THE PENNSYLVANIA STATE UNIVERSITY
THE GRADUATE SCHOOL

DEPARTMENT OF ELECTRICAL ENGINEERING

MINIMIZATION OF CIRCUITRY IN LARGE FORMAT LITHIUM-ION BATTERY MANAGEMENT SYSTEMS

A Thesis in
Electrical Engineering
by
Jerin Miller

Submitted in Partial Fulfillment
of the Requirements
for a Degree of

Master of Science

December 2012

The thesis of Jerin Miller was reviewed and approved* by the following:

Jeffery S. Mayer
Associate Professor of Electrical Engineering
Thesis Advisor

Karl Reichard
Research Associate/Assistant Professor of Acoustics

Robert O. Richards
R & D Engineer

Jack Mitchell
Professor of Electrical Engineering

Kultegin Aydin
Professor of Electrical Engineering
Head of the Department of Electrical Engineering

* Signatures are on file in the Graduate School.

ABSTRACT

Lithium-ion based batteries are the most energy and power dense rechargeable batteries currently available. However, to operate within safety limits battery voltages, currents, and temperatures must be monitored throughout the charge-and-discharge cycle. Battery Management Systems (BMS) monitor, report, or equalize the cell voltages of large packs to ensure operation within safety limits and to maintain balanced cells within the pack. For large Lithium-ion series packs, monitoring two or more cells in series instead of monitoring individual cells can reduce the size, weight, and complexity of a BMS, which is often desirable to strict space, weight, and reliability requirements. Monitoring and balancing every cell is desirable because when the battery pack is charged all of the cells will be charged to the same voltage and if an individual cell dropped below a certain voltage on discharge, the load could be disconnected from the pack. By monitoring multiple cells and controlling the current limits of the pack, a small amount of resolution is lost but the system can still function safely.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to thank my family for their patience, help and understanding during the busy three semesters of my master's degree.

I would like to thank my mentors and advisors for helping me throughout the thesis process and their faith in the completion of my degree.

Chapter 1

Introduction

Lithium-ion based batteries are the most energy dense and power dense rechargeable batteries on the market today. Safety concerns in some applications, however, dictate that a battery be accompanied by a Battery Management Systems (BMS) that increases the volume of the battery thereby reducing this advantage while also increasing the cost and complexity of the battery. A basic BMS monitors the voltages and temperatures of individual cells[1] during the charge-and-discharge cycle and provides signals to interrupt the cycle, if there is a danger. More sophisticated BMS's for large batteries provide additional functionality such as estimating the state of charge of the battery and balancing cell voltages to ensure operation within safety limits. The objective of this thesis project was to investigate the advantages and disadvantages of a BMS that monitors and balances multiple cells or blocks instead of individual cells to maintain proper cell voltages and safety margins.

Brief History

Benjamin Franklin coined the term "Electrical Battery" in 1749 to describe an apparatus that could be charged and discharged like the batteries we use today. However, Franklin's "Electrical Battery" was not a battery by today's definition but rather a set of capacitors made of glass, lead plates, silk and lead wire (1). Luigi Galvani, while dissecting a frog affixed to a brass hook, found that when he touched the frog's leg with an iron scalpel, the leg twitched. He

[1] In this thesis, the term "cell" refers to an individual electrochemical cell. An array of such cells is connected to form a battery.

consulted his friend and fellow scientist Alessandro Volta who postulated the phenomenon was caused by joining two metals by a moist intermediary. Volta then invented the first battery in 1800. It was comprised of copper and zinc discs piled on top of each other but separated by cloth soaked in brine (2). It subsequently became known as the voltaic pile. Frenchman Gaston Planté invented the first practical rechargeable battery based on lead-acid chemistry in 1860 (3). Lead-acid batteries have been widely used since then in many applications from powering telegraph stations to automobile starters. Lead-acid batteries have the advantages of being able to supply high currents and the ability to self-balance through controlled overcharging (4).

Lithium-ion batteries were commercialized in 1991. Lithium-ion cells offer high energy densities and high power densities. Because the nominal voltage of lithium-ion cells is around 3.5±0.2 V depending on the particular chemistry, most lithium-ion batteries consist of multiple cells connected in series. Overcharging can cause thermal runaway and cell rupture. Over discharging may cause the cell to short-circuit. These two problems are typically avoided through use of a Battery Management System, which increases the volume, cost, and complexity of the battery (4). This will be described further in the Battery Management Systems section later in this Chapter.

Lithium Ion Chemistry

Batteries with lithium active materials typically have higher energy densities, lower self-discharge rate, and longer cycle lifetimes compared to other battery chemistries. A schematic diagram of a typical Li-Ion cell is shown Figure 1.1. The active materials are a lithium metal oxide ($LiMO_2$) and lithiated carbon (Li_XC) in the positive and negative electrodes, respectively. Typically the metal in the positive electrode is the transition metal Co, but the cells that are being used for this project are manufactured by A123 and contain $FePO_4$ in the positive electrode. The positive electrode reaction that takes place for a Co-based cell is as follows (5):

$$Li_{1-x}CoO_2 + xLi^+ + xe^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} LiCoO_2$$

The negative electrode reaction is (5):

$$Li_xC \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} C + xLi^+ + xe^-$$

This reaction produces a higher voltage than most other battery chemistries: 4.1 V. The A123 cells used in this project produce 3.6 V.

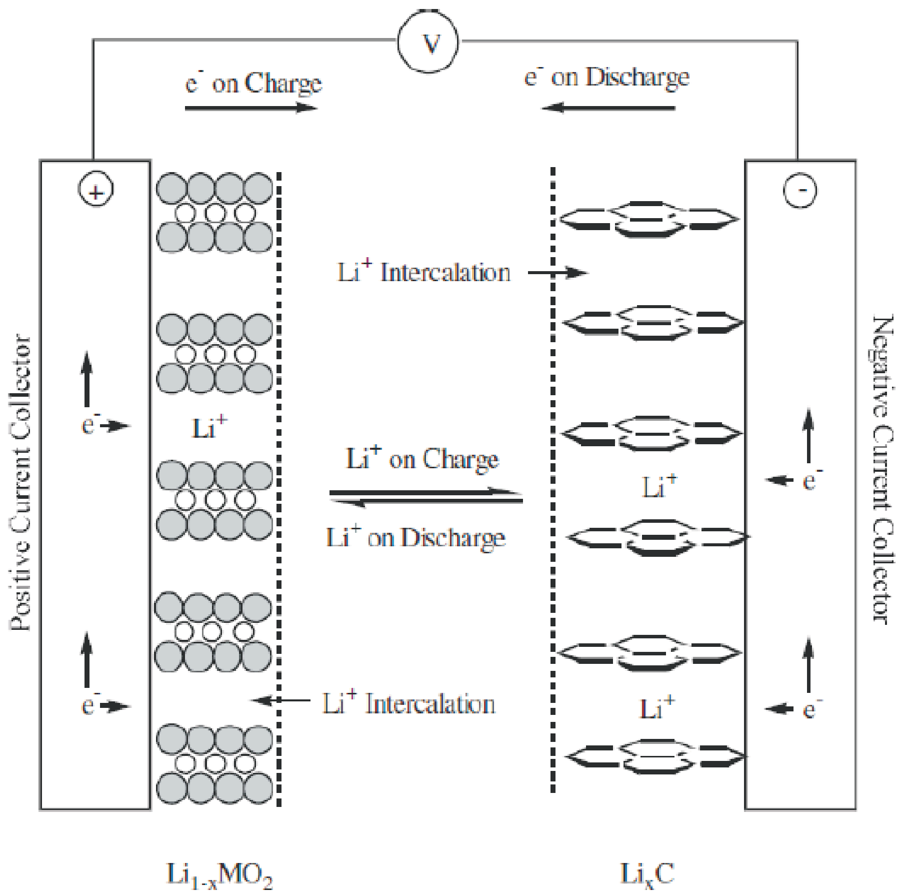

Figure 1.1 Schematic Diagram of a Lithium Ion Cell [6]

Degradation Factors

No battery chemistry is capable of discharging and recharging indefinitely. The various chemistries have diverse degradation characteristics with varying degrees of performance loss. Degradation can be caused by an increase in resistance in the cell or by a degradation mechanism in the positive and negative electrodes or the electrolyte. These mechanisms include but are not limited to: solid electrolyte interface layer growth, lithium corrosion, contact loss, and lithium plating. The solid electrolyte interface creates higher impedance as it grows on the negative electrode. Lithium corrosion causes the battery's capacity to decrease because Lithium previously used for reactions permanently corrodes in the active carbon material of the negative electrode. Contact loss is caused by the solid electrolyte interface layer separating from the negative electrode and increases the cell's resistance. Lithium plating occurs at low temperatures, high charge rates and low cell voltages and decreases the cells capacity by consuming lithium that would otherwise be used in a reaction (5).

Performance

Lithium based batteries currently have the highest energy and power densities. Much of this is due to the higher theoretical voltage. A comparison of the four most commonly used cell chemistries is shown below in table 1.

	$LiFePO_4$	Lithium Cobalt	Ni-MH	Pb-Acid
Theoretical Voltage	3.6 V	4.1 V	1.35 V	1.93 V
Practical Specific Energy	110 Wh/kg	150 Wh/kg	75 Wh/kg	35 Wh/kg
Approximate Efficiency	80%	80%	60%	60%

Table 1 Cell Performance Comparison

The energy efficiency is calculated as watt-seconds out divided by watt-seconds in. In addition to higher voltage, energy density, and energy efficiency, lithium based batteries are capable of higher charge rates than other chemistries. They also have longer cycle lives than other chemistries. To measure cycle life cells are cycled from 100% State of Charge (SOC) to 0% SOC at a typical charge/discharge rate. Lithium based batteries typically last approximately 3,000 cycles compared to 500 for Ni-MH and 200 for Pb-Acid (5).

Cell Characteristics

Lithium based cells have a much "flatter" open circuit voltage (OCV) vs. SOC curve than other chemistries. This means the OCV does not change much with respect to the SOC. This is beneficial when regulating voltages but a hindrance when estimating SOC. Figure 1.2 shows the cell voltage vs. capacity and the discharge capacity vs. cycle (6).

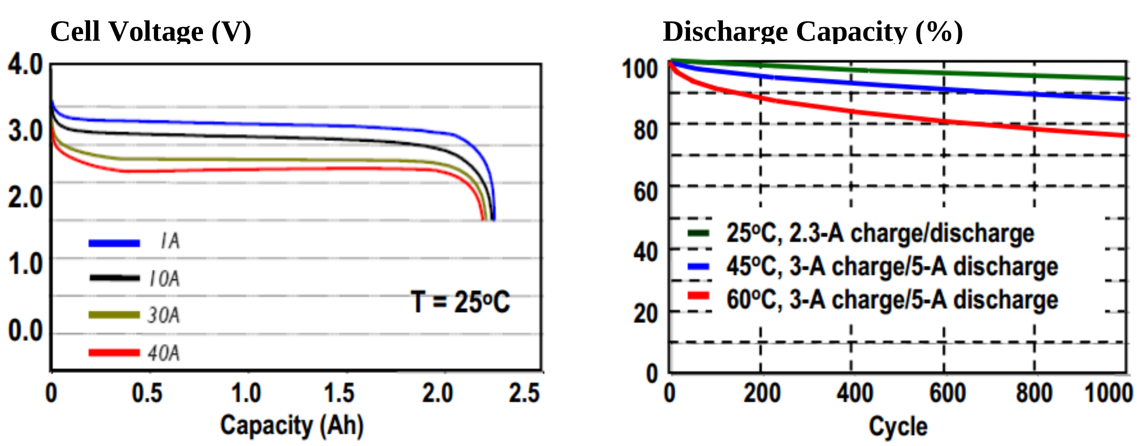

Figure 1.2 Lithium Iron Phosphate Cell Characteristics

State of charge is the presently available capacity of the cell divided by the total available capacity at full charge. For the A123 cells shown in figure 1.2 the available capacity available at full charge is 2.3 A-h. After 0.2 A-h (about 91% SOC) the voltage changes very little until after 2.0 A-h (about 13% SOC) have been extracted from the battery. This feature is much more prevalent in the A123 $LiFePO_4$ cells than other chemistries. Fortunately the voltage is not completely flat throughout the entire range of SOC. Near 100% SOC (above 90%) the voltage increases exponentially with respect to SOC. This effect can also be seen below 15% SOC when the voltage decreases exponentially with respect to SOC and is much more pronounced. This allows small changes in SOC near the end of a charge or discharge to be seen very easily.

