

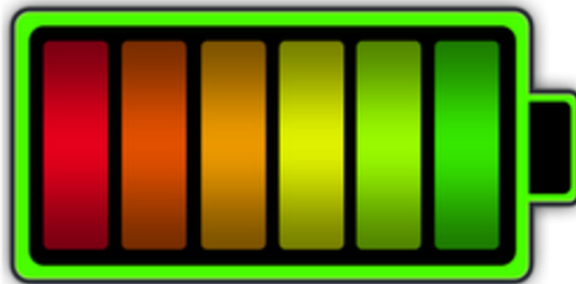
# Battery Management System

## Senior Project Design

6/6/2014

EE 463

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# Acronyms

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*BMS: Battery Management system*

*COV: Cell Overvoltage*

*CUV: Cell Undervoltage*

*EVM: Evaluation Module*

*IC: Integrated Circuit (chip)*

*LCD: Liquid Crystal Display*

*Li-Ion: Lithium Ion*

*MCU: Microcontroller Unit*

*SPI: Serial Peripheral Interface*

*SOC: State of Charge*

# Acknowledgements

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# Abstract

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## **Problem Statement:**

There have been recent reports of multi-million dollar companies having to recall entire projects due to their BMS's malfunctioning or operating incorrectly. The purpose of this project is to analyze the future of batteries, the Lithium-Ion cell, and to exercise a BMS to better understand its capabilities and possible cases for errors. Lithium ion batteries are intolerant of overcharge and overdischarge. Abuse of this kind can result in high temperatures, venting of gases, fire, or explosion. Therefore battery management systems have been devised to prevent such abuse. Recent events such as fires on the Boeing Dreamliner and the Tesla Model S have shown that these dangers are real. These products do have highly developed battery management systems, and the incidents were caused in spite of these systems. This study was undertaken to illustrate how one system from Texas Instruments, functions to monitor and control a simple battery pack.

## **Part I: Battery Data Acquisition**

Preliminary battery tests were conducted to fully understand the operations of charging and discharging the battery. These tests were essential to gain a better understanding of typical battery behavior and to be able to perform calculations necessary in analyzing the characteristics of the batteries. Also, these tests were ran to ensure that the Lithium-Ion batteries being used correctly corresponded to the graphs and values provided by the datasheet. The knowledge gained from Part I was vital for a better comprehension of the functions needed to balance the cells for Part II as well as the importance of safety precautions necessary when dealing with multiple batteries.

## **Part II: Exercising the BQ76PL536 & GUI**

The BQ76PL536 Evaluation Module (EVM) was tested using the BQ7PL536 BMS chips. An Aardvark adapter acts as a link between the EVM and PC allowing the user to read data from the BMS chips on a GUI. The BMS chips are validated by reading voltages of individual battery cells, pack voltage, and pack temperature. The GUI allows for enabling cell balancing between the cells but this feature is not automatic and must be engaged by the user.

## **Part III: BMS Application**

A MSP430fr5969 microcontroller was implemented to create a BMS system that can read data from the BMS chips such as cell voltage, pack voltage, pack temperature, fault statuses, alert statuses, and a variety of other useful cell parameters. This data is displayed on a LCD screen through different menu options. The user scrolls through the menus using a capacitive touch slider on the microcontroller and selections a given option using the option select button. There is also a cell balance mode that will check the cells to see if they are out of balance and then enable cell balancing if the cells are unbalanced. This section is designed to remove the Aardvark adaptor and the GUI from the system.

# Chapter 1: Introduction

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A battery management system is any system that monitors and/or manages batteries. Since batteries are found in nearly all portable systems that require power, the need for battery management systems is tremendous.

A Tesla Model S experienced a fire due to collision with a road hazard. A video of the incident went viral on the internet and prompted a safety analysis. The battery management system was not able to prevent the penetration of the pack by the road hazard, but the fire was contained.

The Boeing 787 Dreamliner experienced at least two overheating incidents of their lithium ion batteries causing destruction, fire, smoke, but did not cause a catastrophe. However, the fleet was grounded for months causing much economic dislocation. An extensive investigation did not reveal the root cause of the fires but the battery management system was not able to prevent the fires.

The requirement of this BMS is to monitor cell voltage, pack voltage, and pack temperature. Each cell needs to be kept within a certain voltage through cell balancing. The cells need to be protected from cell over-voltage (COV) and cell under-voltage (CUV) by performing the necessary tasks depending on the statuses of the cells. This system also needs to mitigate the effects of fires in the cells by shutting the system down if there are thermal excursions beyond the set temperature limits.

The first part of this project focuses on the characteristics of batteries' charge and discharge. Knowing what currents are needed and what voltages are expected at every step in the charge and discharge is important when developing the BMS. The BMS is capable of alerting the user of cell over-voltage and cell under-voltage which is only understood by testing the specific cells and comparing the results to the datasheet specifications. Testing the batteries also provides the current which is used for draining the cells for cell balancing. This current along with the power resistor value from the datasheet give an estimation for how long cell balancing will take for a given voltage difference between cells.

The second part of this project focuses on the BMS chips. This design uses the BQ76PL536 which is a three to six series cell Lithium-Ion battery monitor and secondary protection integrated circuit. This chip supports all Li-Ion chemistries and has high-speed SPI for data communications. This chip has six cell voltage measurements, one pack voltage measurement, two pack temperature measurements, along with cell balancing pins which can be set to control external cell balancing circuitry. The BQ76PL536 Evaluation Module (EVM) used in this design includes three BQ76PL536 chips with the external cell balancing circuitry. In the second part of this project, the BQ76PL536 EVM is exercised by connecting it to a six-cell battery pack and using an Aardvark SPI to USB adaptor and a Graphical User Interface (GUI) to monitor the cells and control the cell balancing as needed. The cell balancing through the GUI must be controlled by a user and is not automatic.

The third part of this project is to create a fully functional BMS that can monitor the cells and display the measurements to a LCD screen for the user to see. This portion of the project uses a MSP430fr5969



microcontroller unit (MCU) with a Sharp LCD Boosterpack. The user uses the capacitive touch slider on the MCU to access several features. Using the option select button, the user can read individual cell voltages, pack voltage, cell state of charge, or pack temperature. The BMS is also capable of automatic cell balancing if selected by the user in which the system looks for cells that are out of balance and then initiates cell balancing as needed. The system has set COV and CUV trip points as well as over-temperature and under-temperature trip points so when the system detects these trip points are reached, the system can shut down completely to protect the batteries and the overall system.

# Chapter 2: Background

## Battery Information

Batteries store electrical energy in chemical form which then provides power to a device or circuit. Batteries can be primary (non-rechargeable) or secondary (rechargeable). This project focuses on the management of secondary Lithium Ion cells because of their energy density compared to other types as shown in the graph below Figure 1.

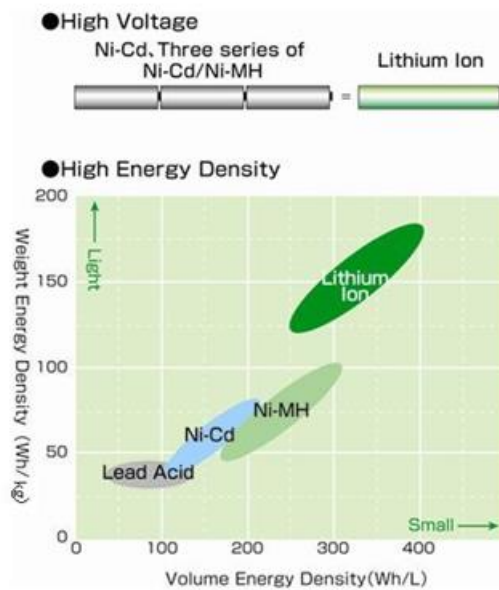


Figure 1: Comparison of various battery types

## Battery Selection

The specific batteries used in this project are Panasonic Lithium Ion NCR18650s shown in Table I.

Table I: Lithium Ion 18650 specifications

Nominal Voltage		3.6V
Nominal Capacity *1	Minimum	2,750 mAh
	Typical	2,900 mAh
Dimensions	Diameter	Max. 18.6 mm
	Height	Max. 65.2 mm
Approx. Weight		45 g

The reason these batteries were chosen is because they are reasonably priced at approximately \$10.00 per cell and deliver high performance when compared to other batteries. These batteries are also very popular and are used in various systems including the battery packs in Tesla cars.

## Battery Equations

Capacity is the charge stored by the battery. It is the number of hours the battery can provide a current equal to the discharge rate at the nominal voltage of the battery.

$$Capacity = \int_0^t I dt = I \int_0^t dt [Ah] \quad (1)$$

Energy of the battery is the capacity to do work. It is equal to the amount of power provided over a given period of time.

$$Energy = \int_0^t P dt = \int_0^t IV dt [Wh] \quad (2)$$

The voltage of the battery is equal to the open circuit voltage minus the voltage drop across its internal resistance.

$$V_{battery} = V_{oc} - I * R_{int} [V] \quad (3)$$

C rate is used to scale the charge and discharge of a battery. At 1C a battery at full capacity will be fully discharged in 1 hour at a constant current. The Li-Ion 18650 batteries we used were rated at 3.1 Ah.

$$1C \text{ rate} = \frac{Full \text{ Capacity}}{1 h} = \frac{3.1 Ah}{1 h} = 3.1 A \text{ to fully discharge the battery in 1 hour.} \quad (4)$$

The time it will take to fully discharge a battery is inversely proportional to its C rate.

$$time = \frac{1}{C \text{ rate}} [hrs] \quad (5)$$

# Chapter 3: Battery Analysis and Set Up

## Introduction

Battery tests were conducted to fully understand the operations of charging and discharging the battery. These tests were essential to gain a better understanding of typical battery behavior, obtain data pertaining to the characteristics of the battery, and compare experimental data with the datasheet.

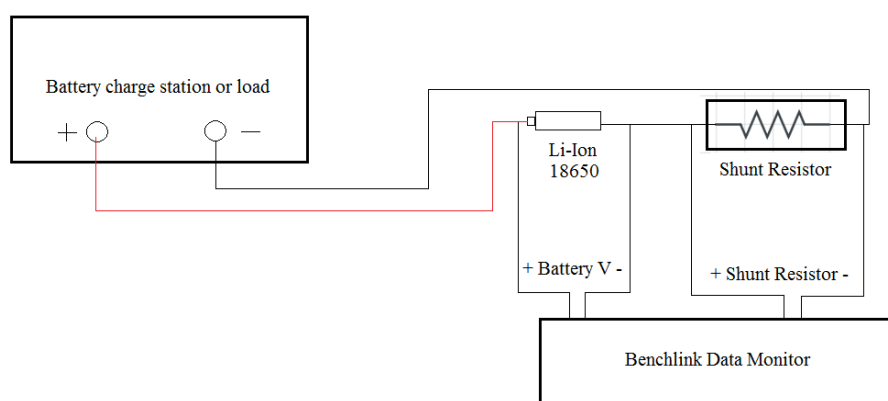


Figure 2: Charge and discharge schematic

## Procedure

The charging and discharging of the Li-Ion 18650 battery was conducted using the set up shown in Figure 2. The charger used was a BK Precision Programmable Power Supply model XLN3640 and the load was BK Precision Load model 8518. A shunt resistor was connected in series with the battery to provide a voltage to current conversion ratio allowing us to find the current through the battery. An Agilent 34972A Benchlink Data Monitor with potentials across the battery and the shunt resistor was implemented to poll data from those components and convert it to a CSV file. The channels of the monitor were set for battery voltage, shunt voltage, and temperature. The information from the CSV file could then be manipulated to match the characteristics of the battery to those of the data sheet. The equipment used for the charging and discharging is shown in Figures 3, 4, 5.



Figure 3: Programmable DC Supply for charging

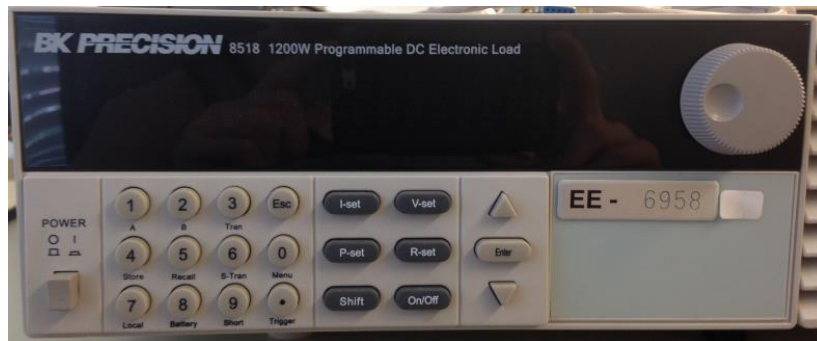


Figure 4: Programmable DC load for discharging

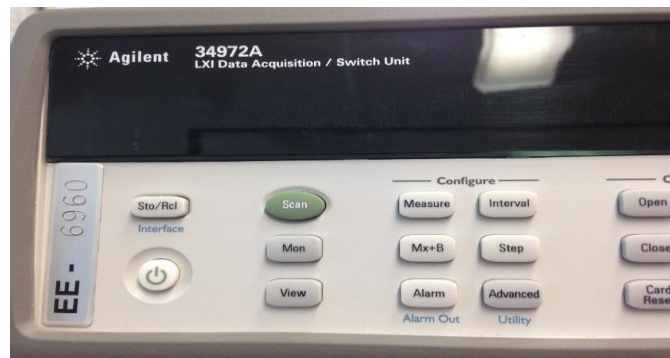


Figure 5: Data acquisition device for extracting data from cells

## Calibration

An electrical shunt was used to obtain the current through the battery. A calibration test was run to ensure that the shunt measurements matched its nominal conversion. From Figure 6 it can be seen the shunt was correctly calibrated for a conversion of 50 mV = 10 A, which it was rated at.

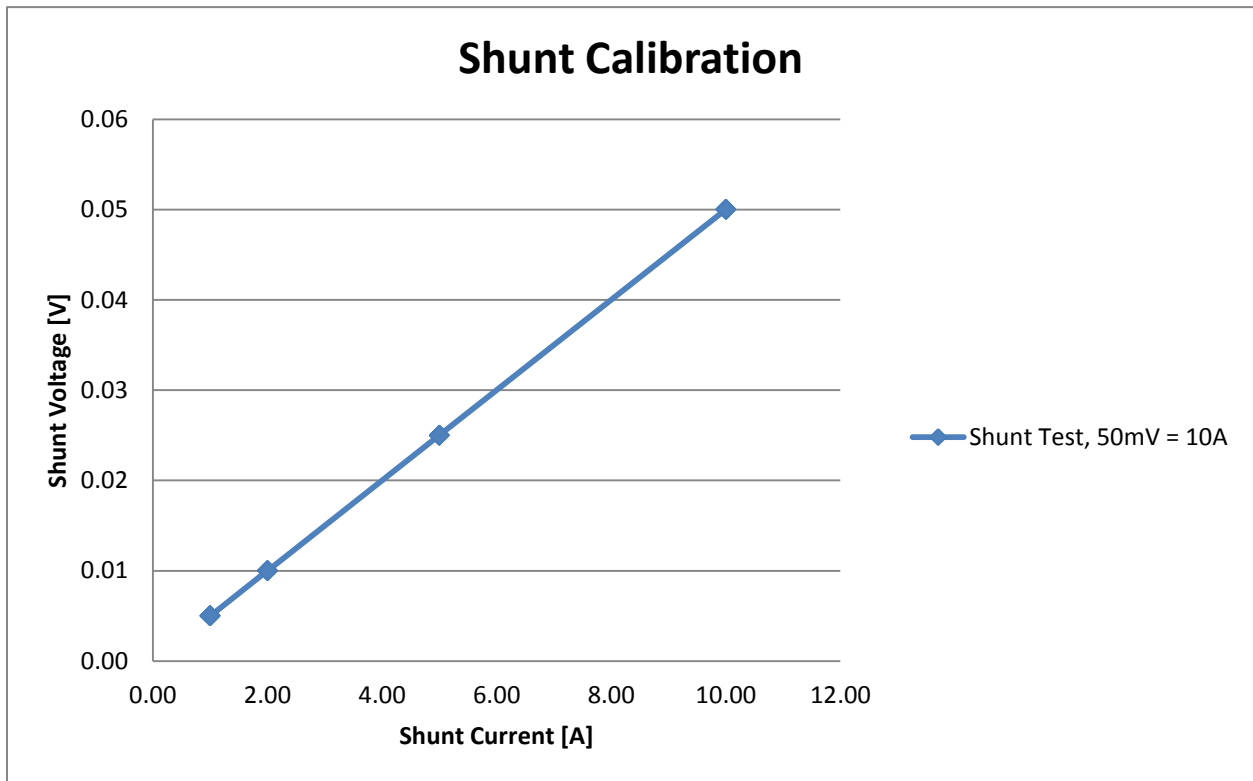


Figure 6: Calibration of shunt

# Chapter 4: Test Results for Battery Data

## Charge

To charge the battery the charger was set to “battery charge” mode and using the charge values found in the datasheet the max voltage was set to  $V = 4.2\text{ V}$  at a charge current of  $I = 885\text{ mA}$ . The test charge characteristics can be seen in Figure 7. From the graph it can be seen that the battery charges at a constant current of 885 mA resulting in the voltage of the battery to increase linearly. However, when the battery is close to being fully charged the current begins to taper to ensure that the max battery voltage is not exceeded and the curve becomes non-linear. Comparing the charge characteristics of the battery to that of the datasheet shown in Figure 8 it can be seen that the battery did not reach 3.1 Ah, which is the nominal capacity rating of the battery. This dissimilarity could be due to variations in the batteries internal design.

