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Optimizing Battery Performance: Investigating the Long-Term Impacts of Bidirectional Battery Management Systems on Battery Cells

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ABSTRACT

OPTIMIZING BATTERY PERFORMANCE: INVESTIGATING THE LONG-TERM IMPACTS OF BIDIRECTIONAL BATTERY MANAGEMENT SYSTEMS ON BATTERY CELLS

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With the increased use of batteries in everyday life, it is crucial to have a robust and reliable battery system that can continue to power our devices. This paper will investigate the reliability, impact on the batteries, and functionality of the bidirectional battery management system (BMS). The design uses two bidirectional switches for each cell, one in series with the cell and one in parallel with the other bidirectional switch and cell. This will allow the cell to be taken in and out of the circuit for any reason determined by the BMS. Taking the battery in and out of the circuit has many benefits, such as balancing the cells, keeping lower-performing batteries out of harsh conditions, and creating unique charging and discharging profiles. In order to show the reliability, impact on batteries, and functionality, a six-cell battery management system was designed. While cycling the batteries, data was taken on the capacity, output of the batteries, and other battery pack parameters to determine the impact on the batteries, functionality, and reliability. This data showed that the bidirectional battery management system was capable of managing the battery with little effect on the batteries under normal operating conditions.

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1: INTRODUCTION

With the increasing prevalence of batteries in various devices, from cars to laptops and even smartphones, the need for an effective battery management system becomes paramount. Such a system is crucial for safeguarding batteries and maximizing their longevity.

A typical battery system is made up of smaller battery cells. In normal use, the battery's cells can become out of balance indicating that the cells do not have the same state of charge (SOC). The SOC of a battery or cell is the amount of charge left in the cell compared to the original capacity. For example, if a cell is rated at 800mAh (800 milli-amp hours) and the current capacity is 400mAh, that means the cell's SOC is 50% or half.

Suppose two different cells are unbalanced or have different SOC, such as one is at 0%, and the other is at 100%. In that case, the battery pack cannot discharge anymore because if the battery continues to discharge, then the 0% SOC cell could become permanently damaged. Balancing circuits are commonly used to balance the SOC so that the battery pack can use its full capacity range. Commonly used balancing circuits are resistor balancing, capacitive balancing, or transformer balancing circuits. All of these balancing systems have limitations and can be slow to balance, inefficient, and do not offer much control over what happens to the cells during charging and discharging. This paper proposes a new battery management system (BMS) called the bidirectional BMS that can give the BMS software much more control over the battery's cells.

The bidirectional BMS comprises two bidirectional switches, one in series with the cell and one in parallel with the other switch and cell. The configuration allows the cell to be removed from the circuit, allowing for proper balancing and even protection of cells closer to the end of life. In order to charge and discharge properly, the bidirectional BMS has a bidirectional converter on each series terminal. Having a system that can take the cells out of the system can be useful but taking the cells out of the system can cause large transients on the battery and the load. This paper will look at the bidirectional BMS's impact on the batteries to ensure that the BMS is not causing more harm to the batteries. This paper will also look at the output on the load during switching, and other safety concerns with the BMS, such as MOSFET failures, and make a cost comparison between commonly used BMS balancing systems and the bidirectional BMS.

A cycling test has been created to measure if the bidirectional BMS damages the battery cells. There will be three main tests, one baseline test, one normal operating bidirectional BMS test, and one switching bidirectional BMS test. In each test, the batteries will be cycled 100 times and have the state of health (SOH) measured before and after the tests. The state of health of a cell can be characterized in various ways. However, this paper will refer to the state of health as the current max capacity over the manufacturer's rated capacity. The baseline test is one cell normally cycled at a 1.5C charge and a 2.25C discharge. 1.5C refers to the C-rating of the battery and corresponds to the discharge or charge rate of the battery in relation to the battery capacity. For example, if a battery has a capacity of 800mAh and the discharge is 2C, then the discharge rate would be 800mAh * 2C = 1.6 amps. The baseline test is meant to analyze the normal SOH decrease for 100 cycles of the batteries. The next test is the normal operating bidirectional BMS test which is meant to simulate the bidirectional BMS under normal conditions. The last test is the switching bidirectional BMS test, which emphasizes switching to help determine if switching the cells in and out of the circuit has a negative impact on the cells.

Using bidirectional switches in a battery management system is not a new idea and was initially designed to bypass damaged cells in the battery pack [1]. There has been a wide range of designs, one of which used a buck converter as the battery pack's output to decrease the number of parts in the design [2]. The buck converter has challenges such as inconsistent output as cells are brought out of the circuit and a much harder control scheme with multiple batteries in parallel. [2] found that the MOSFET's on-resistance can significantly impact the entire circuit's efficiency, but found an efficiency greater than 90% for the entire voltage and current range of the BMS. With advancements in semiconductor technology, the possible on-resistance of MOSFETs is very low, with some MOSFETs having an on-resistance of lower than one milliohm, which makes the power loss from the bidirectional switches almost nonexistent. The most significant loss in the bidirectional BMS is the bidirectional converter which can have an efficiency range of 80% to 95% depending on the design and load.

This paper will have five main sections: BMS background, design, results, safety, and cost comparison. The BMS background will cover various important information about what a BMS is, what type of BMS balancing systems are used, and important terminology in the battery industry. The design section will review the experimental design, the hardware design of the bidirectional BMS, and the software used to control the BMS. The results section will review the results from the experiments described in the experimental design. The safety section will review MOSFET failure modes, effects on series and parallel terminals when batteries are removed from the circuit, and output stability during switching. Then the final section, cost comparison, will compare the cost of a bidirectional BMS to the capacitor balancing circuit.

2: BMS BACKGROUND

A battery management system is connected to a battery pack to ensure efficient and safe operation of the battery's cells. The BMS background section has four parts, measurements, state of charge, state of health, and cell balancing. The measurement section will go over the importance and how to measure each cell's voltage, current, and temperature. The state of charge section will go over what state of charge is and how to measure the state of charge of a battery. The State of health section will also go over the definition and how to calculate the state of health in a battery. The balancing section will review various commonly used balancing methods, the importance of balancing, and the proposed BMS method for this paper.

2.1: Measurements

Accurate measurement of voltage, current, and temperature is crucial for precisely estimating the state of charge and health of individual cells and battery packs [3]. Therefore, it is essential to understand the techniques for measuring these quantities when designing a battery management system. Measuring the voltage of the output of the entire battery pack is essential. However, it is also important to measure the voltage of each cell to ensure an undervoltage or overvoltage condition has not occurred on any of the cells. Voltage is typically measured using a voltage divider which is what is used in the bidirectional BMS in order to measure the voltage of each cell.

The cell's voltage will vary with the individual cell's current and temperature. It is essential to realize that voltage during charging and discharging depends on voltage polarizations, hardware voltage drops, and cell series resistance, which does not perfectly correlate to the percent of capacity left in the battery or the number of ions left in the anode [4]. Open circuit voltage better estimates the capacity left in the cell because the internal chemistry and voltage levels have reached a stable state, and there is little to no current flowing. The problem is that batteries cannot output power in open circuit mode, and due to the settling time of the battery, it usually takes several hours for a good open circuit voltage to be measured. Another problem with open circuit voltage is that depending on the chemistry, the open circuit voltage can be almost independent of the state of charge, making it difficult to measure the battery's capacity since the voltage-measuring device only has a specific accuracy. In Figure 1, the open circuit voltage of a Lithium Iron Phosphate (LiFePO) cell is compared to its state of charge. Between 0.1 and 0.9 state of charge, where 1 is 100%, the open circuit voltage only changes 0.2V. The slight change in voltage makes determining the state of charge using open circuit voltage measurements very difficult for this chemistry.

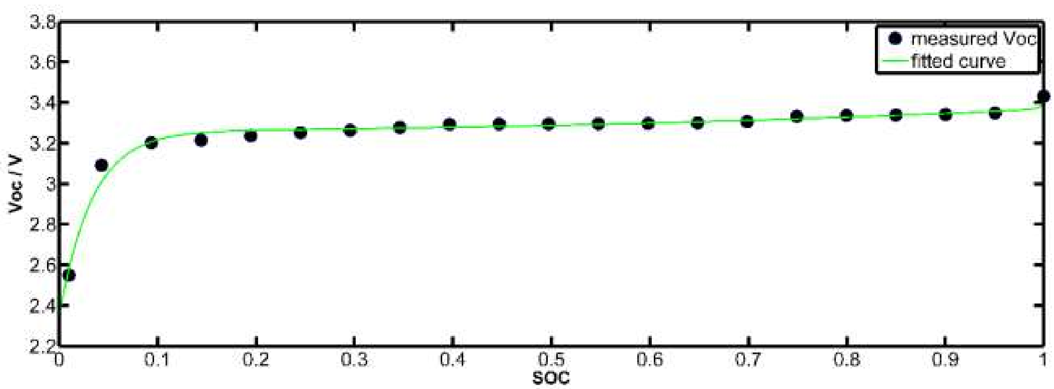

Figure 1 [5]: The OCV vs SOC graph for a LiFePO cell.

Current measurements can help determine the state of charge and state of health of a battery. Typically, the measurement of the current flowing in and out of the battery utilizes a current sense resistor. Suppose the current is anticipated to be too high for a shunt resistor to provide reliable measurements. In that case, another potential alternative is using Hall modules with a closed-loop system. The shunt resistor will be used in the bidirectional BMS design. In many battery systems, the continuous charge current and the max discharge current can be widely different. For example a high discharge lithium polymer battery with a Lithium Cobalt Oxide chemistry has a 1C for charging and 60C for continuous discharging. The wide range can make it challenging to achieve high accuracy for both charge and discharge current. Figure 2 is a typical circuit for a current sense resistor.

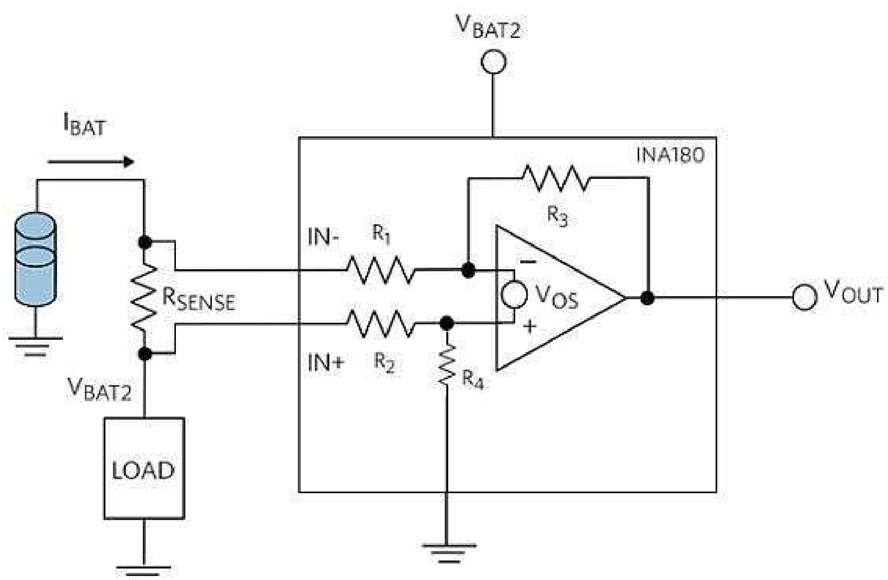

Figure 2 [6]: Schematic for a typical current sense circuit for a battery.

Temperature measurements of the batteries are vital because they can cause drifts in current and voltage values and can cause damage to the batteries if the temperature goes too high and out of range. For example, in some lithium-ion batteries, the operating temperature is typically between 15ºC to 45ºC. If the temperature gets above 60ºC, the chance of thermal runaway increases significantly and the chances of severe battery failure are likely [7]. Thermal runaway can cause the internal temperature of the batteries to rise very quickly until the cell or battery combust.

Temperature measurements are generally done in two ways: measuring each cell directly or measuring the pack's temperature. Measuring the pack is not the best approach since the state of health differences in the batteries can cause one cell's temperature to rise faster than the others. It is essential to measure each individual cell temperature when possible.

Various temperature sensors can be used, and the surface temperature of the battery is typically measured. The bidirectional BMS will use multiple thermistors to measure the temperature of each cell. Since the surface temperature and the internal temperature can vary, it is a good practice to have a thermal model of the battery to estimate the difference between the internal temperature and surface temperature. Suppose a thermal model cannot be created. In that case, the battery management system must cut off the battery at a slightly lower temperature than the battery's rated max temperature. In the case of lithium-ion batteries, the battery management system can expect the surface temperature to be 6ºC to 7ºC lower than the internal temperature of the battery [7].

2.2: State of Charge

The state of charge is the current capacity of the battery divided by the total possible capacity of the battery at the current state of health or the percentage of the total capacity left in the battery. The state of charge is important to measure because overcharging or over-discharging the cell can cause permanent harm to the battery. Such over-discharged cells can cause degradation and internal short circuit [8]. There are a few common ways to estimate the state of charge: voltage measurement, coulomb counting, and using a Kalman filter.

Open circuit voltage is one of the easiest ways to measure the state of charge. However, voltage during charging and discharging is also a factor of other battery variables, such as temperature, current, and internal resistance, which makes it challenging to find a correct state of charge based entirely on the voltage measurement. Some battery chemistries have a flat voltage vs. state of charge graph, making it difficult to estimate the SOC correctly. The open circuit voltage method is reliable for many battery chemistries. However, the battery must reach equilibrium to get the accurate open circuit voltage, which can take a long time [9].

Coulomb counting is another way to estimate the state of charge. Coulomb counting uses a current sensor to measure the current going in and out of the battery. Once the current is measured, the value is integrated over time to get the electric charge. This value is then compared to the max capacity of the battery to estimate the state of charge, as shown in Figure 3. The problem with this method is that the current sensor circuit has a certain amount of error in its measurement. The error build-up means that the actual electric charge estimate will drift from the actual value over time. In order to recalibrate the sensor, the battery management system can get an open circuit voltage and use the method above to estimate the state of charge. If an application cannot measure open circuit voltage, then other techniques for recalibrating can be used.

$$SOC(t) = SOC(to) + \frac{\int_{to}^{t0+\tau} I_{bat}.d\tau}{Q_{rated}} \times 100\%$$

SOC: State Of Charge
I_{bat}: battery current value
Q_{rated}: rated capacity (nominal capacity)

Figure 3 [10]: Equation to find SOC using coulomb counting.

The last way to measure the state of charge is by using a Kalman filter. This method involves more computation than the other methods. First, a model has to be created for the battery. Then variables such as voltage, current, and temperature are put through the model, which allows the Kalman filter to estimate the state of charge [11].

2.3: State of Health

Battery state of health can have multiple definitions but is generally calculated by finding capacity fade or measuring equivalent series resistance [12]. State of health is the present maximum possible capacity of the battery in the present state divided by the manufacturers rated maximum capacity. The battery's maximum capacity decreases after many cycles or over time, as shown in Figure 4. In Figure 4, the change in depth of discharge decreases with the number of cycles, which means the amount of capacity the battery can dissipate decreases with time. Depth of discharge is the total capacity of the battery that has been discharged. For example, if a batteries SOC is 60% then the depth of discharge is 40%.

The degradation rate depends on the operating condition of the battery and the battery chemistry. Lithium-ion batteries' fade is caused by multiple processes depending on the specific chemistry. The lithium within the cell can react at low potential with the cell's electrolyte solvent. At high potentials, nickelate cathode materials can oxidize the electrolyte. Certain transition metals in the cathode can dissolve and migrate to the anode. Some cathode and anode materials can mechanically fail due to volume changes and the corresponding strain on lithiation and de-lithiation, and this mechanical failure can lead to different reactions with the electrolyte or electrical disconnection from the rest of the electrode.