The graph on the right hand side of Figure 1.2 shows the discharge capacity or state of health (SOH) vs. number of cycles. There are three factors involved in each of the three plots: charge current, discharge current, and temperature. As temperature or either current increases the SOH degrades faster with the same number of cycles. Note that at higher charge and discharge rates the SOH degrades the fastest at the beginning of the cycling.

Large Format Batteries

A battery consists of one or more cells that convert stored chemical energy into electrical energy connected in series or parallel. There are two ways of connecting parallel cells in series. First, the parallel cells are connected in parallel then they are connected in series this is written as nPmS where n is the number of cells in parallel and m is the number of cells in series. The second method is to connect the series cells in series then connect those series cells are connected in parallel this is written as mSnP.

Figure 1.3 displays both methods of connecting cells in series and parallel. The 2P4S battery on the left has four pairs of two cells in parallel, connected in series. This configuration can reduce the amount of circuitry in a standard BMS because by balancing one cell, its' parallel cell is balanced as well. A balancing circuit and voltage monitor is only needed for every group of parallel connected cells. The 4S2P battery on the right in Figure 1.3 has two pairs of four cells in series, connected in parallel. This configuration does not reduce the amount of circuitry in a standard BMS because a balancing circuit and voltage monitor is needed for every cell.

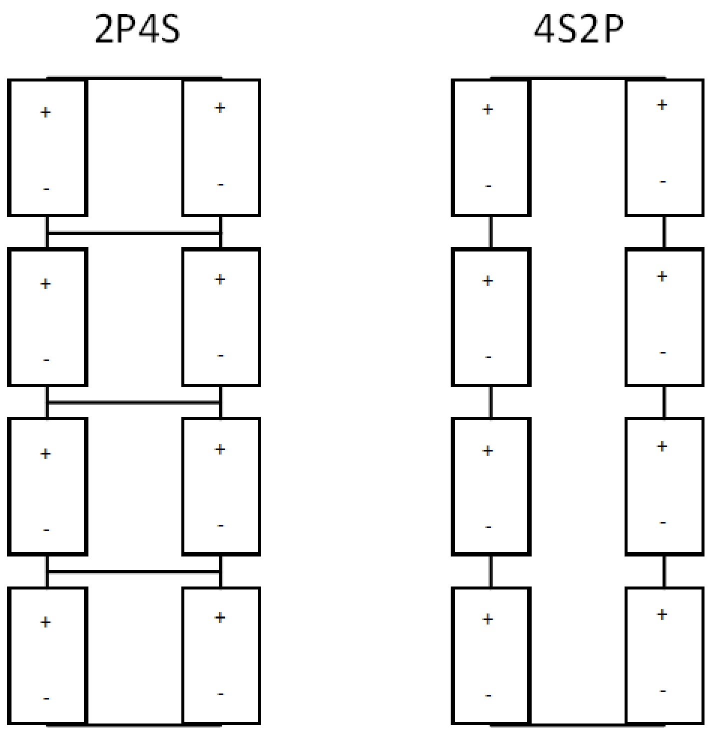

Figure 1.3 Series and Parallel Cells

Battery Management Systems

It might not be obvious why a battery management system is needed in a large lithium ion battery pack. In the summer of 2011 a Chevy Volt was tested by the Insurance Institute for Highway Safety. It was subjected to a side-impact crash just like any other car. Three weeks after the crash test the battery pack caught fire. Had the battery management system properly discharged the cells after the crash, the battery pack would likely not have caught fire (7). This is one of many reasons a battery management system is needed. Other reasons to include a battery management system in a pack are: prevent thermal runaway, allow the use of the entire capacity of the battery, prevent over charge or discharge of individual cells, prevent large charge or discharge currents, and extend the life of the battery pack.

A BMS has been defined by Andrea (8) as a product or technology that performs any of the following functions:

- Monitor the battery;
- Protect the battery;
- Estimate the battery's state;
- Maximize the battery's performance;
- Report to users and/or external devices.

Battery management systems use two techniques to balance multiple cell packs: active cell balancing and passive cell balancing. A common active cell balancing method is charge shuttling. This can be implemented by flying capacitors or two cell capacitor shuttling, described in later sections. The most common battery management method is a passive cell balancing technique known as charge shunting (4).

Battery management systems can be classified by their function, technology, topology and how balancing is achieved. Stephen Moore and Peter Schneider discuss how balancing is achieved with two categories: active cell balancing and passive cell balancing (4). Andrea uses the four categories stated earlier to classify battery management systems, giving them a wider scope (8).

Battery Management System Functionality

Battery Management Systems can have various functions and methods to perform those functions. The functionality of each system can be classified into six basic categories as described by Davide Andrea in his book (8). The categories in increasing order of complexity include:

- Constant current/constant voltage (CCCV) chargers;
- Regulators;

- Meters;
- Monitors;
- Balancers;
- Protectors.

Davide Andrea states that the most basic BMS is a CCCV charger. A CCCV charger has a current limit and a voltage limit. A generic CCCV charger could be a 12 volt, 5 ampere power supply. The power supply delivers 5 amperes until the battery is charged to the 12 volt limit. Then as the internal resistance of the battery increases, the current decreases. A BMS in this category cannot infer individual cell voltages or SOC. This method does not provide the safety needed for most applications (8).

Regulators can be used to balance individual cells when the cell is fully charged. A BMS in this category typically is used by hobbyists who are looking for a low-cost, low-complexity method. The advantages of regulators are the reduced cost and they are least complex balancing option. However, regulators do not provide protection for over discharging cells or overcharging cells. Overcharging can be prevented by reducing the charger voltage to the capacity of the regulator (8).

Meters will not be discussed in detail because they are only beneficial when one is monitoring the output of the meter. A meter requires a human to constantly monitor it and cannot balance the battery. A meter that can control the input and output (power supply and load) of the cells is called a monitor.

A monitor can be used to charge or discharge a battery as long as the cell limits are taken into consideration. It can provide full protection from each cell going over its’ maximum or under its’ minimum voltage but cannot balance the pack. A monitor differs from a meter by not being able to control the power supply or the load. This type of system can be used to cycle or test battery packs (8).

Balancers and protectors are very similar in function and implementation with the only difference being that a protector has a switch to control the input and output instead of controlling the input and output via a form of communication between the BMS and the load/power supply. They both balance and protect the cells from over and under voltage conditions. A protector is not normally used in large lithium ion battery packs because of the large voltage that the switch needs to handle (8).

Active Cell Balancing

Active cell balancing methods, as described by Moore and Schneider, employ an active charge-shuttling element or voltage or a current converter to move energy from one cell to another to maintain equal charge. Charge shuttling can be accomplished by a method known as a flying capacitor shown in Figure 1.4.

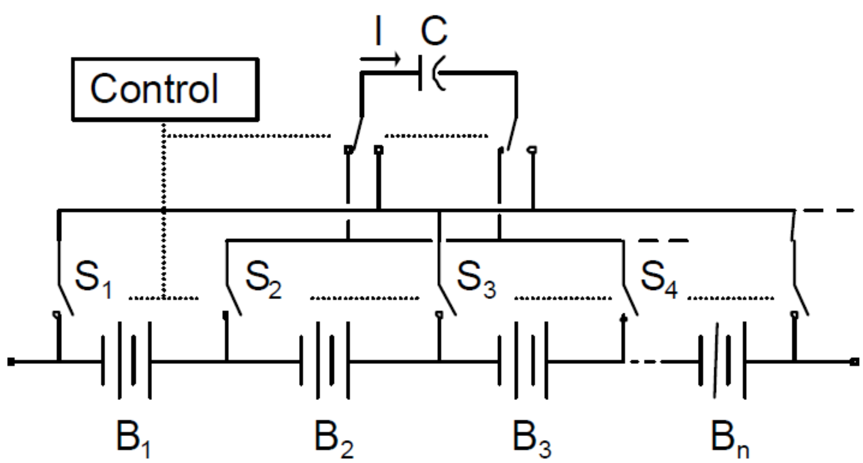

Figure 1.4 Flying Capacitor Charge Shuttling Method [4]

The flying capacitor discharges the highest charged cell and charges the lowest charged cell (given a strictly increasing state of charge vs. voltage charging curve). The switches can be operated by a fixed sequence or by a smart controller that charges the lowest cell from the highest cell (4).

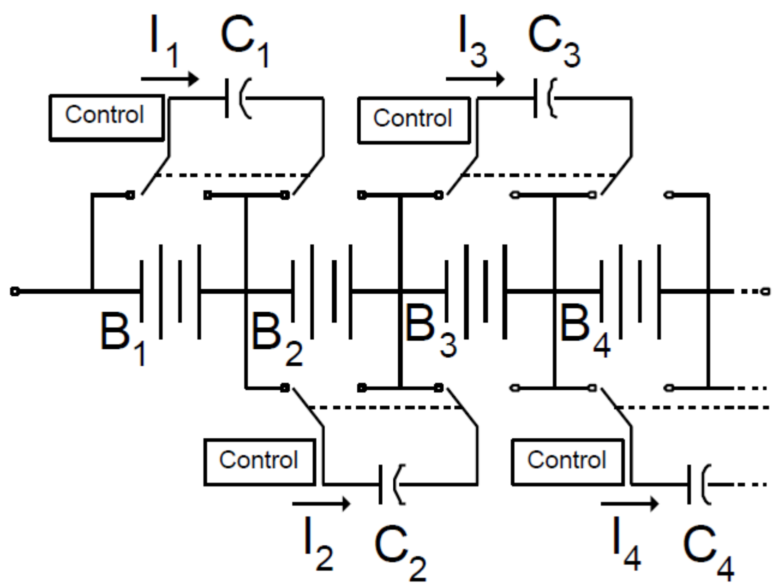

Figure 1.5 Charge Shuttling with Several Cells [4]

Other active balancing methods are: switched capacitors for every two cells (shown in Figure 1.5) and energy converters (shown in Figure 1.6). Switched capacitors every two cells decrease the control complexity but are slow to balance cells if the high cells and low cells are on opposite ends of the pack because the charge is transferred from one cell to the next. Energy converters can balance low cells quickly but are costly and inefficient (4).

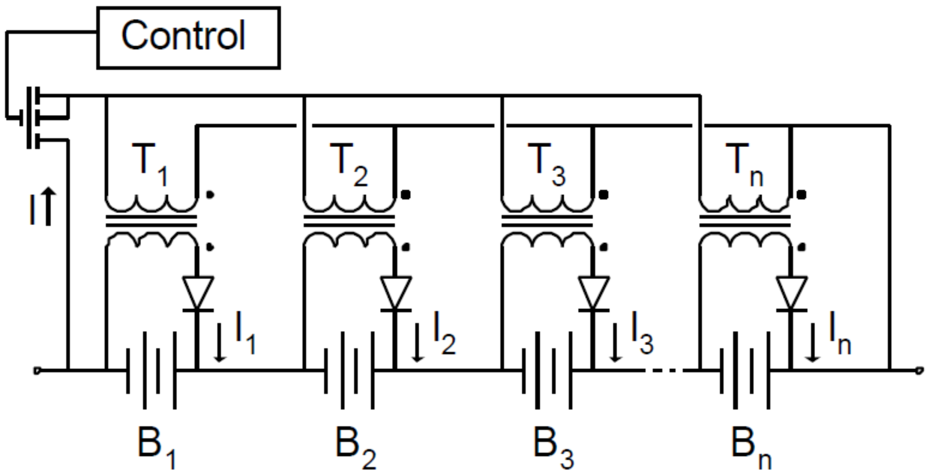

Figure 1.6 Multiple Transformers [4]

Passive Cell Balancing

The most common cell balancing technique is passive cell balancing. Charge shunting, the most common form of passive cell balancing, is depicted in Figure 1.7. Charge shunting can be used as the cells become fully charged or at any time in the charge cycle. The SOC vs. Voltage curve of the A123 $LiFePO_4$ cells are relatively flat over much of the charge/discharge cycle. As a result, it is much easier to balance cells using this BMS at the end of the charge cycle in a system of a known charge rate. The resistors are sized such that the entire charge current, I, flows through R at the fully charged cell voltage (3.6 V for the A123 $LiFePO_4$ cells) (4).