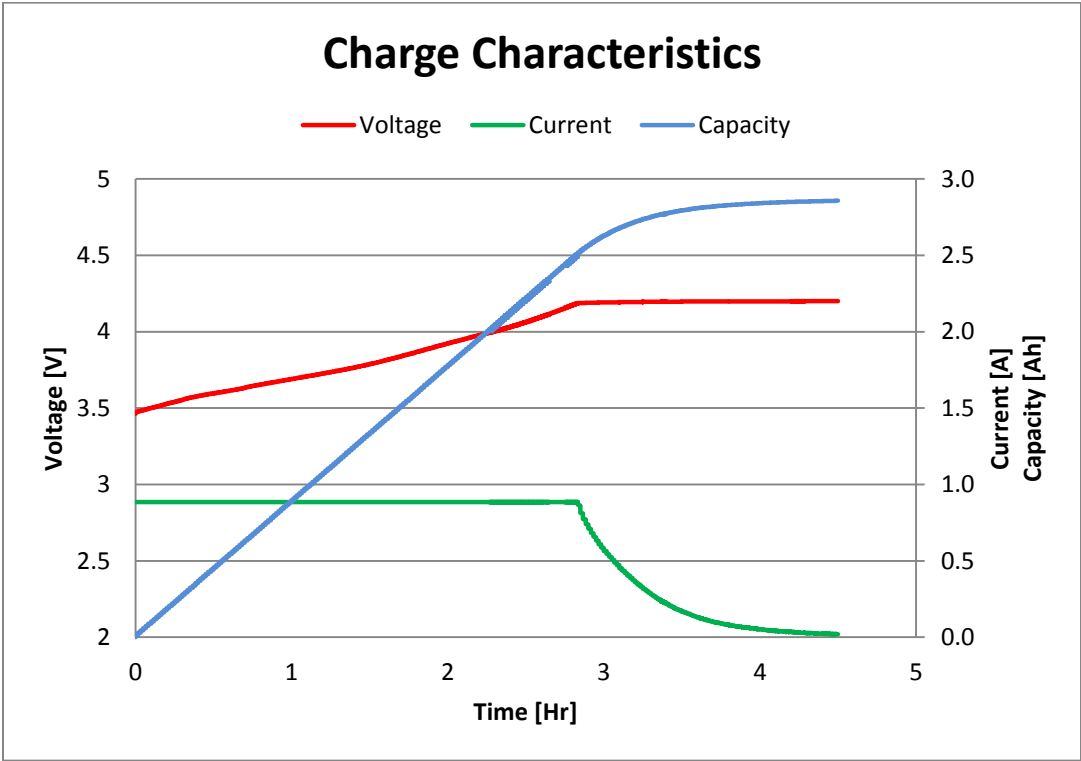


Figure 7: Test Charge characteristics of battery

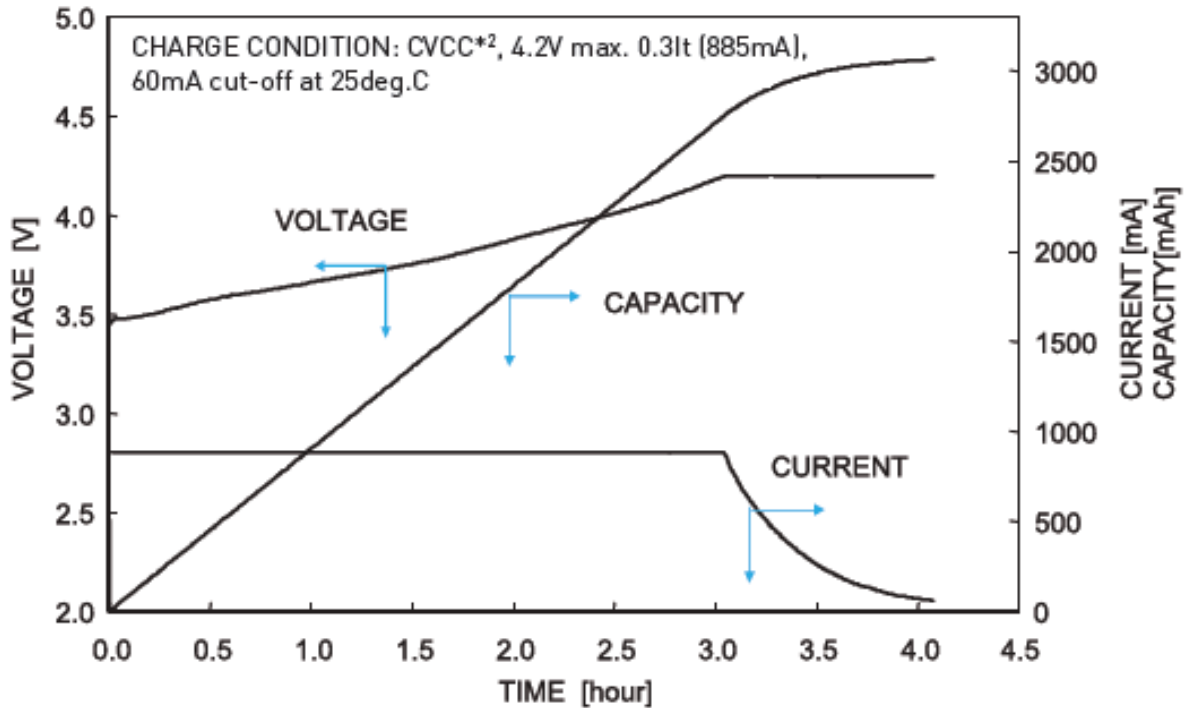


Figure 8: Datasheet charge characteristics of battery

### Discharge

To discharge, the battery was connected in the same setup as to charge the battery with the charger being replaced with a load. A voltage was then set for the battery to not discharge past as well as the current at which the battery would be discharged at. As seen in Figures 9 and 10, the battery was discharged at C rates of 0.2C and 2C respectively. The 0.2C rate was equal to 590 mA and using the equation to find discharge time from C rate, it took  $time = \frac{1}{0.2} = 5$  hours to fully discharge the battery. Using the same equation for the 2C rate equal to 5.9 A it took  $time = \frac{1}{2} = 0.5$  hours to fully discharge the battery.



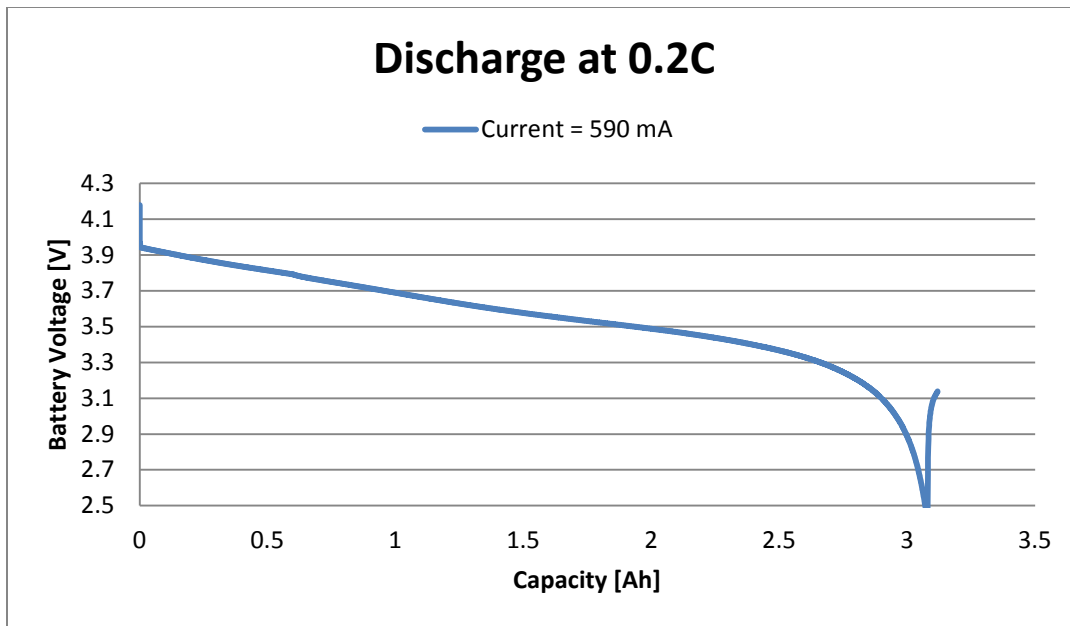


Figure 9: Discharge of battery at 0.2C

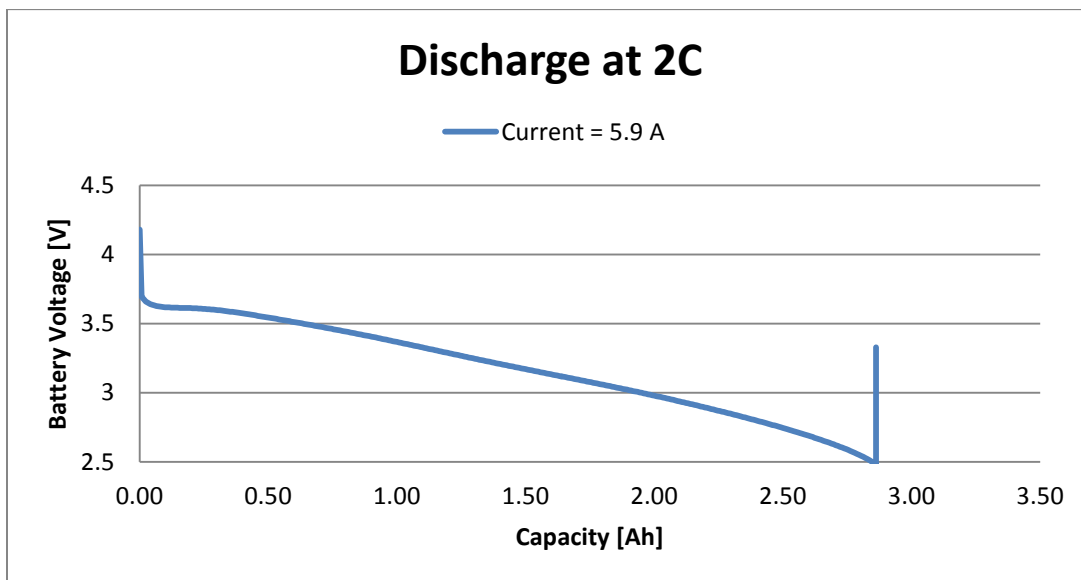


Figure 10: Discharge of battery at 2C

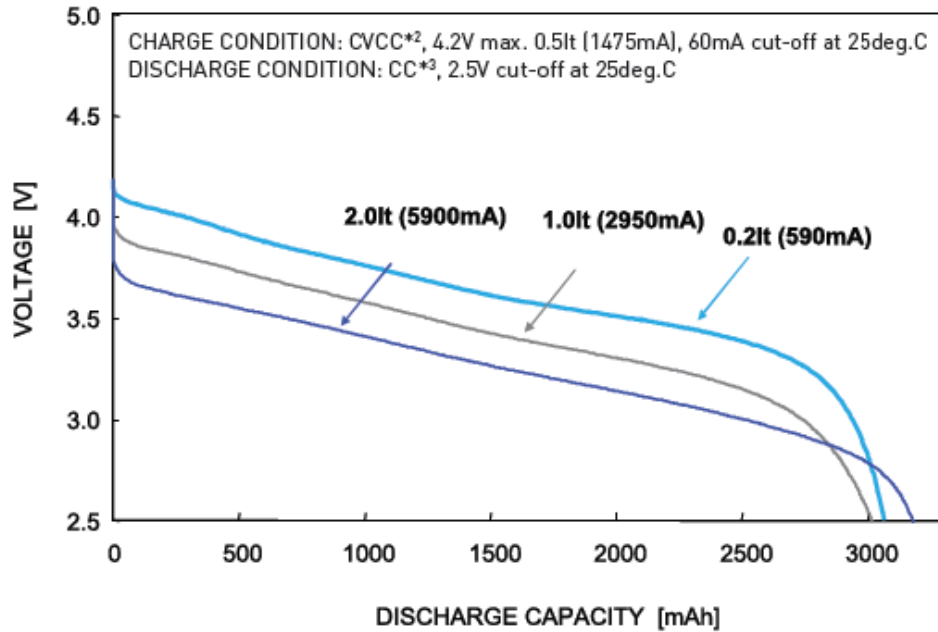


Figure 11: Datasheet discharge characteristics of battery

Comparing these discharge results to that the datasheet shown in Figure 11 it can be seen that the discharge of the battery at 2C did not reach the nominal capacity of 3.1Ah. This is because the charge before this discharge test was ended prematurely and the battery did not reach its full capacity. It is impossible to take out more energy from the battery than is put in.

## Temperature

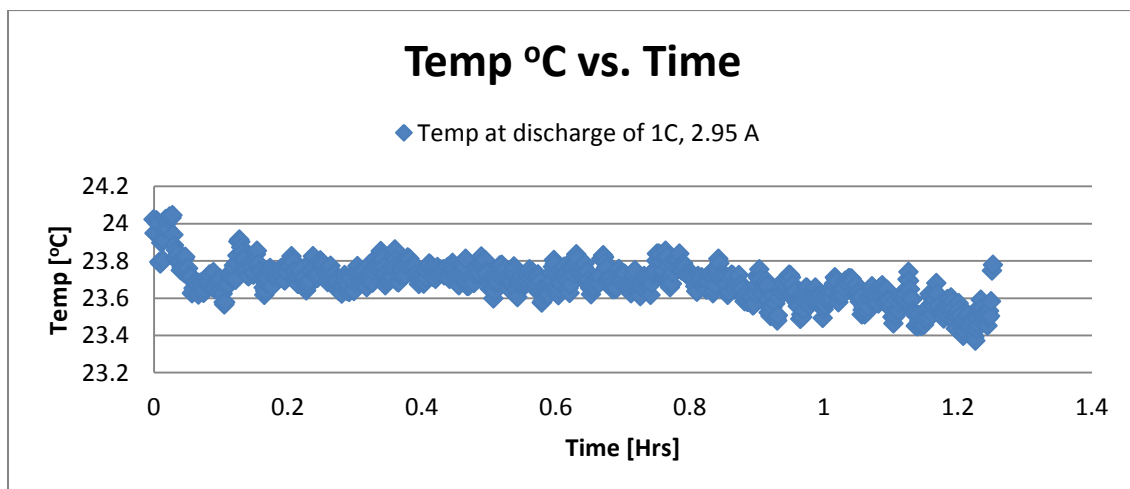


Figure 12: Temperature of battery at 1C discharge

The temperature of the battery varied very little throughout all battery tests and was considered a non-factor to any operations. As seen in Figure 12, the temperature ranged approximately 0.6 °C from between extremes, which will have no effect on the characteristics of the battery tests.

### Open Circuit Voltage from Interruption (Technique #1)

Figure 13 shows the output graph using the data acquisition Benchlink tool. This software was not only needed for extracting the data to be converted to a CSV file but was also helpful for monitoring the current and voltage of the system. Discharge current is shown in red and battery voltage is shown in teal.