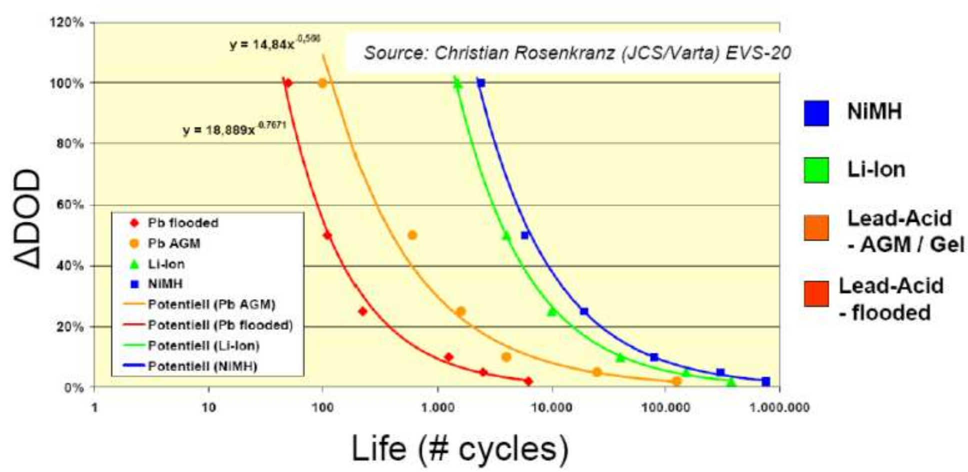

Figure 4 [5]: Graph showing change of depth of discharge vs cycles.

Another way to determine the state of health is to look at the equivalent series resistance, shown as Rs in the battery model in Figure 5. Throughout the life of the battery, the series resistance increases. There are two main methods to measure series resistance: electrochemical spectroscopy or a method similar to the DC load method. Electrochemical impedance spectroscopy allows many battery variables to be determined, but the process can be long. Electrochemical spectroscopy is done by sweeping through multiple frequencies and measuring the battery's impedance. A Nyquist plot maps the results that can be used to determine the equivalent circuit parameters of the battery. The open circuit voltage is measured for the DC load method, then a load is applied to the battery, and another voltage measurement is taken. With all of these values, the equivalent series resistance of the battery can be calculated. An 18-second direct current pulse can find the equivalent series resistance of the battery by $\frac{V_{source} - V_{OpenCircuit}}{I_{battery}}$ [13].

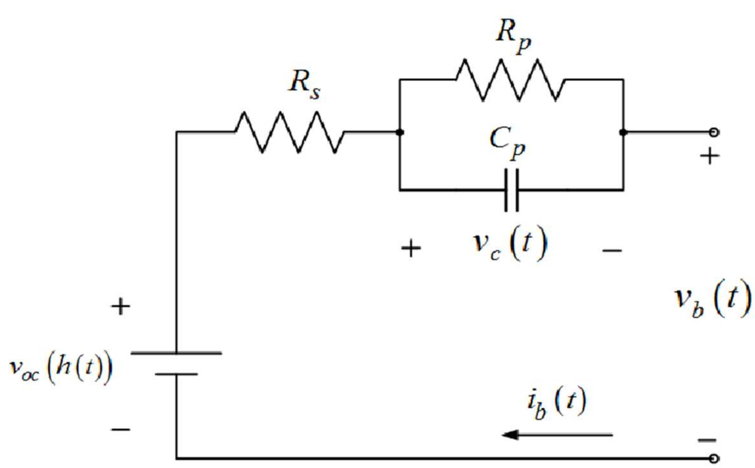

Figure 5 [14]: Simple equivalent circuit model of a battery.

2.4: Cell Balancing

In a battery system, the state of charge and the state of health of each cell can be different. The differences can cause the overcharging or over-discharging of cells when the average of the entire pack has not reached 100% or 0% state of charge. Such as, in Figure 6, if charging continues, cell two will be overcharged. Battery management systems need balancing circuits to ensure the state of charge of each cell is the same. There are two main types of balancing circuits; one is passive balancing, and the other is active balancing. Passive balancing takes charge in a cell with a higher charge state and dissipates it over a load, usually a resistor. Active balancing takes charge from cells with a higher state of charge and distributes it to other cells with a lower state of charge. Balancing occurs when the battery is close to fully charged or discharged, but the timing can change depending on the application. The choice of balancing circuit type depends on the cost, efficiency, and time required for balancing. A few balancing topologies are used, such as the shunt resistor technique, the switched capacitor, and the switched transformer technique.

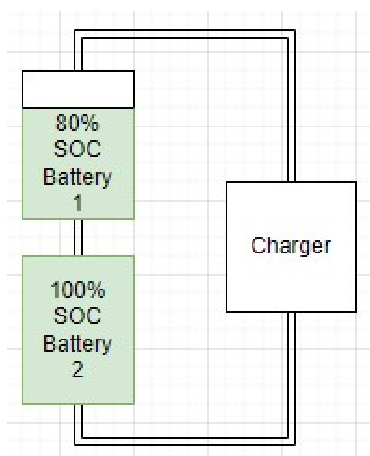

Figure 6: Representation of unbalanced batteries.

Using a shunt resistor is one of the most inefficient ways to balance a battery system since heat energy dissipates the extra energy. The shunt resistor technique uses a resistor in parallel with a single battery cell. It uses a control system to dissipate energy in a cell across the resistor until all cells are balanced. This straightforward design is often used in cheap systems that do not require high efficiency.

The switched capacitor technique uses one or more capacitors to move charge from one cell to another, as shown in Figure 7. This system is very efficient since most of the energy in the cells is transferred via the capacitor. However, the capacitor method is slow since the flow rate depends on the difference in voltage between the two battery cells, which is usually very small [15]. For this reason, the capacitor technique is suitable for circuits that do not need fast balancing time and require high efficiency.

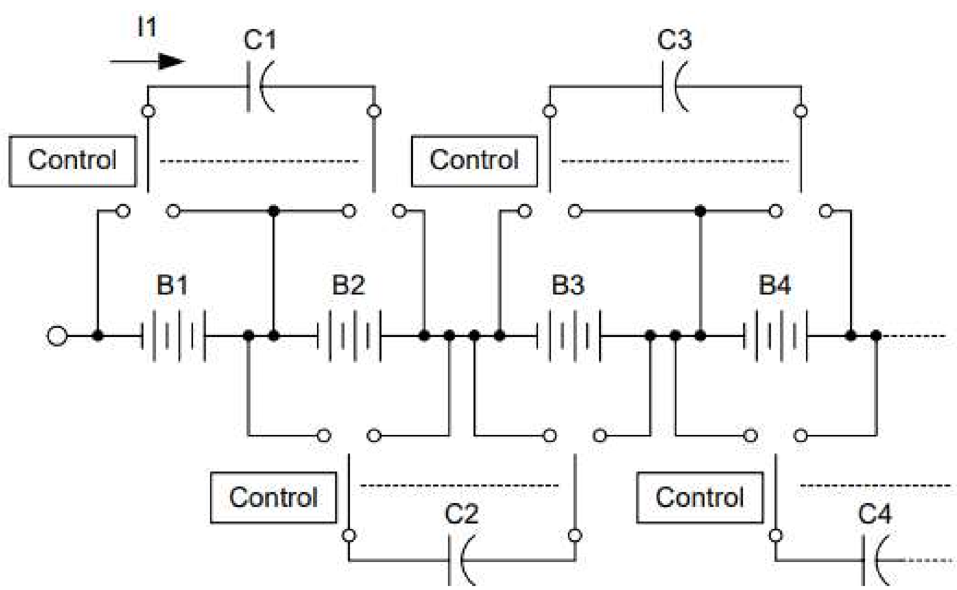

Figure 7 [15]: Representation of a capacitor balancing circuit.

The last technique is the switched transformer, represented in Figure 8. This technique uses a transformer to move energy from one cell to another. The switched transformer is much faster than the switched capacitor technique but may be more expensive due to transformer cost [15].

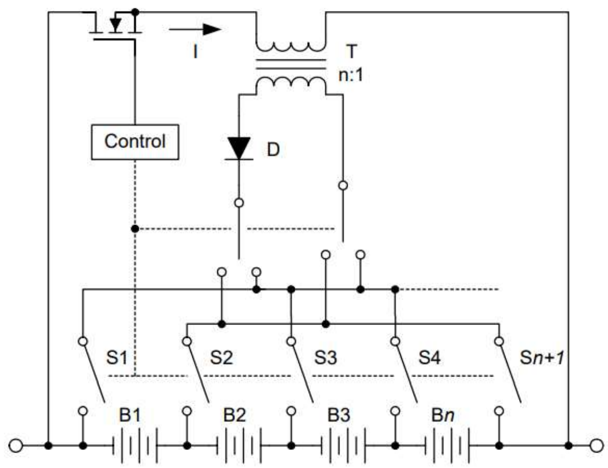

Figure 8 [15]: Battery balancing circuit using transformers.

This paper proposes a new technique called bidirectional BMS. This technique will use bidirectional switches, one in series with a cell and one in parallel with the cell and switch one. The bidirectional switches will allow individual cells to be taken in and out of series during the operation of the battery system. For each series of cells, there will be a bidirectional converter that will keep the output constant during discharge and deal with charging for the batteries. A simple representation of this circuit is shown in Figure 9. The advantages of this system will be that no additional balancing circuit will need to be added, the ability to use different capacity batteries at different stages of life, more control over individual cells, and efficient output. The possible challenge areas are cost, safety, effects on battery cells, and output consistency.

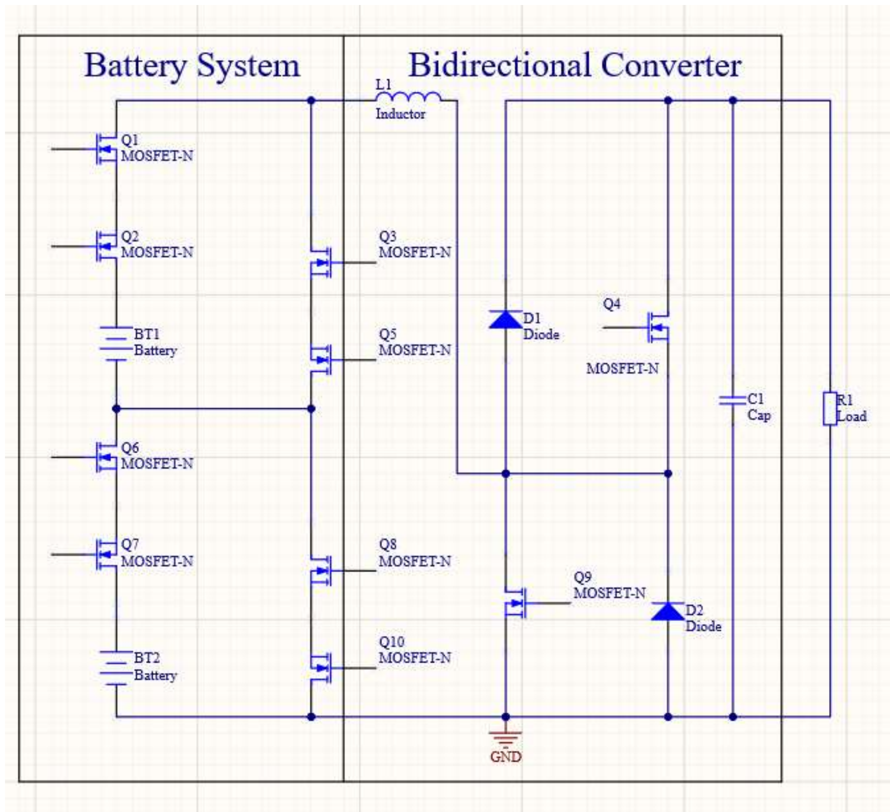

Figure 9: Representation of bidirectional BMS with bidirectional switches and a bidirectional converter to control the battery system.

3: DESIGN

This section will go over the experimental design, the hardware design, and the software design required to make the six-cell BMS.

3.1: Experimental Design

This section describes three experiments: the baseline experiment, the six-cell normal operation, and the six-cell switching operation. The first experiment is the baseline experiment. In the baseline experiment, individual cells from the same supplier will be charged at 1.5C and discharged fully at 2.25C. The baseline cells will be charged and discharged 100 times, and the capacity will be measured before and after the 100 cycles. The capacity loss will show the expected loss for normal operating conditions of the battery. A one-cell BMS PCB (printed circuit board) for capacity testing must be created to run this test. This block diagram shown in Figure 10 uses coulomb counting to estimate the battery capacity. The batteries that are planned to be used are lithium cobalt oxide vs. graphite chemistry.

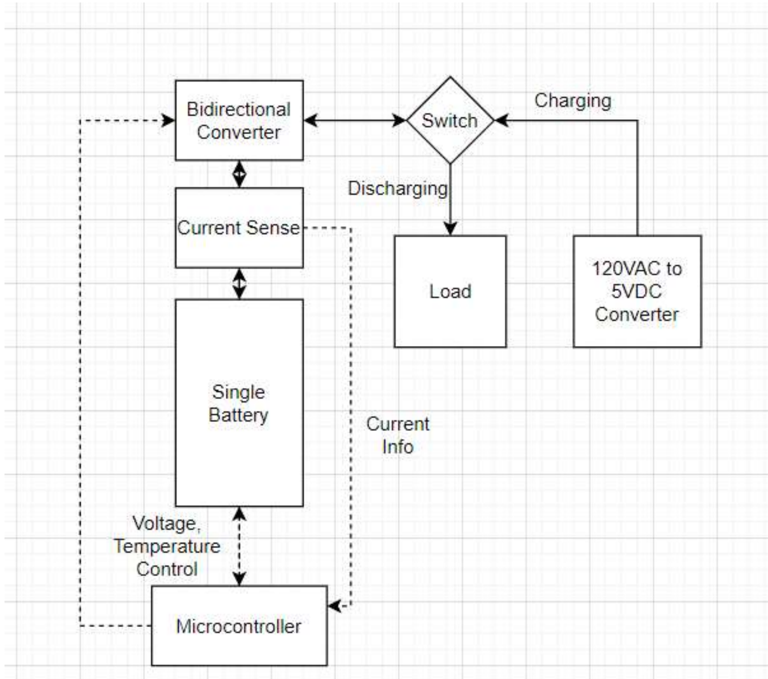

Figure 10: Block diagram of one-cell BMS PCB to measure the capacity of a single battery.

The second experiment will simulate the normal operating conditions of the batteries using the new circuit technique. First, the cells will be fully charged and discharged two times on the one-cell PCB circuit (Figure 10) to get the initial capacity value. Once the initial capacity value is found for each cell in the test, the six cells will be placed in the six-cell BMS. Using voltage measurements, all the batteries will be charged and discharged 100 times together at the 1.5C charge and 2.25C discharge rate for the batteries, then placed back in the one-cell BMS PCB to get the capacity rating of the cells after the test. The capacity results will be compared to the baseline capacity losses to determine if the circuit damages the cells in a significant way.

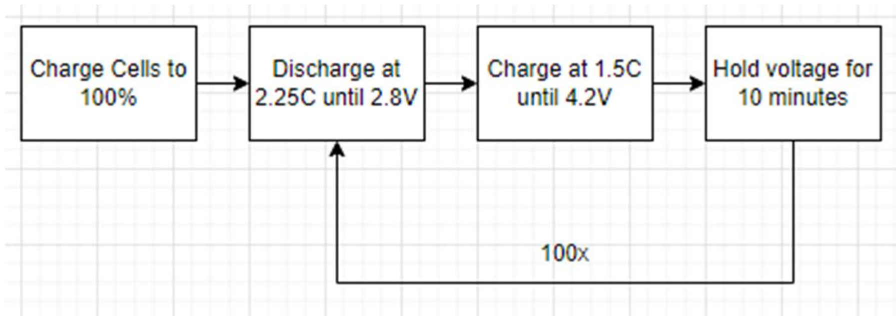

Figure 11: General flow diagram for battery cycle experiments.

The third experiment will test the effect switching cells in and out of the circuit has on the output and the life of the batteries. Six new cells will be used, and each cell will need to have the capacity value of the cell measured before placing it in the balancing circuit. Once placed in the balancing circuit, the cells will be charged and discharged 100 times, as shown in Figure 11. The experiment flow will be similar to the one shown in Figure 12. The cells will be discharged at 2.25C and charged at a rating of 1.5C. During charge and discharge, the output voltage and current of the battery system will be monitored to show what is happening when the batteries are placed in and out of the circuit. When the batteries have been charged and discharged for the final time, the capacity value will be taken and compared to the baseline capacity value to confirm if significant damage occurred to the batteries.

Figure 12: This image shows the charging and discharging pattern of experiment three.