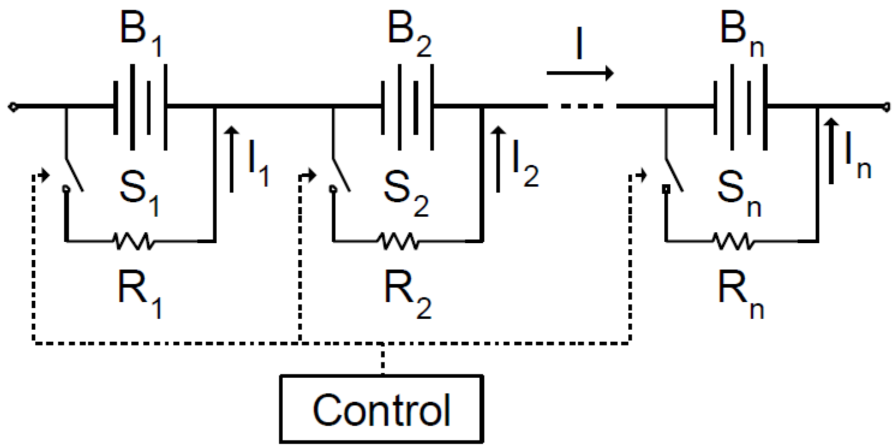

Figure 1.7 Charge Shunting [4]

State of Charge Estimation

State of Charge (SOC) estimation can be accomplished by monitoring individual cell voltage and current. There are many methods such as voltage lookup, coulomb counting, and using physics-based mathematical models. For voltage lookup, the cell voltage is measured and then mapped to estimated SOC using a look-up table based on curves such as those shown previously in Figure 1.2. Due to the shape of the curves, to obtain an estimated SOC that is within 10% of the actual SOC, the resolution of the voltage measurement must be on the order of 10 mV for an SOC below 20% or above 80% and on the order of 1 mV for an SOC between 20% and 80% (8). Moreover, this method requires the cell to be in a steady state, which is normally not the case. Coulomb counting can be used to measure SOC directly. However, it requires an extremely accurate current sensor, as any measurement error introduced by the current sensor is integrated and can result in large errors in estimated SOC. The last method, using a physics-based mathematical model, is the least susceptible to errors but is the most complex to implement. Moreover, modeling of lithium ion batteries is still an active area of research (5).

Chapter 2

Proposed Solution

A battery management system that monitors and balances individual cells requires a significant amount of space and adds significant levels of cost and complexity in a battery pack. It seems plausible that the volume, cost, and complexity of a BMS could be reduced by monitoring and balancing blocks containing multiple cells. The testing performed as part of this project provides data from which to determine the optimal number of $LiFePO_4$ cells per block that a future BMS would monitor and balance. This future system would operate just as a typical BMS utilizing the passive charge shunting technique. The test apparatus and analysis procedures developed for this project could be used to determine the optimal number of cells for a different cell chemistry and/or set of charge and discharge current rate limits.

Design

The design of a BMS that monitors and balances multiple-cell blocks would be similar to that of a BMS that monitors and bypasses individual cells. A module is a unit within the BMS that monitors or balances M cells and report to a master BMS module or operates independently. Typically, there are modules for 10-12 cells sometimes with a master module. However, a system with 4 cell blocks would have 10-12 blocks per module. Each module would then monitor and bypass 40-48 cells.

Figure 2.1 shows a BMS based on the proposed solution outlined in this thesis. Numbering in the figure start at cell 0, block 0, module 0 ending with cell (N*K)-1, block K-1, module M-1.The BMS consists of N*K total cells with K Blocks containing N cells each. The figure shows four blocks per module with a total of M modules. The modules could consist of any number of blocks; however, voltage limitations dictate the maximum voltage and thus the maximum number of blocks per module.

With this system, the voltage of individual cells would not be known. Individual cell voltages would have to be estimated from block voltages. The BMS would monitor and balance cells based on the voltages of each block. In order to reduce the likelihood of a single cell going out of balance from other cells in its block, the BMS could implement a conservative control scheme. For example with the A123 $LiFePO_4$ cells, instead of bypassing blocks at an average of 3.6 V per cell and terminating discharge when a block reaches an average of 2 V per cell, the BMS could bypass blocks at an average of 3.55 V per cell and terminate discharge at 2.4 V per cell. This control method would only decrease the useable capacity of the battery pack by a few percent.

Currently there are no BMS modules on the market that monitor and balance on a block-by-block basis. Some off-the-shelf systems could be modified to monitor and balance groups of cells, but the disadvantages of doing so would outweigh the benefits. Another approach to implement this method is to use low-power microcontrollers to monitor and balance blocks of cells. This style of BMS would not require the modules (low-power microcontrollers) to communicate with one another, reducing the cost of the system. The problem with using microcontrollers is their efficiency. Even most low-power microcontrollers have more capability and hence consume more power than is required to monitor voltages and balance the blocks of cells.

If possible the smallest and most efficient BMS would be a custom chip designed for the specific needs of the battery that it is monitoring and balancing. A simple custom chip would have op-amps for comparing the isolated voltage of each block and MOSFETs to balance each block. This chip wouldn’t require as much power or space as the two other implementations discussed previously. A drawback to this method is that custom chips are costly to design and build.

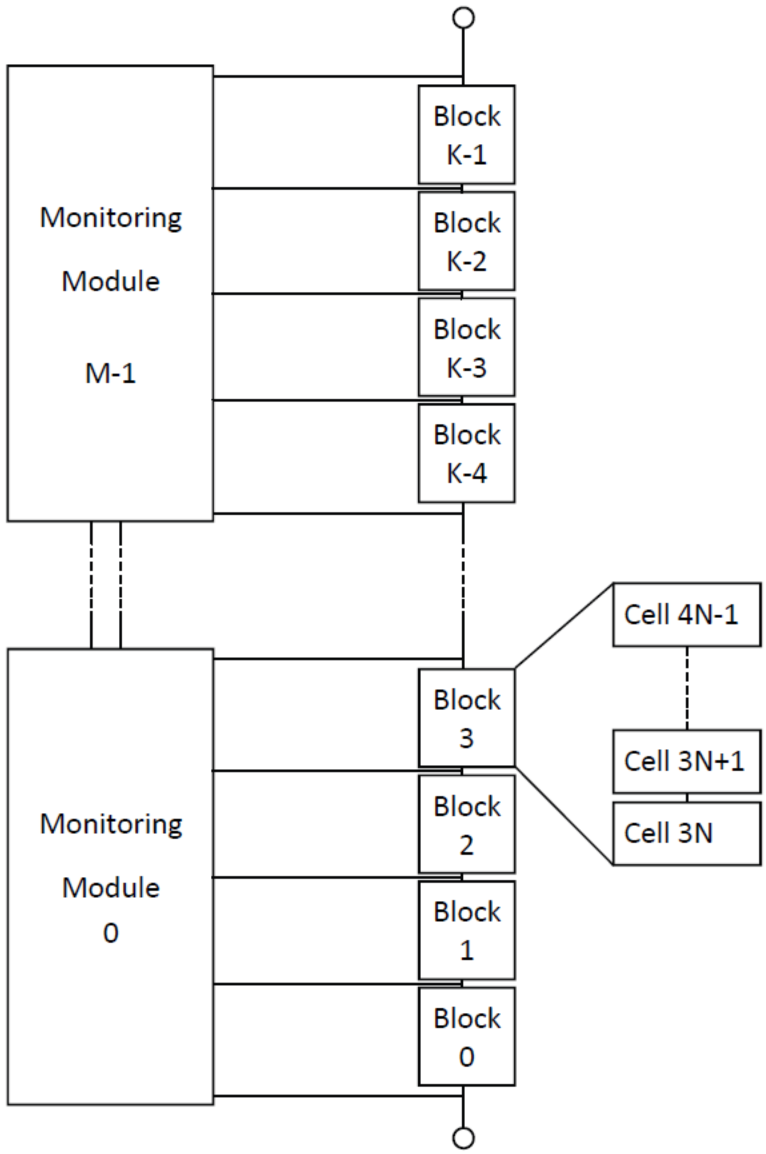

Figure 2.1 Proposed Battery Management System

Advantages

There are several advantages to the proposed solution. Suppose the BMS manages blocks of N cells, the battery management system will have N-1 fewer wires per block of cells, where N is the number of cells per block. The new BMS will also have 1/N the number of the bypassing circuits that a BMS would have that balances every cell. If a modular BMS is used, each module will monitor and balance more cells, reducing the total number of modules. Assembly could be done in blocks and could be faster and simpler than a system connected to each cell.

Disadvantages

Like any system, this battery management system has its disadvantages. This system could be difficult to implement when each block has a large number of cells. The voltage of each block would be corresponding high and more difficult to monitor or isolate from other blocks. Off-the-shelf battery management systems will most likely not support monitoring and bypassing groups of cells. A custom management system is almost always needed. Creating a custom BMS is expensive and time consuming. If turn-around time and cost are important, a BMS consisting of microcontrollers monitoring and balancing groups of cells could be used. This method wouldn't be the most efficient or compact. For efficiency and compactness, a custom BMS chip with voltage comparators and bypassing resistors could be designed. The custom chip would require high isolation internally.

Chapter 3

Test Setup

Lithium iron phosphate cells usually exhibit little variance in capacity or internal resistance. Consequently, in some cases a battery management system is not used to avoid extra weight and complexity. Without a BMS, however, there is greater uncertainty regarding battery voltage and state of charge. The testing performed for project was intended to determine if by monitoring or balancing a block of cells in series while operating within predetermined limits that one could safely assume that the cells are operating within safe limits. The method described in this chapter mimics a BMS that would monitor and bypass the number of cells in series for that test.

Requirements

The test setup had to be able to mimic a BMS while recording the voltage of the group of cells as well as the individual cell voltages and the current flowing through the pack. The charge and discharge rates of the system should be similar to what a typical battery would have. An implemented BMS that monitors and balances groups of cells as illustrated in the following chapters must be less expensive and less complex than that of a BMS that monitors and balances individual cells.

Charge and Discharge Cycling

To charge and discharge the cells, a manual system is not practical because of the time requirements for a charge and discharge cycle. For this reason an automatic charge and discharge cycling system was created using LabVIEW. This automatic charge and discharge system used a National Instruments compact data acquisition (cDAQ) system to monitor each cell's voltage and current while controlling an AMREL eLoad and ePower Supply over Ethernet.

System Components

A NI 9221 Analog Input Module was used for data acquisition. This module has eight channels with an operating range of ±60 V and 12-bit word size leading to a resolution of 29-mV/bit. This resolution is sufficient to determine the state of charge of a cell when it is over 90% charged or above 3.5 V. A LEM HASS 50-S with a 0 to 5 V output was used as the current sensor. The eLoad or electronic load used in this test was an AMREL PLA5k-800-100 with a peak power of 5 kW, a peak voltage of 800 V, and a peak current of 100 A. The ePower or electronic power supply was a dual channel AMREL SPD120-3-KOE0 with a peak voltage of 120 V dc and a peak current of 3 A dc per channel. Both the eLoad and ePower have Ethernet control capabilities. To control these components a Dell Semi-rugged laptop with LabVIEW was used. The laptop specifications were: Windows 7, 4 GB RAM, 120 GB SSD, Intel Core i5 processor.