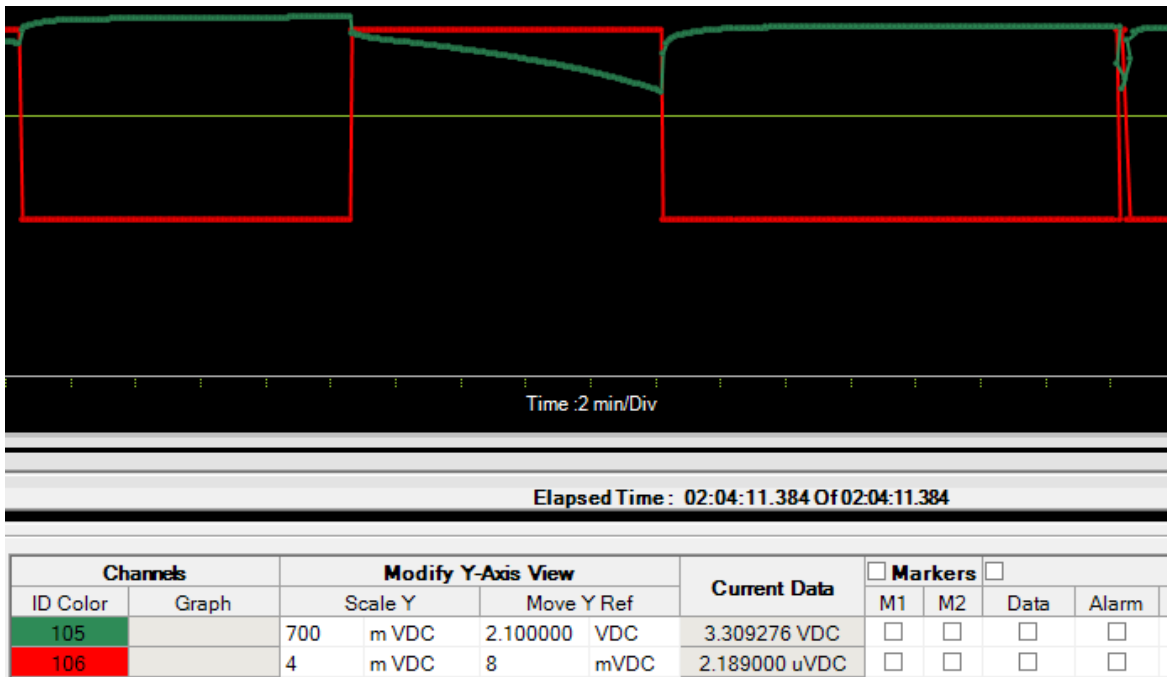


Figure 13: Benchlink data for 1C discharge interrupted to obtain Voc

The open circuit voltage was obtained by disconnecting the system from its discharge load and then recording the voltage of the battery after it had let equilibrate for ten minutes. The open circuit voltage is the voltage the battery recovers to without being connected to any load. The open circuit voltage is found after a short recovery time to allow the internal chemistry of the battery to settle. From Figure 14 it can be seen that the spikes represent the points when the battery was disconnected from its load and recovered to a greater open circuit voltage. From Figure 15 it can be seen that as the capacity of the battery decreased the open circuit voltage decreased and the linear fit turned out quite well. The relation between open circuit voltage and state of charge is extremely useful when comparing different batteries and will be discussed in later sections.

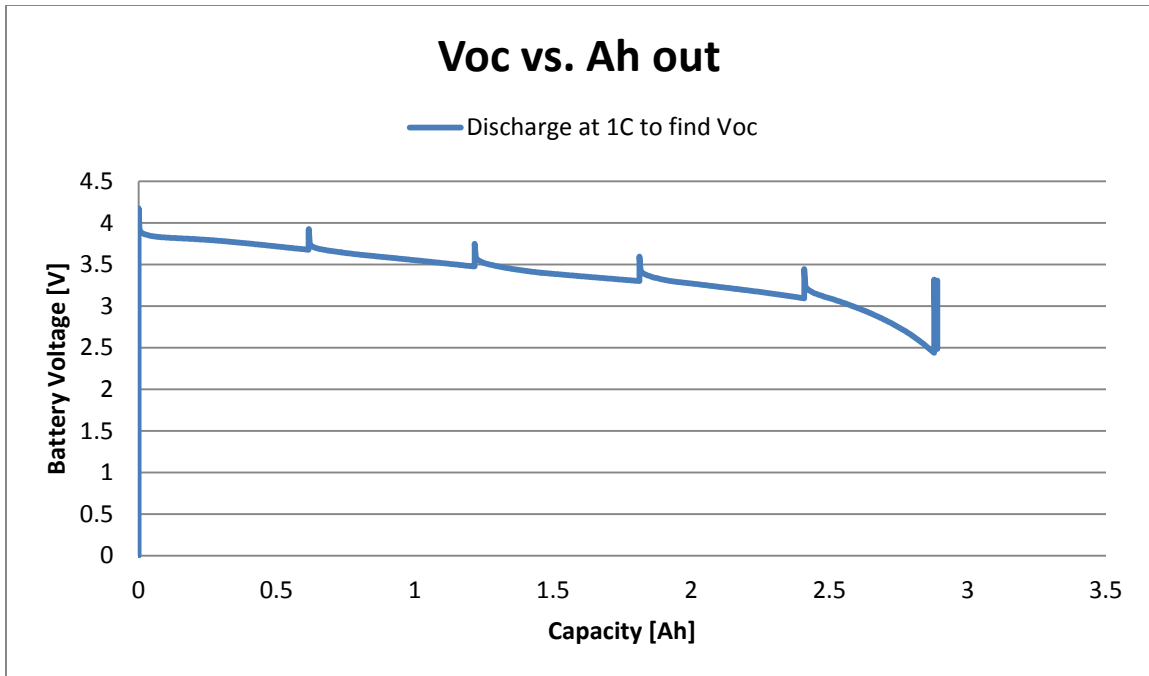


Figure 14: 1C discharge interrupted to obtain Voc

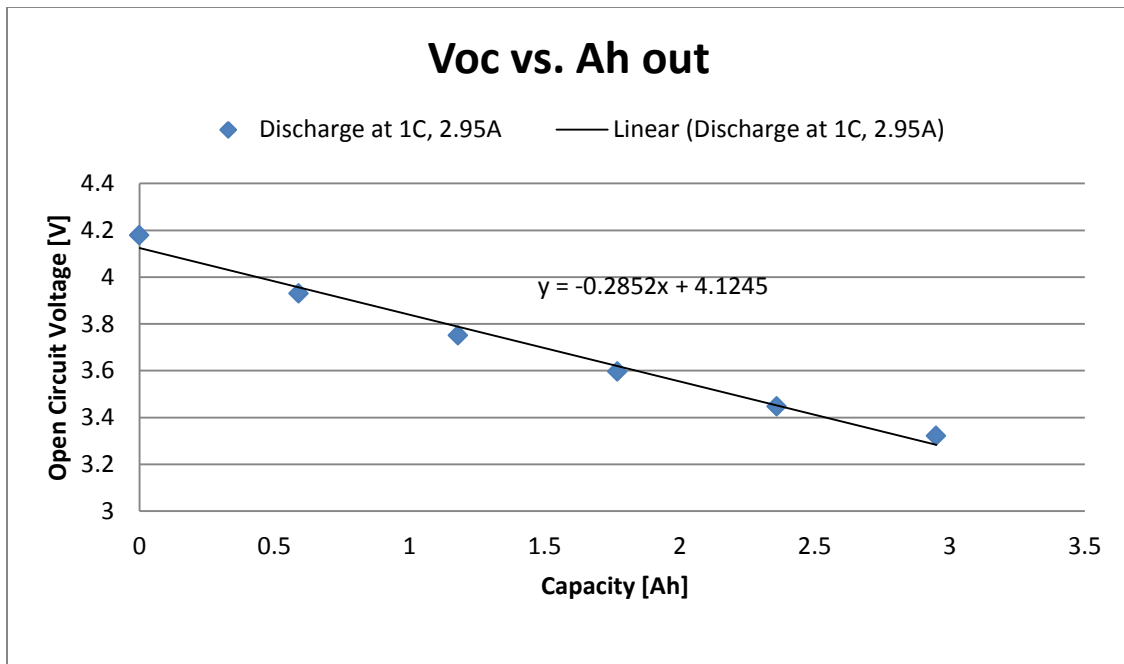


Figure 15: Open circuit voltage at 1C during discharge

## Internal Resistance

The internal resistance was found for different states of charge shown in Figure 16 by finding the slope of the lines using the equation  $R_{int} = \frac{V}{I} \Omega$ . The lines correspond to different states of charge of the battery. The three points of each line correspond to C rates of 0.2C, 1C, and 2C respectively. It can be seen that as the SOC of the battery decreased, the slope or internal resistance increased. This is the correct behavior for internal resistance of a battery solidifying that our data analysis was correct.

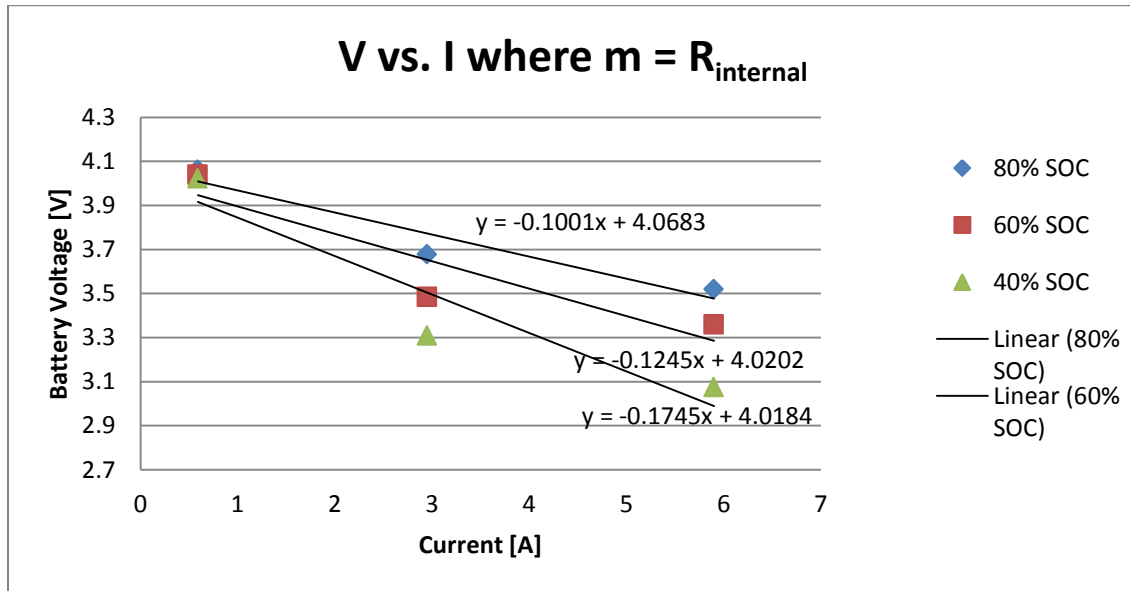


Figure 16: Internal resistance for different SOC

Taking the internal resistances found from the slopes found in Figure 16, a graph was created comparing the internal resistance as capacity was displaced from the battery. From Figure 17 it can be seen that as the battery was discharged the internal resistance increased. The internal resistance for the battery was found down to 40% SOC because at lower SOC it was unclear whether the battery had been fully charged. If the battery was not fully charged the data at the end of the discharge could have been faulty. By analyzing the data above 40% SOC it ensured that the data being obtained was correct.

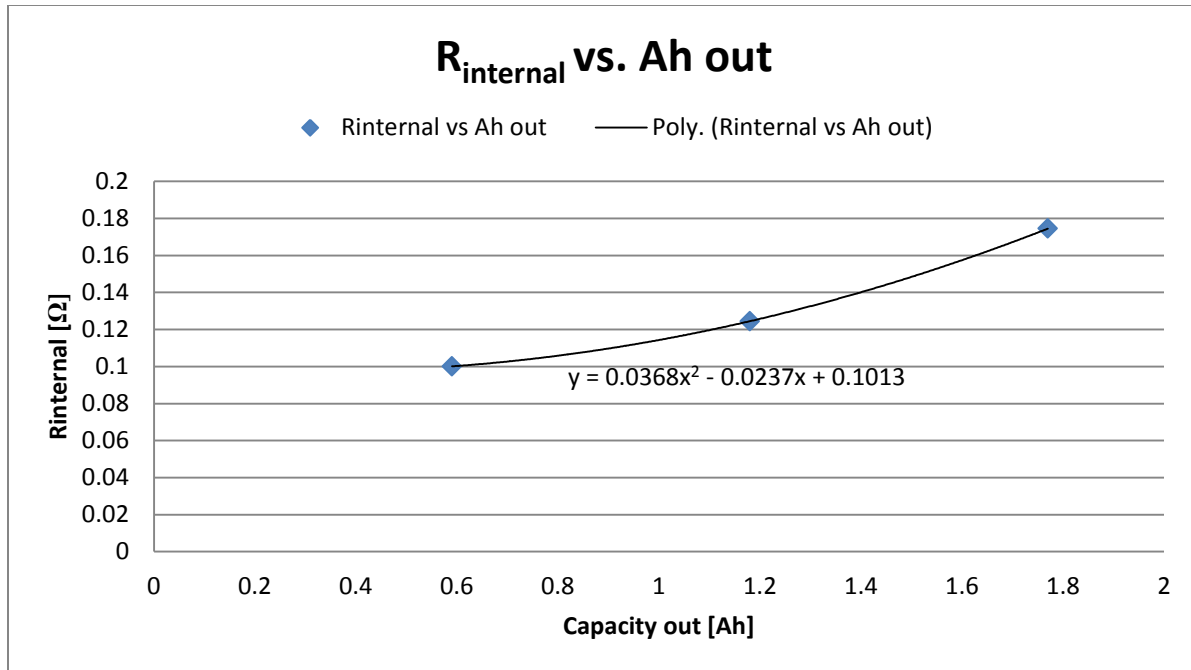


Figure 17: Internal resistance increases exponentially as capacity is displaced

### Open Circuit Voltage from Extrapolation (Technique #2)

Using the internal resistance lines from Figure 16, the points could be extrapolated back to the Y-axis and the open circuit voltage could be found for different states of charge. This extrapolated experimental open circuit voltage had slight differences in voltage values as the open circuit voltage found using the interruption technique in Figure 15. This is due to the 2C discharge capacity not reaching the rate 3.1 Ah and the 1C discharge values being experimental from the plot digitizer. The extrapolated open circuit voltage is found in Figure 18.

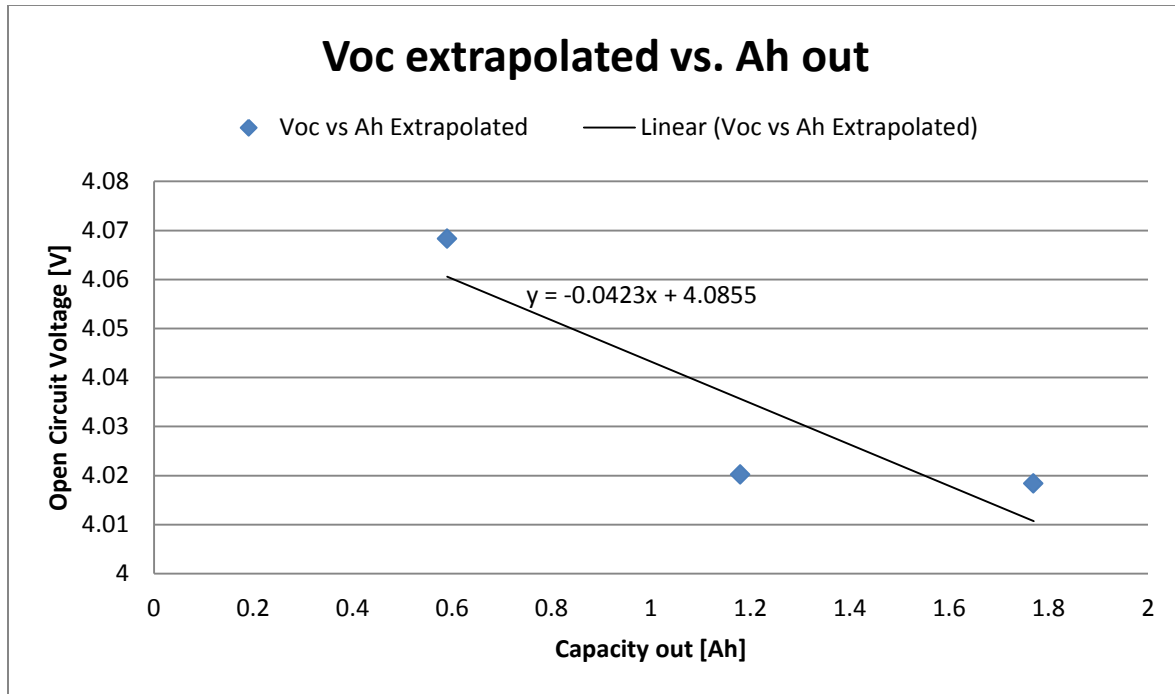


Figure 18: Open circuit voltage found from extrapolation

### Using the Plot Digitizer

The Plot Digitizer tool was another useful software aid that allowed the datasheet discharge curve to be formulated into digitized points to be analyzed against the experimental data. The .pdf datasheet discharge curve was copied and pasted into the digitizer and then traced over by the digitizing tracer. The traced line then outputted a set of digitized data points that represented the line, as seen in Figure 19.