Additional challenges that need to be solved include the design of the six-cell BMS PCB and the one-cell BMS PCB, cost analysis, and safety analysis. The one-cell BMS and six-cell BMS are PCBs designed to fit the batteries and breakouts for additional analysis and logging. The one-cell BMS (Figure 10) and the six-cell BMS (Figure 13) will use a Teensy 4.1 for data logging through an SD card. The Teensy 4.1 is Arduino compatible, so all the additional controls for the BMS will be programmed in Arduino. Further analysis after the experiments will be done with Python using NumPy and Matplotlib. Additional safety analysis should be done, such as the probability of failure and ways to minimize damages using the BMS control system. One example would be what happens if one of the switches fails in the closed position. The final challenge that needs to be addressed is a cost analysis of the entire system and how it compares to the already used systems.

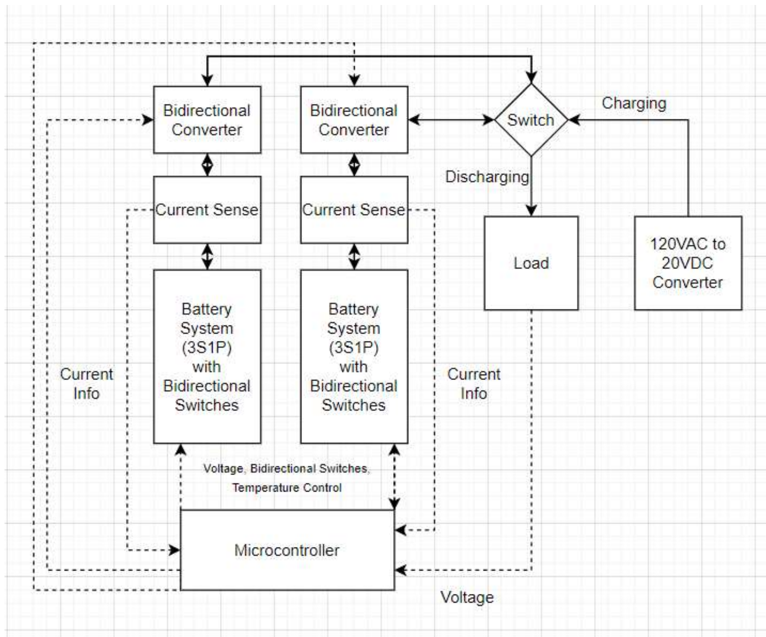

Figure 13: Block diagram of the six-cell BMS connected to the load and the charger.

3.2: Hardware

Some other design decisions must be considered to make the bidirectional battery management system operate correctly. The system needs bidirectional switches, one in series with the cell and one in parallel with the cell and the other switch. The system will need something to drive each switch and a bidirectional converter on each series battery terminal. The BMS will then need to have a way to measure the condition of the battery pack and determine how to respond. There are many ways to design each part of the battery management system. The design choices in this thesis were made to demonstrate how the bidirectional battery management system can work with a six-cell battery pack. Other design choices will need to be considered based on the application of the battery pack. The hardware designed in this thesis was designed to handle a battery pack with two sets of three batteries in series (3s2p). The batteries used are the ICR14500 800mAh 3.7V lithium-ion battery from PKCELL. The rated max continuous discharge current is 1.5C, and the rated max constant charge is 1C, as shown in Table 1.

3.2.1: Bidirectional Switches and Converter

Each cell in the bidirectional BMS requires four MOSFETs, as shown in Figure 14. It is essential to choose MOSFETs that can handle the voltage and the current that they will see in the converter. The max voltage that the MOSFETs will see is the max voltage of the cells, and the max current is the max charge or discharge current of the cells. Depending on the chemistry of the batteries, these values can change. In this design, the AON7400A MOSFET was chosen, with a max drain to source voltage of 30 volts and a max current of 15 amps. Another option is to use a relay or another switching device. The BMS also needs a bidirectional converter on each series element of the batteries, as shown in Figure 14. The buck converter part is used to charge the batteries at varying voltages depending on which cells are in the circuit at the time. The boost converter is used to boost the voltage of the batteries so that each series component can power the load. The original MOSFETs used in the bidirectional converter are the AON7400A, but due to the drain to source voltage, the MOSFETs were changed to IRFZ44N to handle the large voltage when the boost converter is outputting across the load.

Table 1 [16]: Battery Specifications

No.	Item	Characteristics	Remarks
1	Nominal Capacity	Minimum: 760mAh Typical: 800mAh	Standard discharge （0.2C) after Standard charge
2	Nominal Voltage	3.7V	—
3	Charging Cut-off Voltage	4.2V	—
4	Discharge Cut-off Voltage	3.0V	—
5	Standard Charge	Constant Current 0.5C Constant Voltage 4.2V 0.01 C cut-off	Charge Time : Approx 4.0h
6	Maximum Constant Charging Current	800mA（1C）	—
7	Standard Discharge	Discharge at 0.2 C to 3.0V	—
8	Maximum Continuous Discharging Current	1200mA（1.5C）	
9	Operating Temperature	Charge 0～45℃ Discharge –20～60℃	—
10	Storage Temperature	-20～45℃ for 1Month -10～35℃ for 6Months	—
11	Storage Voltage	3.7-3.85V	—
12	Environmental request	RoHS	If the materials of the product and packaging accord with RoHS standard，there will be a RoHS Id on the box.

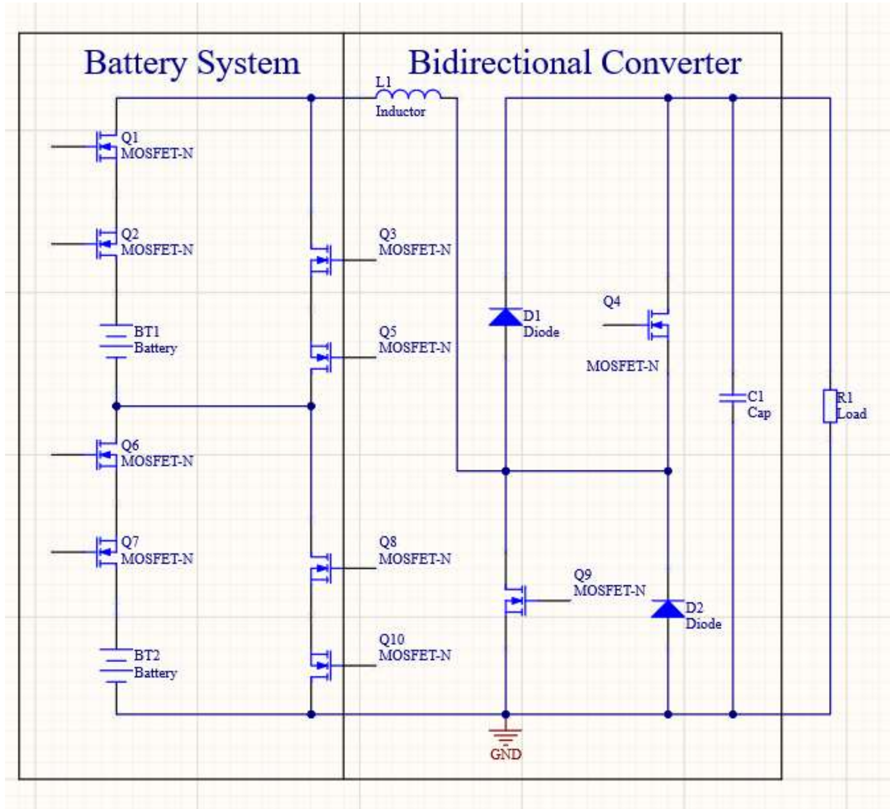

Figure 14: Representation of bidirectional BMS with bidirectional switches and a bidirectional converter to control the battery system.

3.2.2: Gate Drivers

There are a variety of different gate drivers that can be used, such as half-bridge, transformer gate drivers, or optocoupler designs [17]. When deciding which gate drivers to use, it is crucial to pick a design where the bidirectional switch can be in continuous conduction mode 100% of the time. It is also essential to design the gate drivers to ensure that both bidirectional switches are not on simultaneously because this would cause a direct short across the cell. In this design, the IR2104 gate drivers were used with the high side powering the MOSFETs in series with the cell and the low side powering the parallel MOSFETs. Originally two IR2117 gate drivers were going to be used, but to have a deadtime that did not require software, the gate drivers were changed to IR2104. The IR2104 uses a bootstrap design to power the high-side MOSFET. The bootstrap design traditionally does not allow for a 100% duty cycle. A power source of 18V was used to power the gate driver to get the 100% duty cycle needed to power the high-side MOSFETs 100% of the time. The 18V power source allows for a 100% duty cycle since the 18V is higher than the max voltage of the three batteries in the series. The IR2104 gate drivers have a 500-nanosecond built-in dead time to ensure that the high and low side MOSFETs are not switched on simultaneously.

3.2.3: Measurement

Each cell's voltage, current, and temperature need to be monitored to react to the battery conditions and determine charging or discharging conditions. Current is being measured with a 0.002 Ohm current sense resistor on the high side of the batteries with the INA186AIDDFT current sense amplifier. A 1.25-volt reference was set so that the amplifier, shown in Figure 15, could measure both the charging and discharging current. The battery voltage was measured using a voltage divider circuit for each battery. The temperature was measured by using the TT7-10KC8-3 thermistor in a voltage-dividing circuit. The Teensy 4.1 microcontroller was used to measure the parameters and control the circuit, and since the microcontroller has a limited number of pins, a multiplexor capable of measuring analog signals was used.

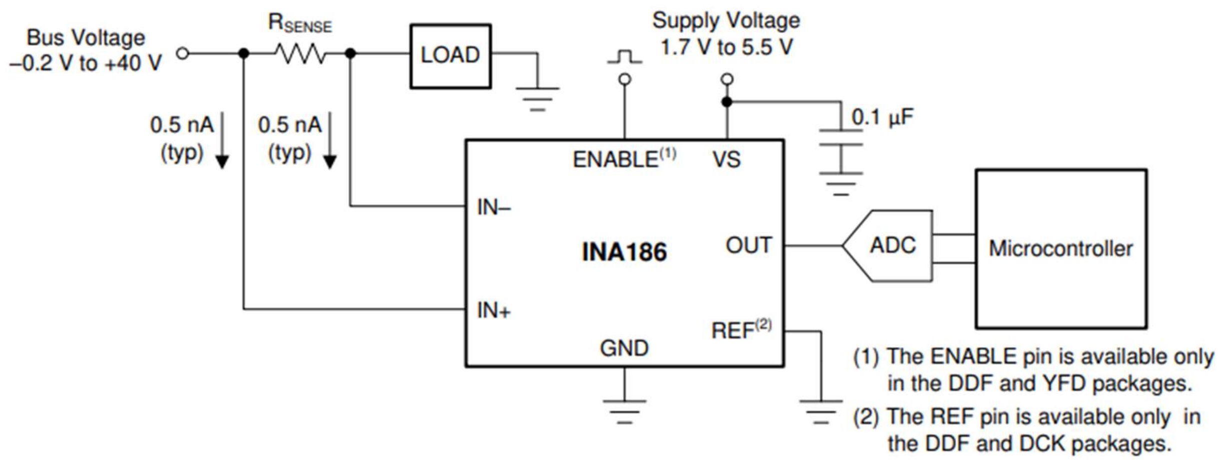

Figure 15 [18]: Typical application for current sense amplifier. REF is set to 1.25V compared to the diagram; this allows for bidirectional current sensing.

3.3: Software

Four different programs were created in this paper. One was to find the initial state of health of the batteries. There was another that ran the long test for the baseline batteries. Then two programs for the six-cell board, one to run as a normal BMS and another that switched through the batteries during charge and discharge. Each program was built off the initial state of health program and then modified based on the program's requirements.

The State of Health program is meant to charge and discharge the batteries at a constant current of 0.5C. For discharge, a constant current is done until the batteries reach a minimum voltage of 3.0V, as shown in Figure 16, then the program changes to constant current charging, where it uses constant current up to a voltage of 4.15V. The program then changes to the constant voltage of 4.15V until the current through the battery reaches 0.13A, as shown in Figure 17. While the battery is charging and discharging, the program is also measuring the capacity of the battery by using the equation in Figure 3 (BMS Background). Each battery goes through an initial and final SOH measurement to figure out if anything happened to the battery during its long test.

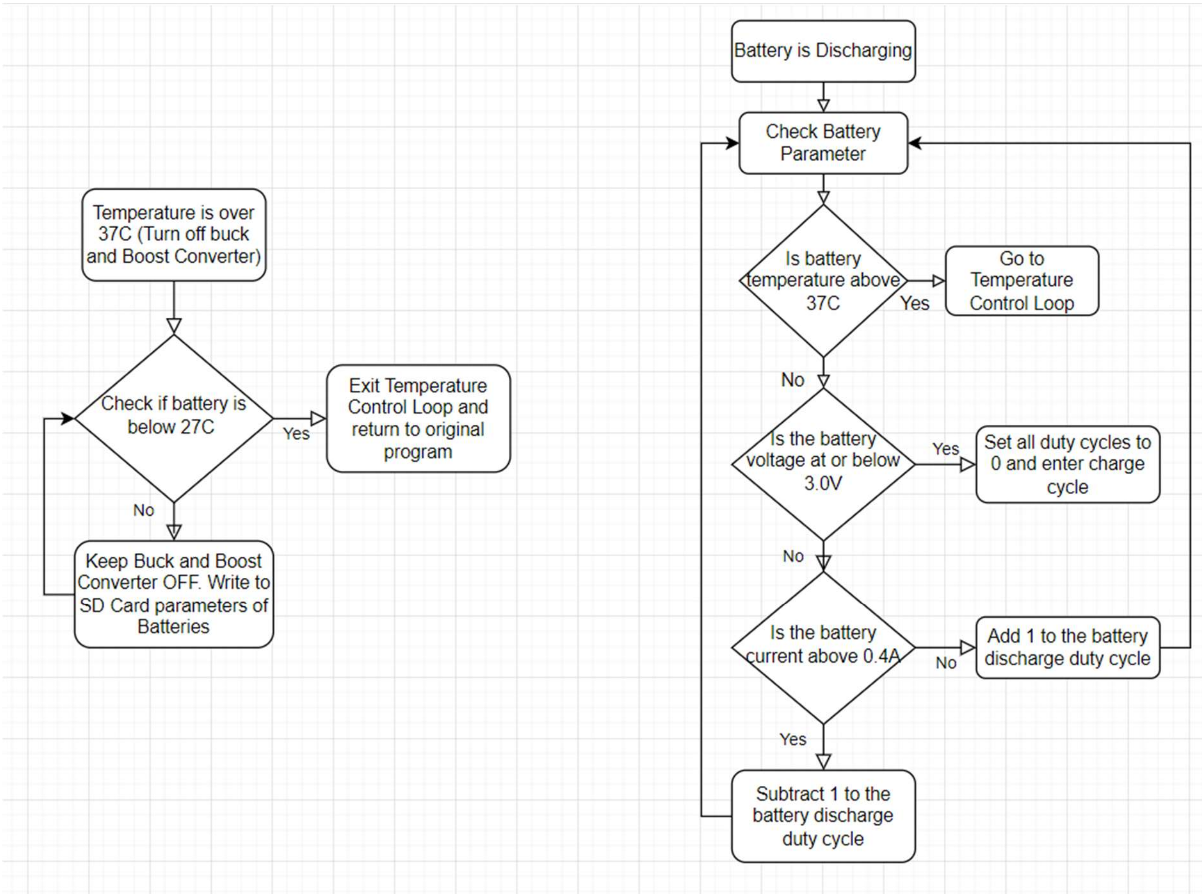

Figure 16: Temperature control structure and the discharging control structure of the one-cell initial SOH program.

