Continuous discharge voltage profile of individual energy cells at 0.633C.

C.1.3 Continuous Discharge at 1.808C

Continuous discharge voltage profile of individual energy cells at 1.808C.
C.2 Pulse Discharge Voltage Profiles

C.2.1 Pulse Discharge at 0.31C

Pulse discharge voltage profile of individual energy cells at 0.31C.

C.2.2 Pulse Discharge at 0.633C

Pulse Discharge Voltage profile of individual energy cells at 0.633C
C.2.3 Pulse Discharge at 1.808C

Pulse discharge voltage profile of individual energy cells at 1.808C.
C3. Parameter Variation with Discharge Current

C3.1 Variation of OCV with Discharge Current

Variation of OCV with the discharge current.

C3.2 Variation of R1 and R2 with Discharge Current

Variation of R1 with the discharge current.
Variation of R2 with the discharge current.

C3.3 Variation of C1 and C2 with Discharge Current

Variation of C1 with the discharge current.
As mentioned in Section 5.5.2, three cells are chosen from the battery pack to observe the parameter variation from one cell to the other. Three cells delivering the best, medium and worst performances are selected for analysis. The parameters presented are obtained at 0.633C discharge.

C4.1 Variation of R1 and R2 across Cells

Variation of C2 with the discharge current.

Variation of R1 with the cell performance.
Variation of R2 with the cell performance.

C4.2 Variation of C1 and C2 across Cells

Variation of C1 with the cell performance.
Variation of $C_2$ with the cell performance.
Appendix D

Discharge Voltage Profiles and Parameter Extraction Results of Power Cells

D1 Continuous Voltage Discharge Profiles

D1.1 Continuous Discharge at 0.47C

Continuous discharge voltage profile of the individual power cells at 0.47C.
D1.2 Continuous Discharge at 3.3C

Continuous discharge voltage profile of the individual power cells at 3.3C.

D1.3 Continuous Discharge at 5.3C

Continuous discharge voltage profile of the individual power cells at 5.3C.
D1.4 Continuous Discharge at 7.3C

Continuous discharge voltage profile of the individual power cells at 7.3C.

D2 Pulse Discharge Voltage Profiles

D2.1 Pulse Discharge at 0.47C

Pulse discharge voltage profile of the individual power cells at 0.47C.
D2.2 Pulse Discharge at 3.3C

Pulse discharge voltage profile of the individual power cells at 3.3C.

D2.3 Pulse Discharge at 5.3C

Pulse discharge voltage profile of the individual power cells at 5.3C.
D2.4 Pulse Discharge at 7.3C

Pulse discharge voltage profile of the individual power cells at 7.3C.

D3 Parameter Variation with the Discharge Current

D3.1 Variation of OCV with the Discharge Current

Variation of OCV of the power cell with the discharge current.
D3.2 Variation of Internal Resistance with Discharge Current

Variation of internal resistance of the power cell with the discharge current.

D3.3 Variation of R1 and R2 with the Discharge Current

Variation of R1 of the power cell with the discharge current.
D3.4 Variation of C1 and C2 with the Discharge Current

Variation of R2 of the power cell with the discharge current.

Variation of C1 of the power cell with the discharge current.
Variation of C2 of the power cell with the discharge current.

D4 Parameter Variation across cells

As mentioned in Section 5.5.2, three cells are chosen from the battery pack to observe the parameter variation from one cell to the other. Three cells delivering the best, medium and worst performances are selected for analysis. The parameters presented are obtained at 3C discharge.
D4.1 Variation of OCV across Cells

Variation of OCV with the cell performance

D4.2 Variation of Internal Resistance across Cells

Variation of internal resistance with the cell performance.
D4.3 Variation of R1 and R2 across Cells

Variation of R1 with the cell performance.

Variation of R2 with the cell performance.
D4.4 Variation of C1 and C2 across cells

Variation of C1 with the cell performance.

Variation of C2 with the cell performance.