A smart battery management system for large format lithium ion cells

Wei Zhu
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A Dissertation
Entitled

A Smart Battery Management System
for Large Format Lithium Ion Cells

by
Wei Zhu

Submitted to the Graduate Faculty as partial fulfillment of the
requirements for the Doctor of Philosophy Degree in Engineering

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Because of their advantages of no memory effect, relatively long lifetime, and high energy density, lithium ion batteries have now become one of the most popular rechargeable batteries. However, there are some limitations on the usage of these batteries such as low temperature tolerance, potential danger of overcharge, and potential damage of over discharge. Therefore, a battery management system (BMS) is required to guarantee the maximum performance and safety.

A traditional battery management system (BMS) for lithium ion batteries can take measurements and turn the system on and off based on the measurement results. This type of BMS also always has an equalization method for balancing the voltages of the series connected cells. However, these standard functions are not sufficient for modern lithium ion battery applications.

The smart BMS is an updated system that inherits the functions of a traditional BMS, and adds new features to meet additional requirements. This BMS is able to store and analyze the measurement data in order to detect defective cells. This is necessary to provide maintenance or replacement before these cells influence the performance of the
whole battery pack. The smart BMS is also able to enhance the safety of the battery by reducing the measurement and communication time intervals, and a study of these new features also has been conducted.

In addition, the smart BMS also has some optimization features such as higher measurement accuracy, EMI reduction, a user friendly GUI, and state of charge (SOC) and state of health (SOH) determination. Some comparisons also have been made with similar BMS products currently available in the market in order to demonstrate the special advantages of the smart BMS.
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List of Abbreviations

BMS……………………………………. Battery Management System
CAN……………………………………. Controlled Area Network
CC……………………………………. Coulomb counting
Central………………………………. Central Control Unit
ECU……………………………………. Electronic Control Unit
EQU……………………………………. Equalization Unit
GUI……………………………………. Graphical User Interface
Labview………………………………. Laboratory Virtual Instrumentation
Engineering Workbench
Local........................................................ Local Control Unit
MCU……………………………………. Microcontroller Control Unit
nvSRAM……………………………….. non-volatile Static Random Access Memory
OCV……………………………………. Open Circuit Voltage
SOC……………………………………. State of Charge
SOH……………………………………. State of Health
SOL……………………………………. State of Life

BMS: refers to a system that monitors, controls, and balances a rechargeable battery pack [37].

CAN: CAN is a communication protocol that enables serial communication between microcontrollers and other devices. It has been widely used in vehicles [25].

Cell: refers to an individually encapsulated electrochemical unit that has differential voltage over two connections [41].

Module/Pack: refers to a unit consisting of several cells that are connected by electrical and mechanical means [41].

SOC: SOC is the percentage of capacity that is available inside a battery, a pack or a cell. The unit of SOC is a percentage: 0%=empty; 100%=full [29].

SOH: SOH is the percentage of the actual capacity of a battery, a cell, or a battery pack, matches the capacity specified by the manufacture. The unit of SOH is percentage: 100%= a cell with fully matches the specified capacity [38].
Chapter 1

Introduction

1.1 Lithium Ion Batteries

Lithium ion batteries are one of the most popular rechargeable batteries, and they have been widely used to power small electronic devices, portable tools, and hybrid and electrical vehicles.

These batteries are able to provide energy by moving lithium ions from the anode to the cathode, whereas during charge, these lithium ions are forced back to the anode from cathode. Taking the lithium cobalt battery as an example, the reactions happen at both anode and cathode as shown in (1.1) and (1.2). The overall electrochemical reaction is shown in (1.3) [1].

\[ \text{LiCoO}_2 \rightleftharpoons Li_{1-x}CoO_2 + xLi^+ + xe^- \quad \text{(Anode)} \]  
\[ xLi^+ + xe^- + 6C \rightleftharpoons Li_xC_6 \quad \text{(Cathode)} \]  
\[ Li^+ + LiCoO_2 \rightarrow Li_2O + CoO \quad \text{(Overall)} \]  

The lithium ion battery has several dominant advantages over similar products, such as higher energy density, longer lifetime, no memory effect, longer shelf time and lower self-discharge rate. However, they also have certain disadvantages such as
temperature limitations, high cost, low overcharge/high voltage tolerance, and related safety issues.

As reported, there have been several accidents/explosions which have happened to lithium ion batteries because of battery overcharge or high temperature. This has led to serious property damage, and thousands of these cells have been recalled for replacement.

1.2 Battery Management Systems

Due to the many issues with lithium ion batteries, a battery management system (BMS) is always used to ensure safe operation.

The traditional BMS mainly has two functions: monitor and protect. The monitoring function includes the measurement of current, cell voltages and cell temperatures. The protection function refers to the system on/off control which depends on whether abnormal measurement values appear.

Some recent BMS products may include a battery charge control function to charge the pack based on a mathematical algorithm. In addition, some equalization method also must be applied to balance the cell voltages in order to maximize the capacity of the battery pack.

1.3 The Proposed Smart Battery Management System

1.3.1 Background

The traditional BMS does not have enough features to guarantee the safety of the battery since it only reacts to the abnormal measurements. In some circumstances this
reaction may be too late since it depends on the measurement frequency. Even if a higher measurement frequency in a traditional BMS prevents an accident from happening, it usually cannot provide any useful information before the accident for diagnostic purposes.

In addition, it is well known that scheduled maintenance on large battery packs will greatly reduce the possibility of accidents. However in practice, users prefer to do very little maintenance to their battery packs. Once the pack performance decreases to a certain point, most users will pay for the replacement of the whole pack, whereas in many cases only a few cells of the pack are defective. Therefore, weak cell indication along with well scheduled maintenance can reduce the operating cost.

There are several recent papers on lithium ion batteries covering the subject of state of charge (SOC), state of health (SOH), state of life (SOL) estimation, and cell equalization. Most of the literature on SOC, SOH and SOL estimation is based on techniques that were used for batteries such as Li-polymer [12-13] and lead acid [3, 5]. They initially collected multiple sets of data for a specific battery model based on different temperatures, or different charge and discharge rates, or cell impedance measurements. After collecting data, they built the math model for a single cell by using an OCV vs. SOC chart, coulomb counting [7], or function/curve fitting. Methods such as Kalman filtering [2, 4-6], artificial intelligence/fuzzy logic [8-11], or statistical and prognostic methods [14-15], also have been reported.

Although the SOC, SOH and SOL estimation has been well established in the literature, there are still some unsolved practical problems. First, most of this previous research was focused on a specific model of lithium ion battery, which usually had a
relatively lower power level. However in practice, it is often necessary and cost effective to use higher capacity batteries which are always more expensive. Second, all of these models were focused on a single cell instead of a battery pack. Obviously, the model will be much more practical, although complex, if multiple cells are considered.

For the equalization feature of the BMS, energy storage devices such as inductors and capacitors, resistors, and external power sources have been used for equalization. Although the performance of the whole battery pack was improved by using these equalization methods [16-22], the processing time and efficiency varied considerably.

In conclusion, no similar work has been done before on high capacity lithium ion battery packs with equalization. Future research also should make an effort to find simpler methods to solve the practical problems that users may face. Therefore, this research focused on build a smart BMS for high power level lithium ion battery packs with user friendly operation and convenient maintenance features.

1.3.2 Research Objective

One of the high energy density 60Ah (Amp-Hr.) lithium ion cells from GAIA used in this research is shown in Figure 1-1 [30]. A full pack has 4 series connected battery modules with 6 cells connected in series in each module. This means that the BMS can service maximally 24 series connected cells. For research purposes, only two Local modules, i.e., 12 cells are used.

A BMS of this type was used previously for improved equalization (EQU) research [16]. This EQU had charge and discharge functions (C/D type), which greatly reduced the time for equalization compared to a traditional discharge only EQU. This
BMS also had other advantages such as reduced wiring harness, simpler operation and diagnostics, and reduced cost compared to earlier BMS versions.

Using this type of system, this research focused on developing a new smart BMS with such features as safety enhancement and performance optimization. Specifically, these features include weak cell identification, increased measurement and communication frequency, certain improvements in EMI reduction, a user friendly GUI written in Labview, and SOC and SOH/SOL prediction. Peer to peer comparisons, especially for the equalization function, were also be done between the smart BMS and other BMS products in the market.

![GAIA 60Ah Lithium Ion Cell](image-url)

Figure 1-1 GAIA 60Ah Lithium Ion Cell [30]
Chapter 2

BMS Safety Enhancement

This section will present a detailed description of efforts to improve the BMS safety, such as weak cell identification and reducing the measurement time interval.

2.1 Weak Cell Identification

In order to detect a weak cell, the characteristics of such a cell had to be studied first. A simulated weak cell was then prepared for further testing. Detection algorithms will also be discussed.

2.1.1 Cell Characteristics

Since charging and discharging a lithium ion cell creates ionization within the cell, the cell will age faster as the number of charge and discharge cycles increase. In some applications, it may have only 2-3 years of lifetime, or even less due to accidental/incidental internal shorts or stresses from usage [23, 31]. Aging cells always exhibit decreasing capacity and increasing internal resistance due to the chemical reactions inside of the cell. Eventually, the cell capacity reaches a certain point at which
the cell is considered to be bad. Figure 2-1 (a) illustrates the common model for a lithium ion cell and (b) presents the capacity change over the lifetime of the cell.

The two key characteristics, higher internal resistance and lower capacity, are the best clues to detect a weak cell. The internal resistance is a simplified concept used to model the complex chemical reactions inside a cell. Since the normal internal resistance of a lithium ion cell of the size used in this study is below 5 mΩ, it is difficult to accurately measure this resistance. As the current changes, the voltage change of a lithium ion cell with higher internal resistance will always be larger than a normal cell. As for capacity, the cells with lower capacity always exhibit lower voltage when there is no current flowing through them. Therefore, the weak cells can be identified in two main situations.

![Lithium Ion Cell Model](image1)

![Lifetime of a Lithium Ion Cell](image2)

(a) Lithium Ion Cell Model  
(b) Lifetime of a Lithium Ion Cell

**Figure 2-1 Lithium Ion Cell Model and Lifetime**

### 2.1.1.1 Non-zero Current.

Non-zero current can be split into 2 categories: constant current and step changing current.

1) **Constant Current.**

7
When there is a constant current flowing through a battery, the internal resistance contributes to identifying a weak cell. For example, if a pack of well-balanced batteries are being charged, the weak cell always exhibits higher voltage because of its higher internal resistance. Therefore, this weak cell requires more EQU discharge (buck) operations than the others in order to keep its voltage balanced with the rest of the pack. Likewise, the weak cell requires more EQU charge (boost) operations when the pack is being discharged. Therefore, counting the EQU boost and buck operations will enable the program to identify the weaker cells.

2) Step Change Current.

A changing current can also identify a weak cell since the voltage of a weak cell has a greater variation than normal cells when a step change in current occurs. The greater the current changes, the more obvious the weak cell deviation. For example, Figure 2-2 shows a two-cell pack under step current change. The cells in this pack have different internal resistances, i.e., $R_{in1}>R_{in2}$. Suppose the initial open circuit voltages of two cells are the same, i.e., $V_{oc1}=V_{oc2}$. During the pulse, $V_{c1}>V_{c2}$ because $V_c=V_{oc}+I\times R_{in}$.

![Figure 2-2 Two Cell Battery Pack under Step Current Change](image)

- **Rin**=Cell Internal Resistance (or Equivalent Series Resistance)
- **Voc**=Open Circuit Cell Voltage

Figure 2-2 Two Cell Battery Pack under Step Current Change
Therefore, a weak cell voltage fluctuates more than a normal cell as the current changes. A good example would be when the power switches are turned on or off. As indicated in the test shown in Figure 2-3 (a), a well-balanced pack has different voltage change when current appears and $V_{\text{min}}$ has the greatest voltage change. Likewise, for Figure 2-3 (b), $V_{\text{min}}$ has the maximum voltage increase of the pack when the switch is turned off. The EQU will pick the most deviant cell to provide the compensation charge or discharge. Therefore, the $V_{\text{min}}$ cell will be selected by the EQU to apply to boost charge in cases (a) and (b) ($V_{\text{min}}$ cell in (a) and (b) are not the same cell).

Figure 2-3 Cell Voltage Fluctuations at Step Current Change
This also can be a very good identification method if a large current change occurs. However, this is recommended for maintenance purpose only since frequent surge currents may induce faster aging.