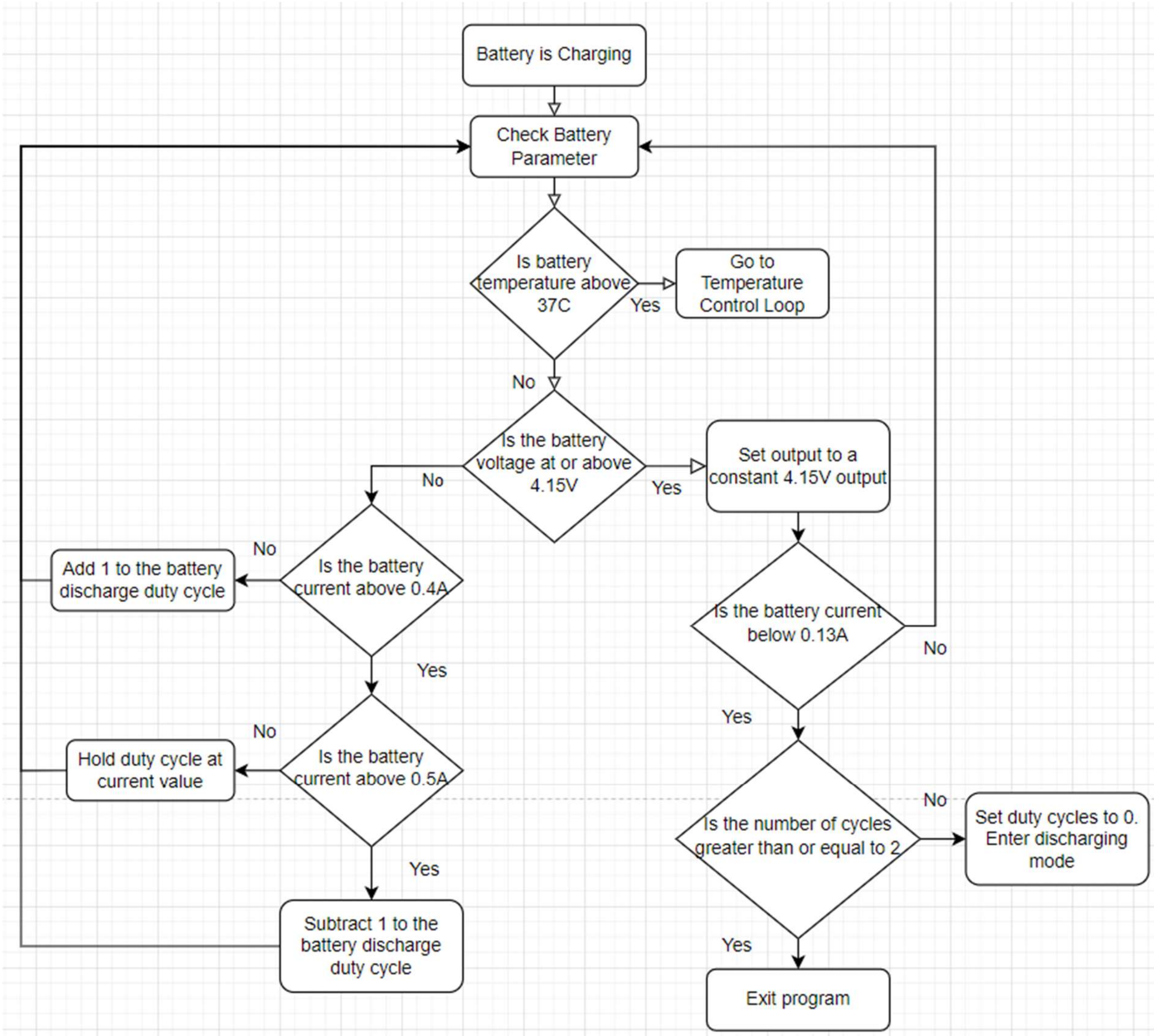

Figure 17: Charging control structure of the one-cell initial SOH program.

3.3.1: One-Cell Software

The one-cell long test is meant to be a baseline compared to the six-cell tests. The one-cell long test does a constant current discharge down to 2.8V, then a constant current charge up to 4.2V with a 10-minute hold at that duty cycle. The 10-minute hold is because the actual voltage is much lower than 4.2V at the constant current due to voltage drops and the battery voltage being different because of charging. The 10-minute hold allows the battery to get to the higher SOC points, as shown in Figure 18. The lower voltage of 2.8V during discharge is also for the same reason. The charge current is 1.8A, and the discharge current is 1.2A. These are slightly higher than the rated continuous current on the datasheet. The high current is due to the time it takes to cycle the batteries and the limited time for testing.

3.3.2: Six Cell Software

The first six-cell program is much like the long one-cell program, except the program balances the batteries after the 10-minute hold. The goal of this program is to see if the batteries end up becoming damaged while being used in the bidirectional BMS circuit. At the end of the 10-minute hold, the charge current is captured. Then the voltage of each cell is measured, and the max voltage of each cell is held. The batteries are then charged up to the max voltage with the same current and drop out of the circuit as they reach the max voltage, as shown in Figure 19. The balancing method chosen is not the best way to balance the batteries because it takes in a lot of assumptions about the batteries, such as similar SOH and similar voltage drops in the hardware. This balancing strategy was chosen for speed, and for other applications, it is recommended to use another technique. Each time a cell is removed from the circuit, the duty cycle is also brought to zero. If the duty cycle is not brought to zero or a smaller value, the charging batteries will have a significant current spike.

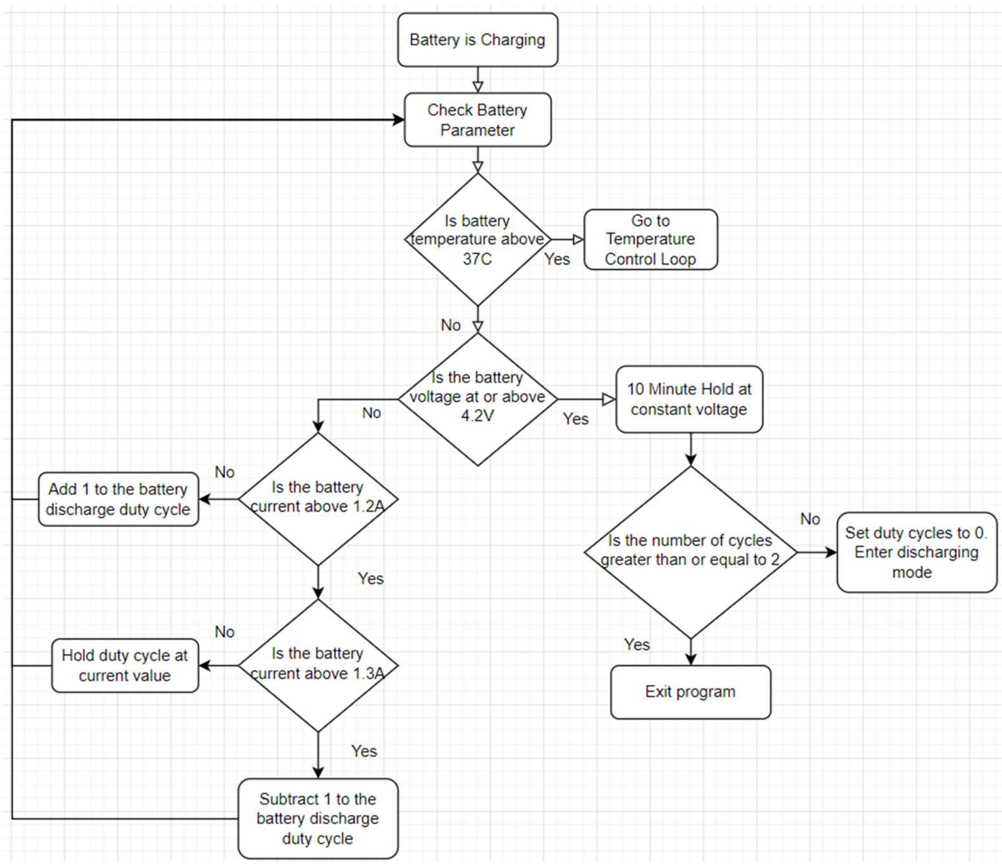

Figure 18: Shows the charging structure of the long one-cell baseline test.

3.3.2: Six Cell Software

The first six-cell program is much like the long one-cell program, except the program balances the batteries after the 10-minute hold. The goal of this program is to see if the batteries end up becoming damaged while being used in the bidirectional BMS circuit. At the end of the 10-minute hold, the charge current is captured. Then the voltage of each cell is measured, and the max voltage of each cell is held. The batteries are then charged up to the max voltage with the same current and drop out of the circuit as they reach the max voltage, as shown in Figure 19. The balancing method chosen is not the best way to balance the batteries because it takes in a lot of assumptions about the batteries, such as similar SOH and similar voltage drops in the hardware. This balancing strategy was chosen for speed, and for other applications, it is recommended to use another technique. Each time a cell is removed from the circuit, the duty cycle is also brought to zero. If the duty cycle is not brought to zero or a smaller value, the charging batteries will have a significant current spike.

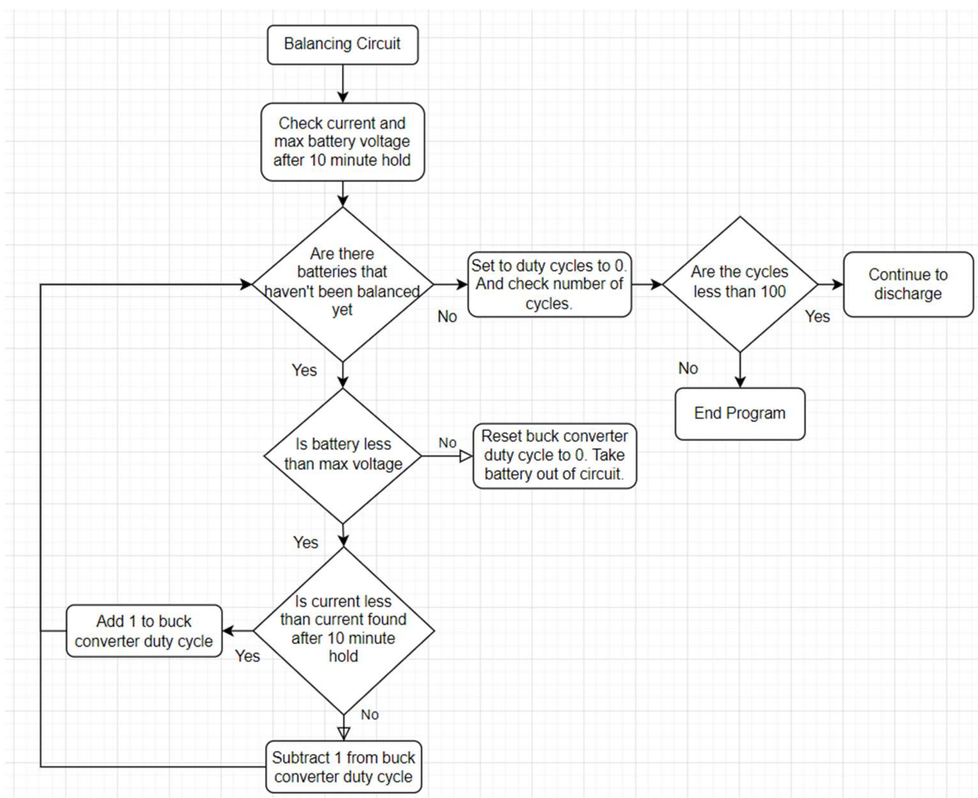

Figure 19: Flow diagram for balancing circuit logic for the six-cell program.

The next six-cell program is meant to show how the bidirectional BMS can switch out the batteries within the series set and to determine if the switching behavior affects the batteries' health. The program is very similar to the other six-cell programs, the only difference being the switching. The program switches through states 101, 110, and 011 shown in Figure 20, where 101 stands for battery one in the circuit, battery two out of the circuit, and battery three is also in the circuit. The first switching point is based on the 50% SOC point. The capacity verse voltage graph of the one-cell test was used to determine the 50% SOC of the batteries. That turned out to be 3.28V for discharge and 3.98V for charge. Each time the batteries switch, the duty cycle returns to zero to eliminate unnecessary current spikes.

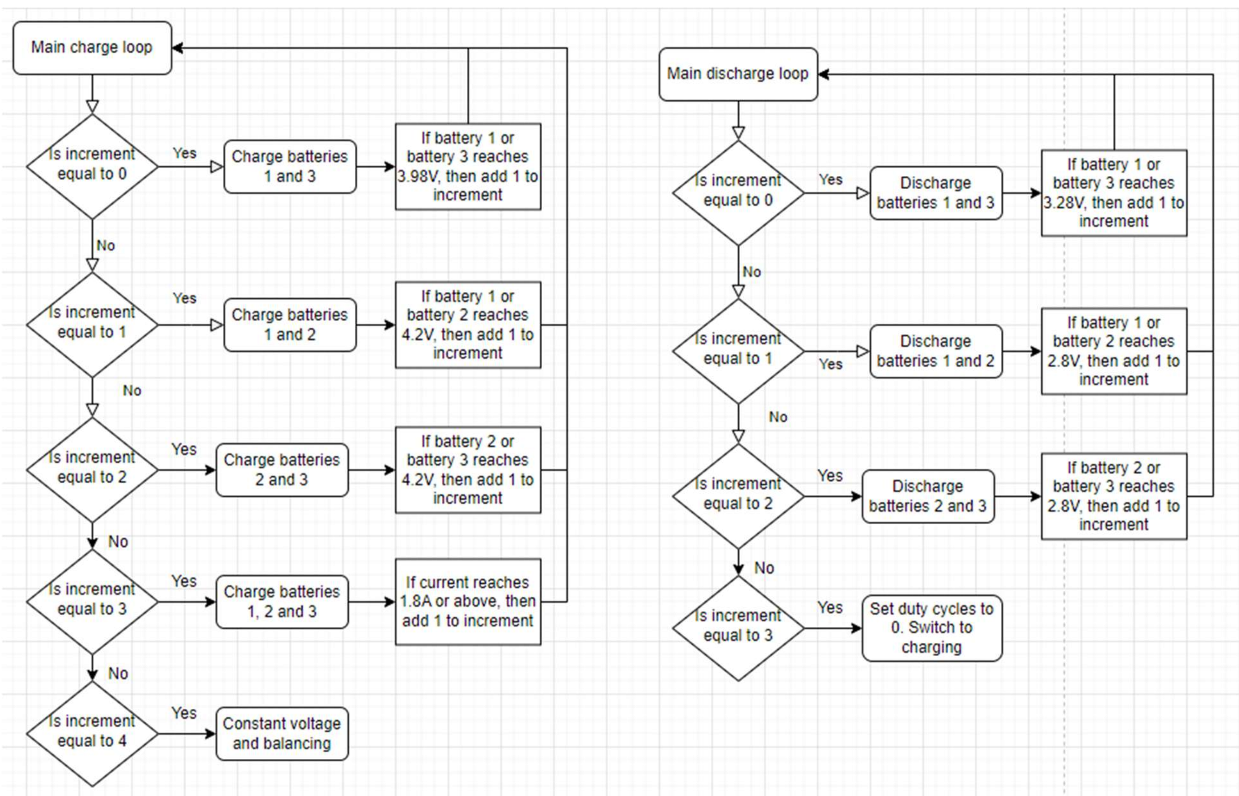

Figure 20: Flow diagram for the switching of the second experiment.

4: RESULTS

After the hardware and software were tested and working, the next step was to start testing. The results section will review the testing for the normal six-cell test, the switching six-cell test, and the baseline tests. Then the results of each will be compared to determine how the bidirectional BMS impacts the batteries.

4.1: Initial and Final Capacity Measurements

Each cell goes through an initial and final capacity measurement to help determine before and after SOH. The cells are charged and discharged with a constant current of 0.4A. Then when the cell reaches 4.15V, a constant voltage of 4.15V is held until the current reaches below 0.13A. In Figure 22, the charge current reaches above 0.4A, and this is because the resolution of the buck converter being used is very low, which means any slight increase in the duty cycle will increase the current significantly. When measuring the initial and final capacity, the program measures the capacity twice. For example, Table 2 has Initial 1 and Initial 2. The initial and final capacity are measured twice in order minimize error and to ensure that the hardware and software are working properly. The voltage, current and temperature are shown in Figure 21, Figure 22, Figure 23.