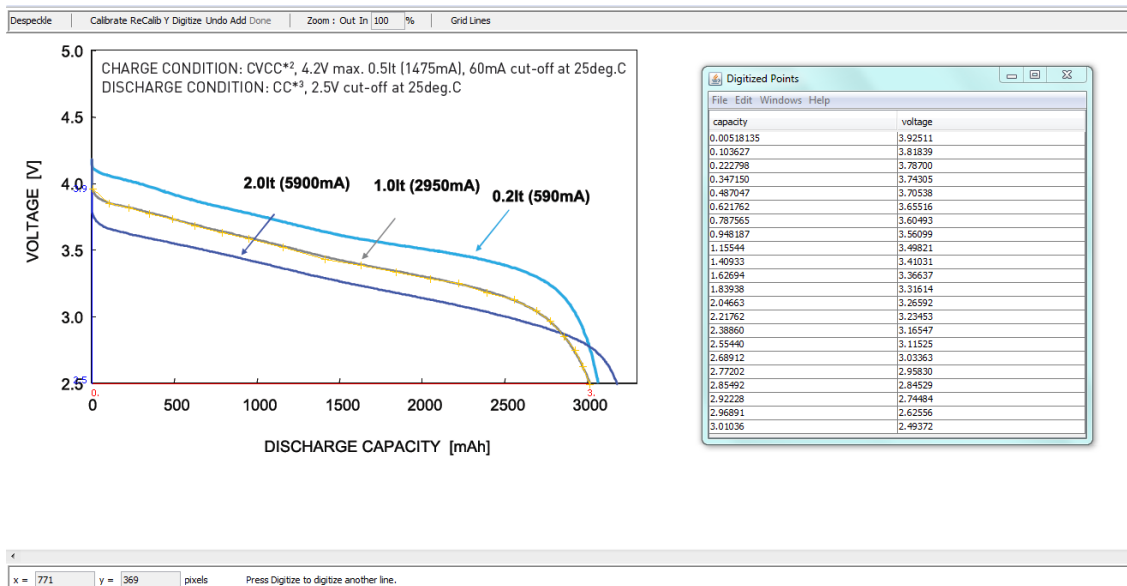


Figure 19: Digitized points for datasheet's 1C discharge

The experimental voltage found from the Plot Digitizer was then graphed against the experimental capacity extracted from the battery as shown in Figure 20. This plot was compared to the 1C discharge plot from Figure 19 to ensure that the digitized points correctly corresponded to the line being traced.

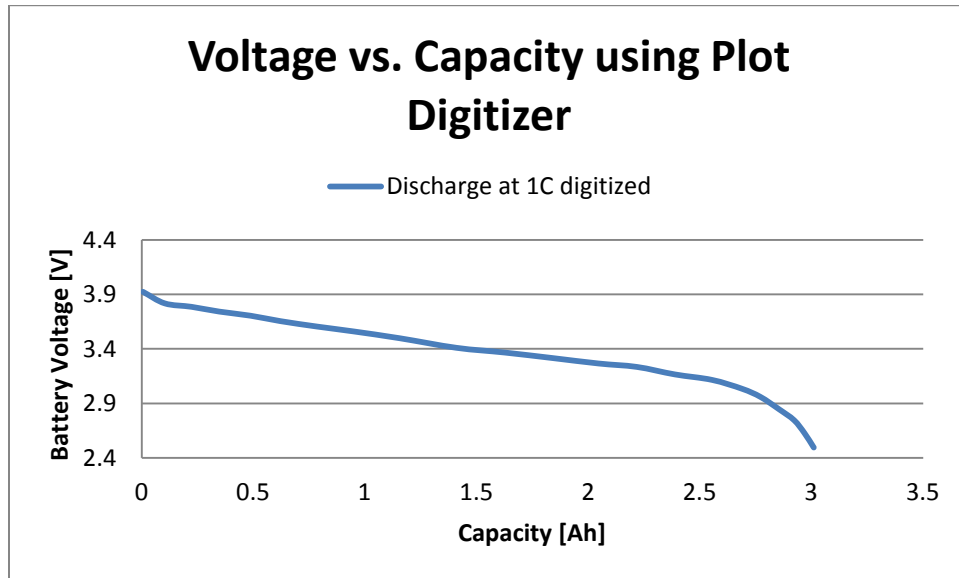
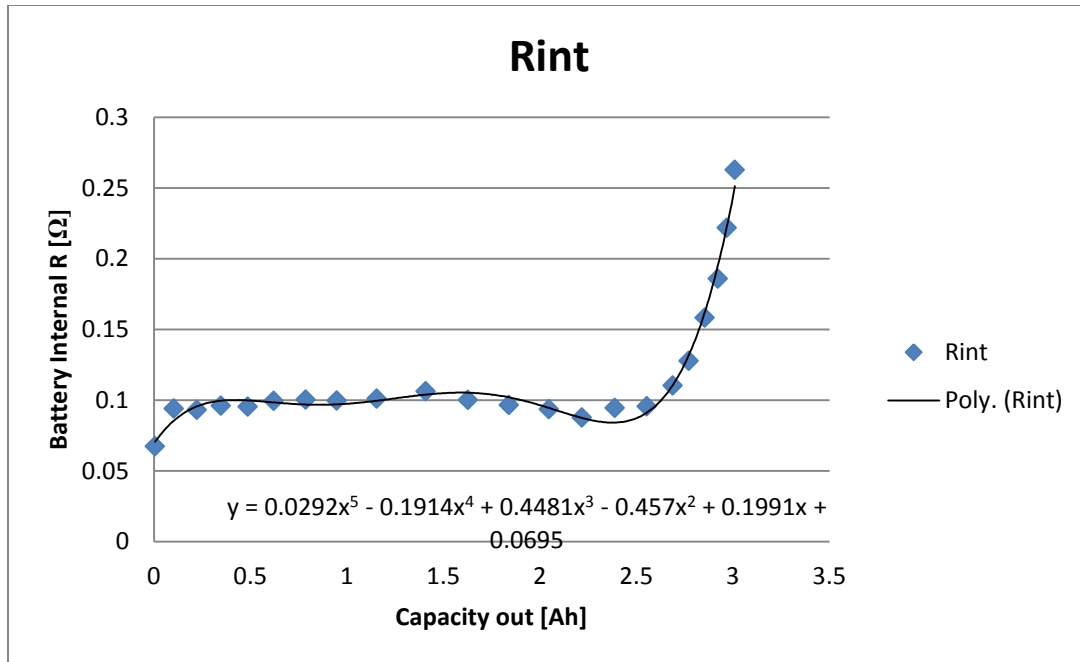


Figure 20: Graph of digitized points for a 1C discharge

An experimental internal resistance of the battery was created using the capacity and voltage found from the plot digitizer for a 1C discharge. The purpose of this is to find the parameters for the state of charge equation for a battery  $V_{\text{battery}} = V_{\text{OC}} - I \cdot R_{\text{int}}$  recognizing that the open circuit voltage and the internal resistance are postulated to be some functions of the state of discharge or Ah out of the cell. A number of approaches can be used to estimate these function and to determine the parameters of the functions.

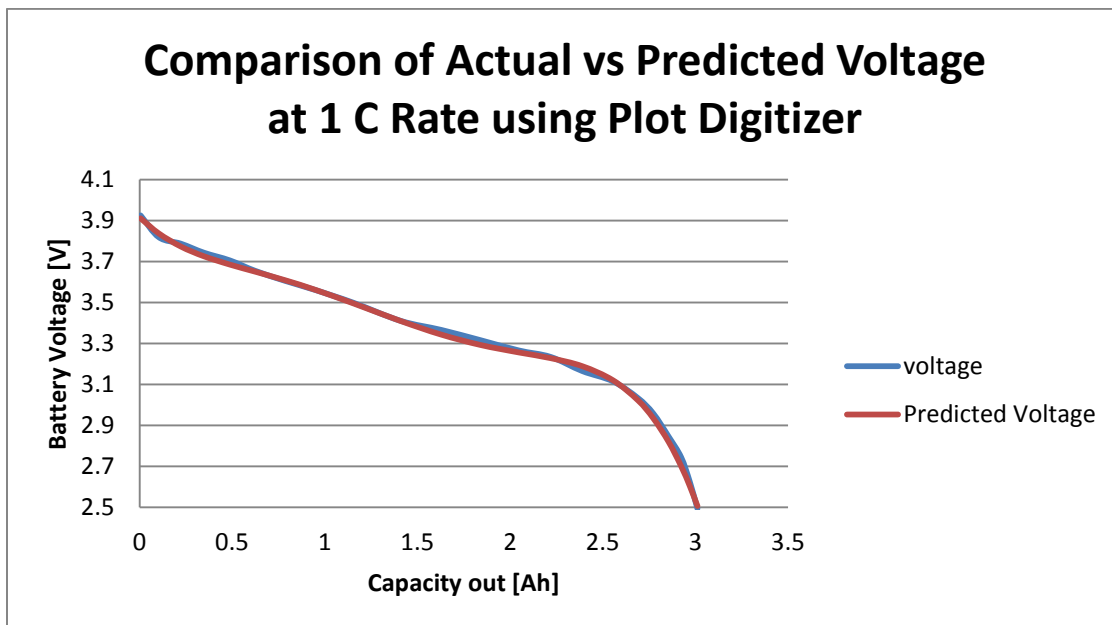
The internal resistance is estimated by first finding  $V_{\text{oc}}$  from the linear equation  $y = -0.28x + 4.1245$  found in Figure 15, where  $x$  is the capacity found from the plot digitizer and  $y$  is the open circuit voltage. The internal resistance shown in Figure 21 was then found from the equation  $R_{\text{int}} = \frac{V_{\text{oc}} - V_{\text{batt}}}{1C}$  where  $V_{\text{batt}}$  was the experimental voltage obtained from the plot digitizer.





**Figure 21: Internal resistance of battery at 1C discharge**

Using the 5<sup>th</sup> order polynomial equation for  $R_{int}$  shown in Figure 21 the predicted battery voltage was found using the equation  $V_{predicted} = Voc - I(0.0292x^5 - 0.1914x^4 + 0.4481x^3 - 0.457x^2 + 0.1991x + 0.0695)$  where  $x$  is the capacity from the plot digitizer. The voltage from the digitized points for the 1C discharge was then compared to the predicted battery voltage as seen in Figure 22 and the prediction was quite accurate. The particular fit is for convenience only and is not a theoretically important equation (although operationally it is quite useful).



**Figure 22: Comparisons of predicted vs actual battery voltages for 1C discharge**

The digitized points were then compared the 2C discharge curve. From Figure 23 it can be seen that the two curves were not as exact as the 1C discharge which is due to the actual 2C discharge being used instead of using the Plot Digitizer, which was the method for the 1C.

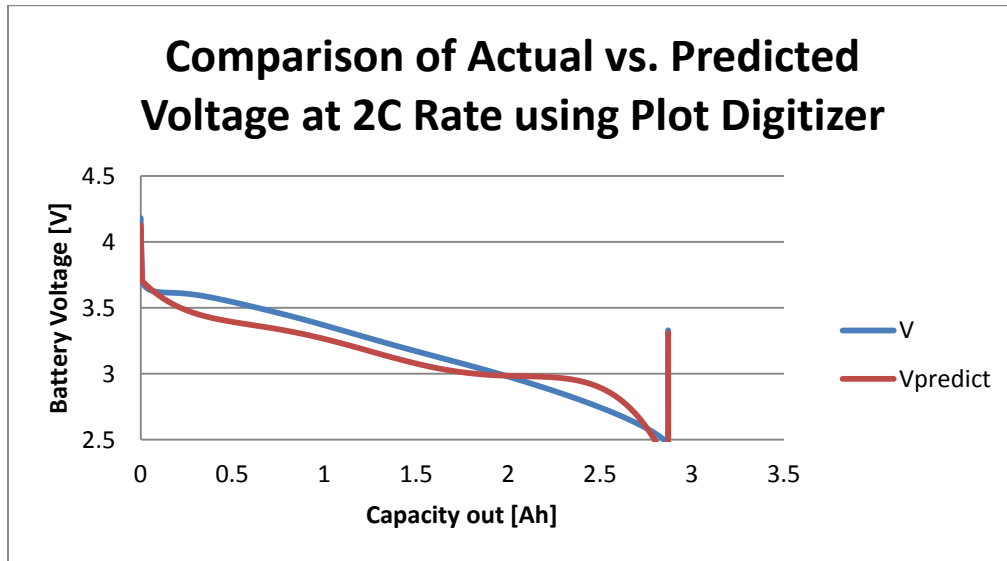


Figure 23: Actual voltage compared to predicted voltage for 2C discharge

The internal resistance was then found using the actual 1C discharge, completely disregarding any Plot Digitizer experimental data. However, using the same method for finding internal resistance for a 1C discharge using the Plot Digitizer, the graph for internal resistance was found shown in Figure 24.

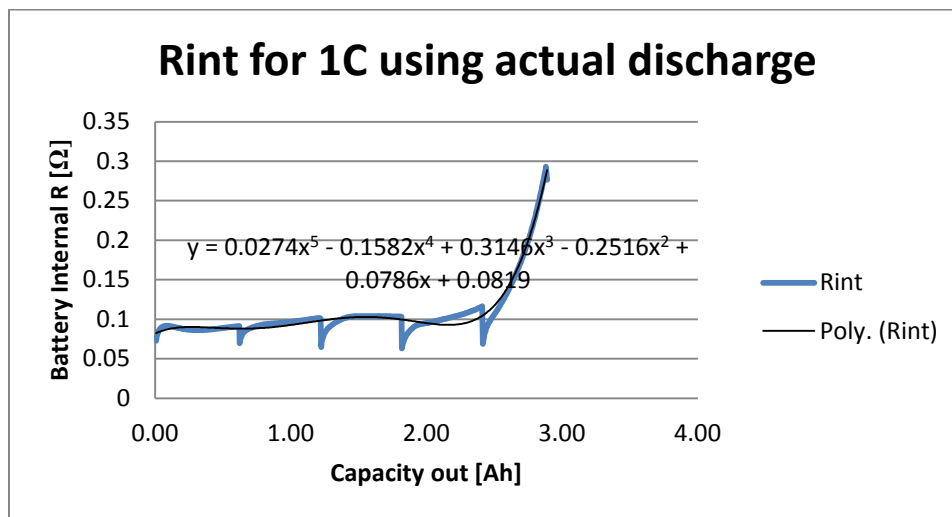


Figure 24: Internal resistance for 1C discharge using actual data

The comparison of actual battery voltage against predicted battery voltage is shown in Figure 25. The reason for doing these experiments of comparing actual against predicted voltage is to show the power of having a function for internal resistance. Given the 5<sup>th</sup> order polynomials found from the internal resistance and one other parameter the discharge curves could be predicted at any state for any discharge. Also, this shows that from the equation  $V_{battery} = V_{OC}(SOC) - IR_{int}(SOC)$  the SOC of the battery can be found and compared to another battery SOC to find how far apart the levels their SOC are. This information can then be used to find the time it will take to balance these batteries which is vital information for a BMS.