Charge and Discharge Equipment Setup

The laptop is connected to an Ethernet switch with an Ethernet cable and the NI DAQ Analog Input Module with a USB cable. The Ethernet switch is connected to the ePower and eLoad with Ethernet cables. The eLoad and ePower supplies are connected in parallel to each other and to the series set of cells. Figure 2.1 shows a block diagram of the test setup used for cycling multiple cells.

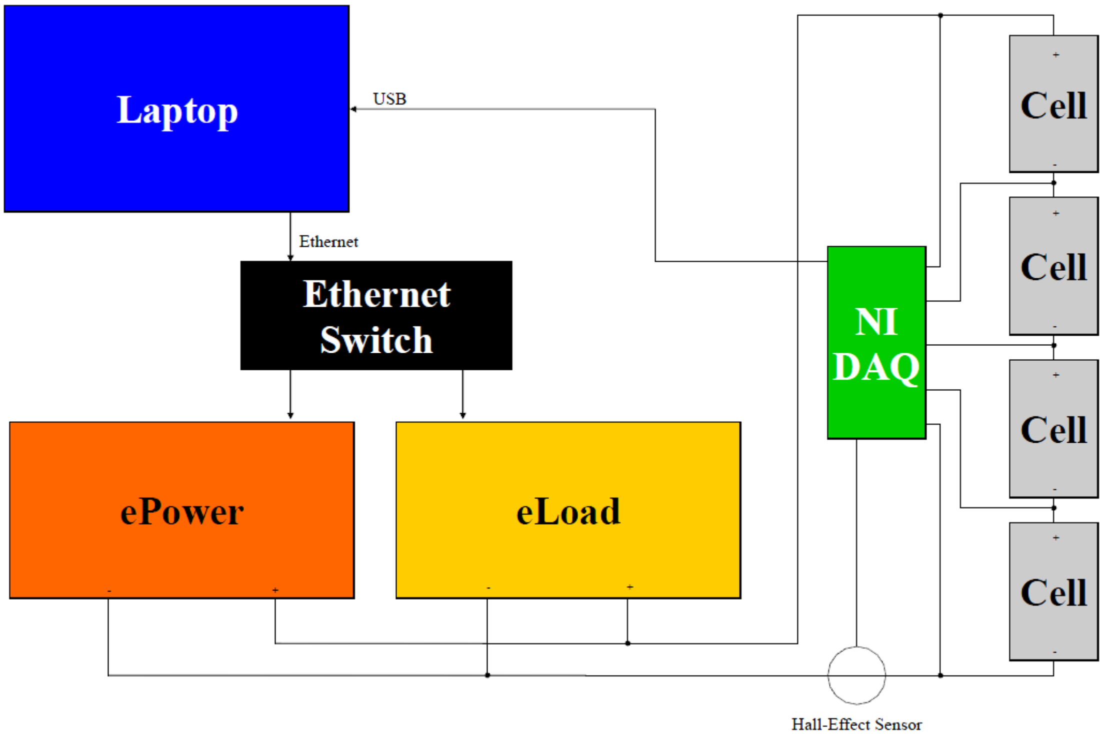

Figure 3.1 Battery Cycling System Setup

The DAQ has eight channels so this setup could be scaled to accommodate as many as eight cells in series or six cells in series while measuring the current though the cells. The ePower supply and eLoad both are capable of driving and loading more than eight cells in series. With this setup more cells could have been tested by using another compact DAQ module. However, due to time constraints the maximum number of cells in series that were cycled was five.

Charge and Discharge Cycling Program

The charge and discharge cycling program was created in National Instruments LabVIEW 2011. Figure 2.2 shows the charge and discharge cycling program front panel, which includes one current gauge for the block and one voltage gauge for each cell When the program is run and the start button is pressed, the program enters a CHARGING state. In this state, the current, voltage, and time are read, displayed and recorded. When the average voltage per cell is greater than 3.58 V and the current is below 100 mA, the program transitions into the COOLING state.

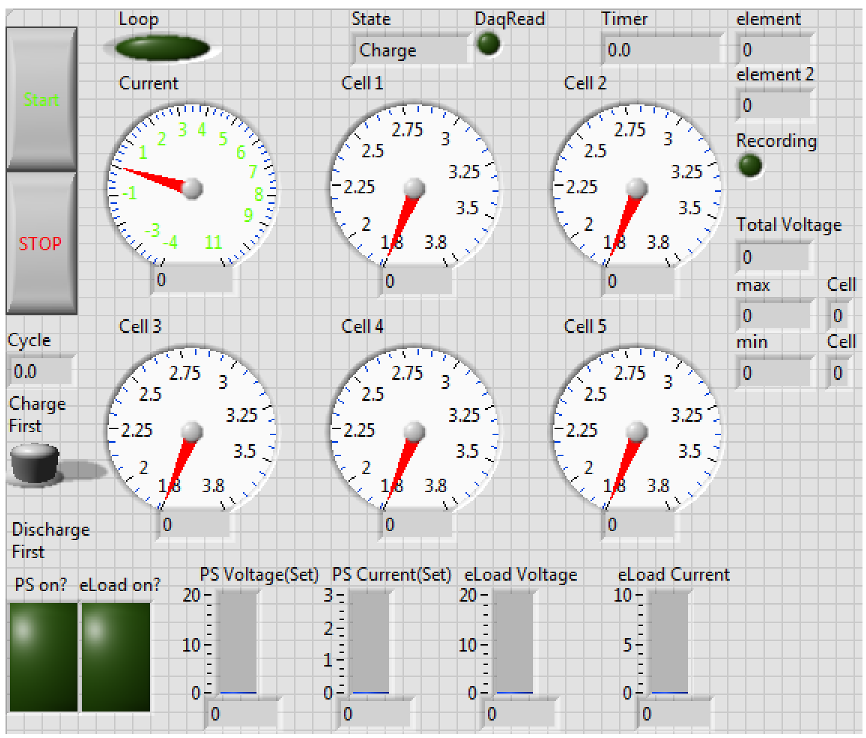

Figure 3.2 Battery Cycling Program

In the COOLING state, the ePower supply and the eLoad are both off so no current flows through the cells. This state is only used for high charge or discharge cycles to dissipate the extra heat from the I^2R losses in the cells. Following the CHARGING state, the COOLING state lasts for 100 seconds. The DISCHARGE state turns the eLoad on while monitoring the voltage of the cells. When the average voltage of the cells drop below a low voltage limit, typically set at 2.3 V, the eLoad turns off and the system returns to the COOLING state. Following the DISCHARGE state, the COOLING state lasts for 1500 seconds. The system then transitions back to the CHARGING state to begin a new cycle. This cycle is illustrated in Figure 2.3.

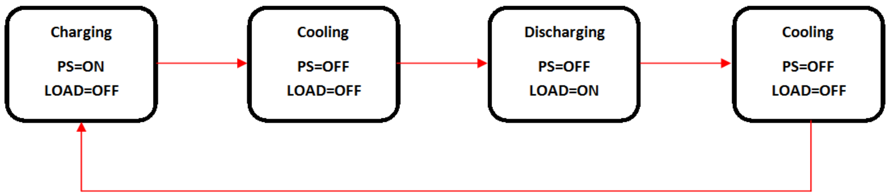

Figure 3.3 Battery Cycling Program State Diagram

The program will run until a single cell drops below 1.90 V or rises above 3.65 V. When the program stops, the eLoad and ePower supply is turned off and the number of cycles until the program stopped is recorded. The saved files are text files with commas separating fields such as time, cell voltages, and state. After each time step a return is commanded and the text file starts a new line. The files can be opened in MATLAB to plot the voltage and current vs. time.

Chapter 4

Testing

To understand the interactions between multiple cells while charging and discharging, two-cell blocks were tested initially; five and four cell blocks were tested subsequently. There are several parameters associated with charging and discharging. First, there are the current rates. Increasing the current rates will decrease the cycle time but may also decrease the life of the cells or lead to greater imbalance between cells. Second, there are voltage limits. Increasing the charging voltage and decreasing the discharging voltage will increase the capacity, if only by a small percentage but it could harm a cell's longevity or the balance between cells. Third, there is the charge current cutoff limit. As the cell reaches the charge voltage limit during the charging cycle the current decays exponentially. The current cutoff limit increases the charge time after the charge voltage limit has been surpassed and only adds a small amount of capacity to the cell.

Initial Testing

The charge and discharge cycling program was designed to cycle up to five cells with the ability to be modified for up to ten cells, if time allowed. To test the program's functionality, however, two cells were cycled first. The goal of this testing was to determine whether the test system was capable of running unattended for several hours. The parameters for the first set of testing were 10 A during discharge and 3 A during charge. The charge current cutoff limit was 0.5 A. The voltage limit during charging was 3.6 V and the voltage limit during discharging was 2 V. To determine the number of cycles for which the cell voltages remain within a safe variance, a decision rule had to be adopted. Prior to testing, the decision rule was selected to be the maximum of the difference from the mean of the two cells:

$$\varepsilon_1 = |v_1 - \mu|$$

$$\varepsilon_2 = |v_2 - \mu|$$

$$\max(\varepsilon_1, \varepsilon_2) > \varepsilon$$

where μ is the mean of the two cells and v_i is the voltage of cell i. This proved to be a good guess for variances in capacity since the state of charge (SOC) or capacity vs. voltage is nonlinear. This means that a small increase in capacity will create a large change in voltage at the end of the charging cycle. A value of 0.1 V was selected for ε. This decision rule was used to stop the cycling at the top of the charge cycle. The top of the charge cycle occurs just before the power supply turns off or the end of the CHARGING state of the cell cycling program. The standard deviation of the cell voltages exceeding a threshold represents another potential decision rule.

Multiple Cell Testing

Once the operation of the test apparatus and cycling program were confirmed for a two-cell block, testing for four- and five-cell blocks were undertaken. The parameters for all tests are summarized in table 2.

Number of Cells	Discharge Current	Charge Current	Discharge Cutoff Average Voltage	Charge Cutoff Average Voltage
2	10 A	3 A	2.5 V	3.6 V
5	10 A	3 A	2.15 V	3.6 V
5	25 A	3 A	2.2 V	3.6 V
4	30 A	3 A	2.3 V	3.6 V
4	40 A	6 A	2.3 V	3.6 V

Table 2 Testing Parameters

Testing vs. Application

The testing performed for this project is not practical in a real-world system. However, the similarities between the testing system and a BMS that balances blocks of cells allow the results of this work to carry over to real-world applications. A balancing system that balances blocks of cells would operate much like a standard system that balances on a cell-by-cell basis. The charger would have to be in communication with the battery management system because the BMSs would only balance cells while the charging system is less than its maximum bypassing current. This stems from the fact that most BMSs are passive balancing systems with resistors as the bypassing device. The resistors used in these passive balancing systems have a fixed resistance with small variations due to temperature. As a result the BMS commands a lower charging current at the beginning of a balancing operation. The BMS would then maintain 3.6 V (for A123 $LiFePO_4$ Cells, 4.2 V for most other Lithium chemistries) across each cell or an average of 3.6 V per cell for a block of cells.

The BMS would bypass the block of cells by drawing a current of $I_{bypass} = \frac{N \times V_{cell}}{R}$ around the cells. Typically, the value of I_{bypass} would be near the value of the charging current during a normal charging process or greater than it during a slower charging process. Once the average cell voltage drops below the cutoff voltage of 3.6 V, the BMS would stop bypassing block of cells. This would occur hundreds or thousands of times per second with the duty cycle of the bypass switches determining the average current flowing into the cell to charge it. The rms value of the current charging the cell would be very similar to a constant current, constant voltage (CCCV) charger charging each cell individually. The voltage of the cell in both cases would be regulated to the 3.6 V charging cutoff limit and the resistance of the cell would increase as the cell's SOC increased. The current flowing through the cell would decrease as the SOC increased in both cases at nearly the same rate. For that reason it is easy to see how the testing done in this thesis can be applied in real world applications because this testing scheme uses a CCCV charger for a block of cells.