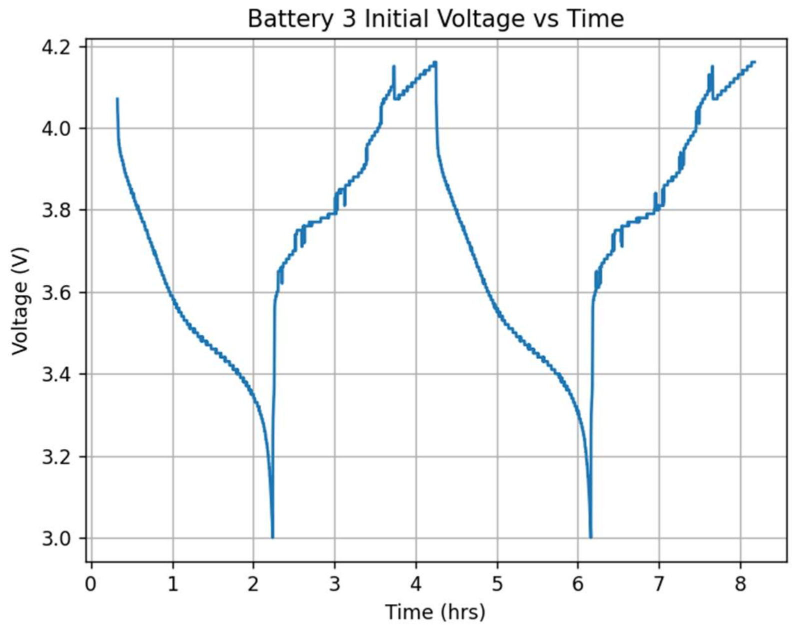

Figure 21: Graph showing the battery voltage for the initial battery three measurement.

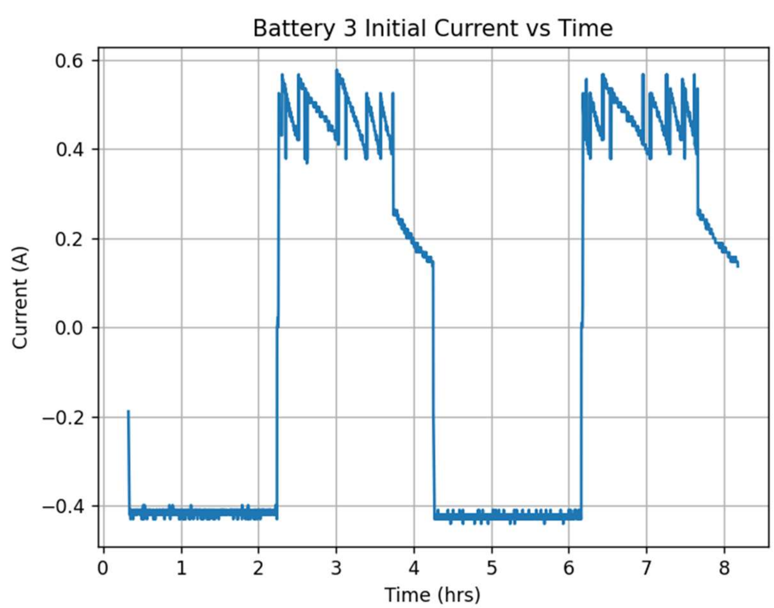

Figure 22: Graph showing the battery current for the initial battery three measurement.

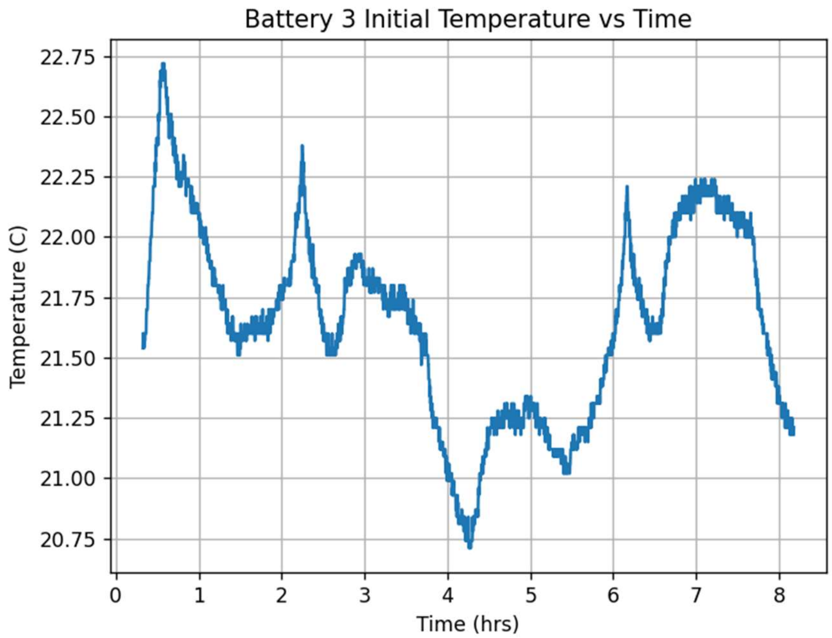

Figure 23: Graph showing the battery temperature for the initial battery three measurement.

4.2: Six-Cell Long Results

The six-cell long test consisted of cycling the batteries 100 times and measuring the capacity before and after. The discharge current was set to 1.8 amps, and the charge current was set to 1.2 amps. The testing took approximately four days to complete. The results shown in Figure 24, Figure 25, and Figure 26 are the halfway point of the testing at cycles 50 and 51. The voltage looks like it drops to zero in Figure 24, and that is because once the batteries are balanced, they are taken out of the circuit until the other batteries are also balanced. Table 2 shows the before and after capacity of the batteries. The batteries are rated with a capacity of 800 mAh by the manufacturer. Also, the batteries A1, A2, etc., reference the location of the battery in the BMS. For example, A1 is the first battery in the A series and is connected to ground and battery A2.

Table 2: Capacity of the Batteries Before and After the Six-Cell Long Test.

Six Cell Long Test Battery Discharge Capacity (mAh)					
Battery	Initial 1	Initial 2	Final 1	Final 2	Capacity Fade %
A1	803	806	803	804	0.310173697
A2	802	806	804	804	1.289134438
A3	822	823	820	820	0.303951368
B1	806	806	819	819	-1.612903226
B2	812	812	814	821	-0.677339901
B3	809	809	803	808	0.43263288

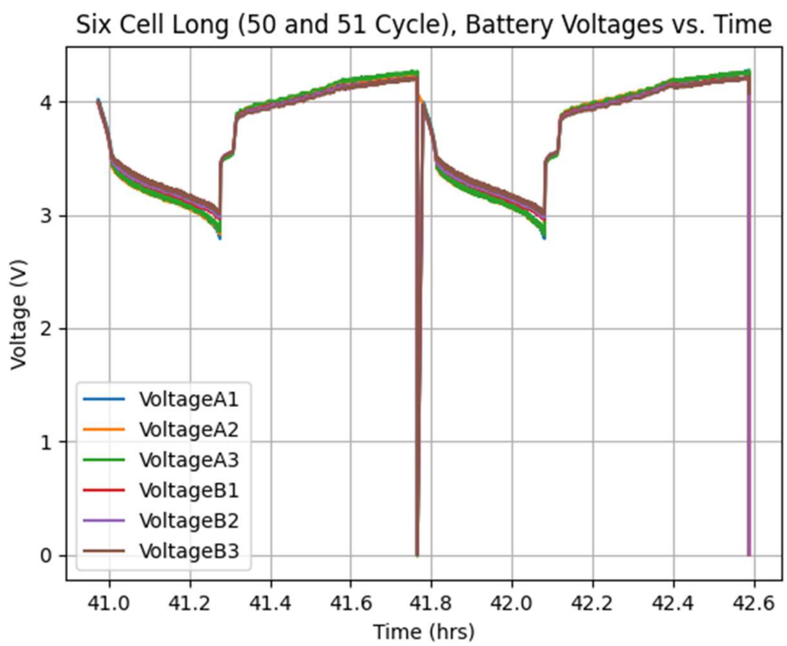

Figure 24: Graph for each battery voltage for the six-cell long test.

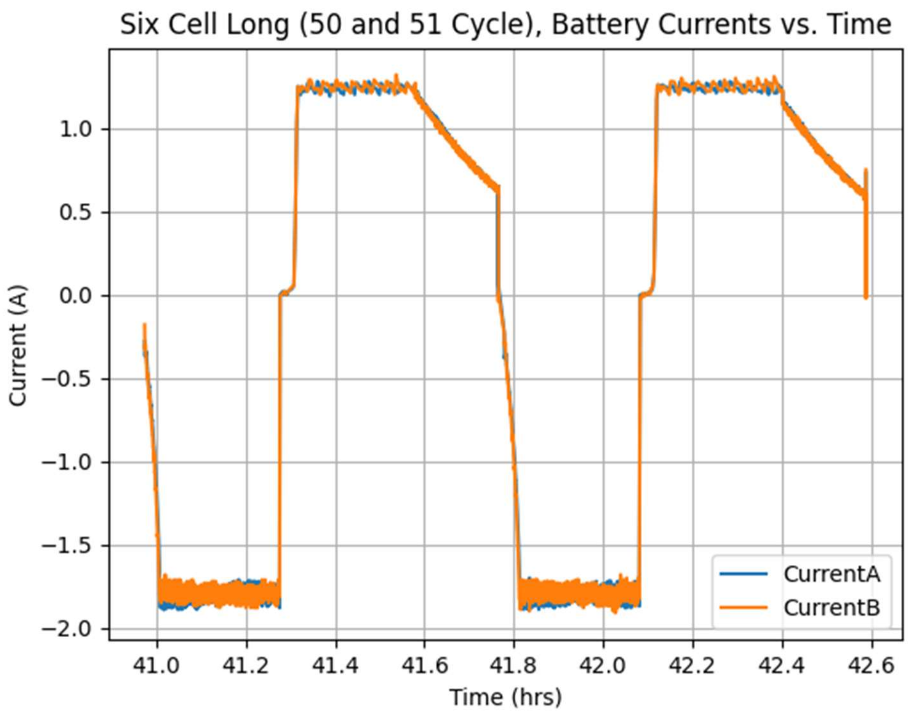

Figure 25: Current profile of the six-cell long test. Negative is discharge, positive is charge.

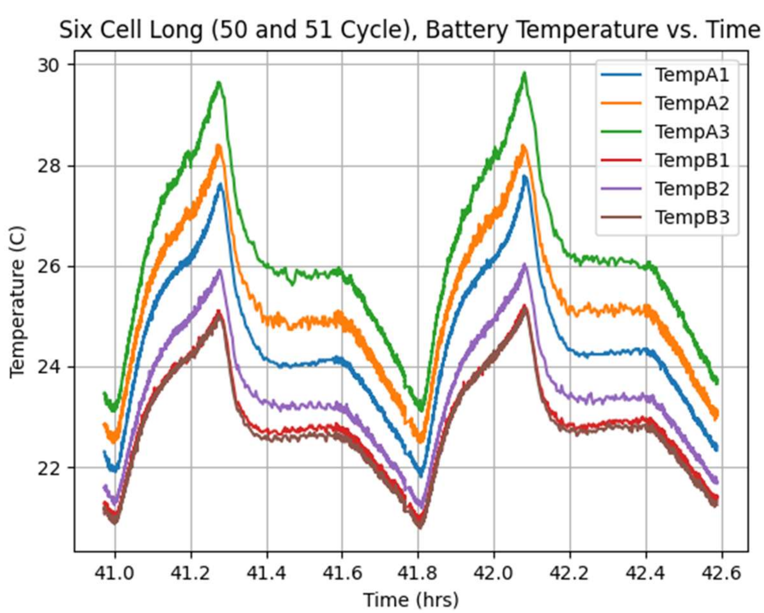

Figure 26: Temperature in Celsius of each battery from the six-cell long test.

4.3: Six-Cell Switch Results

The six-cell switch test has similar parameters to the other six-cell test, except the cells are switching in and out of the circuit. Table 3 indicates how the battery capacities changed at the end of the test. Figure 27, Figure 28, and Figure 29 show the voltage, current, and temperature during cycles 50 and 51, halfway through the test. Figures 27 and 28 show that the voltages and currents drop to zero. This is caused by switching the cells in and out of the circuit.

Table 3: Capacity of the Batteries Before and After the Six-Cell Switch Test.

Six Cell Switch Test Battery Discharge Capacity (mAh)					
Battery	Initial 1	Initial 2	Final 1	Final 2	Capacity Fade %
A1	802	804	774	785	2.926525529
A2	815	823	805	812	1.282051282
A3	788	788	833	833	-5.710659898
B1	832	832	831	832	0.060096154
B2	850	850	816	816	4
B3	830	831	828	828	0.30102348

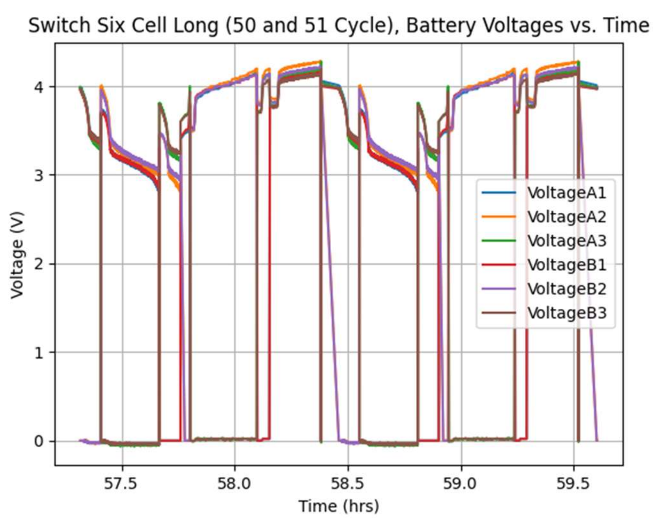

Figure 27: Graph showing each battery voltage of the six-cell switching test.

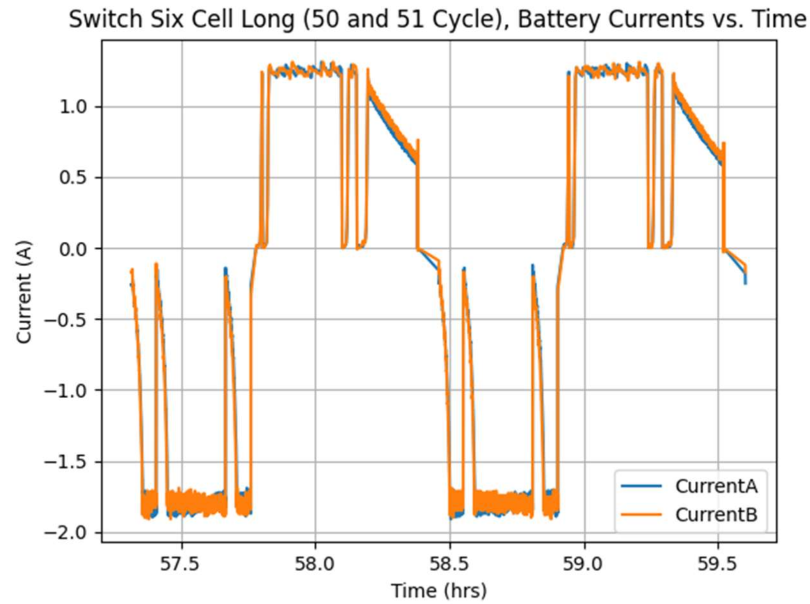

Figure 28: Graph showing the current from the six-cell switch test.

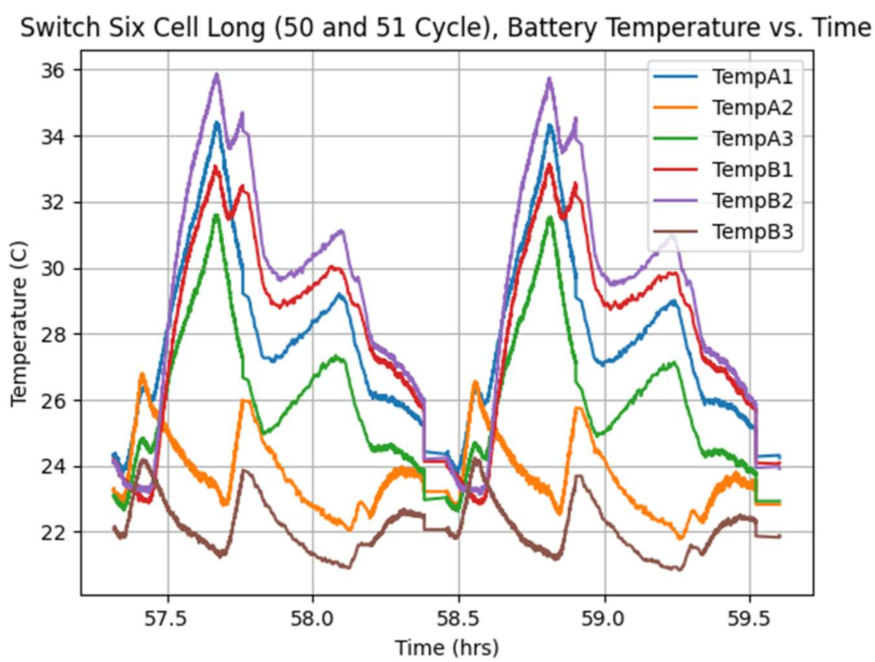

Figure 29: Graph showing the temperatures from each battery in the six-cell switch test.