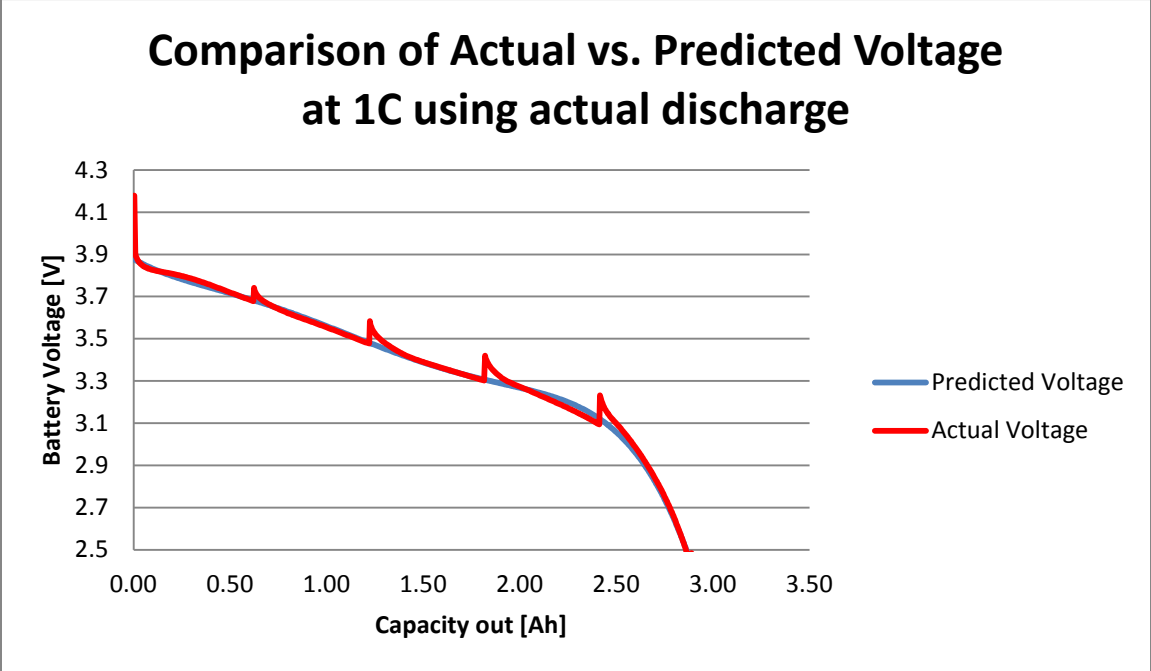


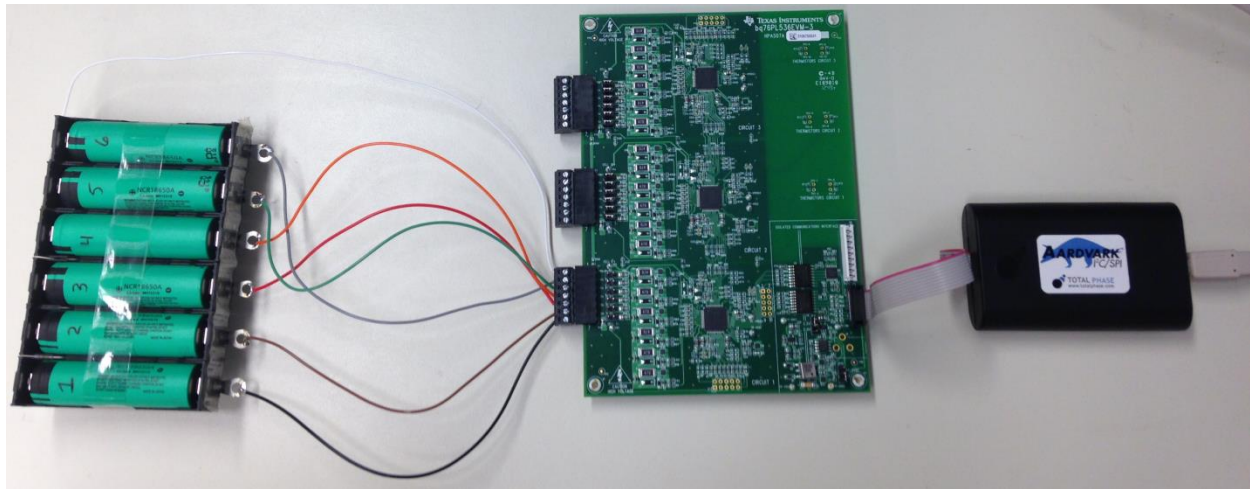
Figure 25: Actual voltage compared to predicted voltage from the 1C discharge using all actual data

# Chapter 5: Utilization of GUI

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## Introduction

Analysis of the BMS was then undertaken following a better understanding of the characteristics of the Li-Ion 18650 batteries. Specifically, cell balancing was analyzed because this would be the functions of the BMS that would be studied the most in Part III. Cell balancing is an essential function of a BMS because it helps protect against cell degradation, over charge/discharge, and ensures that the system and its batteries are operating safely as to not damage more areas of the system.



**Figure 26: System set-up for GUI operation**

The connection setup for the entire system is shown in Figure 26 and consists of the Li-Ion battery pack, BMS, and Aardvark data communication device which was then connected to the console.

## Procedure

This BMS uses passive cell balancing where the excess energy in the cells is dissipated as heat through resistors until all batteries are at the same state of charge as the lowest cell as seen in Figure 27. This is not the most efficient form of cell balancing but is one of the more cheaper, less complicated methods. A thorough analysis of the procedures required for balancing the cells was completed and the BMS operations were exercised to support these claims.



Figure 27: Cells dissipate to lowest SOC for passive cell balancing

### Cell Balancing via BQ76PL536 EVM

The balancing of the cells is controlled by two pins shown in the lower right corner of Figure 28: VCx (voltage of cell) and CBx (cell-balance control output). The VCx pin allows for the voltage of the battery to be read and the CBx pin allows for the balancing of the cell to occur. The CBx pin is active low and causes the NFET to remain open while a logical '0'. When the CBx pin is toggled to a '1' the NFET closes, providing a path for current to flow. The zener diodes are needed for safety to limit the max voltage seen across the diodes which corresponds to the voltage across the cell. The capacitors are present to hold the state of charge of the battery by not reacting to sudden changes or variabilities in the batteries. A 47 Ω power resistor is placed in series with the NFET to dissipate the excess energy of the cells.

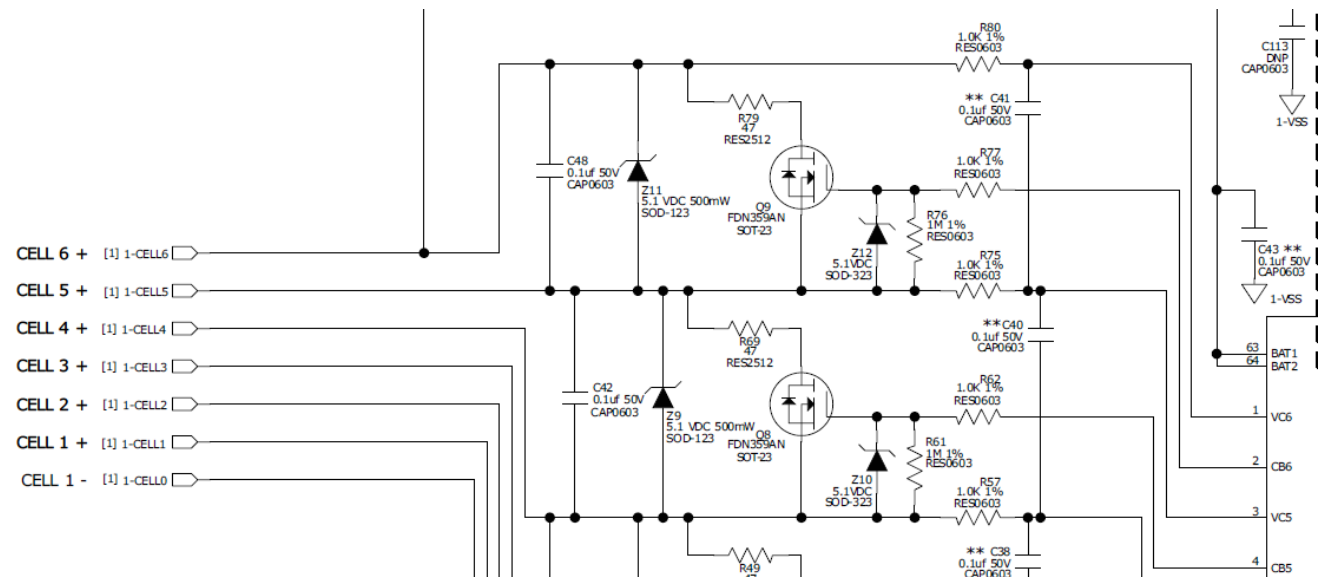
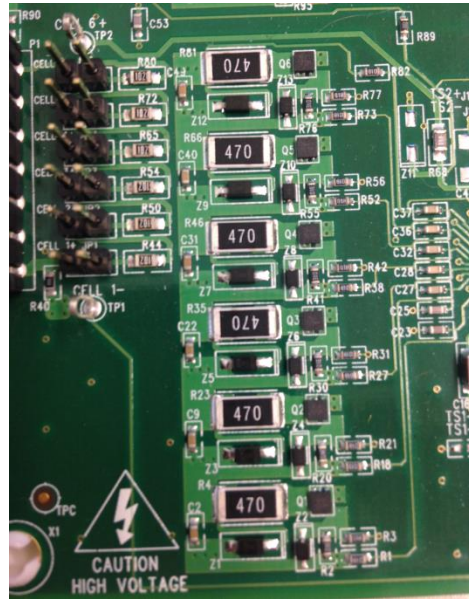


Figure 28: Datasheet schematic of cell balancing portion of BMS



**Figure 29: Power resistor of 47 Ω labeled 470 across each cell**

The power resistor shown in Figure 29 was measured with a multi-meter and verified to be 47 Ω. Using the resistor value and voltage of the cell the current through the cell and the power dissipated was calculated:

$$R_p = 47 \Omega$$

$$V_{\text{cell}} = 3.6 \text{ V}$$

$$I = \frac{V}{R} = \frac{3.6 \text{ V}}{47 \Omega} = 76.59 \text{ mA} \quad (6)$$

$$P_{\text{diss}} = \frac{V^2}{R} = \frac{3.6^2}{47} = 0.276 \text{ W} \quad (7)$$

The cells being balanced were intentionally set at unequal states of charge to perform the balancing. Cells 2-6 were set to approximately 3.6 V while cell 1 was set to 3.5 V. Using the 0.2C discharge rate the capacity discharged was calculated:

$$\text{Cells 2-6} = 3.6 \text{ V} \rightarrow 1.372 \text{ Ah}$$

$$\text{Cell 1} = 3.5 \text{ V} \rightarrow 1.933 \text{ Ah}$$

$$\text{Capacity difference} = (1.933 - 1.372) \text{ Ah} = 0.561 \text{ Ah}$$

The time to balance the cells was then calculated to be:

$$\text{Time} = \frac{0.561 \text{ Ah}}{76.59 \text{ mA}} = 7.32 \text{ hrs} \quad (8)$$

Performing this analysis was extremely informative because through the data collection it was found that a difference of 0.1 V, although a small difference, is quite large when balancing cells using a BMS. As seen from the calculations above it would have taken 7.32 hours to balance the cells being used.

The knowledge gained from analysis of the cells in Part I gave insight into the importance of  $V_{\text{opencircuit}}$  vs. SOC. The open circuit voltage has a direct correlation to the SOC of the battery. The equation  $V_{\text{battery}} = V_{\text{oc}} - I * R_{\text{int}} [V]$  found in the equations section above can be re-written as  $V_{\text{battery}} = V_{\text{oc}}(\text{SOC}) - I * R_{\text{int}}(\text{SOC})$ . Using this equation, the discharge current, and the known variability of  $R_{\text{int}}$  we can determine how far from being balanced one cell is from another.

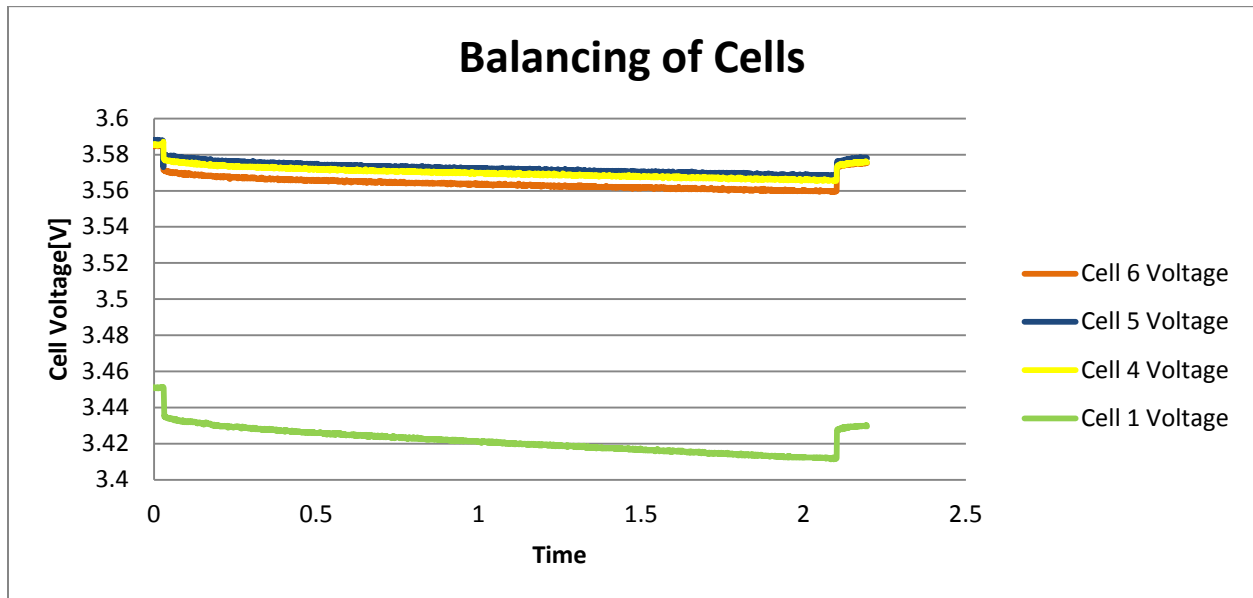


Figure 30: Balancing cells 4-6 at approx. 3.582 V with cell 1 at 3.35 V

Figure 30 shows a test attempting to balance cells 4-6, at 3.584 V, with cell 1, at 3.45 V. Although this voltage difference was only approximately 0.13 V, it can be seen it took over 2 hours to dissipate the cells 0.02 V. All cells are being dissipated because during this test we learned that the GUI does not have a setting to automatically dissipate to the lowest valued cell. It is manually set in the GUI which battery cells the user would like to have dissipated.

## GUI: Graphical User Interface for BQ76PL536 EVM

The GUI was an easy to use interface whose functions allowed some control over the operations of the cells. The main functions that were exercised by the GUI were the cell balancing controls. The automatic features of the BMS are the secondary protection functions and although read about in detail it was hard exercising these functions carefully without damaging the board.



Figure 31: GUI main screen

Once the interface was downloaded to the console the GUI was then accessible as shown in Figure 31. The GUI allowed the user to poll data from the batteries which was then converted to a CSV file. This was extremely useful to the project because in Part III the data was then able to be extracted from the SPI interface pins through the Aardvark to be used in conjunction with a host microcontroller.

The interface of the GUI is very intuitive. The cell voltages are shown on the left side of the GUI as well as the voltage of all the cells added together labeled V BRICK as shown in Figure 31. The differential temperature sensor input labeled TSx measures the temperatures of the cells by incorporating a two-bit thermistor.



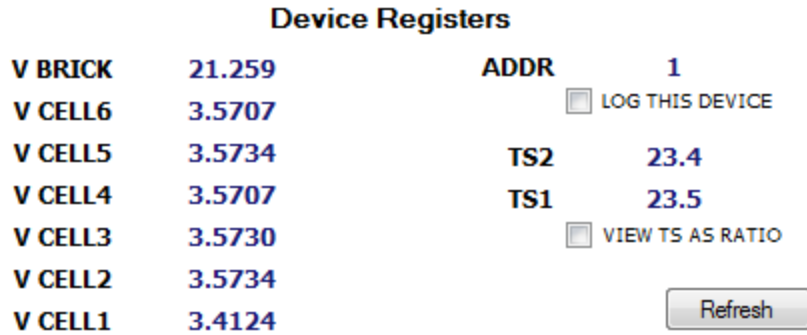


Figure 32: GUI interface of cell voltages and V BRICK

### Safety Features

Some of the fault capabilities were exercised although it was not possible to test them all, such as under/over voltage or under/over temperature in case of damaging the system. Each individual cell is monitored for protection in case of an under or over voltage as shown in Figure 33. When we first attempted to cell balance, cells 2-6 were at equal SOC but cell 1 was at a voltage much lower than these. The GUI would not allow balancing to occur and the fault pin turned on, informing us there was an issue with the system. The two signals to inform the user something outside of normal operating conditions is occurring are ALERT and FAULT. The ALERT register consists of validation for various registers: AR, PARITY, ECC\_ERR, a force fault pin to ensure correct operation and connectivity of the pin, and over temperature alerts. The FAULT register consists of I\_FUALT which is an internal consistency check of the BMS, POR indicating a reset has occurred, and under and over voltage faults.

COV_FAULT	-	-	OV[6]	OV[5]	OV[4]	OV[3]	OV[2]	OV[1]	R
CUV_FAULT	-	-	UV[6]	UV[5]	UV[4]	UV[3]	UV[2]	UV[1]	R
ALERT	AR	PARITY	ECC_ERR	FORCE	TSD	SLEEP	OT2	OT1	RW
FAULT	-	-	I_FAULT	FORCE	POR	CRC	CUV	COV	RW

Figure 33: Safety pins on GUI

### Balancing via GUI

The balancing of the cells by the GUI consists of two controls: CB\_CTRL and CB\_TIME. First, the user chooses a time for which they would like the cells to balance which is controlled by the CB\_TIME pin. They have the option of balancing between 1 second to 63 minutes and the timer begins when one of the CB\_CTRL pins has been toggled from a '0' to a '1' state. The CB\_CTRL is used to toggle the bits that turn the NFETs on, allowing power to dissipate from the batteries. If the CB\_CTRL pin is turned off then the pin will be toggled back to a '0' and the NFET will open, not allowing current to flow through the power resistor. The batteries will either dissipate until the given time runs out and the CB\_TIME pins are

toggled back to a zero or the batteries have being fully dissipated. Figure 34 shows the CB\_CTRL and CB\_TIME user interface buttons. The CB\_TIME is set first and begins when the user clicks on one of the CB\_CTRL buttons, turning it green.