2.1.1.2 Zero Current

The lithium ion cells of a pack usually have only minor differences in capacity when they are brand new. However, as the cells age, these differences become larger. Figure 2-4 (a) shows a two-cell battery pack circuit with load, and Figure 2-4 (b) shows the increase of the capacity difference as the number of cycles increase. Cells with lower capacity always have lower cell voltages. Therefore, for the case in Figure 2-4 $V_{c1}$ is greater than $V_{c2}$. For such a battery pack with unbalanced cell voltages, the EQU module is able to charge or discharge the cells in order to compensate for the capacity loss due to aging. Therefore, the older the cell, the lower voltage it has. And the lower voltage the cell has, the more EQU boost operations it needs. Thus, the number of EQU operations on each cell can identify the aged or weak cell while at rest.

![An Example Model of 2 Cell Battery Pack](image)

![Capacity vs. Number of Cycles](image)

Figure 2-4 Capacity Difference in a Two Cell Pack

(a) An Example Model of 2 Cell Battery Pack  (b) Capacity vs. Number of Cycles
In practical applications, the above situations can be described as (1) power switch on, (2) operation, (3) power switch off, and (4) rest. For a pre-balanced pack, the weak cell performance and the EQU operations for each of these processes are listed in Table 2.1. Therefore, the EQU record appears to be a possible method of identifying one or more weak cells.

Table 2.1 EQU Operations for Weak Cell Identification

<table>
<thead>
<tr>
<th></th>
<th>Switch on (step change current)</th>
<th>During Operation (constant current)</th>
<th>Switch off (step change current)</th>
<th>Rest (zero current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pack Charge</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
</tr>
<tr>
<td></td>
<td>High Buck</td>
<td>High Buck</td>
<td>Low Boost</td>
<td>Low Boost</td>
</tr>
<tr>
<td>Pack Discharge</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
<td>$V_{\text{weak}}$ EQU</td>
</tr>
<tr>
<td></td>
<td>Low Boost</td>
<td>Low Boost</td>
<td>High Buck</td>
<td>High Buck</td>
</tr>
</tbody>
</table>

2.1.2 Simulated Weak Cell

As discussed previously, a weak cell always has a higher internal resistance and lower capacity. In order to simulate a weak cell with a higher internal resistance, the actual internal resistance of the lithium ion cell has to be determined.

2.1.2.1 Internal Cell Resistance Measurement

For the 60Ah cells used in this study, the internal resistance is normally below 5 mΩ [39], which is difficult to measure directly. Manufacturer provided cell internal resistance data for similar cells is shown in Figure 2-5. However, the internal resistance also can be measured using a pulse current test. This method was used to perform a series of internal resistance measurements on a pack of lithium ion cells.
Six GAIA 60Ah cells at a nominal voltage of 3.75V (about 65% SOC) from Local #2 were tested separately with an AeroVironment ABC150 programmable power source. The current was measured using a LEM Hall effect current sensor, model LT-500s.

Figure 2-5 Manufacturer Provided Internal Resistance at Different Temperatures

In this test, a pulse discharge current of 150A is applied to each individual cell for 2 seconds. Use of a two-second pulse is long enough to allow the cell voltage to stabilize, but with negligible effect on the SOC. Figure 2-6 shows a block diagram of the test circuit, where a lithium cell is modeled as a voltage source with a small resistance connected in series. The 150A current pulse is transformed into a much lower level current flowing through a small resistor $R_c$. The voltage drop across $R_c$ and the cell voltage are measured by the oscilloscope. Figure 2-7 shows a lab set up for testing the internal resistance. Figure 2-8 shows a screen shot from the oscilloscope for this internal
resistance test. Table 2.2 lists the measurement data from all 6 cells of this test. Equations (2.1) and (2.2) are used to determine the internal resistances for all six cells from Local 2, which are shown in Figure 2-9.

\[
\frac{1}{5000} = \text{ratio} = \frac{V_{\text{current}}/R_c}{I}
\]

(2.1)

\[
R_{in} = \frac{\Delta V_{\text{cell}}}{I}, \quad I = 149A
\]

(2.2)

Figure 2-6 Block Diagram for Measuring Lithium Ion Internal Resistance

Table 2.2 Cell Internal Resistance Test Measurement Results for Local #2

<table>
<thead>
<tr>
<th>Cell #</th>
<th>OCV (V)</th>
<th>(\Delta V_{\text{cell}}) (mV)</th>
<th>(V_{\text{current}}) (V)</th>
<th>(R_c) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.75V</td>
<td>580</td>
<td>9V</td>
<td>302</td>
</tr>
<tr>
<td>2</td>
<td>3.75V</td>
<td>540</td>
<td>9V</td>
<td>302</td>
</tr>
<tr>
<td>3</td>
<td>3.75V</td>
<td>620</td>
<td>9V</td>
<td>302</td>
</tr>
<tr>
<td>4</td>
<td>3.75V</td>
<td>550</td>
<td>9V</td>
<td>302</td>
</tr>
<tr>
<td>5</td>
<td>3.75V</td>
<td>520</td>
<td>9V</td>
<td>302</td>
</tr>
<tr>
<td>6</td>
<td>3.75V</td>
<td>520</td>
<td>9V</td>
<td>302</td>
</tr>
</tbody>
</table>
Figure 2-7 Lab Set Up for Testing Lithium Ion Internal Resistance

Figure 2-8 Sample Oscilloscope Screen Shot for a Cell Internal Resistance Test

(Cell #3 from Local #2)
2.1.2.2 Weak Cell Internal Resistance Test

As shown in Figure 2-9 and Table 2.2, Cell #3 is a weaker cell since it has a larger voltage drop under pulse current discharge and therefore a higher internal resistance. The actually resistance of a weak cell can vary widely, but a cell with 2× internal resistance should be considered a weak cell. Therefore, cell #3 was selected to simulate a weak cell by connecting (2) 2 mΩ resistors in series with its positive terminal as shown in Figure 2-10.

A discharge pulse current of 100A for 2 seconds was used to measure the total resistance of this simulated cell. This reduced discharge current of 100A instead of 150A was used to protect the external series resistors. Figure 2-11 shows the screen shot for testing the total simulated resistance for this cell. This indicates a much larger noise level compared to Figure 2-8, which is probably due to the exposed surface of the two external resistors. This is shown in Figure 2-12.
Figure 2-10 Block Diagram for Measuring the Simulated Internal Resistance of a Weak Cell

Figure 2-11 Oscilloscope Screen Shot for the Simulated Weak Cell Internal Resistance Test

In Figure 2-11, $\Delta V_{\text{cell}}$ is about 900mV, and $V_{\text{current}}$ is at about 6.2V. According to equation (2.1) and (2.2), the calculated current level is 102.64A, and the total internal
resistance is 8.77 mΩ. This is a reasonable value as shown by the calculation in equation (2.3), where $R_{\text{in, cell}} = 4.16$ mΩ, $R_{\text{ext}} = 4$ mΩ, and therefore, $R_{\text{contact}} = 0.61$ mΩ.

$$Total\ Internal\ Resistance = R_{\text{in, cell}} + R_{\text{ext}} + R_{\text{contact}}$$ (2.3)

Figure 2-12 Larger Exposed Area of Attached External Resistors

### 2.1.3 Weak Cell Identification Methods

#### 2.1.3.1 EQU Operation Record

According to the discussion above, an EQU operation record should help to identify the weak cell. There are two algorithms can be used for analyzing the number of EQU operations on each cell.

1) Algorithm 1: Total Cell EQU Operations

Counting the number of EQU operations on each cell is the simplest algorithm to identify the weak cell. The weak cell always requires more EQU operations, no matter whether the pack is charging or discharging (refer to Table 2.1). In other words, the weak cell always takes a larger percentage of the EQU service. This algorithm should only be
considered for one Local since there is only one EQU that services each Local. Similar comparisons among cells for several Locals may not provide an accurate result.

This algorithm should be used with a well-balanced pack and at least one counter to count the EQU operations. It also requires at least one charge or discharge cycle or a full charge/discharge cycle.

2) Algorithm 2: Cell EQU Operations under Charge and Discharge

Using the higher internal resistance as the only criterion to detect the weak cell, another algorithm is to compare the sum of the EQU discharge operations when the pack is under charge and the EQU charge operations when the pack is under discharge.

This algorithm can identify the weakest cells in the whole pack, since the EQU always selects the cell with the most deviant voltage. This algorithm uses two counters to record the EQU charge and EQU discharge operations separately, and it requires that the pack goes through one full charge/discharge cycle in order to create an accurate list for weak cells.

3) Implementation

Both algorithms require the storage of the EQU operations for each individual cell for further analysis. These records are stored in a non-volatile Static Random Access Memory (nvSRAM). This device is pin compatible with the SRAM on the microcontroller development board, and it functions the same as a standard SRAM when it is powered on. A conventional SRAM loses everything after the power is off, but an nvSRAM can store data without the need for any external power sources [24]. A photo of the modified circuit with the nvSRAM replacement on the mini-module PCB of the
C515CA microcontroller is shown in Figure 2-13. The schematic is shown in Figure 2-14.

For this method, an EQUC (EQU charge) list and an EQUD (EQU discharge) list are stored in a 32kB nvSRAM STK15C88 to store the number of EQU operations of each cell. Every time the EQU operates, one count is added to the corresponding list. For example, if cell #5 in a 12 cell pack has one EQU charge operation, EQUC=[0,0,0,0,1,0,0,0,0,0,0,0] while EQUD is unchanged. Both lists can either be reset to zero or retain the prior record each time the system starts. The upper limit of EQU operations for each cell is 65535.
2.1.3.2 Current Step

As discussed previously, a second method to identify a weak cell is by utilizing a step current change. When a current pulse is applied to a series connected battery pack, the weak cell can be identified since its voltage change is higher due to its higher internal resistance. Figure 2-15 shows that cell 5 has a larger voltage change when the pack is under charge and discharge.

![Cell Voltage Changes under Pack Charge and Discharge](image)

(a) Pack Charge

(b) Pack Discharge

x-axis: Cell Number

Figure 2-15 Cell Voltage Changes under Pack Charge and Discharge
A graphical user interface (GUI) computer monitor display is recommended for the weak cell detection. Figure 2-16 (a) presents an example showing the cell voltage changes when the current is increased from 9A to 11A. Three consecutive cycles of measurement results were stored and displayed simultaneously by the GUI. This pack was initially balanced, but cells 3 and 5 show deviant cell voltages on the 1\textsuperscript{st} cycle. The measurement results for the 2\textsuperscript{nd} cycle are very close to the 1\textsuperscript{st} cycle. However, for the 3\textsuperscript{rd} cycle all cell voltages have a small increment since the current increases from 9A to 11A, but cells 3 and 5 still have the most deviant voltages.

Figure 2-16 (b) shows the point when the power switch is turned on at pack discharge. This demonstrates that the cells of an initially well balanced pack have different voltage changes when a step current change occurs. Similar to the situation in Figure 2-16 (a), the current and cell voltages for cycle 1 and 2 overlapped; however in the 3\textsuperscript{rd} cycle, when current starts to flow, cells 3 and 5 still have the largest deviant voltages.

2.1.3.3 Evaluation of Both Methods

After discussing both methods for weak cell identification, it is useful to compare the differences between them, as shown in Table 2.3. Both methods provide a simple means to detect weak cells. However, they have different applications, mostly because of their different speeds. For example, the EQU record method takes more time to collect data, which is suitable for daily operation, whereas the current change method is much faster, and it is appropriate for quick identification during maintenance.
(a) Voltage Changes when Current Increases from 9A to 11A*

(b) Voltage Changes when Current Drops from 0A to -15.6A*

x axis: Cell Number.

*1.5, 2.5, and etc., exist because this graph is enlarged, and these should be ignored.

Figure 2-16 Cell Voltage Variations as Current Changes Shown in GUI
Table 2.3 Comparisons between Both Methods of Weak Cell Identification

<table>
<thead>
<tr>
<th></th>
<th>EQU Record</th>
<th>Current Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recognition Speed</td>
<td>Relatively slow</td>
<td>Quick</td>
</tr>
<tr>
<td></td>
<td>(at least one full cycle)</td>
<td></td>
</tr>
<tr>
<td>Tools/Support</td>
<td>nvSRAM</td>
<td>GUI</td>
</tr>
<tr>
<td>Application</td>
<td>Operation</td>
<td>Maintenance</td>
</tr>
</tbody>
</table>

2.2 Reduced Measurement Interval

Preventive measures such as weak cell identification and well scheduled maintenance are important options to detect weak or marginal cells. However, a reduced measurement period will provide a faster detection of a developing problem. This is because a minimized measurement interval will allow the MCU to more rapidly collect the latest status of all the cells, and it would be able to respond more quickly.