Cycling Five Cells

After the initial two cells were cycled to test the program, the system was modified to accommodate five cells. Testing started with a charge current of 3 A and a discharge current of 10 A. The A123 cells are capable of much higher currents than 10 A or about 4C. The “C rate” or charge rate can be defined as 1C = rate to charge the cell in 1 hour. So, 4C is the rate to charge (or discharge) the cell in 15 minutes. Typically these are manufacturer parameters and are not always obtainable. Even after balancing five cells at the top of charge, one of the five cells would go below the cutoff voltage (2 V) while the average voltage was above the stop discharging voltage (2.3 V). So a current discharge “step” was added at 5 A after the average voltage dropped below 2.5 V per cell. In practice 2.5 V would have to be the cutoff voltage for the average of a block of cells during discharge.

After the initial cycling of five cells, it was observed that the cells maintained a reasonable voltage difference between them to operate in a safe manner. The current for discharge was increased to 50 A while maintaining other parameters constant. With this new higher current, the voltage after discharge of one cell dropped below the 2.0 V single cell limit to 1.99 V before the average voltage of the five cells dropped below 2.3 V per cell when the program stopped the discharge. So, the current was reduced to 46 A, and the cells were balanced again before further testing. Again the same cell dropped below the 2 V single cell limit to 1.996 V before the average voltage dropped below 2.3 V per cell and the program stopped. The discharge current was reduced to 40 A and the single cell voltage limit was reduced to 1.9 V after this instance. However this proved to be inadequate. The voltage of the same cell dropped to 1.88

V before the average cell voltage dropped below the cutoff. This cell was determined to have a lower capacity than the other cells and all of the cells were replaced with new cells.

A little over halfway through the first five cell cycling test the program was changed. The data that was being read was fairly noisy because the compact DAQ module was only an eight-bit analog –to-digital converter. After testing different methods to reduce the noise, it was decided to sample each channel at a faster rate and average over a particular length of time. The data was sampled at 10 kHz and averaged over ¼ second.

The five new cells were balanced. The current for this test was reduced to 25 A, and the single cell voltage limit on discharge was reduced to 1.85 V. Since a cycle is typically on the order of one hour, the testing was run overnight. During the second night of testing, there was a storm. A power glitch disrupted the communication between the program and the eLoad and the ePower supply. This resulted in the cells discharging completely. These cells were discarded to be recycled.

Cycling Four Cells

Since rechargeable lithium-ion cells are fairly expensive and are in limited supply, the five previous cells were replaced with four new cells. The cycling with four cells started with a current of 30 A. The cells kept a fairly tight voltage difference between cells so the current was increased to 40 A and the program was altered. The temperature of the cells were monitored as they were being discharged and charged and it was determined that a break needed to be added after each charge and discharge cycle for cooling. The cooling time after discharge was set to 1500 seconds and the cooling time after charge was set to 100 seconds.

Chapter 5

Results

Cycling two, four and five cells has given insight into the interactions between cells. While cell resistance hasn't influenced the voltage variance as much as anticipated, cell capacity has been the limiting factor in most of the tests. The results taken have been saved in text files and can easily be plotted in MATLAB.

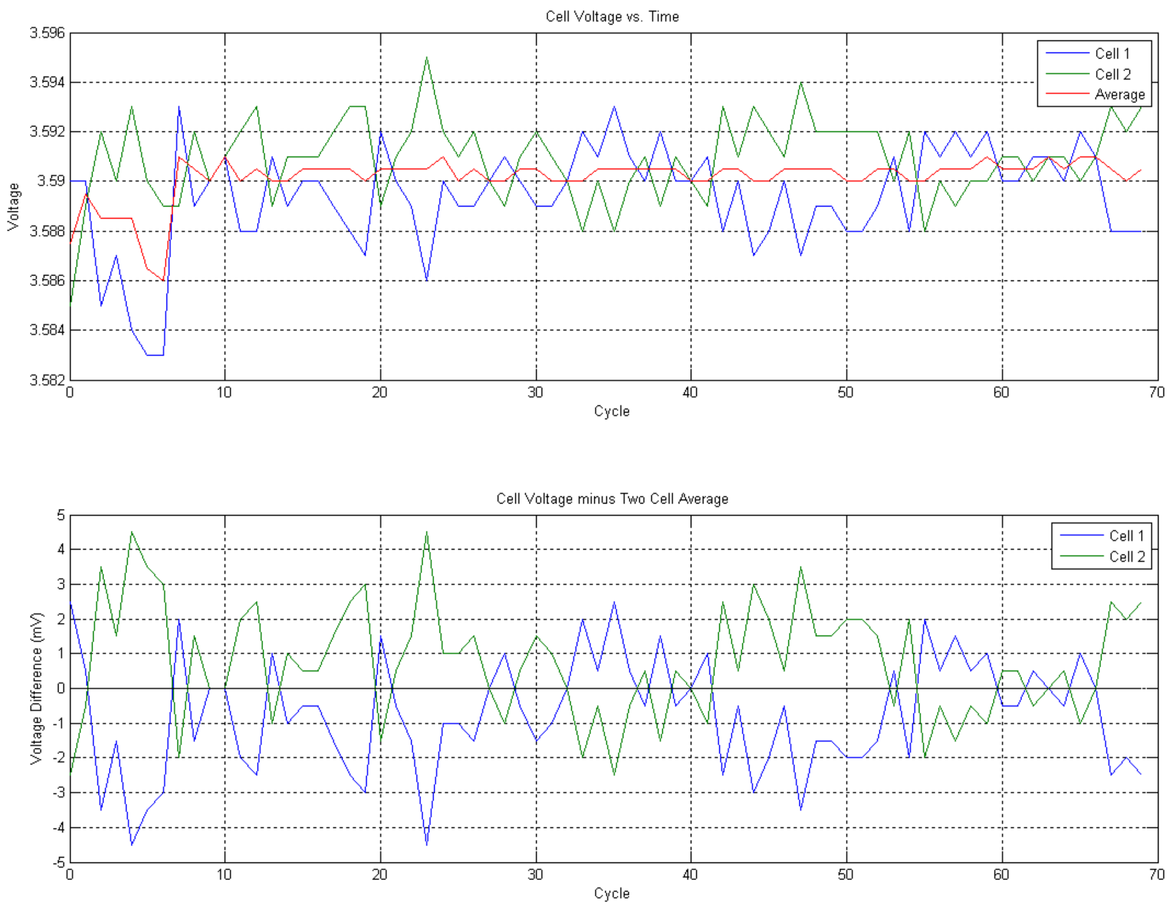

Figure 5.1 Two Cell Cycling Voltages at Top and Bottom of the Charge Cycle

Cycling Two Cells

Cycling two cells worked as expected. The voltage difference was very small between the cells and the cells voltages did not diverge after 69 cycles. Figure 5.1 shows the individual cell voltage at the top of the charge cycle for each cycle. After charge number 21 the charge program reset and discharged the cells to only a few percent of their total capacity before charging them again.

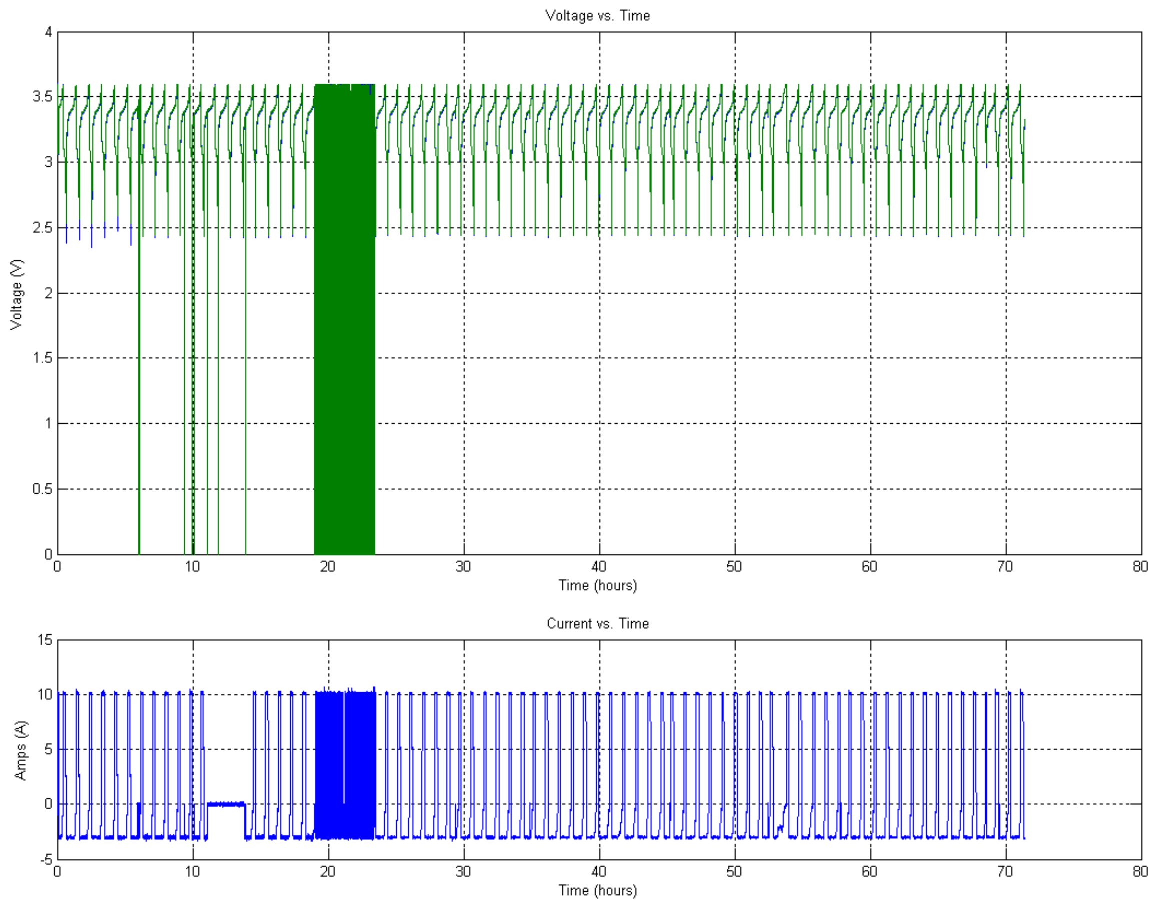

Figure 5.2 Two Cell Voltage and Current vs. Time

After looking into the data and the LabVIEW program, it was concluded that the input buffer for the USB data actuation system would fill up and empty a portion of the recorded data and fill in the rest of the data with 0's. Before this there were a few instances of the voltage dropping to zero for a few seconds then returning to the correct voltage. It wasn't clear as to why the voltage dropped to zero at random times before this happened. It was thought that the buffer cleared and returned zeros for the remainder of the reading. The program was always stopped before the buffer filled up again. When the rapid charging and discharging occurred it was the first time the buffer filled up and the program was left to run. This was fixed before the 22nd cycle according to Figure 5.1 and Figure 5.2 by increasing the buffer size and clearing the extra data points in the buffer after it was read.

There was an instance after the 12th cycle where the current sensor lost the 5-V power supplied to it. This resulted in a current of zero amps being recorded until the supply was restored to the current sensor. The voltage recording was unharmed during this time so the testing with these cells was resumed where it left off. The duration of the rapid switching between charge and discharge lasted for the same length of time as 4.5 regular charge and discharge cycles. With the parameters used in the first two cell test, the duration of a cycle is about fifty-five minutes to one hour. At the end of this test the two cells voltages varied only 5 mV from one another.