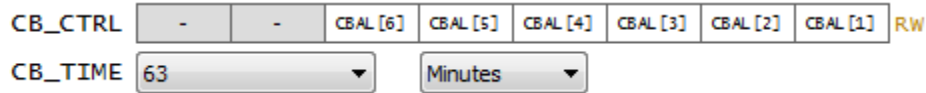


Figure 34: CB\_CTRL and CB\_TIME pins on the GUI

To let the user know that cell balancing timer is running, under the status tab on the GUI the CBT pin is turned green during active use. Also, on the status tab is the DRDY pin which indicates that data is ready to be read. During active low the pin lets the user know that there are conversions running. When the CB\_TIME pin is set and one of the CB\_CTRL pins is toggled, allowing for balancing to occur, the DRDY pin is white which corresponds to conversions are occurring.

The CB\_CTRL pin was switched on in the GUI and the data converted to a CSV file to ensure that the NFET closed when toggled. Figure 35 shows cells 4-6 being toggled to a '1' state to allow for cell balancing while cell 1 is left in the '0' state.

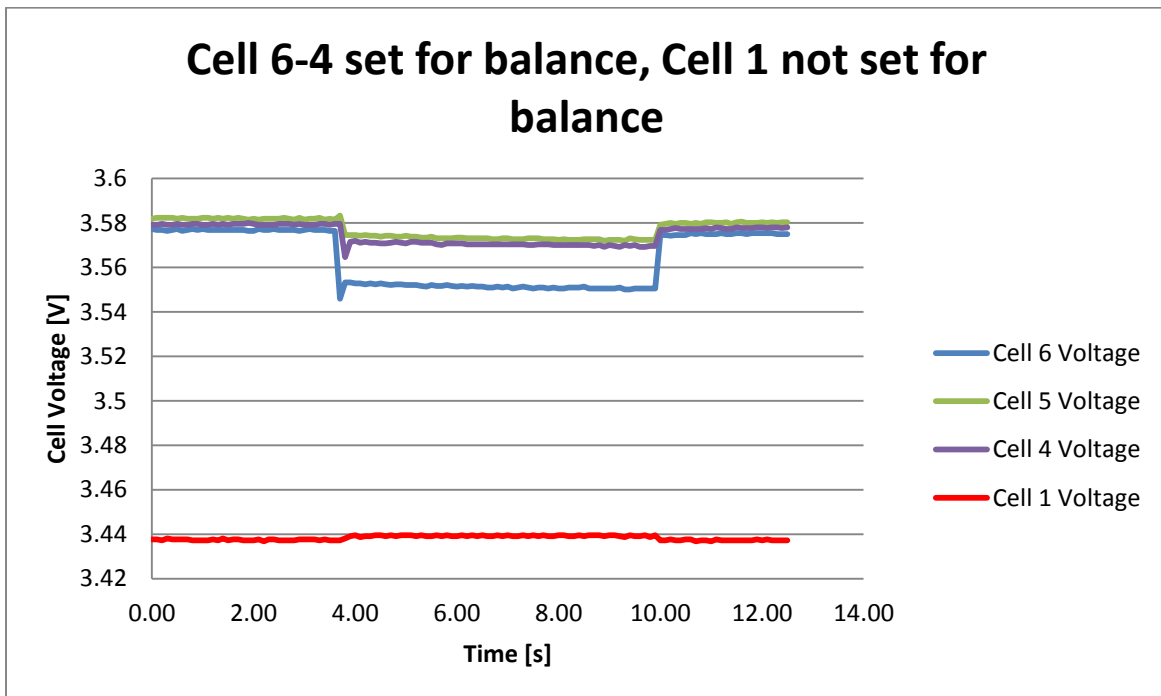


Figure 35: Toggling of the CB\_CTRL pin

## Summary of GUI

Upon exercising the GUI, it was discovered that the automatic cell balance capability must be programmed and loaded to a host microcontroller. The GUI does nothing more than send commands to the BQ76PL536 chip. The BMS does not have any automatic balance-to-threshold intelligence. The BQ76PL536 simply responds to commands from the host controller to take measurements or start or stop balancing. The only automatic features are the secondary protection functions. To perform any intelligent functions such as balance to a threshold a host microcontroller will need to be integrated into the system. Part III explains the BMS application with a host microcontroller (MSP430fr5969). This allows for automatic cell balancing and removes the need to use the Aardvark adaptor or the GUI.

# Chapter 6: BMS Application Requirements

The requirements for the Battery Management System are as follows:

1. Able to monitor battery characteristics for Lithium Ion Cells.
2. Monitors multiple cells.
3. Cell balancing capability.
4. Safety features that protect the user and the system.
5. User friendly interface on LCD screen.
6. Little power required and no additional maintenance necessary.

**Table II: Marketing requirements & engineering specifications**

Marketing Requirements	Engineering Specifications	Justification
Monitor	Monitors all chemistries of Lithium Ion cells from 1V to 4.5V	This is a very common battery type making this BMS relevant.
	Monitors three to six cells per BQ76PL536 chip. The EVM has three BQ76PL536 chips providing cell monitoring for up to 18 cells.	The supply voltage for the BQ76PL536 chip is 7.2V to 27V which determines the minimum and maximum number of cells per chip.
	Monitors individual cell voltage, pack voltage, state of charge, and pack temperature.	These are key characteristics to monitor in any BMS. These values determine the status of the cells and the overall BMS.
Cell Balancing (optional)	Cells that differ in voltage can be balanced to the lowest cell through external cell balancing circuitry provided by the EVM. This function is chosen by the user in the main menu.	Cell balancing is essential in a BMS to make sure all of the cells are at the same voltage.
	When cell balance is chosen by the user, the system detects if any cells are out of balance and then begins balancing if they are.	Automatic cell balancing is a feature that is not provided by the GUI that comes with the EVM.
Safety Features (optional)	The BMS has cell over-voltage, cell under-voltage, cell overtemperature, and cell under-temperature trip points that set Alert and Fault flags if reached.	These are the main issues with batteries so this provides the most essential battery protection.
	The BMS can be designed to do different tasks when a certain Alert or Fault is set. Shutting down the system is one possibility.	Shutting down the system can prevent permanent damage to the user or the BMS.
User Interface	The BMS displays the menus for the user on a LCD screen. The user navigates through the menus using the LEFT Capacitive Touch Sensor and the Option Select Button.	The user needs to be able to choose what mode they want to execute. This includes all of the monitoring and cell balancing.
	The user can return to the main menu by clicking the Menu Button.	This allows the user to change the current mode.
	No maintenance is required. The user has the ability to change trip points and system tasks only by changing the software.	Easy to use system while still providing flexibility for expert users.

# Chapter 7: Design of BMS Application

## Hardware

The BMS is based on the modules shown below Figure 36.

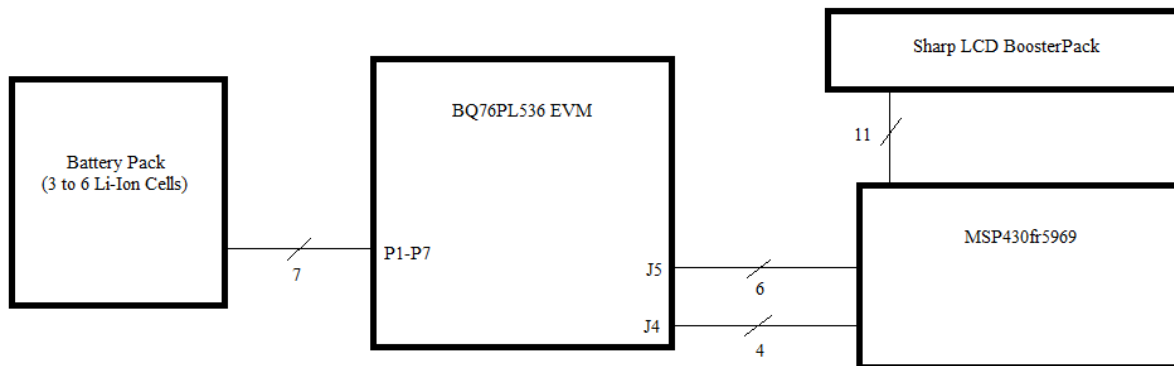
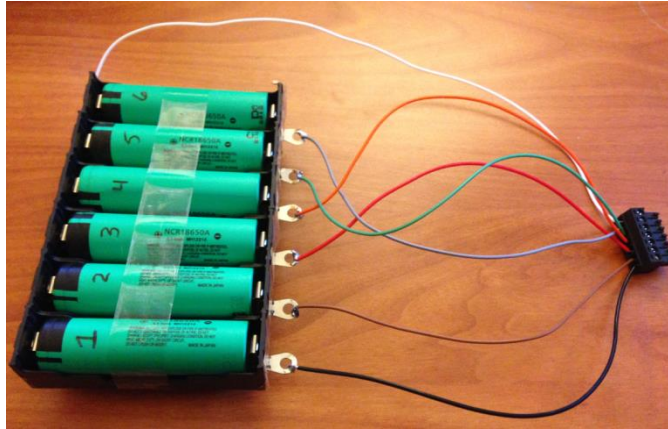


Figure 36: BMS block diagram

### Battery Pack

The battery pack contains between three and six Lithium Ion cells. The minimum allowed voltage for each cell is 1V and max voltage is 4.5V. The batteries are connected in series with the negative of the first cell connected to P7 and the next cell connecting to P6 and so on until the positive of the last cell is connected to P1. Another pack of three to six cells can also be connected to the other two plugs but only one pack is used for this project.

The pack is connected to the EVM at the Port 1 plug. It is essential that the batteries remain secure and the lines from the battery are secured in the plug with the metal screws before it is connected to the EVM. The negative of the bottom cell connects to P1. For more information on the specific cells used see the 18650 datasheet [1]. The specific cell holders used are Arbin Instruments high power cell holders for cylindrical cells.



**Figure 37: Battery pack containing 6 Li-Ion 18650s**

### **BQ76PL536 EVM**

The EVM shown in Figure 38 has three BQ76PL536 BMS ICs shown in Figure 39 which monitor the battery packs. Note that only one BMS chip is used since only one battery pack is used in this project. The BMS chip is connected to cell balance circuitry as shown in Figure 40 which is then connected to the cells. The EVM has an isolated communication interface that allows SPI and Input/Out communication with a host device.

Information regarding the BMS chip which includes the cell monitoring and cell balancing can be found in the BQ76PL536 datasheet in reference [2]. Information regarding the setup of the EVM and the operation of the GUI it comes with can be found in the EVM Start Up Guide in reference [3].