The previous BMS used a 10 second timer to control the measurement cycle. However, the microcontroller actually is idle for most of this time since the A/D conversion time and the code execution time is much less than 10 seconds. The CAN bus transmission and receiving times are also much less than 10 seconds, and they can be reduced even further. Therefore, the best way to minimize the measurement interval is to reduce the time consumed by CAN communication. Before introducing the procedures to reduce the CAN period, the pertinent CAN features should be explained.

2.2.1 CAN Features
The Controlled Area Network (CAN) protocol is a multi-master and system that allows microcontrollers and electronic devices to communicate with each other. CAN has been widely used in automotive communications because of its high reliability and immunity to electromagnetic interference (EMI). The CAN interface is a DB9 connector shown in Figure 2-17 and the speed can be configured from 125 Kbit/s up to 1Mbit/s, depending on transmission distance [25].

![Figure 2-17 CAN Connector](image)

**2.2.2 CAN Application in Smart BMS**

The Infineon C515CA microcontroller used in the BMS Central and Local modules has 15 CAN Message Objects (M.O.), which are groups of registers. Each Message Object contains up to 8 bytes of data. The data is accepted at the nodes (modules) based on an 11 bit Message Object ID and a mask at the receiver. This Message Object ID also defines the priority of the message. The lower the ID, the higher the priority. A Message Object can only be transmitted when the bus is idle, and once started, a Message Object transmission cannot be interrupted.

In this application, the Central and Locals communicate via CAN, and the CAN bus diagram is shown in Figure 2-18. Two 120Ω resistors connected in parallel are
located at the Central directly between CANH and CANL. A CAN driver circuit is needed for transferring the CAN transmitting signal to CANH and CANL as shown in Figure 2-19 [16]. Both the MCU and ECU boards have this CAN driver circuit.

![Figure 2-18 CAN Bus in Smart BMS](image)

(a) CANH and CANL

![Figure 2-19 CAN Driver Circuits](image)

(a) CAN VCC

Figure 2-19 CAN Driver Circuits
2.2.3 Methods to Reduce the CAN Time Period

Three procedures were used to reduce the CAN period, the first being,

2.2.3.1 Reduced the Number of Message Objects

The original BMS, which will be used for comparison, used the same 14 message objects for each Local. However, the smart BMS utilizes only 13 message objects to process all the information of a battery pack of 4 Locals. Therefore, message object processing time for the traditional BMS will be about 4 times that of the smart BMS. Table 2.4 describes the detailed message object functions.

Table 2.4 Contents of CAN Message Objects

<table>
<thead>
<tr>
<th>Message Object</th>
<th>Contents or Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>From Local #1</td>
</tr>
<tr>
<td>#2</td>
<td>From Local #1</td>
</tr>
<tr>
<td>#3</td>
<td>From Local #1</td>
</tr>
<tr>
<td>#4-6</td>
<td>From Local #2</td>
</tr>
<tr>
<td>#7-9</td>
<td>From Local #3</td>
</tr>
<tr>
<td>#10-12</td>
<td>From Local #4</td>
</tr>
<tr>
<td>#14</td>
<td>To 4 Locals</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Table 2.4, Local #1 will transmit Message Objects 1-3 and Local #2 will transmit Message Objects 4-6, etc. This message object configuration will reduce the time required to request the message objects for each Local separately. Taking Local 1 as an example, the message object configuration is shown in Table 2.5. Since these message
objects have different ID numbers indicating different priorities, there will not be any conflicts if all Locals are trying to transmit messages at the same time. The Message Object #13 configuration is also shown in Table 2.5, which uses 2 bytes for each Local to define the type of EQU operation and the selected cell.

Table 2.5 CAN Message Objects Configuration for Local #1

<table>
<thead>
<tr>
<th>M.O #</th>
<th>Byte 0</th>
<th>Byte 1</th>
<th>Byte 2</th>
<th>Byte 3</th>
<th>Byte 4</th>
<th>Byte 5</th>
<th>Byte 6</th>
<th>Byte 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>V_1L</td>
<td>V_1H</td>
<td>V_2L</td>
<td>V_2H</td>
<td>V_1L</td>
<td>V_1H</td>
<td>V_2L</td>
<td>V_2H</td>
</tr>
<tr>
<td>No.2</td>
<td>V_5L</td>
<td>V_5H</td>
<td>V_6L</td>
<td>V_6H</td>
<td>T_1L</td>
<td>T_1H</td>
<td>T_2L</td>
<td>T_2H</td>
</tr>
<tr>
<td>No.3</td>
<td>T_3L</td>
<td>T_3H</td>
<td>T_4L</td>
<td>T_4H</td>
<td>T_5L</td>
<td>T_5H</td>
<td>T_6L</td>
<td>T_6H</td>
</tr>
<tr>
<td>No.13</td>
<td>EQU#1</td>
<td>EQU#1</td>
<td>EQU#2</td>
<td>EQU#2</td>
<td>EQU#3</td>
<td>EQU#3</td>
<td>EQU#4</td>
<td>EQU#4</td>
</tr>
<tr>
<td></td>
<td>op</td>
<td>cell</td>
<td>op</td>
<td>cell</td>
<td>op</td>
<td>cell</td>
<td>op</td>
<td>cell</td>
</tr>
</tbody>
</table>

(M.O = Message Object, H = high byte, L = low byte, op= operation, op = 01h stands for charge, op= 02h stands for discharge, op= 00h stands for no operation)

The second time reduction procedure is,

2.2.3.2 Maximized Transmission Speed

The CAN communication speed was 500 kbits/sec for the original BMS, but it was changed to 1 Mbits/sec which is the fastest speed available. This speed will allow any message can be transmitted more rapidly. CAN communication speed ranges from 125 Kbit/sec to 1 Mbit/sec based on a tradeoff between communication speed and network length. For the speed of 1 Mbit/sec in the smart BMS, the maximum allowable network length is about 40 meters [25], which is long enough for the current application. The reason for the speed/transmission length tradeoff is that there is a possible sampling error due to the signal rise and fall time which is caused by cable capacitance. The CAN bus cable model is shown in Figure 2-20.
For example, the “on” voltage is determined by $V_L = V_s \left(1 - e^{-\frac{t}{\tau}}\right)$, where $\tau = RC$, $R =$ source resistance, and $C =$ cable capacitance. Therefore, the ideal signal which is a square wave is deformed into a quasi-square waveform with slower rise and fall times. This is directly related to the time constant which is the product of the resistance and the capacitance.

Therefore, CAN transmission speed must be reduced when the transmission length is extended. This is because the line capacitance increases with its length, and therefore the time constant increases. Otherwise, a higher baud rate may produce a sampling error as shown in Figure 2-21. For a lower baud rate the sample point is always after the signal is stabilized. However, for a higher baud rate the point at which the microcontroller samples may not have reached the value of this bit.

The CAN bus, consisting of CAN-H, CAN-L and GND, uses twisted wires to reduce the EMI noise that may induce transmission bit errors. According to Faraday’s Law, $V_n = N \frac{d\phi}{dt}$. The noise voltage, $V_n$, is directly proportional to the time change rate of the EMI magnetic flux, $\phi$. The magnetic flux $\phi$ is the EMI flux density, $B$, across a
surface area, $A$, i.e., $\phi = \iint B \cdot dA$. Therefore, to minimize the surface area $A$, all wires of the CAN bus cable are twisted together to minimize $A$ and thus $\phi$.

![Diagram](image.png)

Figure 2-21 CAN Baud Rate Induced Sample Error

The third time reduction technique is to use a,

2.2.3.3. CAN Interrupt Service Routine (ISR)

The cell voltage message data is embedded inside the CAN interrupt service routine in the smart BMS. By doing this, the idle time can be minimized. When M.O #13 from the Central is received by the Locals, the program of each Local will halt its present operation and jump to the CAN ISR. In the ISR, the Local first reads the bytes specifying its EQU cell number and operation type. Then, the Local will measure the cell voltages and temperatures and store the measurement results into the proper Message Objects. When this is completed, the Message Objects will be sent immediately, and the Local EQU will set to operate as the M.O. #13 specified.

2.2.4 Minimized CAN Communication Period
After applying these innovations, the communication period was reduced by almost 96%. For 2 Locals, the cycle time was reduced from 10 seconds to 0.368 seconds. Figure 2-22 (a) shows a screen shot of CAN bus monitor software for a BMS with 2 Locals, and this confirms that the CAN communication has been reduced to a period of 0.368 seconds. In practical applications which must include EQU relay operation time, larger data files and synchronization with the GUI, the communication cycle must be extended to about 2.55s as shown in Figure 2-22 (b). In this case, the EQU relays switch every other cycle at 5.1 second intervals.

(a) Minimized Cycle Duration

Figure 2-22 Screen Shots of the CAN Communication Monitor
(b) Practical Cycle Duration

Figure 2-22 Screen Shots of the CAN Communication Monitor (Continued)
Chapter 3

BMS Performance Optimization

This chapter will describe several techniques that were developed to improve the performance of the smart BMS. These include higher precision measurements, an advanced graphical user interface (GUI) display to interpret measurements, more precise methods to determine state of charge (SOC), and state of health/state of life (SOH/SOL) estimates.

3.1 Accuracy Improvement

Higher precision measurements of cell voltages, current, and temperatures are extremely important to improve battery performance. However, electromagnet interference (EMI) and certain lithium ion internal chemical reactions are two factors that may affect these measurements. A detailed study on both of these factors will be presented after an explanation of the analog measurement circuits.

3.1.1 BMS Measurements

Accurate measurement results are the key to ensure the BMS reacts correctly to any dangerous situation.
Each Infineon C515CA microcontroller in the Central and Local modules has 8 A/D channels which provide 10 bit analog to digital conversion resolution in either continuous or single conversion mode. Voltage, temperature and current measurements are implemented using these A/D channels in the continuous conversion mode. Table 3.1 shows the channel usage for these measurements.

Table 3.1 A/D Channel Usage for Analog Measurements

<table>
<thead>
<tr>
<th>Microcontroller on ECU</th>
<th>Microcontroller on MCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Voltage</td>
<td>P6.6</td>
</tr>
<tr>
<td>Cell Temperature</td>
<td>P6.3</td>
</tr>
<tr>
<td>Pack Current</td>
<td>P6.1</td>
</tr>
</tbody>
</table>

Lithium ion cell voltages normally range from 3.0V to 4.2V, which is within the range of the microcontroller A/D conversion voltage range, i.e. 0 to 5V. The cell voltages of a series connected battery pack must be measured individually to avoid the possibility of an overcharged cell. Therefore, cell voltage measurements must utilize a level shifting circuit to transfer all voltages to the same ground level before connecting to the multiplexer as shown in Figure 3-1. However, the current and temperature measurements do not require a level shift since they use the same ground as the microcontroller.

![Figure 3-1 Cell Voltage Measurement Block Diagram](image-url)
In Figure 3-2, cell voltage $V_{B1}$ is measured directly at the battery terminal, and cell voltage $V_{B2}$ is transferred directly by using a resistive voltage divider. Cell voltages $V_{B3}$ to $V_{B6}$ are shifted by the LM324 operational amplifier (op-amp), which is powered by the battery pack itself between the (+) terminal of cell #6 and the (+) terminal of cell #2. Figure 3-2 shows $V_x$ as the cell voltage being measured. Each shift circuit creates a path of current flowing through a ZVP1320F P channel FET, resistors $R_1$ and $R_3$ and the battery junction at $R_1$. There is virtually no current flowing through the input terminals of the op-amp due to its very high impedance, and the op-amp gain is so high that the input voltage is virtually zero [16]. Therefore,

$$V_x = I \times R_1, \quad V'_x = I \times R_3, \text{ and } R_3 = R_1,$$

thus $V_x = V'_x$ \hspace{1cm} (3.1)

![Figure 3-2 Voltage Shift Circuit for 6 Cell Local](image)

Voltage and temperature measurements connect to the A/D channels via a multiplexer. Each cell is selected logically by 3 port pins of the microcontroller. Table 3.2 shows the selection logic for cell voltage and temperature measurements.
Table 3.2 Cell Selection during Voltage/Temperature Measurements

<table>
<thead>
<tr>
<th></th>
<th>P3.2</th>
<th>P1.7</th>
<th>P1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1/T1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V2/T2</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>V3/T3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>V4/T4</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>V5/T5</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V6/T6</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

3.1.2 EMI Reduction

An accurate measurement always requires a relatively low EMI (Electromagnetic Interference) environment. EMI is often caused by high frequency switching circuits, such as the DC-DC converter for the EQU charger. In this case, the EQU charger was found to be the main source of EMI due to its high frequency switching circuit and its close proximity to the measurement circuit. An example is shown in Figure 3-3, where the voltage increased about 150 mV as soon as the EQU charger is started and dropped back as soon as the EQU charger is turned off.