4.4: Baseline

The baseline test consists of similar parameters to the six-cell long test but does not consist of balancing because the test is one cell. Table 4 shows the capacity change for the batteries in the baseline test. Figure 30, Figure 31, and Figure 32 show the voltage, current, and temperature for cell four as an example of the baseline test.

Table 4: Capacity of the Batteries Before and After Each Baseline Test.

Baseline Test Battery Discharge Capacity (mAh)					
Battery	Int 1	Int 2	Final 1	Final 2	Capacity Fade %
1	789	789	784	785	0.570342205
2	806	812	826	826	-2.101359703
3	803	803	802	804	0
4	820	820	815	823	0.12195122
5	806	806	820	820	-1.736972705

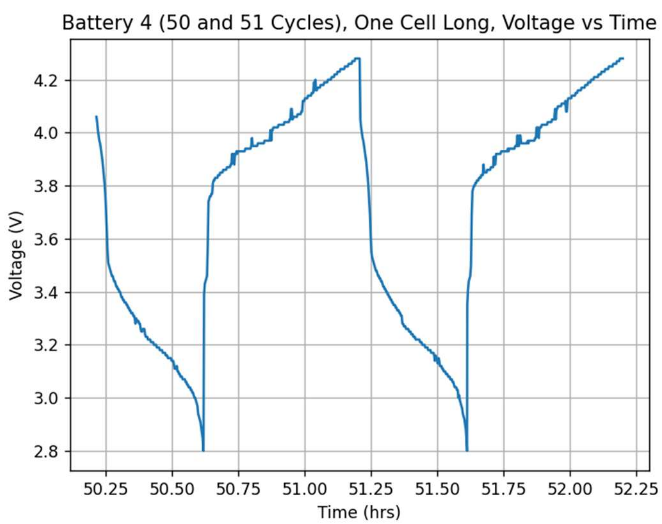

Figure 30: Graph of cell 4 to show the current during the baseline test.

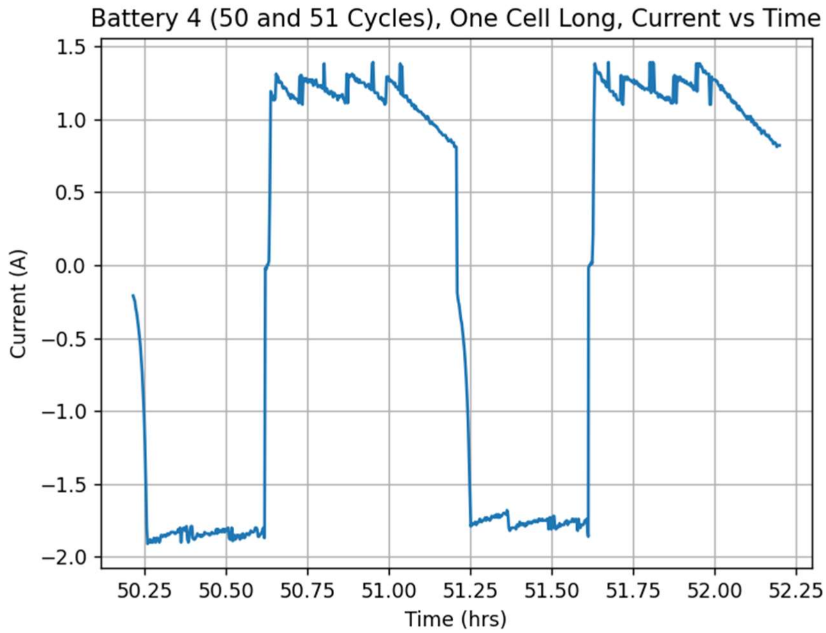

Figure 31: Graph of cell 4 to show the current during the baseline test.

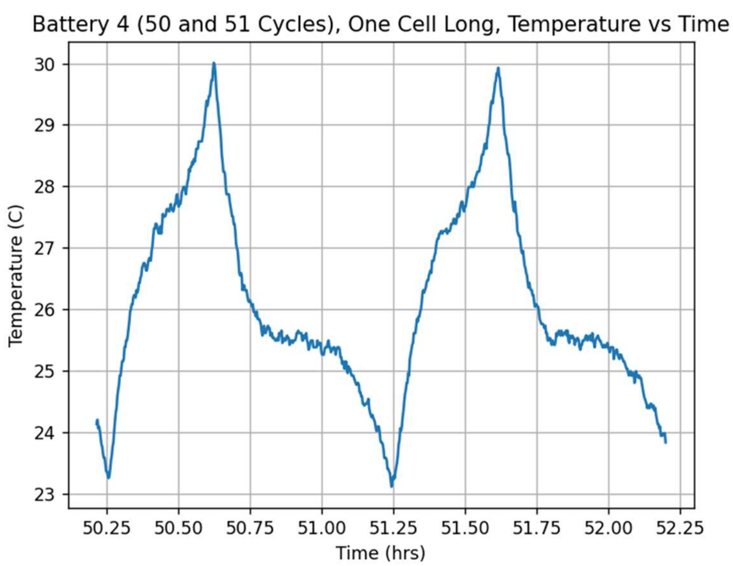

Figure 32: Graph of cell 4 to show the temperature during the baseline test.

4.5: Discussion

In the experiments, there are five cells in the baseline, six in the six-cell long test, and six in the six-cell switch test. Table 2, Table 3, and Table 4 show the before and after capacities of the cells. In the baseline cells average capacity fade was -0.6 percent, meaning the cells, on average, increased in capacity. In the six-cell long test, the average capacity fade was 0.006 percent, and in the six-cell switch test, the average capacity fade was 0.4 percent. Having the capacity fade higher in the six-cell switch and the six-cell long tests indicates that the bidirectional BMS did impact the battery's cells.

Looking at the temperature graph in Figure 29 compared to the temperature graphs in Figures 28 and Figure 32, the temperature of the batteries in the six-cell switch test was much higher than the other tests. The extra increase in temperature could be attributed to the transient effects on the battery cells while switching. A higher cell temperature over time can lead to faster degradation of the cells.

Overall, the data points to the bidirectional BMS harming the battery's cells, due to the higher temperatures seen in the six-cell switch test. It should also be noted that to make a better prediction; there should be more batteries tested and an increase in the number of cycles each cell goes through.

5: SAFETY

Everything eventually fails, so it is essential to consider what happens when the bidirectional battery management system has failures or conditions not expected by regular use. This section will investigate what happens if a bidirectional switch fails and how the system can mitigate its impact. This section will also look at what happens when an odd number of batteries are in series, such as if two cells are in one series block and then three cells are in the other. The BMS must be able to manage the output of the batteries so that they do not cause more stress on the batteries still in the circuit. Finally, this section will also examine how the output looks when the batteries are taken out quickly. This is important because the user may have batteries become damaged in certain conditions, but the system should keep the output stable.

Eventually, one of the bidirectional switches will fail. Luckily this is not the end for the bidirectional BMS, and there are a few different protocols the BMS can go through to manage these failures. A bidirectional switch has the potential to fail either in the closed position or the open position. If the switch fails in the open position, then that means that current cannot flow through the switch. If the switch fails in the closed position, the switch is short, and current can flow through the switch. The chart in Table 5 shows the possible failure conditions and how to mitigate their effect on the overall battery pack, while the switches can be referenced in Figure 33.

Table 5: Failure Conditions when the Bidirectional Switches in Figure 33 Fails.

Bidirectional Switch		
Series	Parallel	Condition
Open	Good	Battery Out of Circuit
Closed	Good	Supportive BMS Mode
Good	Open	Supportive BMS Mode
Good	Closed	Battery Out of Circuit
Open	Open	Series Element cannot be used
Open	Closed	Battery Out of Circuit
Closed	Open	Supportive BMS Mode
Closed	Closed	Shoot Through

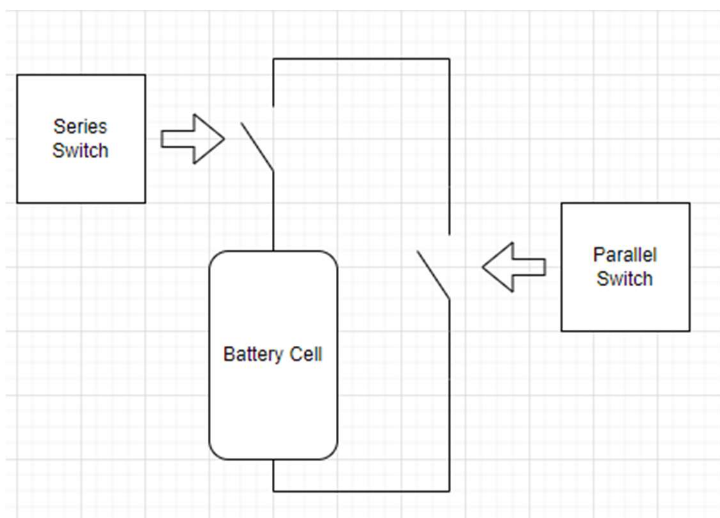

Figure 33: Bidirectional switches indication.

The BMS can go into four different modes when a bidirectional switch fails. The first mode is the battery out of the circuit, which acts as if the switch is not there when the switch fails. This is not a problem for the bidirectional BMS because it is normal for batteries to be taken out of the circuit. The only problem is that the pack has lost one cell, which means the entire system will be down one cell's capacity. For a more extensive system, this is a small problem, but for more miniature battery packs, the cell being lost can have a higher impact on the overall capacity.

The next condition is the supportive BMS mode. In this failure condition, the switches fail, so the battery cannot be brought out of the circuit. In order to mitigate this problem, the series element can be programmed to charge and discharge based on the conditions of that cell. Such as, while charging, if the battery stuck in the circuit reaches one hundred percent SOC first, all the batteries can be brought out of the circuit. Then the battery can be discharged until it reaches a similar or below SOC of the other batteries. On discharge, a similar condition can occur where the battery is switched to charge mode to charge the battery up to close to the other cells.

The next conditions can have a higher impact on the battery pack. The series element cannot be used means that both switches failed in the open condition, and the current can no longer flow. This means the entire stack of series batteries can no longer be used. In order to get around this problem, an additional switch can be added, or a midpoint switch can be added to connect the mid-point to ground or the voltage common collector. An additional switch would allow for half of the batteries to still be operational and can be beneficial for large battery systems where output reliability is a high priority.

The last condition is if both bidirectional switches fail closed. This would mean that the cell will be shorted directly. A short across the cell is a problem and can cause damage to the battery. One way to protect the battery is to have a fuse in series with the battery. That would cause the fuse to open and allow the BMS to operate as if the battery is out of the circuit.

The purpose of the bidirectional BMS is to be able to take the batteries out of the circuit to protect them. It is essential to know that the other batteries still in the circuit are not being damaged. Part of ensuring that the batteries are not being damaged is to ensure that when multiple batteries are taken out of the circuit, the series element can still have a stable current output. This means that the battery current still in the circuit is not forced to go much higher than the BMS wants the batteries to. In this safety experiment, all three batteries of section A of the bidirectional BMS will still be in the circuit, and only the cells from section B will be in the circuit. The BMS will then try to apply a constant current discharge of 1.8A. This will show if section B can hold a constant current output even though there is only one battery in the series system compared to section A which has three.

In Figure 34, the current from A rises much faster than the current from section B. After about 12 seconds, current B catches up to current A and stays at 1.8A. This means that the bidirectional BMS can still control the battery's current flow even though the overall voltage of series A and series B are not close to being equal to each other. This is important to ensure that BMS does not cause an overcurrent on the batteries. The amount of power being given to the load should be smaller than if all the batteries are in the circuit.

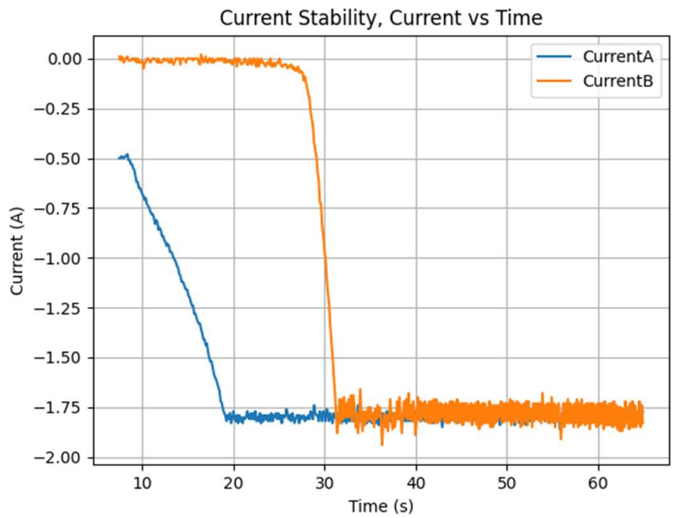

Figure 34: Shows the current held at 1.8A with one battery in the circuit for series B.

The next part is to look at the output of the bidirectional BMS when the batteries are taken out of the circuit. The six-cell bidirectional BMS designed for this thesis was not designed to have load output control. Investigating what happens to the output is still important, so a theoretical analysis will still be done. The simulation will examine the current increase required when each battery is removed from the circuit. The start current will be 1 amp with the six cells in the circuit, and an efficiency of 85% will be assumed for the bidirectional converter.

Table 6: Current Rise to Hold Constant Output Power.

Batteries	Voltage (V)	Efficiency	Output Power (W)	Current (A)
6	3.7	0.85	18.87	1
5	3.7	0.85	18.87	1.2
4	3.7	0.85	18.87	1.5
3	3.7	0.85	18.87	2
2	3.7	0.85	18.87	3
1	3.7	0.85	18.87	6

From Table 6, it is shown that with the first few batteries dropping out of the circuit, the current does not rise that much. However, after three cells are left in the circuit, the current required to keep the same output power rises much higher than the battery can handle. In an application circuit, the BMS can have a max power estimation based on the number of cells still in the circuit and ensure that the limit is never exceeded. Compared to a regular BMS, the output power decrease is a downfall for the bidirectional BMS. In a typical balancing system, the capacity is distributed, and the power drop is less severe than taking out an entire battery.

6: COST COMPARISON

In Engineering, many things must be considered when choosing a new design. One of those things is cost. This section will examine the cost difference between a capacitive balancing BMS and a bidirectional BMS. It is not easy to compare without knowing the requirements for the actual design, so that these comparisons will be made based on the six-cell design. However, it is recommended to redo this analysis if operating parameters change. This section will look at the number of components per battery, the cost of components per battery, and the probability of failure to look at maintenance costs.