Cycling Five Cells

With the program more refined, the data from the test was slightly cleaner than the two cell cycling. The first five cell test used the previous two cells with three new cells. The first two cells were marked 1 and 2 as they were before and the next three cells followed with cells 3, 4, and 5. This was done to observe the difference between new and slightly used cells in the same pack. The first series of cycling was performed with the same parameters as the end of the two cell test. The charge current was 3 A and the discharge current was 10 A with a reduced current of 5 A after the voltage dropped below 2.5 V. The 5-A current reduction was implemented to allow for a deeper discharge which is a known factor for degrading cells.

Test One

After over 50 cycles the voltage difference between the cell with the highest voltage and the cell with the lowest voltage was less than 50 mV. Figure 5.3 shows the cell voltage at the end of the charge cycle after each cycle. The most notable change is in the first 10 cycles where the individual cell voltages diverge. After the initial 10 cycles the cell voltage differences settle and remain more or less constant. In Figure 5.3 blue is cell 1, green is cell 2, red is cell 3, cyan is cell 4 and magenta is cell 5. Figure 5.4 shows the cell voltage vs. time and cell current vs. time. The most important detail is that the voltages consistently follow each other.

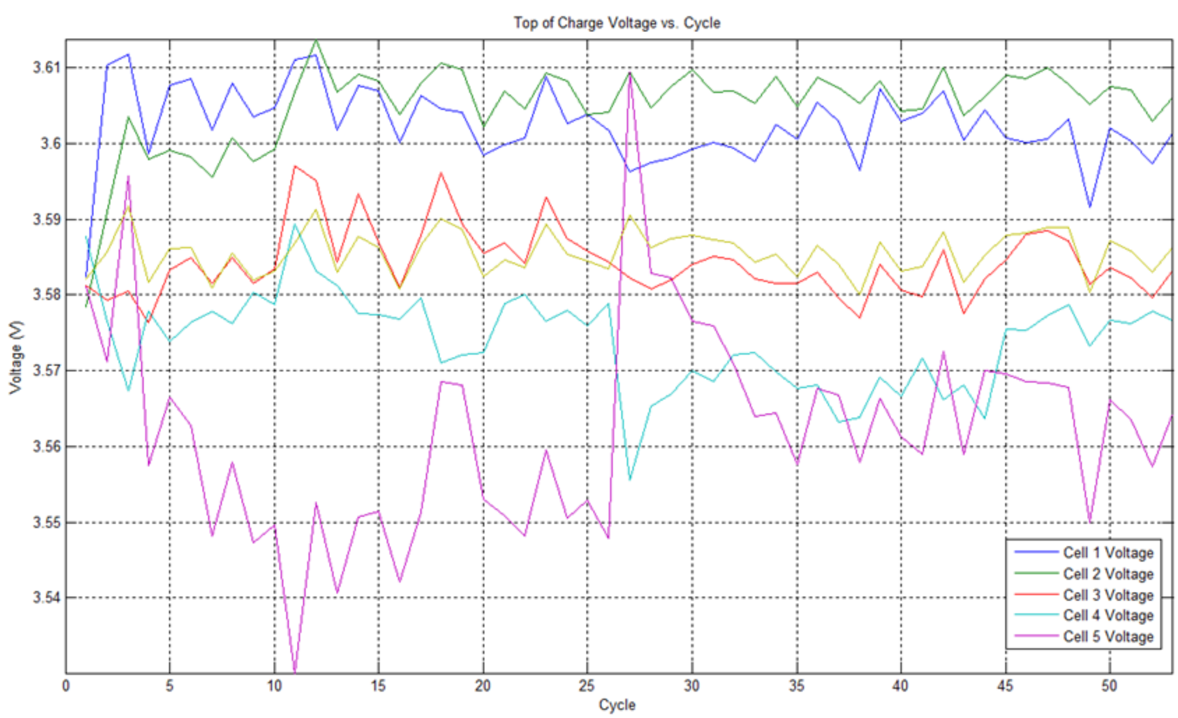

Figure 5.3 Cell Voltage at the End of Each Charge (Five Cell Test 1)

Figure A.1 in the appendix shows the last 80% of the first cycle and the last 80% of the final discharge cycle. When balancing at the beginning (top) of the charge cycle, the most important factor is the voltage difference at the end (bottom) of the discharge cycle. Figure A.2 shows the voltage at the end of each discharge cycle. The voltage difference between the cell with the highest voltage and the cell with the lowest voltage at the end of the discharge cycle is over 0.300 V for most of the testing on cells 1 through 5.

Since the maximum voltage difference at the end of the charge cycle is 50 mV, this means that the cells are further out of balance at the end of the discharge cycle, the cells internal resistance or their capacities are different. In any case, if the cells are balanced at the top of the charge cycle, before a BMS is implemented the discharge voltage cutoff must be determined such that the lowest cell voltage is above the unsafe voltage determined by the manufacturer or by internal testing.

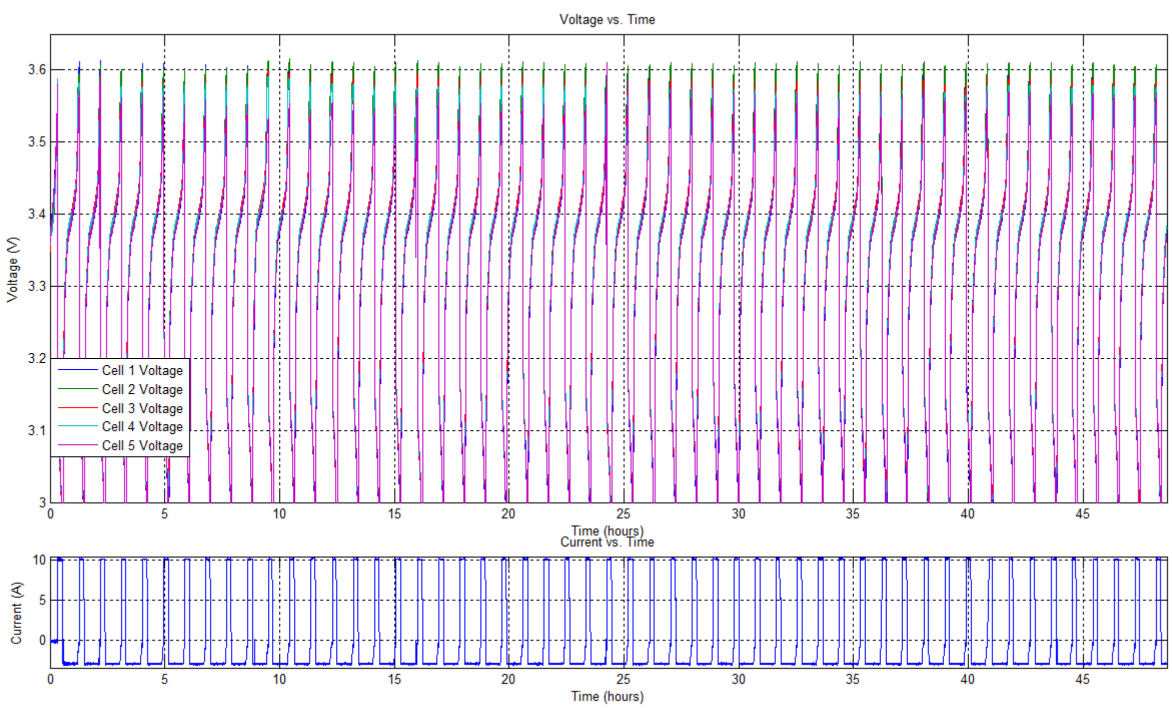

Figure 5.4 Cell Voltages and Current vs. Time (Five Cell Test 1)

Test Two

In the second test with five cells, the discharge current was increased to 25 A while keeping the other parameters the same. The cell voltage differences were less than the prior test with the exception of Cell 3. Cell 3 immediately after the first cycle was consistently 0.07 V lower than the other cells at the end of the charge cycles and it was near the highest voltage of all of the cells at the end of the discharge cycle. This was most likely due to Cell 3 having a higher capacity than the rest of the cells. Figure 5.5 plots the cell voltages vs. time and the cell current vs. time. Figure 5.6 plots the individual cell voltages at the end of each charge cycle.

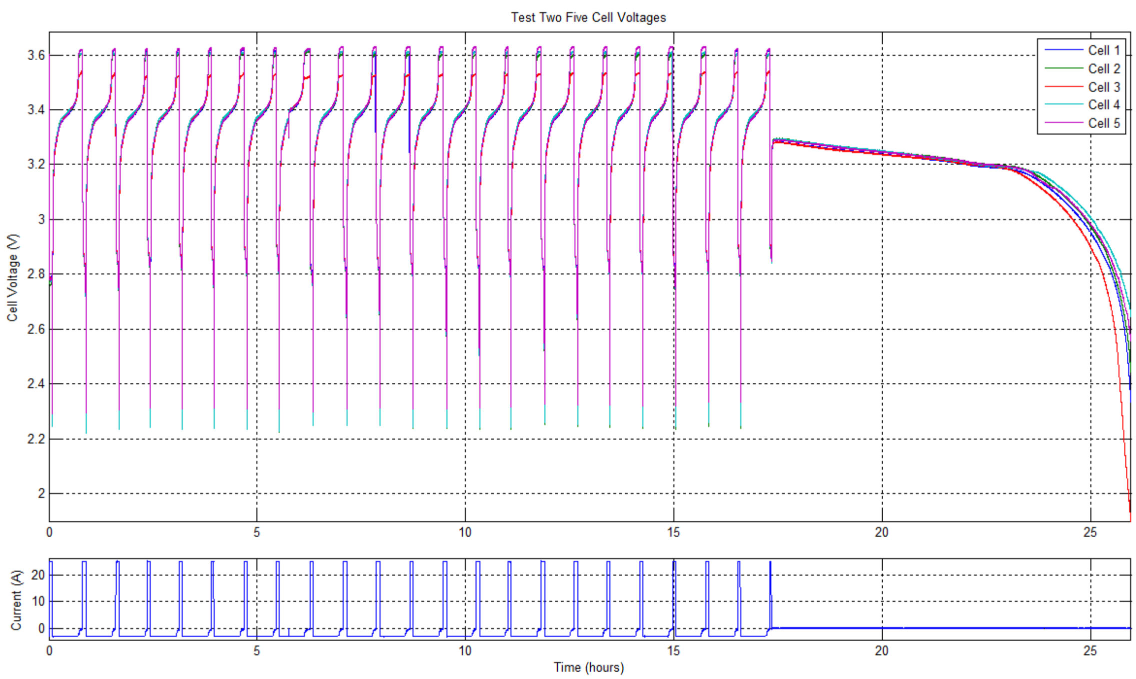

Figure 5.5 Cell Voltages and Current vs. Time (Five Cell Test 2)

It is clear that after the 22nd cycle the cells stopped cycling and the voltage dropped due to a small leakage current. By plotting the data it's hard to see the current but by filtering the data after the cycling stopped it was determined that 100 mA was flowing through the cells eventually discharging them. This test was performed on the night of an electrical storm. A power glitch caused the communication between the laptop and the ePower supply and eLoad to cease. A small impedance in the eLoad allowed for the 100 mA current to flow. Even though the cycling stopped, the data from the first 22 cycles was valid. The cell voltages differed from the first five cell test because of the higher current.