Figure 3-4 presents oscilloscope screen shots when the EQU charger is placed at different locations. It shows that the peak to peak EMI voltage (Vp-p) can reach up to 265.5 mV as seen in Figure 3-4 (a) when the EQU charger is very close to the measurement circuit. However, a larger distance significantly reduces the EMI to 75mV as seen in Figure 3-4 (b), which is still larger than the EMI value in EQU discharge mode. Figure 3-4 (c) and 3-4 (d) have about the same EMI in discharge mode regardless of the distance, and this EMI value is considered acceptable.
(Blue: $V_{\text{max}}$; Green: $V_{\text{avg}}$; Red: $V_{\text{min}}$)

Figure 3-3 EMI Effects on Cell Voltage Measurements for a 6 Cell Local

(a) EQU in Charge Mode (2” distance)  (b) EQU in Charge Mode (35” distance)

$V_{p-p} = 265.6$ mV  $V_{p-p} = 75$ mV

(c) EQU in Discharge Mode (2” distance)  (d) EQU in Discharge Mode (35” distance)

$V_{p-p} = 31.25$ mV  $V_{p-p} = 30$ mV

Figure 3-4 EMI Levels for Various Conditions
However, it is impractical to move the EQU charger much further away from the measurement circuit or to eliminate the EQU EMI completely. Thus, the practical thing to do is to minimize it. The common techniques include the use of a ground plane (GP) and bypass or decoupling capacitors, and these were done during the PCB design [26]. In addition, a software delay of 0.005s in the EQU operation is used during voltage and temperature measurements. This greatly reduces the EMI impact on the measurement circuit.

The circuit was first built on a laboratory breadboard without a ground plane (GP), and later a PCB version with a GP was designed and constructed. A comparison of the EMI values between the bread board and the PCB board is included in Table 3.3.

Table 3.3 EMI Value Comparisons between Breadboard and PCB Board

<table>
<thead>
<tr>
<th>Board Type</th>
<th>Distance</th>
<th>EQU Operation</th>
<th>Vp-p (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadboard</td>
<td>Close (2&quot;)</td>
<td>Charge</td>
<td>265.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discharge</td>
<td>31.25</td>
</tr>
<tr>
<td></td>
<td>Further (35&quot;)</td>
<td>Charge</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discharge</td>
<td>30</td>
</tr>
<tr>
<td>PCB Board</td>
<td>Close (2&quot;)</td>
<td>Charge</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charge (at pause)</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discharge</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discharge (at pause)</td>
<td>68</td>
</tr>
</tbody>
</table>

3.1.3 Influence of Cell Internal Chemical Reactions

Due to the internal chemical reactions, all battery cell voltages require time to reach equilibrium after their current reaches zero. Figure 3-5 shows the oscilloscope screenshots during two pulse current tests at 150A lasting for 2 seconds, one for the
3.6V/60Ah lithium ion cell from GAIA and the 6V/220Ah lead acid battery 6CE220 from Embassy. The lithium ion cell voltage stabilizes almost simultaneously with the current. However, the lead acid cell displays a significant voltage drop about 100mV even 10 seconds after the current returns to zero.

To verify the effect of the EQU operation pause during cell voltage measurements, a series of drifting tests at lower current levels were conducted. The test current ranges from 1.0A to 5.0A with a 1.0A increment. For each test current level, there are 3 groups of charge/rest tests on a single lithium ion cell. The charge-time/rest-time are 10s/1min, 1min/5min, 5min/10min. Test data was stored every 0.3s using a Voltech Power Analyzer PM6000. The diagram for the drifting test set up is shown in Figure 3-6. Figure 3-7 shows the test data plots at different current levels.

(a) Lithium Ion Cell (GAIA 3.6V/60Ah @ 2.5C)

Figure 3-5 Voltage Stabilization Time Comparison between a 3.6V Lithium Ion Cell and a 6V Lead Acid Battery
Figure 3-5 Voltage Stabilization Time Comparison between a 3.6V Lithium Ion Cell and a 6V Lead Acid Battery (Continued)

Figure 3-7 shows that lithium ion cells are sensitive to charge currents and the larger the current, the higher the cell voltage changes. The cell voltage in the steady state does fluctuate slightly so equilibrium does not mean an absolutely constant value, but a relatively stabilized value. The cell voltage rises immediately when the current is applied, but it may take a few seconds to return to equilibrium.

![Block Diagram for Drifting Test](image)

Figure 3-6 Block Diagram for Drifting Test
Figure 3-7 Drifting Test Results for 3.6V/60Ah GAIA Cells

(a) Current =1A

(b) Current =2A

(c) Current =3A

x axis: Time Scale = 0.3 sec/div.

Figure 3-7 Drifting Test Results for 3.6V/60Ah GAIA Cells
3.1.4 Measurement Accuracy Test and Analysis

Although the calibration procedure may reduce initial tolerance errors such as those caused by the resistor ratio, there may be other measurement errors, such as those caused by temperature, EMI and the A/D conversion. The 10bit A/D converter of the microcontroller has a ±2LSB error, which is ±9.7mV for a +5V reference [9]. Correction factors were added to compensate the measurement errors. Table 3.4 shows
the voltage, temperature and current values from both the software measurement and the digital voltage meter (DVM)/thermometer measurements.

As shown in Table 3.4, the BMS voltage measurements have been adjusted to be within 10mV of the actual measurements. Due to the precision of the infrared thermometer OS-600, the temperature measurements do not include any decimals. Thus, the temperature measurement has been less than a 1°C error. The current measurement has been reduced to within a 0.7A error. Although there are some offsets that are higher than expected, this may be because the measurement was taken during a rising current transient.

<table>
<thead>
<tr>
<th>(a) Cell Voltages</th>
<th>(b) Cell Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vsoftware (V)</td>
</tr>
<tr>
<td>V1</td>
<td>3.456</td>
</tr>
<tr>
<td>V2</td>
<td>3.413</td>
</tr>
<tr>
<td>V3</td>
<td>3.446</td>
</tr>
<tr>
<td>V4</td>
<td>3.436</td>
</tr>
<tr>
<td>V5</td>
<td>3.441</td>
</tr>
<tr>
<td>V6</td>
<td>3.432</td>
</tr>
<tr>
<td>V7</td>
<td>3.428</td>
</tr>
<tr>
<td>V8</td>
<td>3.433</td>
</tr>
<tr>
<td>V9</td>
<td>3.433</td>
</tr>
<tr>
<td>V10</td>
<td>3.433</td>
</tr>
<tr>
<td>V11</td>
<td>3.429</td>
</tr>
<tr>
<td>V12</td>
<td>3.433</td>
</tr>
</tbody>
</table>
Table 3.4 BMS Measurement Accuracy Table (Continued)

(c) Pack Current

<table>
<thead>
<tr>
<th>Pack Charge</th>
<th>Iset(A)</th>
<th>Imeas(A)</th>
<th>ΔI=Iset-Imeas(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.22</td>
<td></td>
<td>0.22</td>
</tr>
<tr>
<td>1</td>
<td>0.77</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>1.54</td>
<td></td>
<td>0.46</td>
</tr>
<tr>
<td>4</td>
<td>4.07</td>
<td></td>
<td>-0.07</td>
</tr>
<tr>
<td>5</td>
<td>4.73</td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>5.39</td>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td>7</td>
<td>6.38</td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td>8</td>
<td>7.48</td>
<td></td>
<td>0.52</td>
</tr>
<tr>
<td>9</td>
<td>8.14</td>
<td></td>
<td>0.96</td>
</tr>
<tr>
<td>11</td>
<td>10.45</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>12</td>
<td>11.22</td>
<td></td>
<td>0.78</td>
</tr>
<tr>
<td>Pack Discharge</td>
<td>16.59*</td>
<td>16.5</td>
<td>0.09</td>
</tr>
</tbody>
</table>

*Discharge current: 16.59A= (V_{avg}*12 cell)/R_{load}, Where V_{avg}=4.01V, R_{load}=2.9Ω.

3.2 Graphical User Interface (GUI) Development

Labview is a graphical user interface development platform from National Instruments [32].

Labview programs are called virtual instruments or VIs, and any VI used in another VI is called a sub VI. A project contains all .vi files and other files, such as a generated executable version of VI. Each .vi file includes a front panel and a block diagram as shown in Figure 3-8. The front panel is the interface layout with controls and indicators that appear on the computer monitor screen. Controls and indicators can be virtual knobs, slides, push buttons, LEDs, etc. The block diagram contains the code.
Coding in Labview consists of connecting different function blocks and subVIs following the order of data flow [40].

### 3.2.1 GUI Front Panel

The Labview GUI for the smart BMS presents the system status in real time. Additionally, it has several convenient functions such as: a clock, BMS data logging, EQU function recording, weak cell analysis, ΔV check window, SOC display, error handling, and alarms. In order to create an effective display, all information on the front panel was divided into four tabs:

1. Tab #1: System Status (Default Display), Figure 3-9
2. Tab #2: EQU Record and Weak Cell Analysis, Figure 3-10
3. Tab #3: SOC and Eff History and Adjustment Traces, Figure 3-11
4. Tab #4: ΔV as Current Changes Graph Display, Figure 3-12

The descriptions for each tab are as follows:

**Tab #1: System Status.**

Tab #1 in Figure 3-9 includes clock, error table, alarm control, a group of digital displays of system key parameters such as $V_{\text{max}}$, $V_{\text{max\ cell\#}}$, $V_{\text{min}}$, $V_{\text{min\ Cell\#}}$, $V_{\text{avg}}$, $T_{\text{max}}$, $T_{\text{max\ cell\#}}$, $T_{\text{min}}$, $T_{\text{min\ cell\#}}$, $I_{\text{set}}$, $I_{\text{meas}}$, SOC, efficiency factor, and EQU #1 and EQU #2 operation details. It also includes a V, I chart vs. time and a V,T graph vs. cell number.

The V, I chart presents the history for the maximum, minimum, and average cell voltages of the whole pack as well as the measured current value. The V,T graph displays real-time voltage and temperature for each individual cell, which clearly presents the pack voltage balancing status.
Figure 3-8 Front Panel and Block Diagram of A .vi File
Figure 3-9 GUI Tab #1: System Status (Default Display)

Figure 3-10 GUI Tab #2: EQU Record and Weak Cell Analysis
Figure 3-11 GUI Tab #3: SOC and Eff History and Adjustment Traces

Figure 3-12 GUI Tab #4: Delta V as Current Changes Graph Display
Tab #1: System Status (Continued)

On the right side of tab #1 is a clock, discharge control, EQU record clean up command, SOC value, breaker status, and digital displays of the cell voltages, current, cell temperatures and EQU operation information. The cells with the most EQU operations also are displayed for warning purposes. An error message box is at the bottom of this tab. This error box displays error messages with blinking and red backgrounds to attract the user’s attention. There is also an audible alarm as long as the error exists. Buttons to hide the error and to turn off alarms are also available.

The color scheme is implemented in the program to present a logical system status. The default color for all indicators is grey. It uses the color rules of traffic lights, from which green stands for ok, yellow stands for caution, and red stands for warning. Rules of color selections for voltage, current, temperature, SOC, EQU and breaker are included in Table 3.5.

Table 3.5 Background Color Selection Code in GUI

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>Yellow</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (Volt)</td>
<td>$V_{cell} &lt; 3.0$ or $V_{cell} &gt; 4.1$</td>
<td>$3.0 \leq V_{cell} &lt; 3.1$ or</td>
<td>$3.1 \leq V_{cell} &lt; 4.0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4.0 \leq V_{cell} \leq 4.1$</td>
<td></td>
</tr>
<tr>
<td>I* (Amp)</td>
<td>$I_{meas} &gt;</td>
<td>I_{set}</td>
<td>+ 0.5$ or $I_{meas} &lt;</td>
</tr>
<tr>
<td>T (ºC)</td>
<td>$T_{cell} &gt; 60$</td>
<td>$T_{cell} &lt; 0$ or $40 &lt; T_{cell} \leq 60$</td>
<td>$0 \leq T_{cell} \leq 40$</td>
</tr>
<tr>
<td>SOC (%)</td>
<td></td>
<td>$SOC &lt; 10.0$ or $SOC &gt; 90.0$</td>
<td>$10.0 \leq SOC \leq 90.0$</td>
</tr>
<tr>
<td>EQU</td>
<td></td>
<td>Discharge</td>
<td>Charge</td>
</tr>
<tr>
<td>Breaker</td>
<td>Open</td>
<td></td>
<td>Close</td>
</tr>
</tbody>
</table>

*: $|I_{set}|$ means the absolute value of the $I_{set}$ since the current is negative under pack discharge.
Tab #2: EQU Records and Weak Cell Analysis

Tab #2 in Figure 3-10 is created mainly for weak cell identification. It includes 2 graphs, which are EQU charge and discharge records and total EQU operations for each cell.