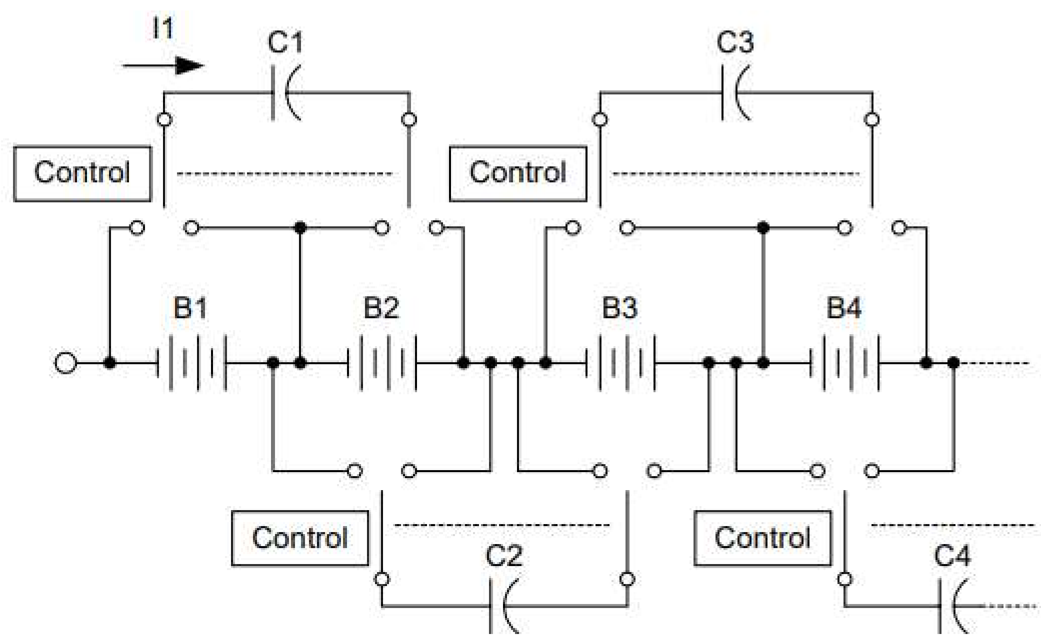

Figure 35 [15]: Representation of a capacitor balancing circuit.

There are a variety of capacitor balancing circuits. The circuit that will be used to compare to the bidirectional BMS is the circuit shown in Figure 35. In this example, there is a capacitor for almost every cell and a switch used to move charge from one cell to another. In order to make this a closer comparison to the bidirectional BMS, the switch mechanism will be represented as two MOSFETs. The capacitor balancing design requires components per battery. The components are two MOSFETs, a capacitor, and a gate driver. The MOSFETs used in this design do not require as much current as those used in the bidirectional switches of the bidirectional BMS but do high switching frequencies to induce reasonable balancing speed. The capacitive balancing technique is known to be a slower balancing system because the capacitors have trouble moving a large amount of charge at one time.

Four MOSFETs and one gate driver are required per cell for the bidirectional BMS. The MOSFETs required for the bidirectional BMS are required to handle more current than the capacitor balancing circuit and are more expensive. The design also requires a control system and a way to measure the parameters of the batteries, which is very similar to the capacitor balancing, so the components are assumed to be the same in both designs. The bidirectional BMS does require a bidirectional converter connected to each series element of the BMS. The parts for the bidirectional converter include two MOSFETs, one gate driver, an inductor, and two capacitors.

Table 7: Estimated Cost for a Capacitor Balancing Circuit.

Cost per Battery					Total Cost of Unit			
Number Required	Component	Cost Per Component	Total Cost		Number Required	Component	Cost Per Component	Total Cost
2	MOSFET	$0.30	$0.60		1	Microcontroller	$10	$10.00
1	Gate Drivers	$2.79	$2.79		2	Mux	$0.70	$1.40
1	Capacitor	$0.50	$0.50		50	Resistors	$0.10	$5.00
					20	Capacitors	$0.10	$2.00
		Total	$3.89		6	Temperature Sensor	$0.46	$2.76
					2	Current Sense Circuit	$1.67	$3.34
					6	Battery Circuit	$3.89	$23.34
							Total	$47.84

Table 8: Estimated Cost for a Bidirectional BMS Balancing Circuit.

Cost per Battery					Total Cost of Unit			
Number Required	Component	Cost Per Component	Total Cost		Number Required	Component	Cost Per Component	Total Cost
4	MOSFET	$0.40	$1.60		1	Microcontroller	$10	$10.00
1	Gate Drivers	$2.79	$2.79		2	Mux	$0.70	$1.40
					50	Resistors	$0.10	$5.00
		Total	$4.39		20	Capacitors	$0.10	$2.00
					6	Temperature Sensor	$0.46	$2.76
					2	Current Sense Circuit	$1.67	$3.34
					6	Battery Circuit	$4.39	$26.34
					2	Bidirectional Circuit	$6.86	$13.72
							Total	$54.56

The price points for these components were estimated based on similar parts used in the six-cell design based on prices from a well-known electronics vendor, Digi-key. The expected total cost shown in Table 7 is $47.84 for the whole system and approximately $3.89 for each battery. This is compared to the bidirectional BMS, which costs $54.56 and approximately $4.39 for each battery shown in Table 8. The bidirectional BMS has a 13% increase in cost per battery over the capacitor balancing method.

Due to budget and time constraints, it is impossible to accurately measure the likelihood of failure and the maintenance required over a long period. In order to truly determine the probability of failure would require a large amount of data and test from each of the designs directly. The system's stresses will be examined, and the ability to operate during a failure will be analyzed to guess which design will require more maintenance from failures. The highest likelihood for failure for each device is the MOSFETs due to the transients from switching and heat caused by switching. In the bidirectional BMS, there are more MOSFETs, and the MOSFETs in the bidirectional BMS must supply higher currents compared to the capacitive balancing system, which means that it is likely that the bidirectional BMS has a higher probability of failure than the capacitor balancing system. However, as described in the safety section, the bidirectional BMS is capable of still operating the BMS in a MOSFET failure mode and is only significantly affected in only one failure condition out of eight. In the capacitor design, it is less likely to have a MOSFET fail, but a failure would mean that the cell can no longer balance. The capacitor balancing system can still operate for a time, but eventually, the battery cell with the MOSFET failure will drift from the SOC of the other batteries. The required maintenance per failure is much lower in the bidirectional converter compared to the capacitor balancing.

7: CONCLUSION

Battery management systems can significantly impact the efficiency and lifetime of the battery it monitors. A designer should choose a BMS that is appropriate for the application of the battery. This paper examined the reliability, impact on the batteries, and functionality of the bidirectional battery management system.

The paper reviewed the design for a bidirectional BMS, the results from various long tests, potential safety concerns and solutions, and a cost comparison to traditional balancing networks. The long test found that when the bidirectional BMS was dedicated more toward switching, the temperature of the batteries was higher than the other long tests, and the capacity of the batteries decreased more. The long test consisted of 17 batteries being cycled 100 times. In order to confirm the results from this paper, more testing should be done, including more cycling times and increasing the number of batteries tested.

The safety section investigated all the possible MOSFET failure modes and how the bidirectional BMS can react to them. There was one failure mode that would make the bidirectional BMS inoperable, but the failure could be routed with an additional switch. The safety section also found that the BMS can operate in constant current mode even if many batteries are out of the circuit. However, the BMS's output power decreases significantly as the batteries leave the circuit.

The cost section found that the overall cost of the bidirectional BMS is reasonably comparable to traditional BMS systems, and a small six-cell BMS only costs 13% more than a capacitor balancing network for the same amount of cells. In the end, the bidirectional BMS system is very robust. However, it should be investigated further to ensure that the system can protect the batteries as it was designed to do.

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APPENDIX A

TUNING

Tunning measurement values:

Voltage:

Procedure (Test 1):

1. The power supply was connected to each of the battery balancing connectors on the BMS board, one at a time.
2. The analog values where measured and tuned at 3.0V per that cell. Example cell 3 would be 3*3 = 9V.
3. The actual voltage was then measured by a multimeter and the R2 resistance of the voltage divider was calculated.
4. The R2 value was then placed into the Arduino code and then the 3V, 3.7V and 4.2V per cell was compared to the actual voltage.

Procedure (Test 2):

1. A battery was connected to the balance terminal of the BMS.
2. The function to measure each cell voltage was used to compare to the actual voltage of each cell.

Table 9: Voltage Measured for Each Cell.

		Test 1				
Cells	BMS Voltage 3.0	Actual Voltage 3.0	BMS Voltage 3.7	Actual Voltage 3.7	BMS Voltage 4.2	Actual Voltage 4.2
1	2.99	2.993	3.68	3.861	4.18	4.179
2	5.98	5.98	7.36	7.37	8.37	8.38
3	8.97	8.97	11.06	11.08	12.56	12.57

Table 10: Voltage Accuracy Test.

	Test 2		
Cell #	BMS Voltage	Actual Voltage	Error %
1	3.72	3.724	0.107411
2	3.68	3.705	0.674764
3	3.68	3.68	0

Current:

Procedure 1:

1. Multiple analog values where taken at different currents. The currents where then measured with a multimeter.
2. The slope of the current vs analog values was then used to find the resistance of the current sense resistor.

Procedure 2:

1. The BMS calculated values were taken at different currents measured by the multimeter. The slope of this line was taken to compare the fit of the measured vs calculated. A slope of 1 is a perfect fit.

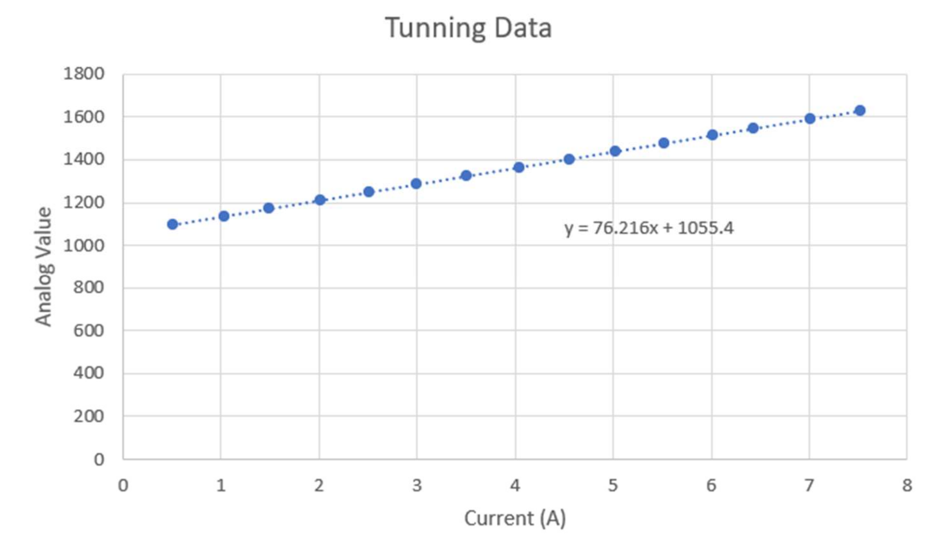

Figure 36: Tunning the current sense resistor.

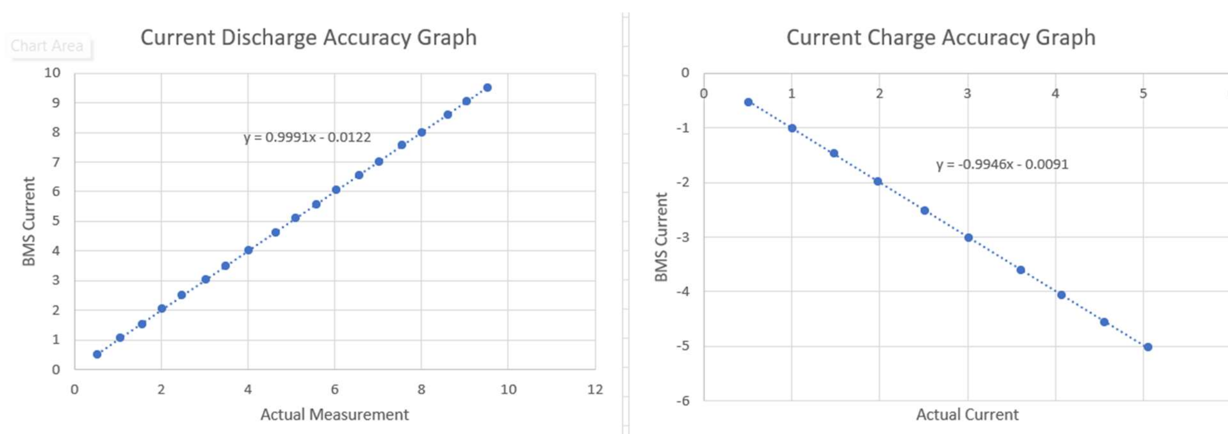

Figure 37: Comparing the discharge and charge currents of the BMS to the calculated.

Temperature Limit:

Procedure

1. A motor was connected as a load to the BMS.
2. The temperature sensor was then increased to a temperature above 45C which was then set as the cutoff.
3. Each sensor was raised to the cutoff temperature.

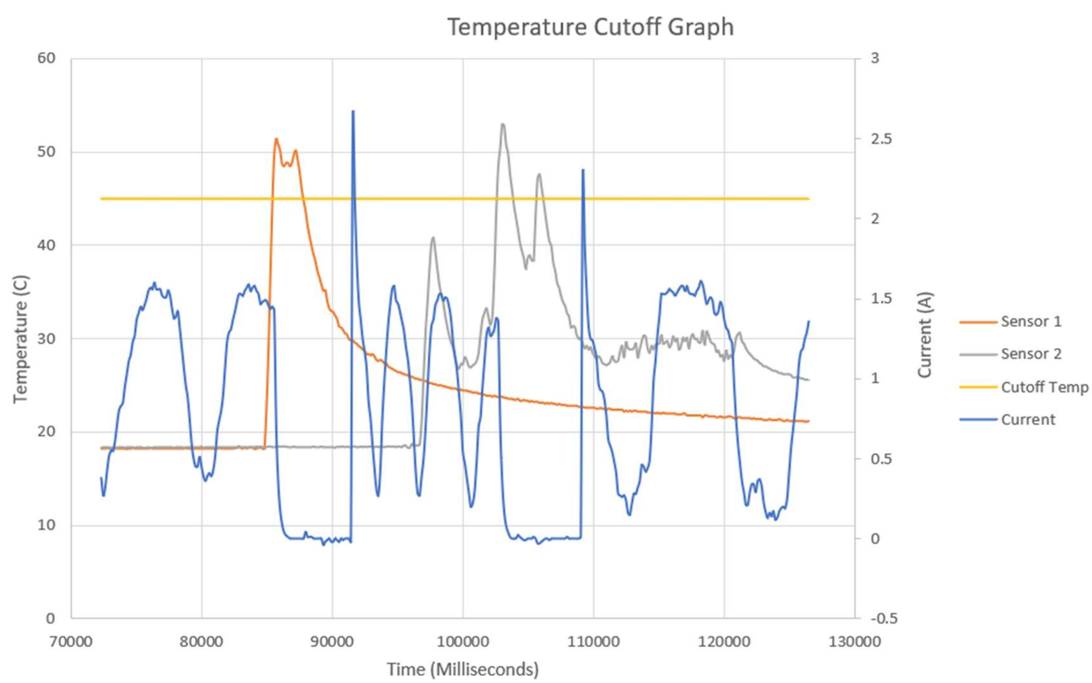

Figure 38: Graph showing the BMS cutting off at the set temperature cutoff.