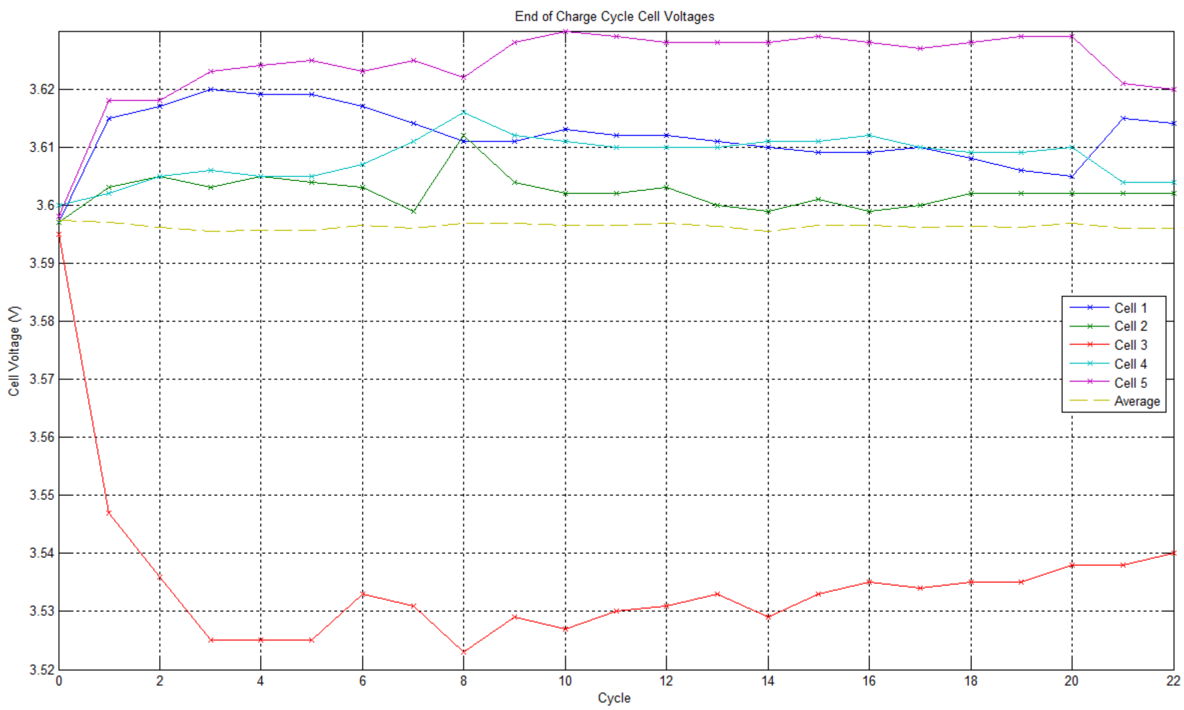

Figure 5.6 Cell Voltages at the End of the Charge Cycle (Five Cell Test 2

Figure 5.6 backs up the results from the first test of the five cells. The cells maintained a constant difference between each other and did no diverge. Again as with the first five-cell test, after the first two or three cycles the voltage of each of the cells at the end of the charge cycle settle. If anything the variance between the cells decreased slightly after more cycles. The next step was to increase the current or lower the discharge voltage cutoff.

Four Cells

As stated before, since the previous five cells were discharged completely and needed to be replaced, four cells were used for the next test. The current for this test started at 30 A. In the first test the cells performed differently from cycle to cycle. It was determined that the cells operate differently when their temperatures were elevated. The temperature was monitored during a charge and discharge cycle. The temperatures increased to over 150°F during discharge and never had time to recover during charge. It was decided that for higher currents, and consequently higher temperatures, a COOLING state should be added after the charge cycle and the discharge cycle.

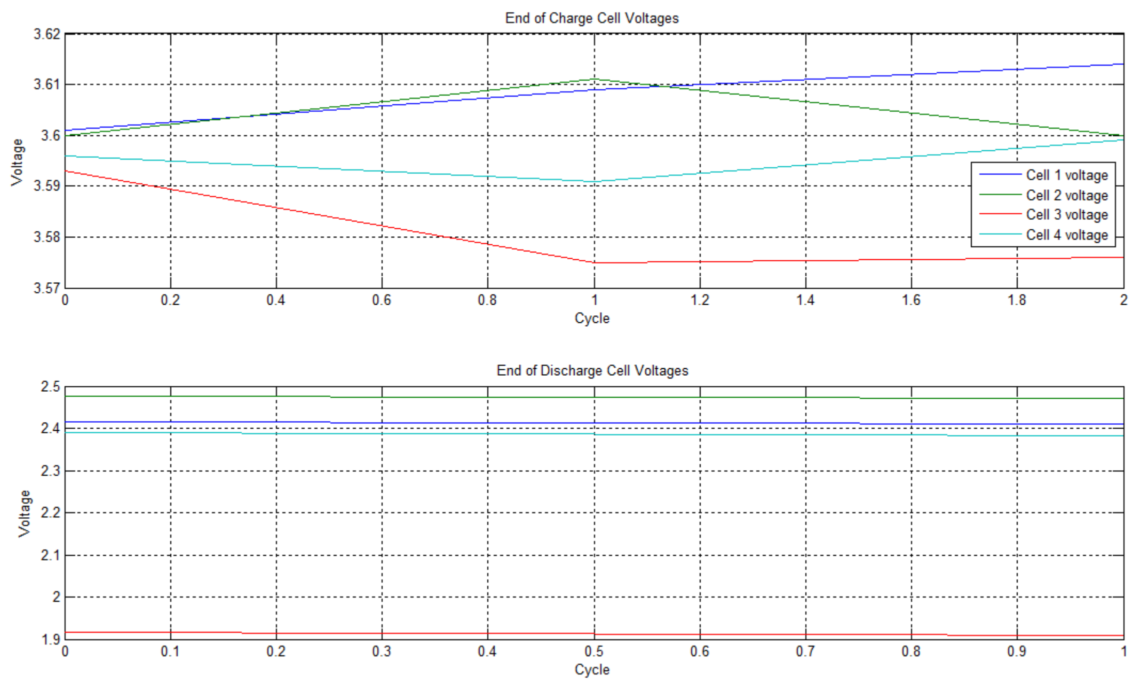

Figure 5.7 Cell Voltages at the End of the Charge Cycle (Four Cell Test 30A)

Figure 5.7 illustrates the cell voltages at the end of the charge cycle for the four cells' 30 A test. There were only two full charge cycles and two full discharge cycles for the four cells' 30 A test. The voltages were very consistent at the end of the discharge cycles. However the voltages at the end of the charge cycles appeared to start diverging. This test was inconclusive because of the limited data.

Four Cell 40-A Test

For the next test, the discharge current was increased to 40 A and the charge current to 6-A. Cell 3 was consistently one of the cells with the highest voltage after charge and had the lowest voltage by 0.4 V after discharge. This cell must have had a higher internal resistance than the other three cells. Figure 5.8 illustrates the end of charge voltage and end of discharge voltage vs. the cycle.

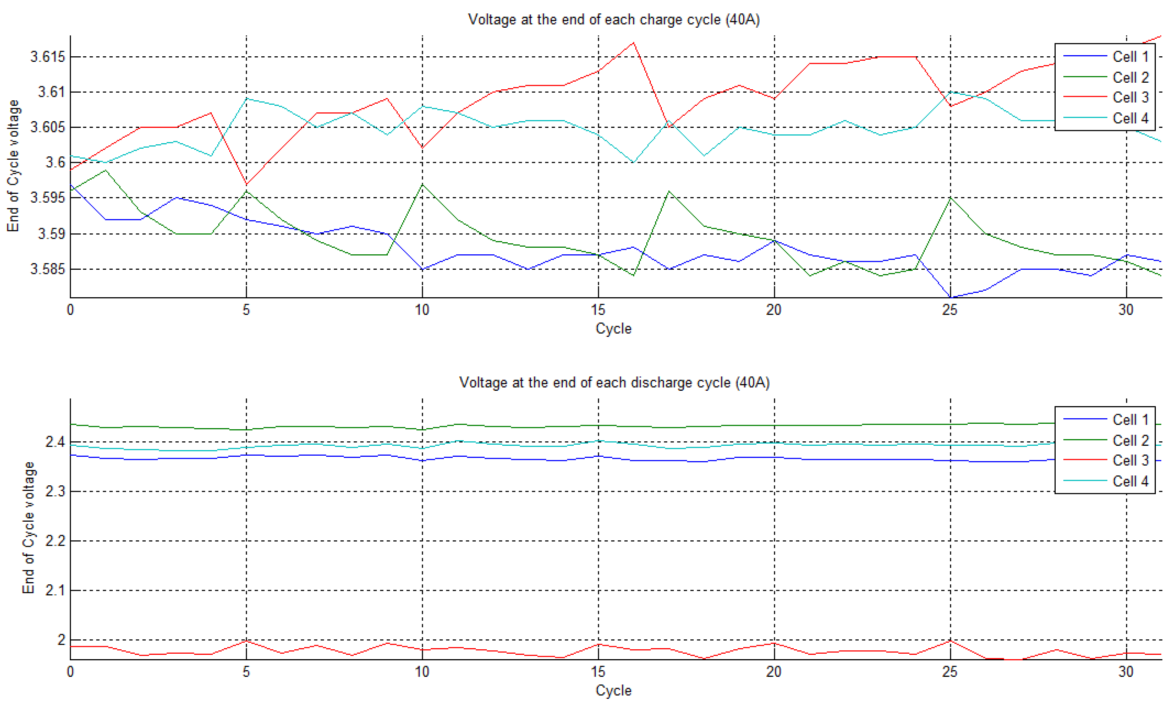

Figure 5.8 Cell Voltages at End of the Charge Cycle (Four Cell Test 40A)

The voltages at the end of the discharge were very consistent. The third cell was under 2.0 V after discharging after every cycle. It is not desirable to allow a cell to go below 2.0 V; however the manufacturer states that the cells will operate safely as low as 1.8 V. As long as the voltages did not start diverging this arrangement would have been sufficient to operate within a safe range. The voltages after charging appeared to diverge but after over 30 cycles the highest voltage cells were still only 10 mV from the average voltage of the cells. This was within the error of the analog to digital converter.

If a large pack used a series four cell arrangement for balancing and monitoring it would be sufficient for all the cells to operate safely. However if the discharge current, charge current, stop discharge low voltage cutoff, top of charge bypassing voltage, or the stop charge high voltage cutoff voltage are higher than was used in these tests it is unknown if the cells will maintain their balance. With a series four cell arrangement, a large lithium ion battery pack would have 25% of the circuitry that a pack monitoring and balancing every cell would have. That pack would have a very similar useable range and be safe to use.

Chapter 6

Conclusions

The testing was a success in that the characteristics of the A123 26650 cells allow for the use of a monitoring and balancing system that monitors every four or five cells. A practical battery could have a bypassing circuit across a four or five cell block and 10 to 12 blocks per monitoring module containing a total of 40 to 60 cells.