The EQU record graph exhibits charge and discharge activities for each cell. Red bars stand for EQU charge operations, and blue bars stand for EQU discharge operations. The total EQU record is a software-programmed graph displaying the sum of the EQU charge and discharge operations for each cell. As discussed previously, a weak cell always experiences more EQU activities no matter if the battery pack is under charge or discharge. The larger the total number is, the weaker the cell is. Therefore, the total EQU operations graph should present the list of cells most likely to be weak.

On the right side of this tab, there is a message box that displays the detailed pack maintenance information, such as total cycle number and installment time. EQU record values are also included in this message box to be displayed as soon as the BMS is powered on.

Tab #3: SOC and Eff History and Adjustment Traces

Tab #3 is created to display the history of the SOC and efficiency factor traces, as shown in Figure 3-11. The values of the current SOC, the initial SOC and the SOC before correction are displayed in numerical indicators. Similarly, the efficiency factor used for SOC calculation is also included in this chart. The initial and present efficiency factor values are shown in numerical indicators as well.
Tab #4: Delta V (∆V) vs. Current Changes Display

This tab has a graph displaying the values of cell voltages and currents for three consecutive cycles in different color traces as shown in Figure 3-12. This tab is especially designed to detect the cell with the most voltage change as the current changes. It is because values from different cycles are programmed to be stored and displayed simultaneously. This is very helpful to detect the pack status and a weak cell if a large current level is applied. The voltage axis is set to be automatic, which zooms in the cell unbalance status.

3.2.2 GUI Programming

Labview block diagrams are functions connected by “wires” (lines) of different colors, thickness, and types. For example, wires for strings are thin, pink and waved, wires for double numerical variables are thin, orange and straight, wires for integers are thin, blue and straight. Wires for arrays have the same wire color and type as the elements, but they are much thicker indicating they consist of multiple components.

The functions used for GUI creation can be categorized into 4 groups; these are initialization, serial communication, string manipulation, and display and logging. Details are discussed as follows:

3.2.2.1 Initialization

Initialization is to reset all values of the indicators and controls to the default values. For example, clearing up the images of the graphs and charts and the messages in
the error box, resetting the background colors of all indicators back to grey and resetting buttons or LEDs to the fault position or dimmed.

This initialization is realized by applying the initial values to the property nodes of each indicator as shown in Figure 3-13.

### 3.2.2.2 Serial Communication and Handshake

Serial communication is the most significant component of this GUI display. There is a function package called VISA, especially for serial communication in Labview. Figure 3-14 is an example of serial communication code. It includes function blocks for configuration, clear input and output buffers, serial read, serial write and port close. All functions are executed one by one in the data flow order. They share the same wires for port reference and errors, which means they share the same communication port and deliver the same error data.

The configuration block configures the settings of the serial port. It is not necessary to wire values to the pins of this function unless there is a difference in the default settings which are baud rate = 9600, data bits = 8, no parity, no flow control, and no error. The timeout number 60000 (60000 ms) configures the bus waiting time. The number 64 configures the termination character which is an “@” in ASCII. Termination character decides the time for the port to stop any further reading process. The number 20000 defines the maximum number of bytes to be read. The pink wire connects to the serial write block will send the user command (Y/N) for cleaning up the EQU record.

A complete message for the BMS status is extremely important. The normal communication cycles between wait and display, during which the message may not be
completed because of a communication error. However, this smart BMS adds one more procedure for the GUI to perform a handshake with the microcontroller to insure the communication success. This additional procedure is to transmit a ready signal. If a communication error happens, the GUI will not be able to transmit the ready signal, and the BMS will be shut down. This reduces the danger of operating the pack without monitoring. Figure 3-15 displays a comparison between the interactivities between the GUI and the microcontroller.

(a) Reset Background Color of Indicators

(b) Cleanup Error Message Box Content, Disable Blinking and Reset Background Color

Figure 3-13 Initialization Indicators Background Color and Error Message Box
3.2.2.3 Message String Manipulation and Display

The messages transmitted from the microcontroller are in form of strings. Selecting the key system status information from these strings is essential. There is a function that comes with Labview called number extract.vi which extracts numbers from a string and places them into an array. Therefore, numbers such as [0]s and [1]s are used to indicate the system status such as EQU operation type, breaker status and so on. Figure 3-16 shows the block diagram of the extract number subVI.

After extraction, all numbers are contained in an array. Therefore, indexing and displaying components by the proper indicator is the next step. For indexing the
components, an example of using this function is shown in Figure 3-17. The blue numbers used for indexing the components in the array are integers. The orange components with name element 1, 2, 3 are the double numerical elements at the indexed locations.

Indicators used in this research are mostly digital displays. Charts and graphs also are frequently used. Charts and graphs differ in the way they display and update data. Graphs collect multiple points such as all the cell voltages and temperatures in arrays and display them on the vertical axis for each cell number, e.g., the V,T graph, the EQU graph, and the ΔV graph. However, charts only accept one additional data point for each trace for each time. Data such as $V_{\text{max}}$, $V_{\text{min}}$, $V_{\text{avg}}$ and $I_{\text{meas}}$ are displayed vs. the time axis on the chart. Therefore, a chart requires a larger cache than graphs. The default chart history length is 1024, which means the latest 1024 points will be kept. In order to retain all history data for the V,I chart, the chart history length has been extended to 10000. A sample chart and graph are shown in Figure 3-18.

![Figure 3-16 Block Diagram for Extracting Numbers SubVI [34]](image-url)
Figure 3-17 Index an Array Block Diagram

Figure 3-18 Chart and Graph Samples
3.2.2.4 Logging

Logging is another important element of the GUI, especially for analyzing and troubleshooting. A group of functions called File IO are included in Labview for this purpose. There are two steps to complete a successful logging: file creation and file read/write.

Every time the GUI is started, one text file and one Excel file are created for user convenience. These files are created using the start time in the format of YYMMDDHHMM as the file name. These are located in a specific folder on the desktop of the PC. Titles for each column in the Excel file are also defined in this step. Figure 3-19 displays the block diagram for the file generation sub VI.

![Figure 3-19 Block Diagram of File Generation SubVI](image)

After receiving data at the serial port, a full message must be checked to ensure each component is stored and read in the right position of the Excel file and the GUI front
panel. Any incomplete message will not be stored or displayed. After checking for the completion of the data, an open and read operation must be done, and this enables the end of file function block which is used to find the location for appending the next set of data. A write to the file function is then proceeds, and this function will write the data to the expected location. In addition, a time stamp is attached in front of the message each time before being written into the file. Figure 3-20 displays the block diagram of the write to file function.

![Figure 3-20 Block Diagram of Write to the File SubVI](image)

**3.2.2.5 Other Functions**

1) **Error Indication**
Error messages are filtered out from the original message and shown in a list box. The size of the error messages is first checked, and this decides if the background is blinking or not. The items are manipulated as an array and fed into the item names of the property node. Also, the background of the error messages is red. The error message indicated on the front panel is shown in Figure 3-21 (a), and the block diagram for error message box is shown in Figure 3-21 (b).

A noticeable alarm is used to accompany the error messages box in case the user is away from the PC. This alarm can be stopped without any impact on the error messages display. The block diagram for the alarm is shown in Figure 3-22.

2) Event Structure in the EQU Memory Cleanup Function

As soon as the BMS is powered on, the BMS will print out the pack maintenance information. The BMS will then jump into an endless waiting loop until it receives the user command for the EQU memory cleanup or not from the GUI. The GUI uses an event structure that waits until the start button is pressed. The event structure in the GUI and the waiting loop in the BMS ensure their synchronization with each other, which reduces the possibility of a communication failure. The block diagram for this event structure is shown in Figure 3-23.

3) Shift Register in ∆V Graph

The shift register is a very handy component which is used along with the while loop. It delivers the wired data from one iteration to the next. The shift register also can be set to be a multiple which enables the access to data from multiple former iterations. The ∆V graph utilizes this feature to detect the cell voltages in 3 consecutive cycles.
Currents are displayed as well for reference purposes. The block diagram of the ΔV graph using the shift register is shown in Figure 3-24.

(a) Error Display for the GUI Front Panel

(b) Block Diagram for the Error Box

Figure 3-21 Front Panel and Block Diagram for Error Message in List Box
Figure 3-22 Block Diagram for the Alarm

Figure 3-23 Block Diagram of the Event Structure

Figure 3-24 Block Diagram of ΔV Graph Utilizing Shift Registers
4) Color Scheme

As discussed earlier, a color scheme is used to attract attention to any abnormal values at first sight. A code example for the temperature measurement values is shown in Figure 3-25. Numerical comparisons with the upper and lower limits determine the background color of the indicator.

![Figure 3-25 Block Diagram of the Color Scheme for Temperature Indicators](image)

3.2.3 Further Development

Webpage and executable versions are also included in the GUI development. The permission to access the GUI in a webpage version is controlled by the viewer’s IP address. The user also can authorize the preferred IPs to control the GUI remotely.

An executable version of the GUI is available for convenience broadcasting and reproduction purposes. Figure 3-26 displays a screen shot of the web page version of the GUI. Figure 3-27 displays a screen shot of the folder consisting of all necessary files for the executable file.
BMS GUI

Text that is going to be displayed before the VI panel image.

Figure 3-26 Screen Shot of the Webpage Version of the GUI

Figure 3-27 Screen Shot of the Executable GUI Folder
3.3 SOC and SOH/SOL Estimation

3.3.1 SOC Estimation

3.3.1.1 Introduction

The state of charge (SOC) is defined as the percentage of capacity available inside a battery or a battery pack [28]. Knowing the exact SOC value is necessary to estimate the remaining capacity of the pack.

There are five main methods that are available for SOC determination. These are the chemical method, pressure method, impedance method, voltage method and current integration method [29, 42]. Because of advantages of easy implementation and low cost, the last two methods are the most commonly used.

The voltage method, also known as the static method, is the simplest way to estimate the SOC. This method measures the open circuit cell voltage (OCV) and then reads the SOC value from a SOC vs. OCV chart provided by the manufacturer. Therefore, the voltage method can be described as a function of OCV, i.e., \( SOC = f(OCV) \). Figure 3-28 shows an example of the SOC vs. OCV chart for the GAIA cells used in this research. However, the voltage method may not be adequate for an accurate SOC estimation, because it does not consider any temperature or ageing effects. As the cell ages, the cell capacity is reduced. Moreover, if the temperature decreases, the cell capacity exhibits a lower value than that at about 25ºC [27-28]. Therefore, the voltage method may not be suitable for some applications.

The current integration method, also known as the dynamic method, measures the amount of charge by integrating the current over time, i.e., \( ΔSOC = \frac{ΔQ}{cap} = \frac{\int_{t_1}^{t_2} i dt}{cap} \). This is
also called the coulomb counting (CC) method. This method calculates the SOC based on the current, time and the capacity of the cell, i.e. $SOC = f(I, time, cap)$. Although the CC method has been widely used, the error caused by the current and/or the time measurements tends to be cumulative and can grow to be very large unless there is a correction from time to time.

3.3.1.2 Proposed Method

Therefore, the SOC estimation method utilized in the smart BMS is to combine the static method and dynamic method. The static method is used for SOC correction before and after the pack charge/discharge. With consideration of the current sensor measurement offset, the static method is utilized when current is between $\pm 0.5A$. The dynamic method is used during pack charge/discharge. The capacity of the pack is considered as a constant which is 60 Ah. However, the impacts from the EQU functions, measurement errors, aging are compensated by using an efficiency factor. Thus, the dynamic method is modified as $SOC = f(I, time, eff)$. This efficiency factor is corrected very time the switch is turned off. This combination of both methods should provide a more accurate SOC value.