APPENDIX B

SIX-CELL SCHEMATICS

Schematic for Six-Cell BMS:

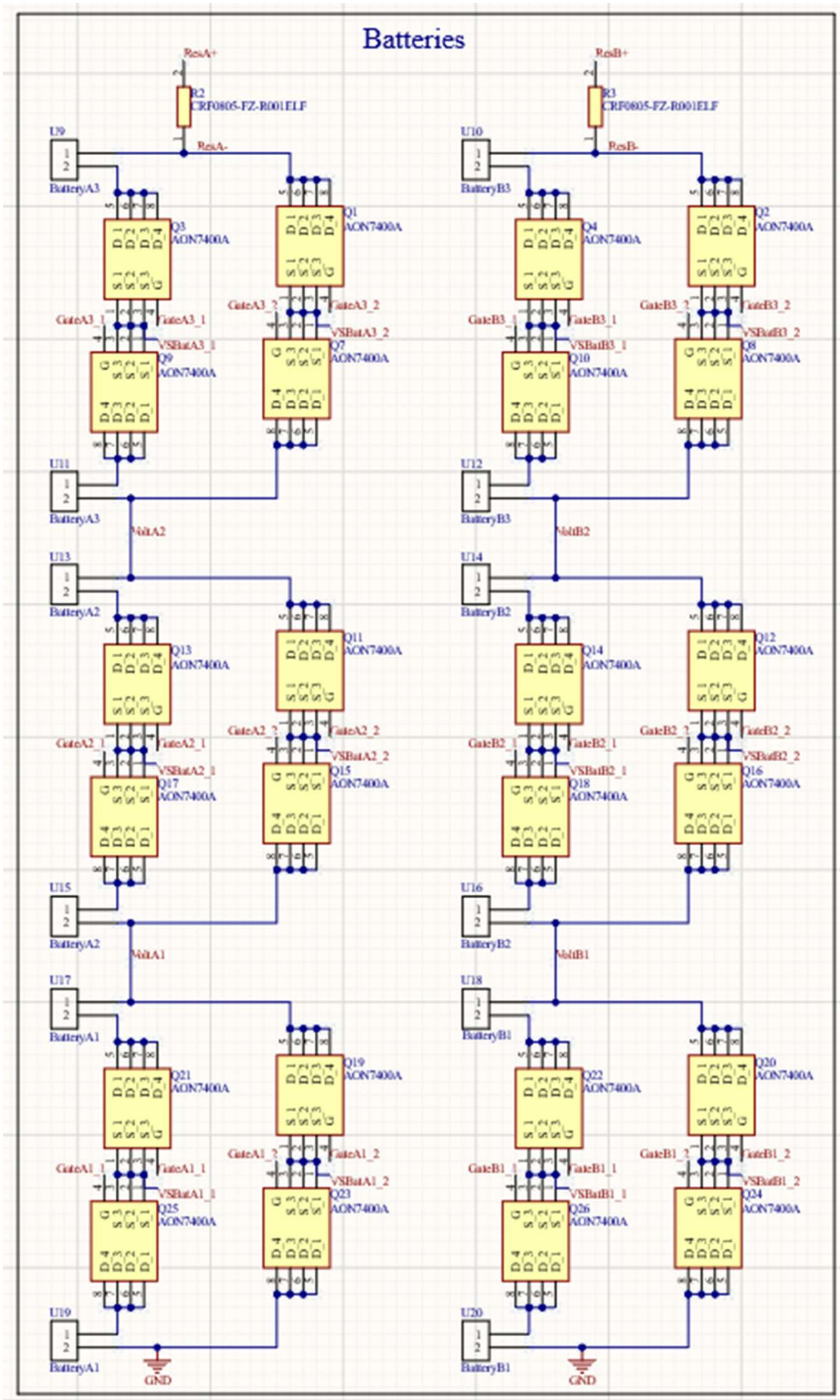

Figure 39: Cell configuration with bidirectional switches.

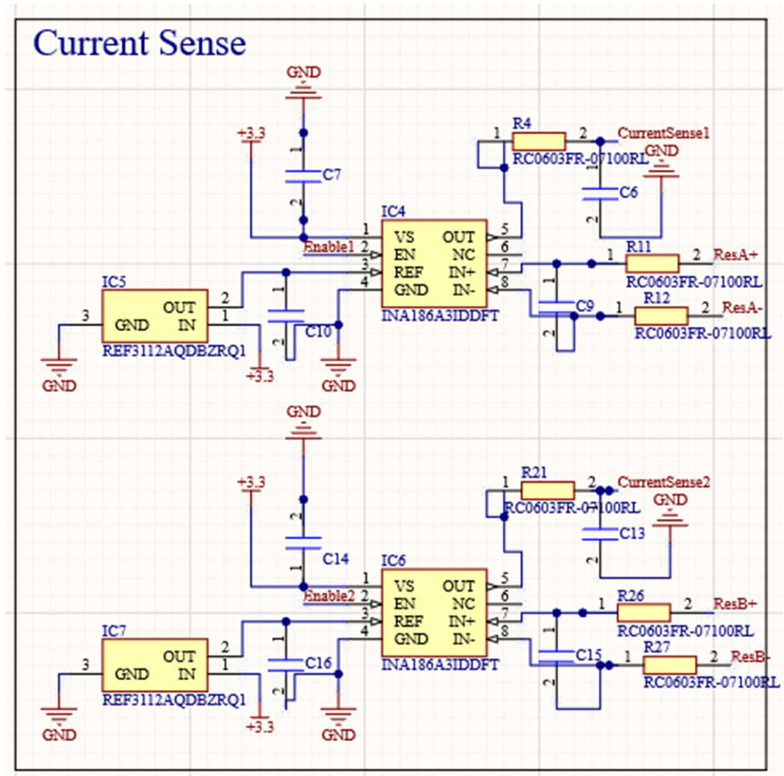

Figure 40: INA186A with current sense resistors.

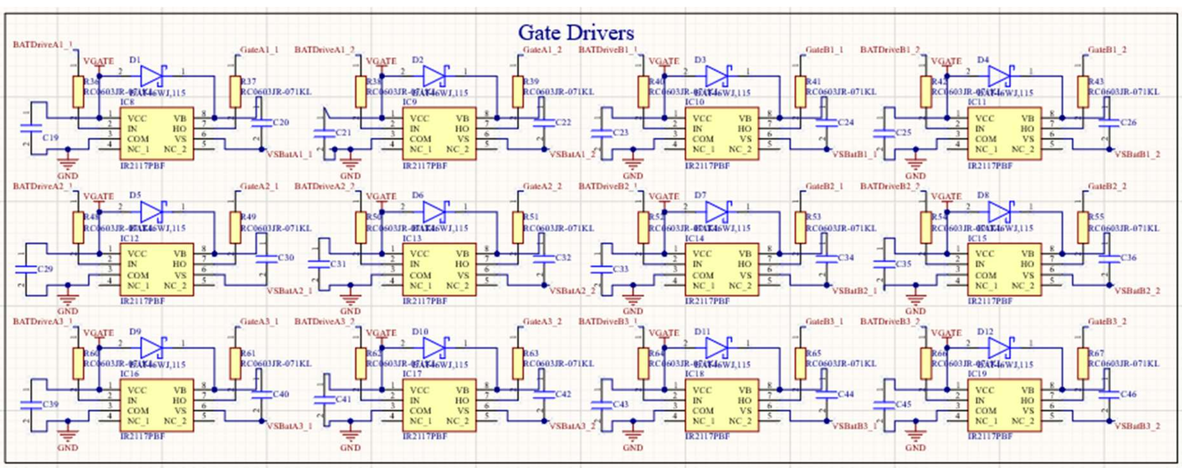

Figure 41: Original gate driver configuration.

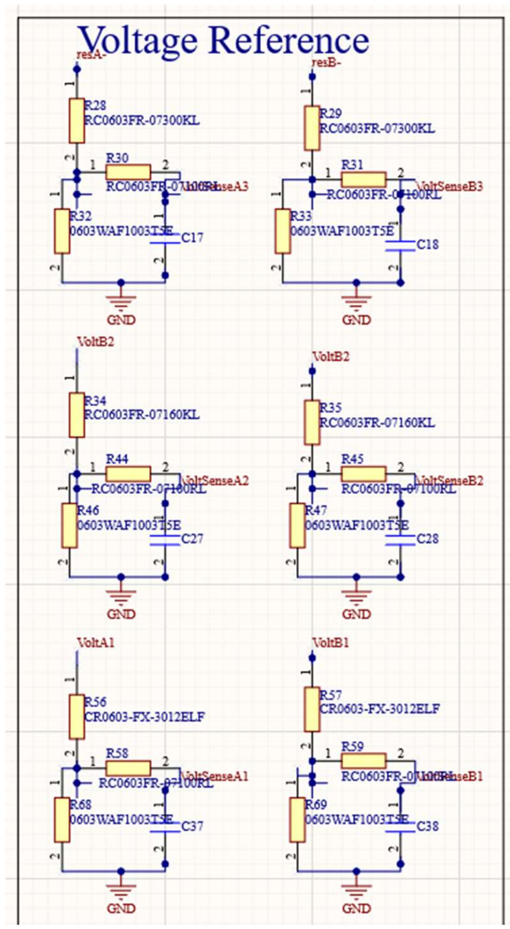

Figure 42: Voltage divider circuit for measuring the voltage of each cell.

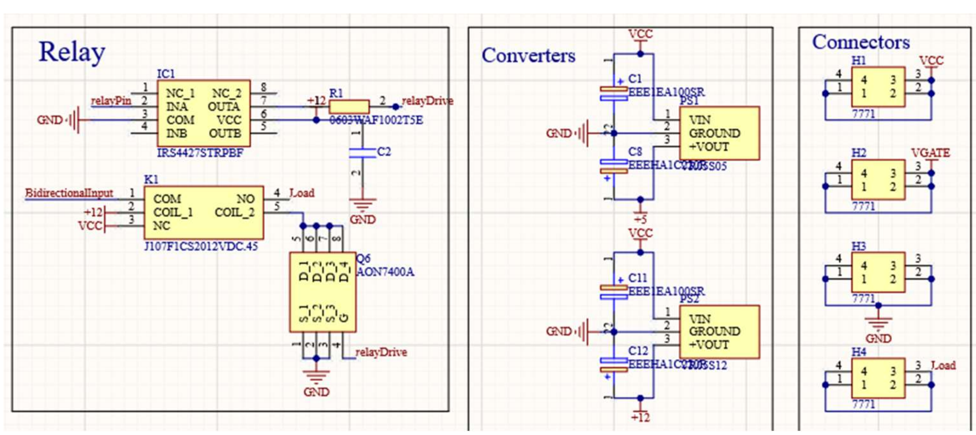

Figure 43: Relay, voltage converters, and terminal connectors for the bidirectional BMS.

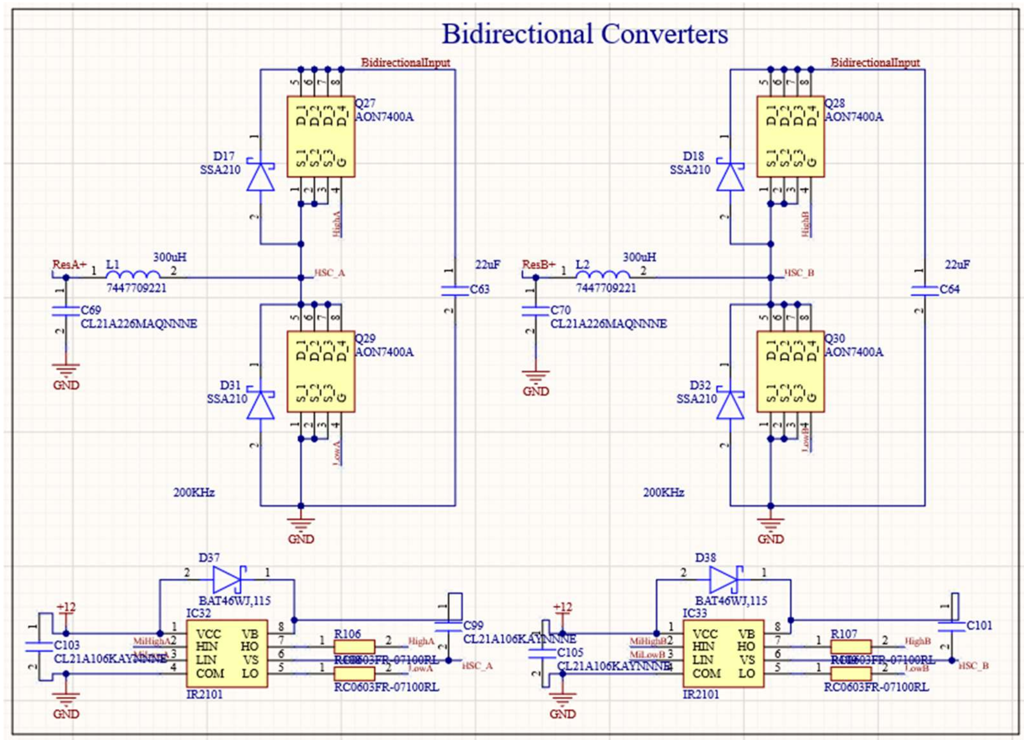

Figure 44: Bidirectional converters and their gate drivers.

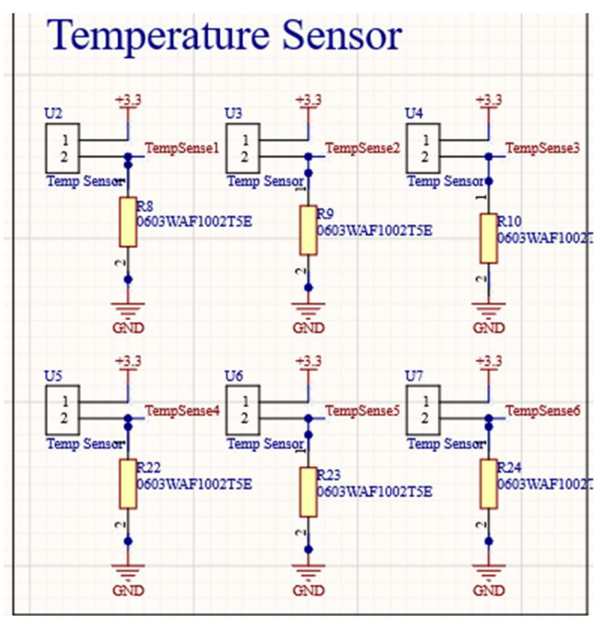

Figure 45: Temperature sensor circuit to measure each batteries' temperature.

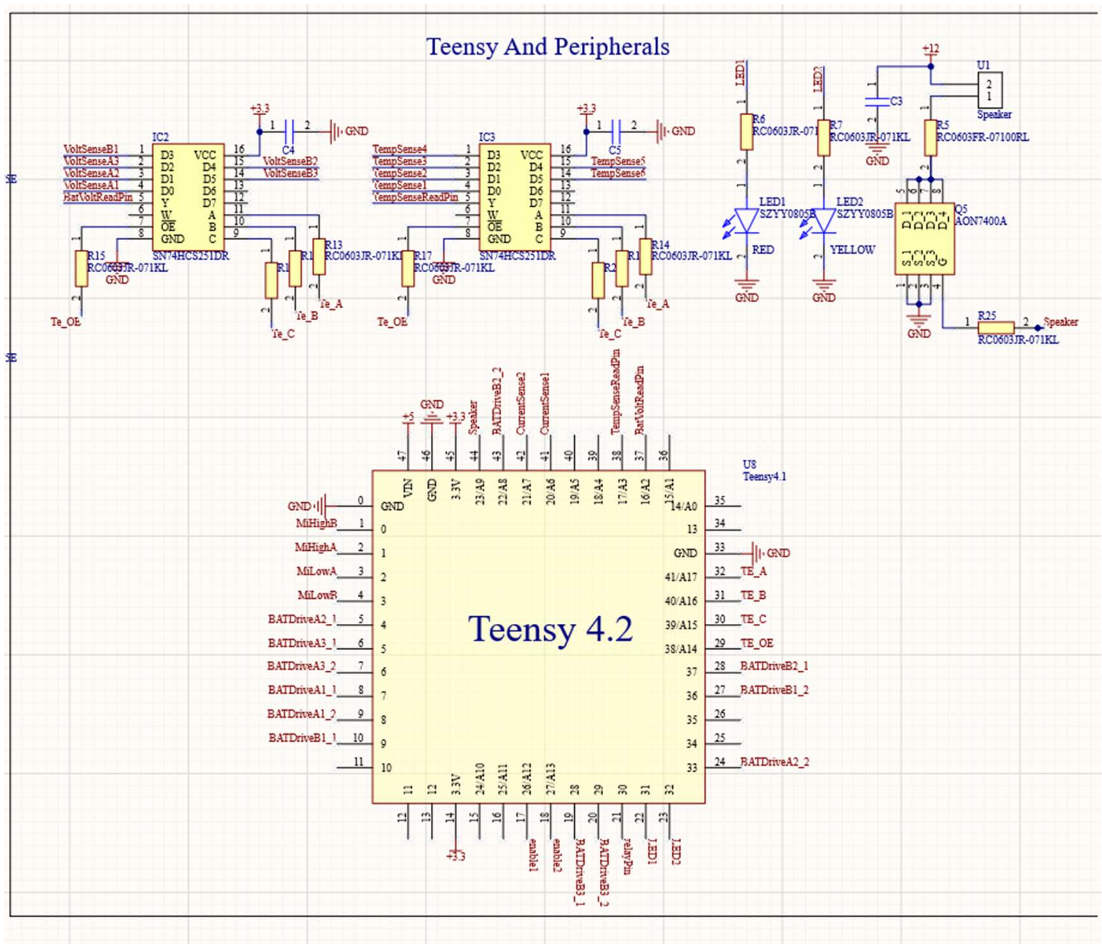

Figure 46: Microcontroller, MUXs, LEDs, and speaker circuit