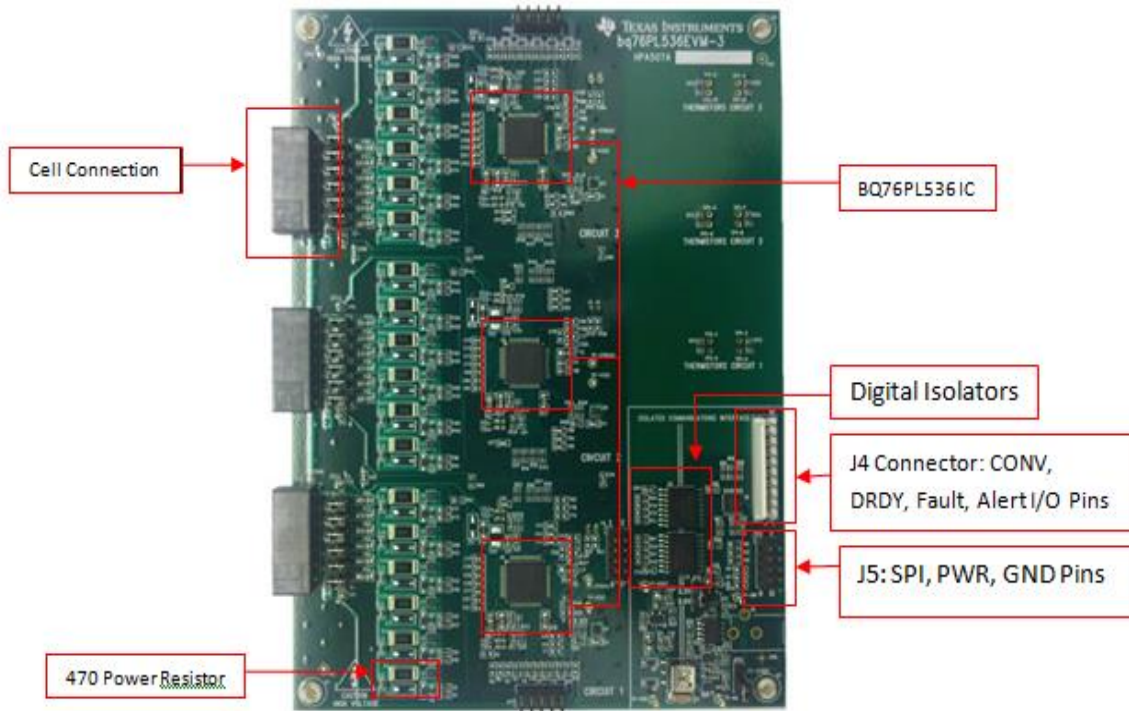


Figure 38: BQ76PL536 EVM

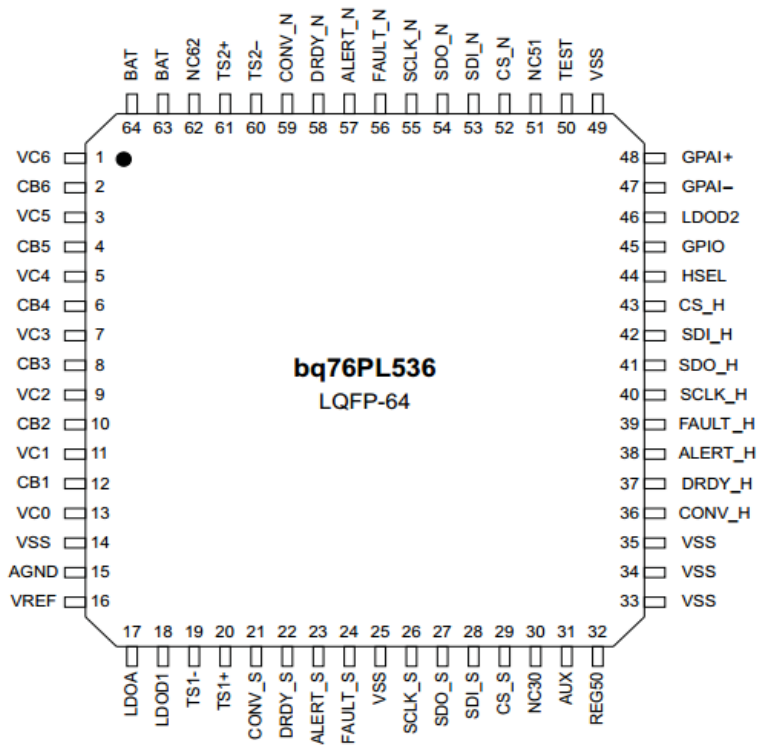


Figure 39: BQ76PL536 BMS IC pinout

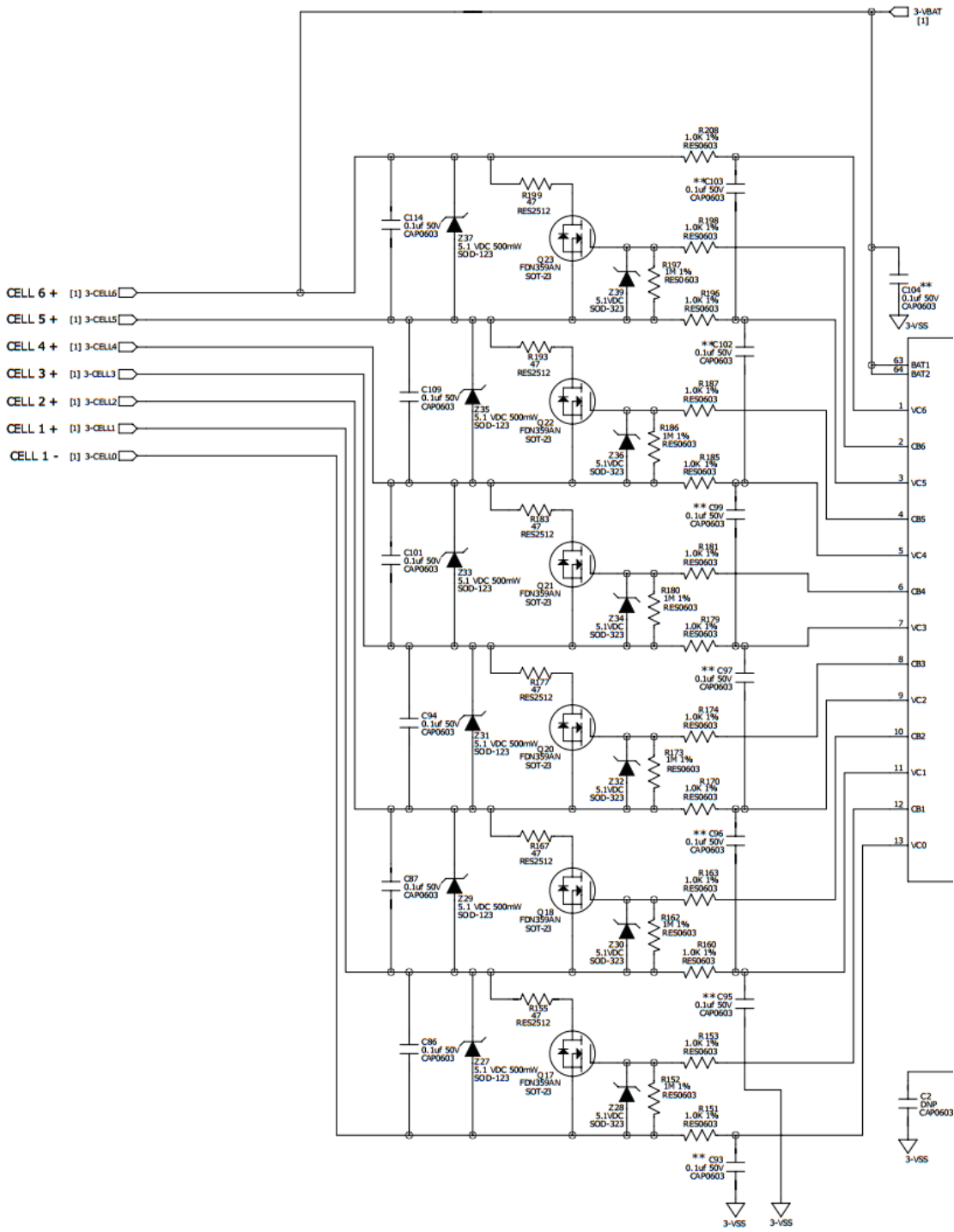


Figure 40: Cell balancing circuitry of EVM



## MSP430fr5969 MCU (host device)

The MCU, shown in Figure 41, communicates to the EVM through SPI. The MCU reads in important data from the BMS chips and then used an LCD screen to display the information to the user. The MCU reads cell voltage, pack voltage, and two pack temperatures. The MCU also calculates and displays the state of charge of the cells. The MCU has control over the cell balance circuitry and can make the EVM detect if cells are out of balance and start balance if they are. The MCU has an option select button (right button) and a menu button (left button) which helps the user navigate through the menus on the LCD screen. More information can be found in the MSP430fr5969 Datasheet [4], MSP430fr59xx Family User's Guide [5], and MSP-EXP430FR5969 LaunchPad User's Guide [6].

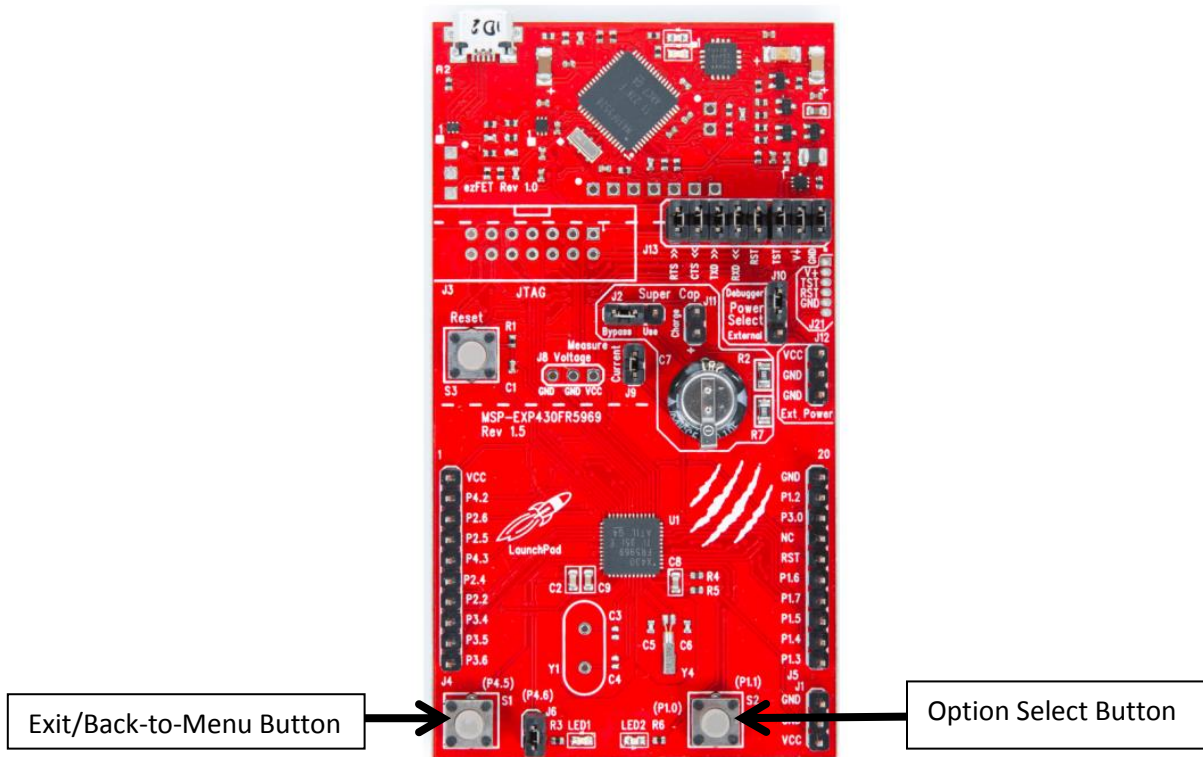


Figure 41: MSP430fr5969 MCU LaunchPad

## Sharp LCD BoosterPack (user interface)

The LCD screen, shown in Figure 42, connects to the MCU through SPI. The LCD BoosterPack also includes two capacitive touch sliders that serve as selection wheels for the menus on the screen. Note that only the left capacitive touch slider is used in this project.

More information can be found in the Sharp LCD BoosterPack User's Guide [7].

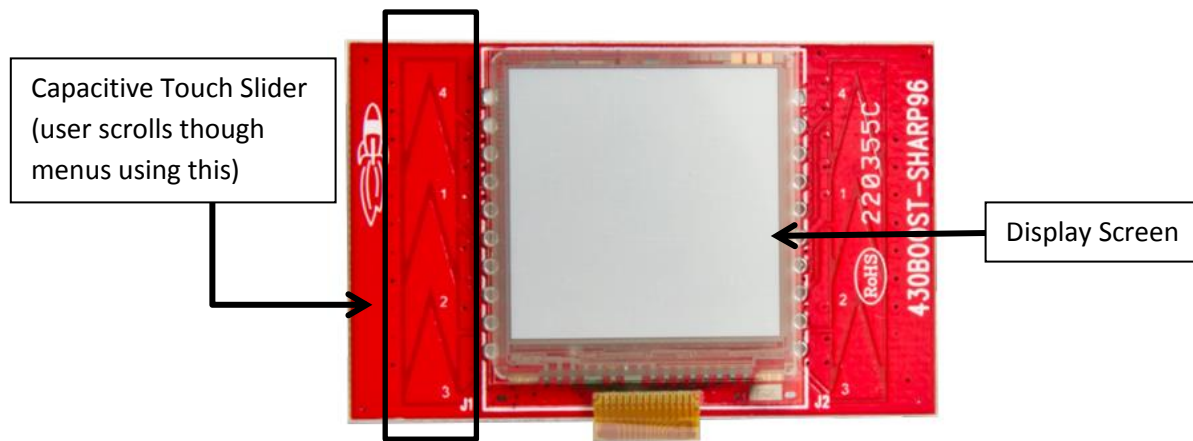


Figure 42: Sharp LCD BoosterPack

## Software

The BMS application state diagram is shown below in Figure 43.

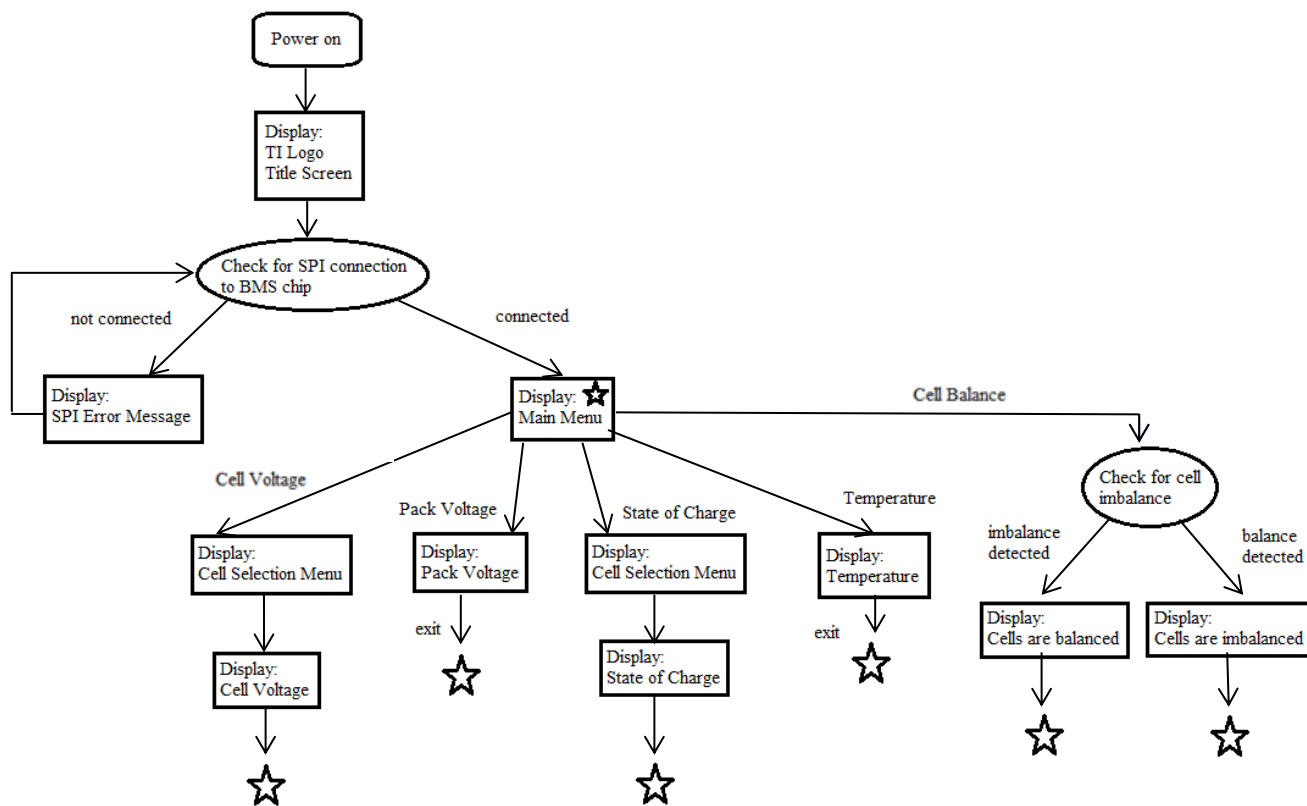


Figure 43: State diagram of BMS application

### SPI Error Message:

If there is an SPI error message displayed before the main menu is displayed, this means the BQ76PL536 device is not detected. There is most likely a problem with the SPI connection between the MSP430fr5969 and the EVM. Check the SPI lines along with the Power and Ground lines.

### Main Menu:

The main menu displays the modes of the BMS. The user uses the option select button to select Cell Voltage, Pack Voltage, State of Charge, Temperature, or Cell Balance.

### Cell Voltage:

Once the Cell Voltage mode is selected, the user then needs to select a cell using the option select button. The cell voltage of the selected cell is displayed in mV. The cell voltage displays for 4 seconds then returns to the cell selection menu. Press the exit button to go back to the main menu.

### Pack Voltage:

When the Pack Voltage mode is selected, the pack voltage for all connected cells is displayed in mV. The user must press the exit button to return to the main menu.

### State of Charge:

Once the State of Charge mode is selected, the user then needs to select a cell using the option select button. The state of charge of the selected cell is displayed by showing a battery with the approximate remaining charge. See the table in fig x below for charge remaining approximation information.

Table III: Voltage to state of charge conversion

Voltage of Cell [V]	Bars of Charge Remaining (State of Charge)
<3.3	1
3.3 to 3.4	2
3.4 to 3.5	3
3.5 to 3.6	4
3.6 to 3.7	5
3.7 to 3.8	6
3.8 to 3.9	7
>4.0	8

### Temperature:

When the Temperature mode is selected, two different pack temperatures at two separate locations in the battery pack are displayed to the screen in degrees Celsius. The user must press the exit button to return to the main menu.

### Cell Balance:

When the Cell Balance mode is selected, the system checks to see if the cells are imbalanced. The cell imbalance threshold is programmed to be 50 mV. This means that if the highest cell voltage differs from the lowest cell voltage by more than 50 mV, the cells are considered imbalanced and the Cell Imbalance

screen is displayed. If the cells are already balanced, the Cell Balance screen will be displayed. The system is capable of controlling the cell balance circuitry shown in fig x but it is recommended to enable cell balancing only if the system is connected to a charger otherwise the higher cells will be drained until the lowest cell voltage is reached. Since this is undesirable, the cell balance feature is currently disabled.

## Connections

### Between battery pack and EVM

Table IV: Connection from battery pack to EVM

Battery Pack	BQ76PL536 EVM
Cell 6 Positive	P1
Cell 6 Negative	P2
Cell 5 Negative	P3
Cell 4 Negative	P4
Cell 3 Negative	P5
Cell 2 Negative	P6
Cell 1 Negative	P7

### Between EVM and MCU

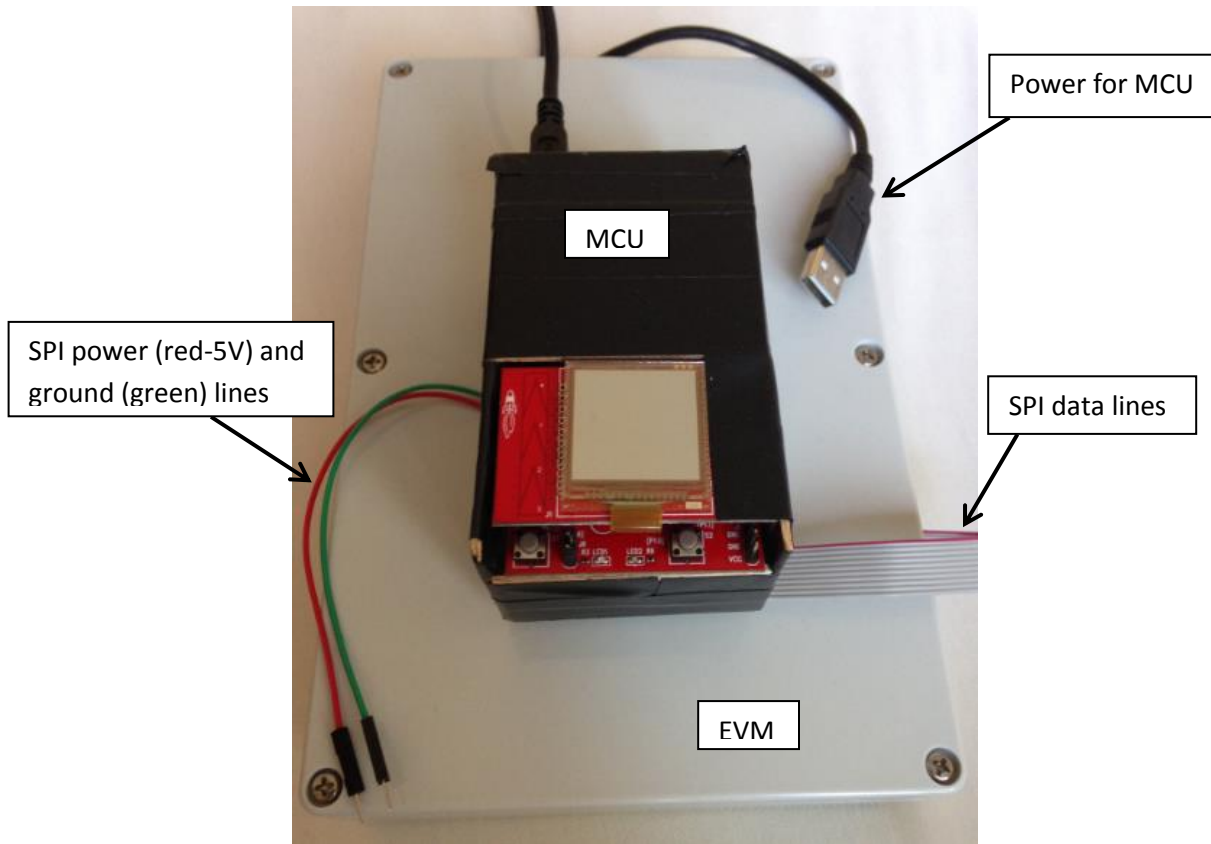


Figure 44: MCU on top of EVM

**Table V: Connection from EVM to MCU**

<b>BQ76PL536 EVM</b>	<b>MSP430fr5969 MCU</b>
VCC	VCC
GND	GND
CS_H	P3.0 (GPIO)
CLK_H	P2.2 (UCSIBOCLK)
SDI_H	P1.6 (USCIBOSIMO)
SDO_H	P1.7 (UCSIBOSOMI)
CONV_H	<i>not connected*</i>
DRDY_H	<i>not connected*</i>
ALERT_H	<i>not connected*</i>
FAULT_H	<i>not connected*</i>

**Table VI: Connection from MCU to LCD Screen**

<b>MSP430fr5969 MCU</b>	<b>Sharp LCD BoosterPack</b>
VCC	VCC
GND	GND
LCD Power Control	P4.2
LCD Enable	P4.3
SPI CS	P2.4
SPI CLK	P2.2(UCSIBOCLK)
SPI SIMO	P1.6 (USCIBOSIMO)
External COM Inversion	P1.2
Left Slider 2	P3.4
Left Slider 1	P3.5
Left Slider 0	P3.6

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# Appendix D: Senior Project Analysis

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**Protect Title:** Battery Management System

**Student's Name:** Michael DeSando & Kyle Woody

**Advisor's Name:** Art MacCarley

Initial:

Date:

**Summary of Functional Requirements:** This project monitors cell voltage, pack voltage, and pack temperature for three to six Li-Ion cells and is also capable of cell balancing and cell protection through communication to the host device. The host device displays menus on an LCD screen in which the user can interact with using the Capacitive Touch Sliders along with the Select and Menu Buttons.