3.3.1.3 Implementation

The static method is implemented by generating a look-up table. Eleven points are selected from the OCV vs. SOC chart in Figure 3-28. The SOC values between any pair of adjacent points are considered linear. Therefore, the SOC value can be calculated according to this slope using points available in the look-up table. For example, for the
point at 3.88V, the adjacent points available in the look-up table are 3.625V and 3.9V, and the SOC slope for this voltage range is about 122.95. The SOC for the point at 3.625V is 50%. Therefore, following formula 3.2, it is derived that the SOC for 3.88V is about 81.35% as shown in equation 3.3. For verification, the SOC value for OCV at 3.9V is about 82.53%. Therefore, the result is reasonably close.

\[
SOC_{ocv} = Slope \ast (V_{avg} - Vi) + SOC_{ini} \tag{3.2}
\]

\[
SOC(\text{at 3.88V}) = 122.95 \ast (3.88 - 3.625) + 50\% = 81.35\% \tag{3.3}
\]

![SOC vs. OCV Chart for GAIA 60Ah Cells](image)

**Figure 3-28 An Example of SOC vs. OCV Chart for GAIA 60Ah Cells**

The dynamic or coulomb counting method is used to calculate the capacity change. The initial capacity value comes from the last calculation by the static method as shown in equation 3.4. Later, the SOC value is calculated based on the value from the previous calculation as shown in equation 3.5.
\[ SOC_{cc} = SOC_{ini} + \Delta SOC \]  
(3.4)

\[ SOC_{cc,n} = SOC_{cc,(n-1)} + \Delta SOC, \ n \in [1, +\infty) \]  
(3.5)

where \( SOC_{ini} = SOC_{o_cv} \)  
(3.6)

\[ \Delta SOC = \frac{\Delta Q \times \text{eff}}{\text{Cap}} \]  
(3.7)

and \( \Delta Q = I \times \text{Time} \).  
(3.8)

As discussed previously, \( \Delta SOC \) is a product of time, current and efficiency divided by a constant capacity. Therefore, each component influences the accuracy. In order to measure an accurate time, a dedicated timer on the microcontroller is reset to 0 at the beginning of every cycle and the SOC calculation is executed at the end of every cycle. The current sensor being used is the ACS754LCB-050 from Allegro. Figure 3-29 shows the circuit implementation in the smart BMS.

![Current Sensor Circuit](image)

**Figure 3-29 Circuit for the Allegro Current Sensor**

The efficiency factor is updated whenever the power switches are turned off as shown in equation 3.6 and 3.7. This efficiency factor compensates for the EQU operation, current measurement error, the time measurement error, and capacity decrease due to aging. Thus, this number could be greater than 1.0. The correction is based on \( \Delta Q \). Equation 3.9 is derived from equation 3.7. Because the capacity is constant, equation 3.10 and 3.11 can be derived. Therefore, the efficiency factor can be calculated using 3.12 and
3.13. This efficiency factor is continuously updated each time the pack is charged or
 discharged. The most recent value of the efficiency factor is permanently stored in the
 nvSRAM. Its default value based on initial data is 1.37.

\[
\Delta Q = \frac{cap \cdot \Delta SOC}{eff} \quad (3.9)
\]

\[
\Delta Q \propto \frac{\Delta SOC}{eff} \quad (3.10)
\]

\[
\frac{\Delta SOC_{est}}{eff_{est}} = \frac{\Delta SOC_{new}}{eff_{new}} \quad (3.11)
\]

where \(eff_{est}\) is the efficiency factor that has been used during the bulk charge and
discharge operations, and the \(eff_{new}\) is the updated efficiency factor.

\[
\frac{SOC_{cc,n} - SOC_{ini}}{eff_{est}} = \frac{SOC'_{ocv} - SOC_{ini}}{eff_{new}} \quad (3.12)
\]

SOC\(_{cc,n}\) stands for the last calculated SOC from the dynamic method, and SOC\(_{ini}\)
is the last SOC value calculated by the static method before the power switch is turned
on. SOC\(_{ocv}'\) is the current SOC value calculated by the static method.

\[
eff_{new} = eff_{est} \times \left(\frac{SOC'_{ocv} - SOC_{ini}}{SOC_{cc,n} - SOC_{ini}}\right) \quad (3.13)
\]

### 3.3.2 SOH/SOL Estimation

The SOH is defined as a percentage of the present status of the cell that matches
its specified status. Since the manufacturer does not always include this SOH information
along with their product, it is very hard to define the SOH status of the pack. However,
they do provide the guaranteed minimum number of full charge and discharge cycles.
Therefore, an alternative method to indicate the SOH of a lithium ion cell is to record the
total number of cycles for each cell. Furthermore, referencing the number of EQU operations may confirm the SOH estimation [44].

Similar to the EQU operations record, the number of charge/discharge cycles for each cell is also recorded in the nvSRAM on a list called cycle[12], where each cell number has a maximum value of 65535. At the end of each cycle, the specific cell on the cycle list increases by one. For test purposes, the cycle list is random. The weak cell always has a larger number of EQU operations.

The stage of life (SOL) of a lithium ion cell is similar to the SOH. In addition to the records for SOH estimation, some operation/maintenance records such as the date each cell was initially installed or replaced are stored on the nvSRAM as well. These maintenance values are stored in a list called maintenance [12] with the format of the data is MDD or MMDD, e.g.,

maintenance[12]=[101,202,303,404,505,606,707,808,909,1010,1111,1212].

The 32k*8bit non-volatile Static RAM (nvSRAM) STK15C88 replaces the traditional 32k*8bit Static RAM K6X0808C1D for the microcontroller in the BMS Central. This nvSRAM does not require any extra power source or software programming for configuration. It shares the same pin layout and physical address range (0000H to 7FFFH) as the original part. The memory map of the nvSRAM is shown in Figure 3-30.

All of these data are kept along with the battery pack and can be accessed each time when the BMS is powered on. The data is presented in a text box located at tab #2 of the GUI as shown in Figure 3-31.
Figure 3-30 Map of External Memory nvSRAM

Figure 3-31 Cycle, Maintenance Record and EQU Operation Record GUI Display
Chapter 4

System Description

Similar to a conventional BMS, the smart BMS consists of one Central module (MCU), and some Local modules with one ECU (Electronic Control Unit) and one EQU (Equalizer) for each Local. In the smart BMS, up to four Locals are controlled by one Central. Each Local controls a sub-pack of series connected cells, e.g. 6 cells in this research. The block diagram indicating the relationship between the Central and Locals is shown in Figure 4-1.

Figure 4-1 BMS Central and Locals
A circuit diagram for the battery pack charger and discharger (Load) is shown in Figure 4-2. Besides the power switch for the battery pack, there is one dedicated switch for pack operations, i.e., charge and discharge.

![Figure 4-2 Battery Pack Charger and Load Connections](image)

### 4.1 Central and Local Functions Overview

The Central Control Unit (MCU) sends instructions to the ECUs in the Local modules via the CAN protocol. The ECUs take voltage/temperature measurements, execute the equalization (EQU) function, and feed the measurement results back to the MCU. Figure 4-3 illustrates a functional block diagram of the smart BMS with 2 Locals.

MCU is short for microcontroller unit, which is the Central control unit of the BMS. It includes a microcontroller, a current sensor, and some other electronic components responsible for:

- Control the system power switch
- Control the supply voltage external +12V to Locals
- Communication with Locals via the CAN bus
- Determine EQU operations for each Local
- Communicate with the user PC monitor via a serial port
- Current level control when the pack is under charge
- Measure pack current
- Recording the EQU operations for each cell
- Recording the maintenance data for each cell
- Recording the total number of cycles for each cell

Figure 4-3 BMS Functional Block Diagram
The ECU in each Local module includes a microcontroller, a voltage/temperature measurement circuit, and an EQU selection latch for implementing the functions of:

- Voltage measurement
- Temperature measurement
- Execute the EQU orders
- Communicate with the MCU

The EQU in each Local module includes a series of relays, their activation circuit, a small cell charger and a small cell discharger. This implements the EQU charge or discharge to balance the voltage of the most deviant cells with the rest of the cells in the pack [16].

4.2 Microcontroller Used in the Central and Locals

The microcontroller used in both the Central and Locals is a Phytec development module with an 8-bit SAB 80C515A chip from Infineon. This microcontroller includes 1 serial port, 1 CAN port, 3 timer/counters and 8 A/D channels. With a maximum external clock rate of 10MHz, it achieves a 600ns instruction cycle time [30]. Figure 4-4 shows the block diagram of the C515CA.

In the Central, Timer 1 is used to time the operating cycle for the SOC calculation. Timer 2 is used to provide a D/A converter to control the pack battery charger by adjusting the duty cycle of a variable PWM form. No timer is used in Locals, but both the Central and Local units use the A/D converter to take measurements. The Central communicates with the Locals via CAN communication, and the Central also uses serial RS232 communication with the PC for monitoring. The CAN communication
protocol is described in Chapter 2 and the serial RS232 communication will be described here. Figure 4-5 shows the serial port DB9 connector diagram which is a very common serial communication interface for connecting the microcontroller to the PC.

Figure 4-4 Block Diagram for C515C [30]
Serial communication has been widely used in industrial automatic devices. The serial port of the C505CA is full duplex, which means it allows concurrent transmit and receive. Similar to parallel communication, the serial communication used here transmits in byte units in the asynchronous mode. In contrast to parallel communication, serial communication only transmits 1 bit at a time with LSB first. The default communication settings are 9600 baud, 8 bit data, 1 stop bit, and no parity. To ensure a successful communication, a software handshake is also added between the Central and the GUI as discussed in Chapter 3.

![DB9 Connector Pin Layout for RS232 Serial Communication](image)

Figure 4-5 DB9 Connector Pin Layout for RS232 Serial Communication [35]

### 4.3 EQU Function

The EQU balances the cell voltages by applying a small charge or discharge to the cells with the most deviant voltages. Since pack capacity is limited by the max and min cell voltage, the EQU is very important in order to maximize the capacity [45-50].

The improved targeted EQU is used with the ECU board for each Local, and both ECU and EQU are controlled by MCU. Hence the MCU can cut off their power if an error occurs. The EQU intelligence also is provided by the MCU, but it is executed by the
Table 4.1 shows the EQU selection logic via a latch controlled by pins P3.2, P1.7 and P1.3 from the ECU.

A single double throw relay, JW2ASN-DC12V, connects the EQU to each cell, which simplifies the logic and is shown in Figure 4-6. Only one relay can be closed at a time. In order to avoid an arc during relay switching, a 0.0025s charger/discharger turn-off is added before each switching operation, which ensures zero current. In Figure 4-6, relays X1-X6 connect the EQU to the cells, while X7 and X8 are switches for EQU operation selection.

As indicated above, this targeted EQU has both charge and discharge functions. A DC-DC converter, ZUS251205 from Cosel, is used as a small charger to the weakest cell. A power resistor of 0.6Ω, 100W is used as a small discharger for the strongest cell. This dual function maximizes the operation flexibility and provides much faster balancing as compared to traditional discharge only EQUs [16]. LEDs indicating EQU status are also included on the PCB.

Several pictures of the smart BMS set up in lab are shown in Figure 4-7. Figure 4-7(a) displays the system power supply, the resistive load of the pack, and switches for power, pack charge and discharge. The MCU board is also shown at the right corner of Figure 4-7 (a). In Figure 4-7 (b), the PC monitor, pack charger, and two pairs of EQU and ECU boards for the two Locals are shown. Figure 4-7 (c) shows the fuse block for the EQU lines and Figure 4-7 (d) displays the battery pack.
Table 4.1 EQU Cell Selection and Operation Logic

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<th>P1.7</th>
<th>P1.3</th>
</tr>
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<tbody>
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<td>0</td>
</tr>
<tr>
<td>Relay 2</td>
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<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Relay 3</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Relay 4</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Relay 5</td>
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<td>0</td>
</tr>
<tr>
<td>Relay 6</td>
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<td>0</td>
<td>1</td>
</tr>
<tr>
<td>EQU Charger</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>EQU Discharger</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</table>

Figure 4-6 EQU Relay Connections
(a) BMS Power Supply, Pack Load, Power Switches and MCU

(b) Local (ECU+ EQU), Pack Charger and Monitor  (c) Fuse Block

(d) Battery Pack (2 Locals)

Figure 4-7 Smart BMS Lab Setup
Chapter 5

System Hardware

Altium Designer is one of the most advanced software systems for printed circuit board (PCB) development. It can route a PCB board automatically, detect the clearance errors, update PCB boards according to the schematic changes, generate the bill of materials (list of components) and so on. A later version of Altium Designer even can create a 3D view of the PCB board according to the models available in the component library. The MCU, ECU and EQU PCB boards in this research were created using Altium Designer 6.0.