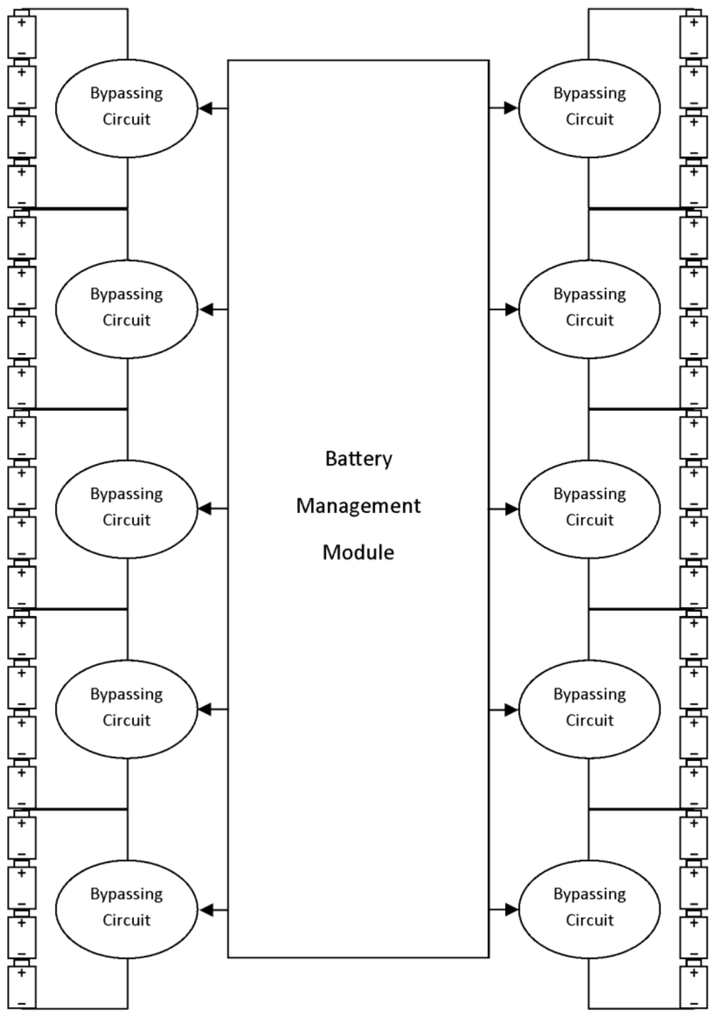

Figure 6.1 Battery Management Module

Figure 6.1 shows a battery with four cells per bypassing circuit with one bypassing and monitoring module covering 40 cells. The single module could be scaled up by placing modules in series to increase the voltage of the pack. A typical module currently used in the industry has one cell per bypassing circuit. The module shown would have 10 blocks and 40 cells with the same amount of circuitry as a 10 cell module that monitors every cell. To restate, as it is shown there are 4 cells per block and one bypassing circuit per block for a total of 40 cells in the module. This would reduce the circuitry significantly in a large format lithium ion battery pack. The pack would have to stay within the parameters used in this testing. The parameters for a monitoring and bypassing every four cell block would be: charge at 6 A to 3.6 V per cell (average), discharge at 40 A to 2.3 V per cell (average), and for about 50 cycles before the blocks of cells need to be examined for cells that are out of balance in each block.

Lithium ion cells have very little variance between each other during operation. Bad cells could be screened out before using them. If a pack was put together in blocks the size of the bypassing circuit, they could be balanced on a cell-by-cell basis before being put into the block of cells. If each block of cells were cycled five to ten times while monitoring each individual cell, a reasonable estimate of the voltage differences between the cells could be determined. From Figures 1.2 and 5.6, it appears that the largest change in balance between cells occurs before the 10^{th} cycle. The variance in the cell capacities of the A123 cells was small enough to allow five cells per block with a maximum charge rates of 3 A and a maximum discharge rate of 25 A without screening. If four cell blocks were used, a maximum charge rate of 6 A and a maximum discharge rate of 40 A could be allowed. Depending on the application, the charge and discharge rates could determine the number of cells in series.

Screening could group similar cells together to increase the number of cells per block while minimizing the variance between cells in each block. This would also allow for higher charge and discharge rates for the larger blocks. Screening would also detect cells with a large difference in capacity from a nominal cell.

Another method to reduce the amount of circuitry and ensure safe operation would be to cycle each individual cell and compare their capacities during charge and discharge to other cells' capacities. Similar cells would then be grouped together and put into blocks. The blocks would have cells that behave comparably to one another. This system would be able to run longer (more cycles) than a system with randomly grouped cells in the blocks. This is because the cells that behave similarly will age at the same rate but cells that are grouped randomly may respond differently from one another. One cell could have a higher voltage than the other cells and will have a shortened life because cells age faster when driven above their recommended charge voltage. The voltages would start to diverge near the end of the charge and discharge cycles. Eventually a cell will short itself by reversing polarity on discharge rendering that cell useless.

There are two ways to arrange two cells in parallel when inserting them into blocks. The two arrangements are 2PNS or NS2P where N is the number of cells in series in the block. The first arrangement will allow the capacities of every two cells in parallel to be combined. This will make the combined capacity more likely to be double the average capacity. This will allow the total system to run longer because the parallel cells will operate similarly to other cells in the block. For the second arrangement NS2P the cells will operate very similarly to the normal case with no cells in parallel.

Future Work

Due to time constraints a higher number of cells were not tested. Future work would expand on what was learned here and test monitoring and bypassing blocks of 6, 9, 12, or more cells. This would allow for constraints to be put on the number of cycles, the discharge current, the charge current, the average charge cutoff voltage, and the average discharge cutoff voltage.

Other future work would revolve around the design of a monitoring and balancing module and the bypassing circuitry. The module would have to have high voltage isolation between channels and would have to consume very little power from the cells or consume power from an external source provided during charge. The design of this module would be in a master-slave or modular format. A separate master module would have to be designed if a master-slave format was chosen. If a modular format was used the individual modules would all be the same and may or may not communicate with one another.

Appendix A

Additional Figures

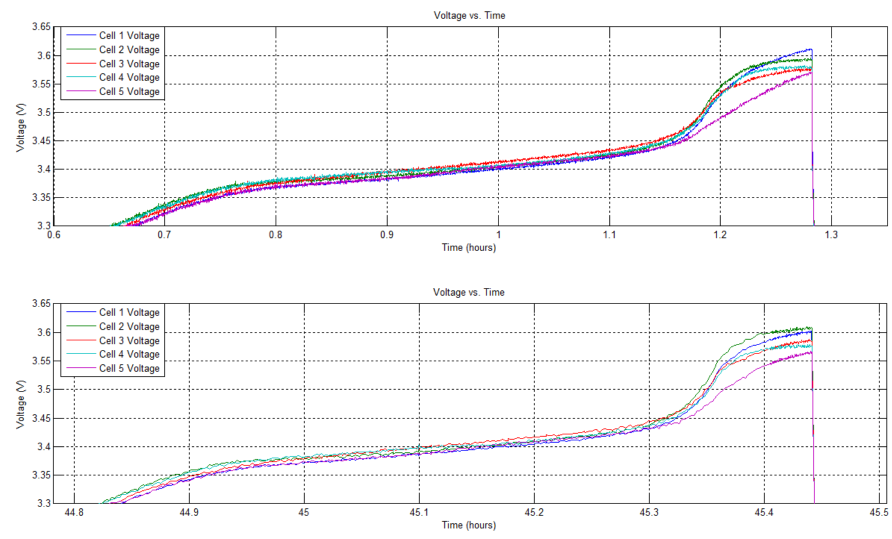

Figure A.1 Cell Voltages at the End of Charge 1 and 53 for the Five Cell Test 1

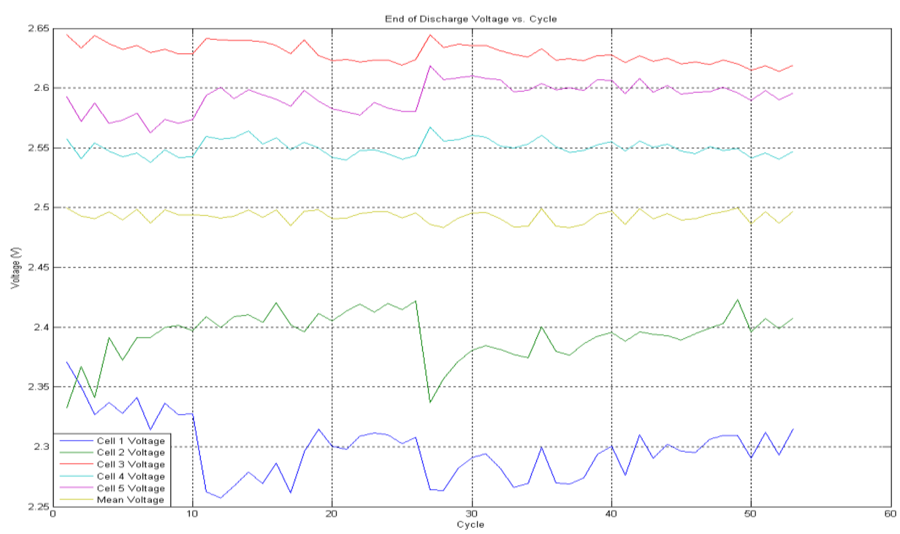

Figure A.2 Cell Voltages at the End of Discharge vs. Cycle (Five Cell Test 1)

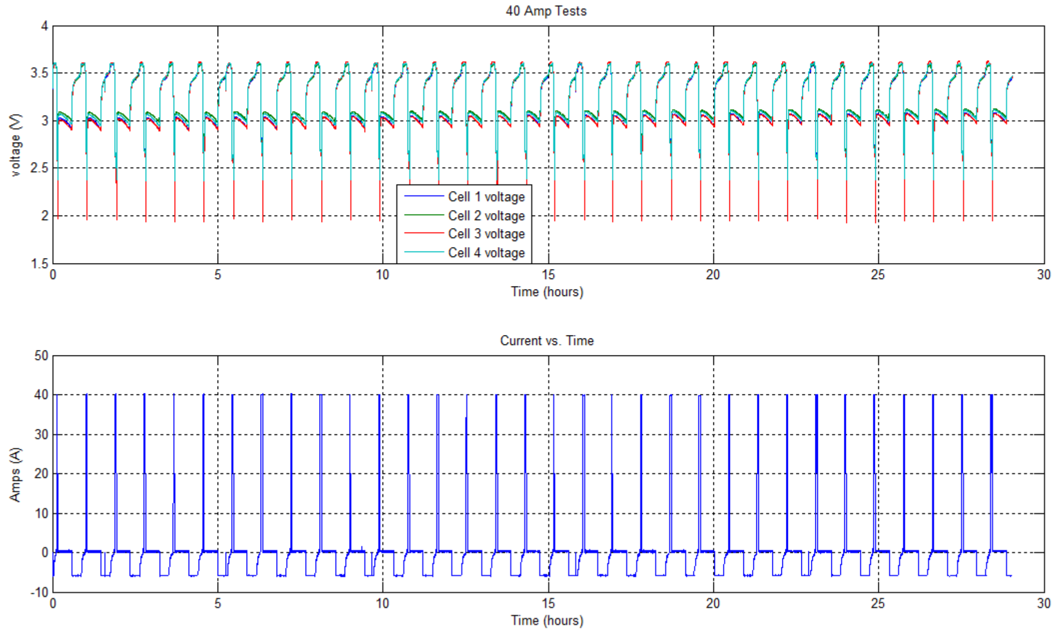

Figure A.3 Cell Voltages at the End of Discharge vs. Cycle (Four Cell Test 40A)

REFERENCES

1. **Franklin, Benjamin.** To Peter Collinson. *Franklinpapers.org.* [Online] April 29, 1749. [Cited: July 06, 2012.] http://franklinpapers.org/franklin/framedVolumes.jsp?vol=3&page=352a.

2. **Dibner, Bern.** *Galvani-Volta : a controversy that led to the discovery of useful electricity.* s.l. : Burndy Library, 1952.

3. *Gaston Plante and his invention of the lead-acid battery - The genesis of the first practical rechargeable battery.* **Kurzweil, P.** 14, 2010, Journal of Power Sources, Vol. 195, pp. 4424-4434.

4. *A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems.* **Moore, Stephen W. and Schneider, Peter J.** 0959, 2001, Society of Automotive Engineers, Vol. 01, pp. 1-5.

5. **Rahn, Christopher D. and Wang, Chao-Yang.** *Battery Systems Engineering.* State College : Draft, 2012.

6. **Qian, Jinrong.** Asia Downloads. *Texas Instruments Focus.* [Online] 2009. [Cited: November 08, 2012.] http://focus.ti.com/asia/download/TechDay09cn_Analog_Power_1_Battery_chemistry_fuel_gauge.pdf.

7. **Jensen, Christopher.** Wheels: Chevy Volt Fire Prompts Federal Investigation Into Lithium-Ion Batteries. *The New York Times.* [Online] November 11, 2011. [Cited: October 14, 2012.] http://wheels.blogs.nytimes.com/2011/11/11/chevy-volt-fire-prompts-federal-investigation-into-lithium-ion-batteries/.

8. **Andrea, Davide.** *Battery Management Systems for Large Lithium-Ion Battery Packs.* Norwood, MA : Artech House, 2010.