**Primary Constraints:** The primary constraints include properly communicating from the host device to the EVM to read the cell values and communicating from the host device to the LCD screen to properly display the information. The host device needs to be communicating with multiple devices and powering multiple devices as well. Creating the software for the BMS system is the toughest challenge. It is also important to not exceed the maximum voltage per cell allowed because this can damage the BQ76PL536 BMS chip. The minimum voltage requirement is necessary in order to power the chip.

## **Economic:**

*Human Capital:* This project required approximately 300 man hours between two people. Time is required to learn about the components by reading datasheets and application notes. Time is required for gather data for the charge and discharge of the cells. Time is required for understanding the functionality of the BMS chips along with the operation of the GUI. Time is required to program the application portion along with debugging and troubleshooting when the system doesn't work properly. Time is also required to fabricate the casing for the system and ordering necessary parts. Depending on how much an individual values their time, the human capital required for this project varies.

*Financial Capital:* This project requires several key components. The cost estimates table is provided on the next page in Table VII.

**Table VII: Cost Estimates**

<b>Component</b>	<b>Function</b>	<b>Cost per Unit</b>	<b># of units</b>	<b>Total Cost</b>
Li-Ion Cells	Required for testing.	\$10.00	6	\$60.00
Battery Holders	Required to create battery pack used for testing.	\$2.75	6	\$16.50
BQ76PL536 EVM	Required for battery management.	\$400.00	1	\$400.00
MSP430fr5969 MCU LaunchPad	Required for data processing and communication to the EVM.	\$20.00	1	\$20.00
Sharp LCD BoosterPack	Required for displaying data to the user.	\$10.00	1	\$10.00
Wire	Required for connecting devices.	\$5.00	1	\$5.00
Casing	Required to enclose devices. This is optional.	\$10.00	1	\$10.00
<b>Total</b>				<b>\$521.50</b>

*Manufactured Capital:* The machine and tooling costs to make the actual parts required for this project is very expensive and requires millions of dollars.

*Natural Capital:* This includes the metal (copper, aluminum, etc), plastic, rubber, and the specific materials that make up each part. These materials are abundant which means there is plenty available from Earth’s resources. The bio-capacity of the system is good because almost all of the system is recyclable except the ICs and the batteries.

The costs accrue throughout the project from buying the components to spending time putting the system together. The benefits don’t appear until the system is complete and fully functional. The project requires an input voltage between 1.8V and 3.6V. A USB can be used to power the MCU LaunchPad due to voltage regulators on the LaunchPad. The Isolated Communication Interface on the EVM requires between 3.3V to 5V which can be externally powered or powered through USB if using the Advark adaptor that comes with the GUI. This project can save companies money if they have problems with their current battery management systems. The company that would profit the most from this BMS is Texas Instruments since they make the BMS chips and the EVM along with the MCU.

*Timing:*

The BMS doesn’t emerge until it is fully functional and complete. This could be created in a very short amount of time (less than one hour) now that the code for the BMS is already created. The only time consuming part now is ordering the necessary components. The majority of time spent in this project was on research, data acquisition, and creating/dugging the code.



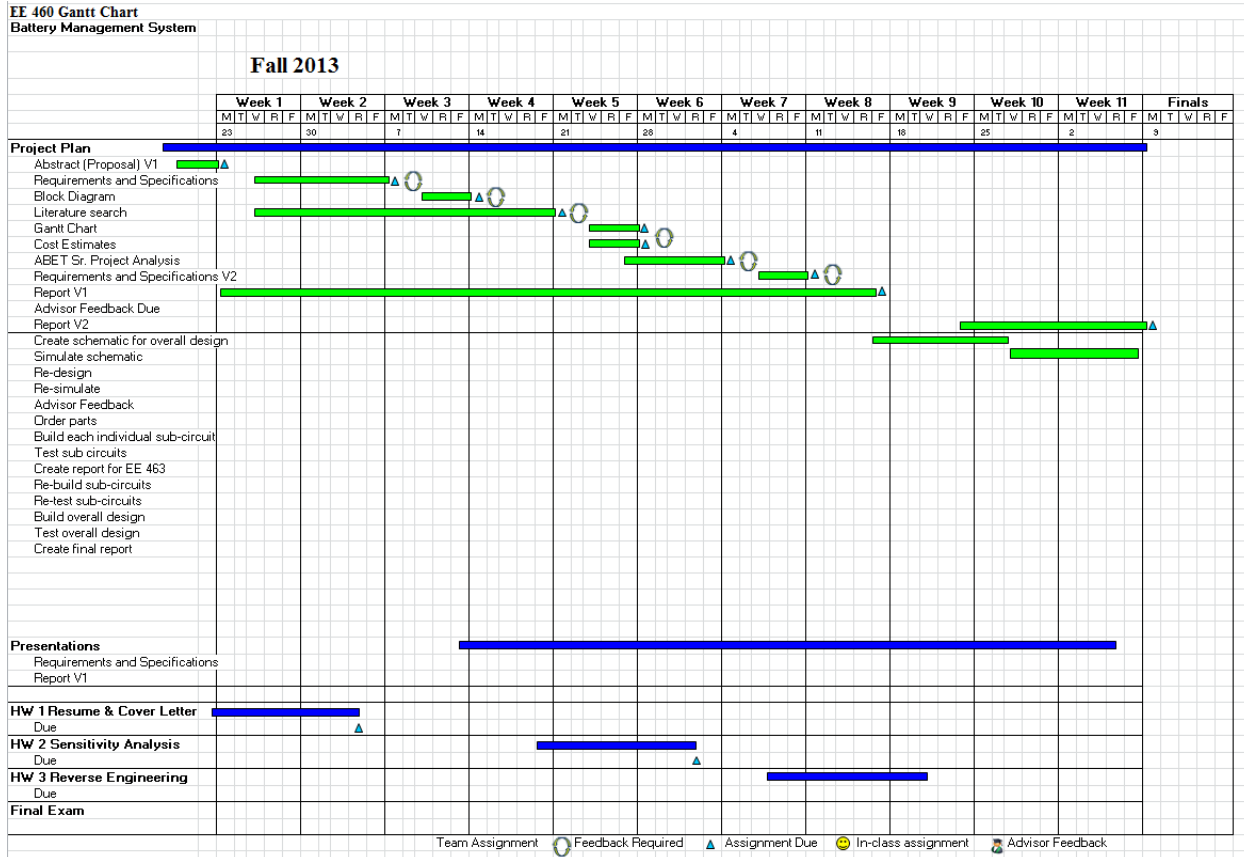


Figure 45: Project Definition Gantt Chart (EE 460-Fall 2013)

Original time development estimation is shown in Figure 46 and Figure 47.

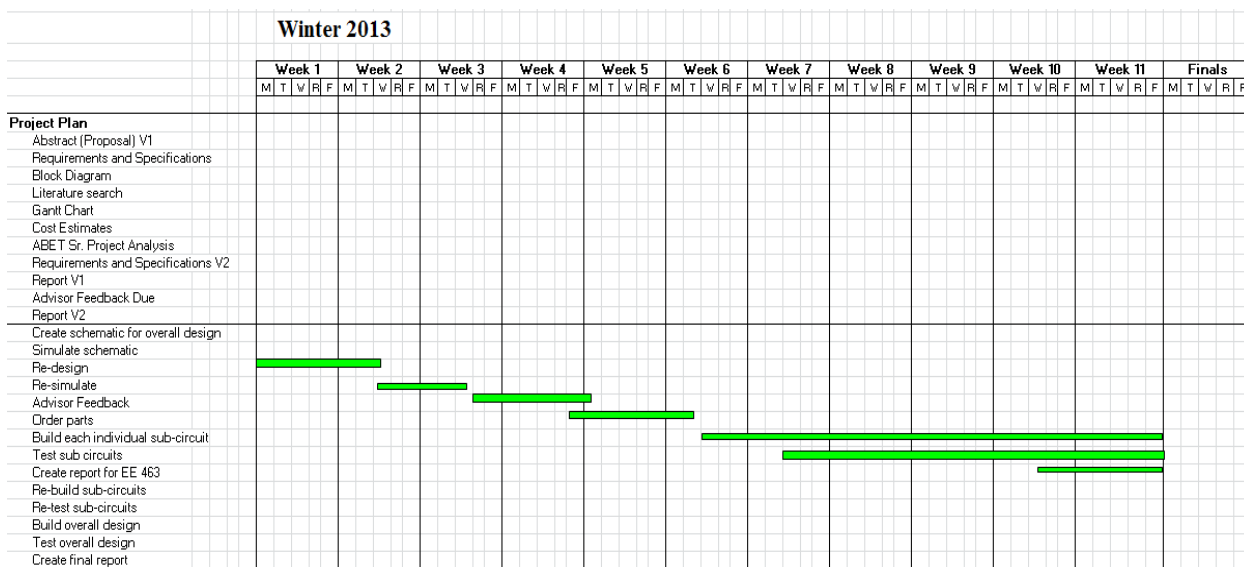


Figure 46: Gantt Chart for Winter 2013 (EE 463)



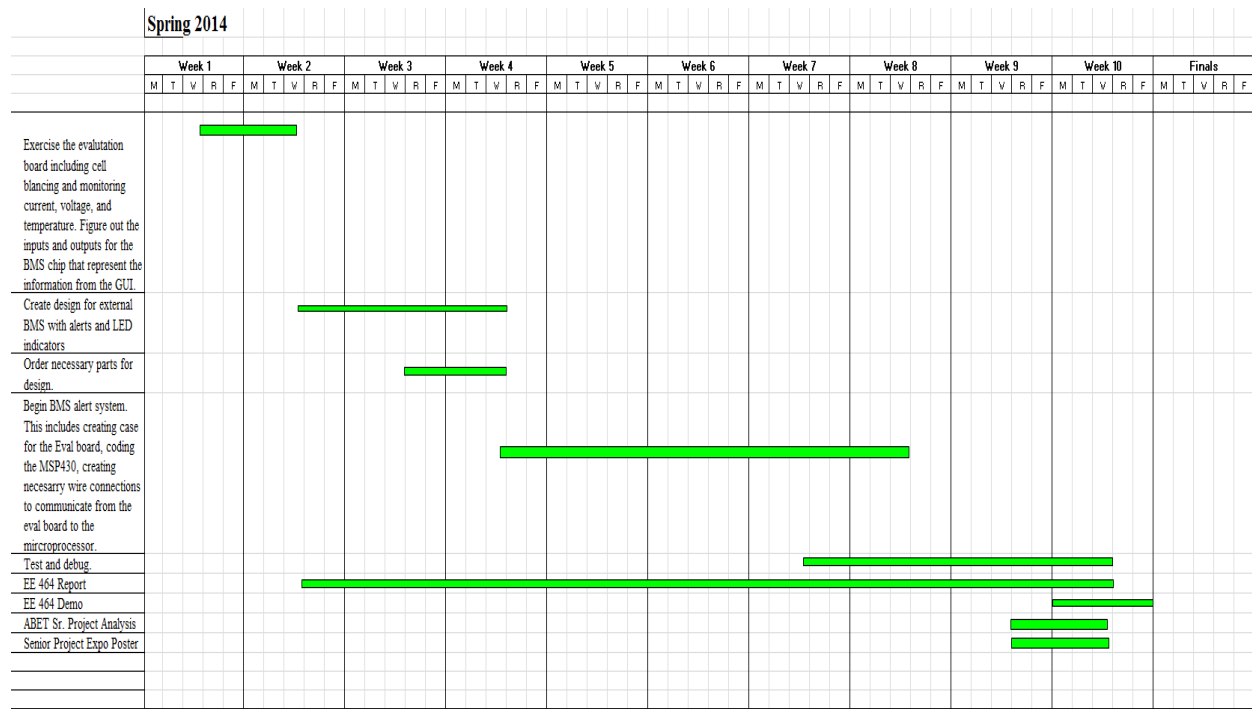


Figure 49: Actual Spring 2014 Timeline

**If manufactured on a commercial basis:**

- Estimate number of devices sold per year: Over 1 Million
- Estimate manufacturing cost for each device: \$500.00
- Estimate purchase price for each device: \$1000.00
- Estimate profit per year: \$500 Million
- Estimate cost for user to operate device: Less than \$10 per year

**Environmental:** This project benefits the environment in that batteries can be managed more efficiently so that they last longer. This is the first step to decreasing battery waste since fewer batteries will be disposed of. As with all electronics, proper disposal is required when the BMS is thrown away. Each BMS is projected to function for years with no maintenance required. This project can impact other species in that the land will be better off with less battery waste.

**Manufacturability:** Manufacturability depends on the number of units needed each year. The tools and equipment needed to manufacture millions of systems will cost millions of dollars. With current infrastructure, Texas Instruments may be able to mass produce this system.

**Sustainability:** The system is self-containing which means there is no maintenance required by the user. Since the system can be used over and over, it positively impacts the sustainable use of resources. Upgrades to improve the design that are software based would not require anything more than a computer. These upgrades include automatic checking for cell balancing opportunities, automatic system shut down if specific faults or alerts are detected, and data logging. Upgrades to improve the design that are hardware based include switching from passive cell balancing to active cell balancing to

make the system even more efficient. Upgrading the design creates challenge of maintaining functionality, safety, and efficiency.

**Ethical:** This BMS is designed with user interaction in mind. The proper use of this system provides a safe and effective way to manage Li-Ion batteries. The improper disposal of this system is unethical and users are responsible for proper use and disposal of this product.

**Health and Safety:** This BMS manages multiple batteries in series which means there are high voltages in this system. The system is designed with the user's safety in mind so each piece of the system is cased in plastic. Additional software protection can be used to automatically shut the system down if cell overvoltage or pack overtemperature is detected.

**Social and Political:** Social issues can arise for battery companies that produce batteries other than Li-Ion in that this BMS can't be utilized by those companies. If this BMS is used in electric vehicle applications, car companies that produce electric vehicles will be positively impacted since they can utilize this system. This project positively affects Texas Instruments and its stakeholders since more TI products are sold with each system sold. This project also benefits the stakeholders involved with batteries and/or electric vehicles. Everyone is benefited a little in that this system helps better the environment as well.

**Development:** The project began with researching different Li-Ion batteries. To learn more about the battery used in this project, see the NCR18650 Datasheet [1]. The next component to research was the BQ76PL536 BMS IC [2] along with the EVM [3]. To communicate with the BMS ICs along with the user, the MSO430FR5969 MCU LaunchPad [6] and Sharp LCD BoosterPack [7] was used. To learn more about the microcontroller used, see MSP430FR5969 datasheet [4] and family user's guide [5]. To communicate with the BMS ICs, a sample battery management system project [8] provided some software but was intended for use with a different microcontroller and a host computer. The communication between the MCU and the LCD screen along with the MCU and the BMS chips is accomplished via SPI. To learn more about SPI, see [10]. The MCU was programmed in C using Code Composer Studio. A logic analyzer was used for troubleshooting and debugging the MCU.