The schematics compiled in the MCU PCB project are shown from Figure 5-1 to Figure 5-5. These include the Central microcontroller and its peripherals, localized +12V and +5V power supplies, external power switch control, external +12V power supply relay control, and the pack charger current level control.

The schematics compiled in the ECU PCB project are shown from Figure 5-6 to Figure 5-8. These include the Local microcontroller and its peripherals, cell voltage and temperature measurement circuits, and the EQU control signal latch. The ECU PCB also includes localized +12V and +5V power supplies as shown in Figure 5-2.
Figure 5-2 MCU: Localized Power Supplies (+12V, +5V)

Figure 5-3 MCU: External Power Switch Control
Figure 5-4 MCU: External +12V Power Supply Relay Control

Figure 5-5 MCU: Pack Charger Current Level Control

The Central and Locals use the same CAN driver circuits as shown in Figure 2-19. The Central also includes a current measurement circuit as shown in Figure 3-29.

The schematics in the EQU project are shown in Figure 5-9 and 5-10, which include the relay arrangement and the relay activation circuits.
Figure 5-6 ECU: Microcontroller and Peripherals
Figure 5-7 ECU: Voltage Measurement and EQU Control Signal Latch
Figure 5-8 ECU: Temperature Measurement
Figure 5-9 EQU: Relay Arrangement and Connections
Figure 5-10 EQU: Relay Controls and LED Indicators
A ground plane is used in the ECU and EQU PCB boards to minimize EMI. Additionally, test points for the EQU activation signals and cell voltages are built into the ECU PCB. Extra spaces also are available on the ECU for possible modifications.

Besides these schematics, a toggle switch is used to determine the pack charge and discharge status. A current sensor is located on the same breadboard to the toggle switch next to the MCU board. Fuses for power lines and EQU lines also are used for safety purposes. Figure 5-11 presents the toggle switch, current sensor and the fuse for the power lines.

The sizes for the MCU, ECU, and EQU PCB boards are 8”×4”, 6”×4” and 6”×4”, respectively. Using the same size for the ECU and EQU boards enables a stackable formation. This compressed space formation is always a good feature in practical applications. Pictures of the MCU, ECU, and EQU PCB boards are shown in Figure 5-12.
(a) ECU

(b) EQU

(c) MCU

(d) Stacked Local Boards

Figure 5-12 PCB boards
Chapter 6

System Software

Several BMS software programs have been developed for this research. The Infineon development package, DAvE (version 2.0), was used for configuration of the microcontroller and its peripherals, such as the A/D converter, CAN, Timer/Counters, serial communication and so on. The programs are written in C language and compiled by µVision IDE (version 3.0) software from Keil before being downloaded to the microcontroller by Flashtools 98 via the serial port.

Labview (version 8.6) software was used for creating the graphical user interface (GUI). The ROS (version 2.1) software is used to execute a programmable code to measure the series resistance of the cells on the bi-directional converter ABC150.

The flowcharts for the MCU control, SOC calculation, and the pack charger current level control are shown in Figures 6-1, 6-2, and 6-3, respectively. The EQU algorithm for each Local is shown in Figure 6-4 and 6-5. The ECU flowchart and the measurement algorithm for voltages, temperatures and current are shown in Figures 6-6 and 6-7. The algorithm for the cell internal resistance test using the ABC150 is shown in Figure 6-8.

The MCU is responsible for the power switch control, the system charger current control, the voltage measurement data request, the EQU cell and operation decisions, and
the communication with all Locals via CAN and the PC monitor display via the USART, as shown in Figure 6-1.

The SOC is calculated following the algorithm shown in Figure 6-2. The magnitude of the measured current is used to select either the dynamic or the static method, which were described in Chapter 3. An efficiency factor stored in the nvSRAM, also is used for more accurate estimation when the dynamic method is applied, and this efficiency factor is updated at the end of the charge or discharge cycle.

In Figure 6-3, the pack charger current level control is different from the traditional Constant Current, Constant Voltage (CCCV) charge control method. To prevent overcharging any individual cell and causing a fire, the current and the max cell voltage are controlled by the MCU during the pack charge mode. The maximum charge current is 12A, and the maximum cell voltage, \(V_{\text{big}}\), is limited to 4.1V max. Table 6.1 shows the lookup table for the current increment with an index.

The EQU algorithms are shown in Figure 6-4 (a) and (b). Figure 6-4 (a) shows that a break time is used after the power switch is turned off and on. The break is specifically used to allow the EQUs to select the weak cell. Figure 6-4 (b) shows the specific balance algorithm that is applied in both the pack charge and discharge processes. The goal for the EQU is to realize a fast equalization by applying a supplemental charge or discharge to the most deviant cells until their voltages are within \(\pm 0.01V\) of \(V_{\text{avg}}\).

<table>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 6-1 Flow Chart for MCU
Figure 6-2 Flow Chart for SOC Calculation
Figure 6-3 Flow Chart for Current Control
(a) Pause Usage for Weak Cell Identification

(b) EQU Algorithm

Figure 6-4 Flow Chart for EQU
Figure 6-5 shows the EQU pause after the power switch is turned on and off. The C points in Figure 6-5 (a) and (b) indicate the breaker switching points, where EQUs are disabled. The A and B points indicate the time that the EQU starts to work. The pauses between C to A allows the current to reach a relatively high value so that the weak cells are able to demonstrate their deviant cell voltages allowing the EQU to select. The pauses between C to B allows the cell voltages to stabilize after pack charge and discharge. Meanwhile, the EQU will re-evaluate the most deviant cells to work on in the future, which are more likely to be the weak cells (Refer to Table 2.1).

(a) Pack Charge

(b) Pack Discharge

Figure 6-5 EQU Break and Selection Points
Figure 6-6 shows the ECU flowchart where the CAN interrupt is used to minimize the response time.

Figure 6-7 shows the algorithm to take accurate measurements of the cell voltages, the cell temperatures and the current. The measurement results come from averaging three out of five measurements by omitting the max and min values.

Figure 6-8 shows the flowchart of the .scr code for testing the cell internal resistance by the ABC 150. The system has a 10 second pause before applying a 150A discharging pulse for 2 seconds. After this pulse discharge, the current is reset back to zero with a 120 second rest.
Figure 6-7 Flow Chart for V, I, and T Measurements

Figure 6-8 Flow Chart for Lithium Ion Cell Internal Resistance Test
Chapter 7

Experimental Results

This chapter presents the experimental results for the weak cell detection, the pack SOC correction, and the use of graphical user interface (GUI).

7.1 Weak Cell Identification

As described in Section 2.1, the weak cells always have a lower capacity and higher internal resistance. Four full charge and discharge cycles with the simulated weak cell #9 (cell 3 in Local #2) were conducted. The same number of tests also were done without the simulated weak cell for comparison purposes. Table 7.1 to Table 7.8 show the experimental records of the EQU operations for each cell respectively in all the tests.

Based on these EQU operation records, both of the weak cell detection methods are discussed below.

7.1.1 Weak Cell Detection Method 1: Total Cell EQU Operations
Table 7.1 EQU Records of Tests without Simulated Weak Cell (Test #1)

<table>
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<th>9-Feb</th>
<th>Charge</th>
<th>Discharge</th>
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<td></td>
<td>EQUC</td>
<td>EQUD</td>
<td>sub-total</td>
</tr>
<tr>
<td>1</td>
<td>718</td>
<td>0</td>
<td>718</td>
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<td>2</td>
<td>4</td>
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<td>0</td>
<td>766</td>
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<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>758</td>
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</tr>
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</tr>
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<td>345</td>
</tr>
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<td>483</td>
</tr>
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Table 7.2 EQU Records of Tests without Simulated Weak Cell (Test #2)

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<td>1</td>
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Table 7.3 EQU Records of Tests without Simulated Weak Cell (Test #3)

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Table 7.4 EQU Records of Tests without Simulated Weak Cell (Test #4)

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<td>EQUD</td>
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Table 7.5 EQU Records of Tests with Simulated Weak Cell (Test #1)

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Table 7.6 EQU Records of Tests with Simulated Weak Cell (Test #2)

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<td>30</td>
</tr>
<tr>
<td>9</td>
<td>300</td>
<td>916</td>
<td>1216</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>182</td>
<td>182</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>374</td>
<td>374</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>541</td>
<td>541</td>
</tr>
</tbody>
</table>

Table 7.8 EQU Records of Tests with Simulated Weak Cell (Test #4)

<table>
<thead>
<tr>
<th>17-Feb</th>
<th>Charge</th>
<th>Discharge</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell #</td>
<td>EQUC</td>
<td>EQUD sub-total</td>
<td>EQUC</td>
</tr>
<tr>
<td>1</td>
<td>1150</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>374</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>872</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>207</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>424</td>
<td>766</td>
<td>1190</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>652</td>
<td>19</td>
<td>671</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>574</td>
<td>1404</td>
<td>1978</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>383</td>
<td>383</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>586</td>
<td>586</td>
</tr>
</tbody>
</table>
This method lists the sums of EQU charge operations and the EQU discharge operations. The weak cell always requires more EQU operations, no matter whether the pack is under charge and discharge. Since only one EQU services each Local, the weak cell will require a higher percentage of EQU operations for that Local. Table 7.9 displays the number of EQU operations for each cell under both test conditions.

In order to provide a better presentation of this weak cell detection method, pie charts have been used to demonstrate the data in Table 7.9 in Figures 7-1 and 7-2.

As shown in Figure 7-1, cells #1, #3, and #5 from Local 1 are likely to be weaker, and cells #1 and #6 from Local 2 are likely to be weaker since these cells take the highest percentage of EQU operations in their Locals. Additionally, Cell #3, which is to be the simulated cell from Local 2, takes less than 10% of the total EQU operations in these four tests. Similar results for Local 1 also were obtained in the simulated weak cell tests. However, as shown in all charts of Figure 7-2, Cell #3 from Local 2 takes the largest amount, which is about 50%, of the total EQU operations in all four tests with the simulated weak cell. Thus, the weak cell #9 can be identified by this method.

7.1.2 Weak Cell Detection Method 2: Cell EQU Operations under Charge and Discharge

This method uses the voltage drop due to the internal resistance while current is flowing as the criterion to detect the weak cell. Thus, the sum of the EQU charge operations when the pack is under discharge and the EQU discharge operations when the pack is under charge can identify the weak cell. The weak cells always require a larger
amount of EQU operations. The EQU operation data in Table 7.1 to 7.8 are analyzed according this method and are shown in Table 7.10 and Figure 7-3.

Table 7.9 Total EQU Operations for Each Cell

<table>
<thead>
<tr>
<th>Test without the Simulated Weak Cell</th>
<th>Cell Number</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1470</td>
<td>1723</td>
<td>1448</td>
<td>1743</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>101</td>
<td>310</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1467</td>
<td>1844</td>
<td>1507</td>
<td>1471</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>71</td>
<td>272</td>
<td>0</td>
<td>114</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2275</td>
<td>916</td>
<td>5004</td>
<td>5846</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>46</td>
<td>414</td>
<td>0</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1114</td>
<td>1637</td>
<td>3177</td>
<td>3876</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>141</td>
<td>244</td>
<td>837</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>334</td>
<td>272</td>
<td>412</td>
<td>368</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>544</td>
<td>392</td>
<td>650</td>
<td>650</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>770</td>
<td>636</td>
<td>783</td>
<td>720</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1499</td>
<td>1504</td>
<td>964</td>
<td>999</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test with the Simulated Weak Cell at Cell #9</th>
<th>Cell Number</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2444</td>
<td>2006</td>
<td>1729</td>
<td>2162</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>560</td>
<td>6</td>
<td>36</td>
<td>472</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1910</td>
<td>3430</td>
<td>6168</td>
<td>3833</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>184</td>
<td>282</td>
<td>0</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1922</td>
<td>3108</td>
<td>1415</td>
<td>1230</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>313</td>
<td>134</td>
<td>247</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1906</td>
<td>1533</td>
<td>2199</td>
<td>1128</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>179</td>
<td>127</td>
<td>100</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3564</td>
<td>3607</td>
<td>3268</td>
<td>4141</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>285</td>
<td>357</td>
<td>363</td>
<td>271</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>637</td>
<td>774</td>
<td>800</td>
<td>811</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1212</td>
<td>1142</td>
<td>1129</td>
<td>1262</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7-1 Pie Charts of Results for the Tests without the Simulated Weak Cell
Figure 7-2 Pie Charts of Results for the Tests with the Simulated Weak Cell
### Table 7.10 EQU Operations under Charge and Discharge

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>114</td>
</tr>
<tr>
<td>5</td>
<td>1362</td>
<td>597</td>
<td>2782</td>
<td>3063</td>
</tr>
<tr>
<td>6</td>
<td>46</td>
<td>414</td>
<td>0</td>
<td>168</td>
</tr>
<tr>
<td>7</td>
<td>119</td>
<td>242</td>
<td>944</td>
<td>1148</td>
</tr>
<tr>
<td>8</td>
<td>131</td>
<td>164</td>
<td>315</td>
<td>106</td>
</tr>
<tr>
<td>9</td>
<td>334</td>
<td>269</td>
<td>412</td>
<td>368</td>
</tr>
<tr>
<td>10</td>
<td>544</td>
<td>390</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>11</td>
<td>770</td>
<td>636</td>
<td>783</td>
<td>720</td>
</tr>
<tr>
<td>12</td>
<td>1468</td>
<td>1480</td>
<td>964</td>
<td>999</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell Number</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>862</td>
<td>2148</td>
<td>1092</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>1310</td>
<td>1707</td>
<td>779</td>
<td>806</td>
</tr>
<tr>
<td>6</td>
<td>313</td>
<td>134</td>
<td>247</td>
<td>157</td>
</tr>
<tr>
<td>7</td>
<td>338</td>
<td>168</td>
<td>598</td>
<td>19</td>
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<td>8</td>
<td>144</td>
<td>127</td>
<td>100</td>
<td>50</td>
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<td>2531</td>
<td>2239</td>
<td>2816</td>
</tr>
<tr>
<td>10</td>
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</tr>
<tr>
<td>11</td>
<td>637</td>
<td>774</td>
<td>800</td>
<td>811</td>
</tr>
<tr>
<td>12</td>
<td>1212</td>
<td>1142</td>
<td>1129</td>
<td>1262</td>
</tr>
</tbody>
</table>

As shown in Figure 7-3, cell #5 from Local 1 takes more EQU operations when the pack is under charge and discharge. All cells in Local 2 require about the same
number of the EQU operations in all 4 tests without the simulated weak cell. However, cell #9 requires the largest number of EQU operations after the simulation resistor is inserted. Thus, the simulated weak cell #9 can be identified by this method.

Figure 7-3 Cell EQU Operations under Pack Charge and Discharge

(a) Pack without Simulated Weak Cell

(b) Pack with Simulated Weak Cell at Cell #9
7.2 SOC Estimation

As discussed in Section 3.3, SOC is estimated by both the static and the dynamic methods. The static method is used when the breaker is open, whereas the dynamic method is used when there is a current flowing. Considering the accuracy of the current sensor, a magnitude of 0.5A is set as the boundary between the static method and the dynamic method. To improve the accuracy and to compensate for the measurement offset and the capacity change due to aging, an efficiency factor is used. This efficiency factor is permanently stored in the nvSRAM, and it is updated every time the algorithm switches from the dynamic method to the static method. The default value of the efficiency factor is 1.37.

Figure 7-4 shows the screen shots of the GUI tab #3 (the SOC and the efficiency factor traces) in a couple of consecutive pack discharge and charge cycles tests. Table 7.11 lists the update history of the efficiency factor in these two consecutive tests. Both Figure 7-4 and Table 7.11 have confirmed that the SOC estimation is very accurate since the SOC value has been frequently updated to avoid the accumulated error in the dynamic method, and the efficiency factors are almost constant in these tests.

<table>
<thead>
<tr>
<th>Table 7.11 Efficiency Factor Update History</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pack Discharge</td>
</tr>
<tr>
<td>From</td>
</tr>
<tr>
<td>Test 1</td>
</tr>
<tr>
<td>Test 2</td>
</tr>
</tbody>
</table>
(a) Test 1: Pack Discharge (SOC updates from 1.11 to 1.37)

(b) Test 1: Pack Charge (SOC updates from 1.37 to 1.35)

Figure 7-4 Test Results for SOC Estimation
(c) Test 2: Pack Charge (SOC updates from 1.35 to 1.38)

(d) Test 2: Pack Discharge (SOC updates from 1.38 to 1.35)

Figure 7-4 Test Results for SOC Estimation (Continued)
7.3 **Graphical User Interface (GUI)**

Each of the four tabs of the GUI has a variety of functions. Tab #1 is the default page and displays the main status of the BMS. Tab #2 is used to demonstrate the EQU operations. Figure 7-5 shows the GUI screenshots with a weak cell at #9 under pack charge and discharge. Figure 7-6 shows the GUI screen shots at the end of the pack charge and discharge cycles without the simulated weak cell.

As shown in Figure 7-5 and 7-6, the weak cell can be identified either from the indicator at the right bottom corner of Tab #1 or from the total EQU operations graph in Tab #2. Moreover, from the V, I chart and the V, T graph in Tab #1, the history of the pack performance and the final balancing status are clearly presented.
(a) Pack Charge (Tab #1)

(b) Pack Charge (Tab #2)

Figure 7-5 GUI Shots when the Pack is under Charge and Discharge with the Simulated Weak Cell
Figure 7-5 GUI Shots when the Pack is under Charge and Discharge with the Simulated Weak Cell (Continued)
Figure 7-6 GUI Shots when the Pack is under Charge and Discharge without the Simulated Weak Cell
Figure 7-6 GUI Shots when the Pack is under Charge and Discharge without the Simulated Weak Cell (Continued)
Chapter 8

Future Improvements

Future improvements are mainly concerned on implementing this smart BMS in practical applications such as energy storage for utilities, hybrid vehicles and portable electronic devices. It also should be advantageous to incorporate many of these new features into BMS equipment for other types of batteries. One area of particular interest is a BMS for some of the new types of lead acid batteries which are much cheaper than lithium ion, especially for renewable energy applications.
Chapter 9

Peer to Peer Comparison

Currently, there are a few commercial BMS products available in the market. The Maxim DS2726 and the TI bq78pl114 8S EVM, were selected for comparison with the smart BMS. A datasheet level comparison is shown in Table 8.1.

Table 8.1 Comparison between Similar BMS Products

<table>
<thead>
<tr>
<th>BMS Brand</th>
<th>Maxim DS2726</th>
<th>TI Bq78pl114</th>
<th>Smart BMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Charge shunting</td>
<td>Inductive shuttle charge</td>
<td>Charge and Discharge</td>
</tr>
<tr>
<td><strong>Power source</strong></td>
<td>Internal: neighbor cells and inductors</td>
<td>Internal: neighbor cells and inductors</td>
<td>External: DC-DC converter</td>
</tr>
<tr>
<td><strong>Current rating</strong></td>
<td>300mA at max.</td>
<td>100mA-1A</td>
<td>About 3A for both charge and discharge</td>
</tr>
<tr>
<td><strong>Activation cell number at a time</strong></td>
<td>Half set (odd and even numbered cells take turns) alternatively</td>
<td>2 (pump up the charge from 1 cell to the other)</td>
<td>1 cell at a time</td>
</tr>
<tr>
<td><strong>Balance voltage threshold</strong></td>
<td>Programmable</td>
<td>Programmable</td>
<td>Programmable</td>
</tr>
<tr>
<td><strong>Heat dissipation</strong></td>
<td>2963mW at 70C</td>
<td>No heat dissipated</td>
<td>Heat on resistor, and on EQU charger</td>
</tr>
<tr>
<td><strong>Pack mode when EQU turns on</strong></td>
<td>charge</td>
<td>Can be programmed at both C and D</td>
<td>Can be programmed at both C and D</td>
</tr>
<tr>
<td><strong>EQU start condition</strong></td>
<td>Any cell voltage over the balance</td>
<td></td>
<td>Any two cell voltage</td>
</tr>
</tbody>
</table>
The TI BMS was studied for further comparison. It was found that this BMS product does have some advantages, such as compact size, low power consumption, and no external power sources are required. Its GUI also has the ability to control all power MOSFETs for pack charge and discharge operations, demonstrate the status and errors, and provide data logging [50].

However, some of its advantages and functions might become the disadvantages in some applications.
1). For the 60Ah cells used in the smart BMS, the EQU current varies from 2A to 3A. This will provide a much faster equalization process than the 70mA EQU current from the TI BMS. Also the EQU algorithm in the TI BMS only allows current to flow between adjacent cells, which also slows equalization.

2). The TI BMS requires very short wiring connections, i.e. 1 or 5 inches, since transients in the wires may damage the ICs [21, 51]. The EQU wires in the smart BMS are more than 20 inches long due to the large cell volume and the number of the cells used in this research.

3). The EQU function in the TI BMS supplies continuous current, which may effect the voltage measurement [21]. However, in the smart BMS, there is a break in the EQU current when taking cell voltage, temperature, and current measurements to avoid voltage drop and EMI effects.

4). All devices in the smart BMS are powered from an external power supply, whereas the TI BMS is powered from the battery pack itself. Thus, it requires a series of must-follow sequence procedures to start and stop the BMS with delays. For example, the TI BMS requests a 10 second application of power to the target circuit before starting the GUI software [21, 49, and 50].

5). All terminals of the TI BMS must be connected before operation, i.e., pack load and charger, and no open connections are allowed [21]. However, the smart BMS allows EQU operation when the pack load and charger are connected or disconnected.

6). The TI GUI does have the feature of storing the manufacturer specifications for the cells. However, when an unknown cell model is connected, it demonstrates either an error of communication or 2000mV as the cell voltage. It then requires a series of
specification changes, learning, and relearning until the TI BMS adapts to the new cells [21, 49, and 50].

Although the TI BMS may be useable for small cells, its operation proved to be very complex and sensitive. Even with great care and the author’s extensive battery/BMS experience, two of the $149 TI BMS development kits failed during lab testing. This indicates it is definitely not as robust and flexible as the smart BMS. It also does not have certain functions such as a fast EQU, weak cell detection, and SOH/SOL estimation which are present on the smart BMS.
Chapter 10

Summary

This research has proved that the proposed smart BMS has certain important advantages compared to the traditional BMS and similar products.

The safety features of the smart BMS have been improved, and the weak cells in a pack can be identified, which expedites their replacement and improves the performance of the whole battery pack. This is realized by recording the number of EQU operations for each cell, and the cells with the most EQU operations tend to be the weakest. These non-volatile records are kept on an nvSRAM which replaces the conventional SRAM in the Central microcontroller. The records can be stored or removed when the unit is turned on, depending on the user request sent from the graphical interface (GUI). Also, the frequency of the V, I, T measurements and thus the CAN communication frequency have been increased for much faster detection and response to potential operating problems.

The performance of the smart BMS also has been optimized, and the PCB boards have been designed in a more compact size to reduce EMI. This allows the cell voltages, cell temperatures and the current to be measured more accurately. A GUI has been programmed in Labview to provide a convenient monitoring environment, and indicators with appropriate colors and shapes are used to display the status of the pack, including limits, warnings and alarms. These are very helpful to alert the user to an abnormal status...
of the pack and to detect a problem at first sight. Executable and webpage enabled versions of the GUI also were created, and SOC, SOH, and SOL estimations were developed with improved algorithms. The SOC is calculated based on both open circuit voltage and the coulomb counting methods and an efficiency factor is used to ensure a more accurate SOC estimation. This efficiency factor is updated frequently and is stored in the nvSRAM, which allows the smart BMS to provide an accurate SOC estimation as the battery ages. Besides recording the number of EQU operations, the SOH estimation also records the total number of charge/discharge cycles for each cell. SOL is estimated by recording the number of cycles and the maintenance record, i.e., the cell installation date. All of these cycle count and maintenance date records are kept on the nvSRAM which provides a permanent record that is attached to the battery pack.

A series of comparisons between the smart BMS and commercial products available in the market have been done at both the literature level and the practical level. The TI BMS was selected for further comparison, but it was found that, the smart BMS provided more effective equalization, weak cell detection and SOH/SOL estimation.

In summary, this BMS is an extension of previous BMS research of the BMS that included the improved EQU feature, and it adds new safety and performance features such as more accurate measurements, weak cell identification, SOC/SOH/SOL estimation, convenient graphical user interface (GUI), and faster measurement cycles.
References


[33] [Online]. http://en.wikipedia.org/wiki/LabVIEW.


[39] **Lithium Technology Corporation**, 60Ah lithium ion cell\Type 45 charge ESR vs. SOC.pdf.


