Low-Cost Active Balancing Battery Management System

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Abstract

This paper presents a design and analysis of a low-cost active balancing battery management system (BMS). The essential requirements for a safe and efficient BMS will be the focus along with the impact of the silicon chip shortage effects on manufacturing. Our solution will work around this chip shortage while providing a highly efficient BMS at a relatively low cost. The design and verification of an such a system is covered in full. Finally, based on the insights gained, several recommendations are put forward for future design improvements.

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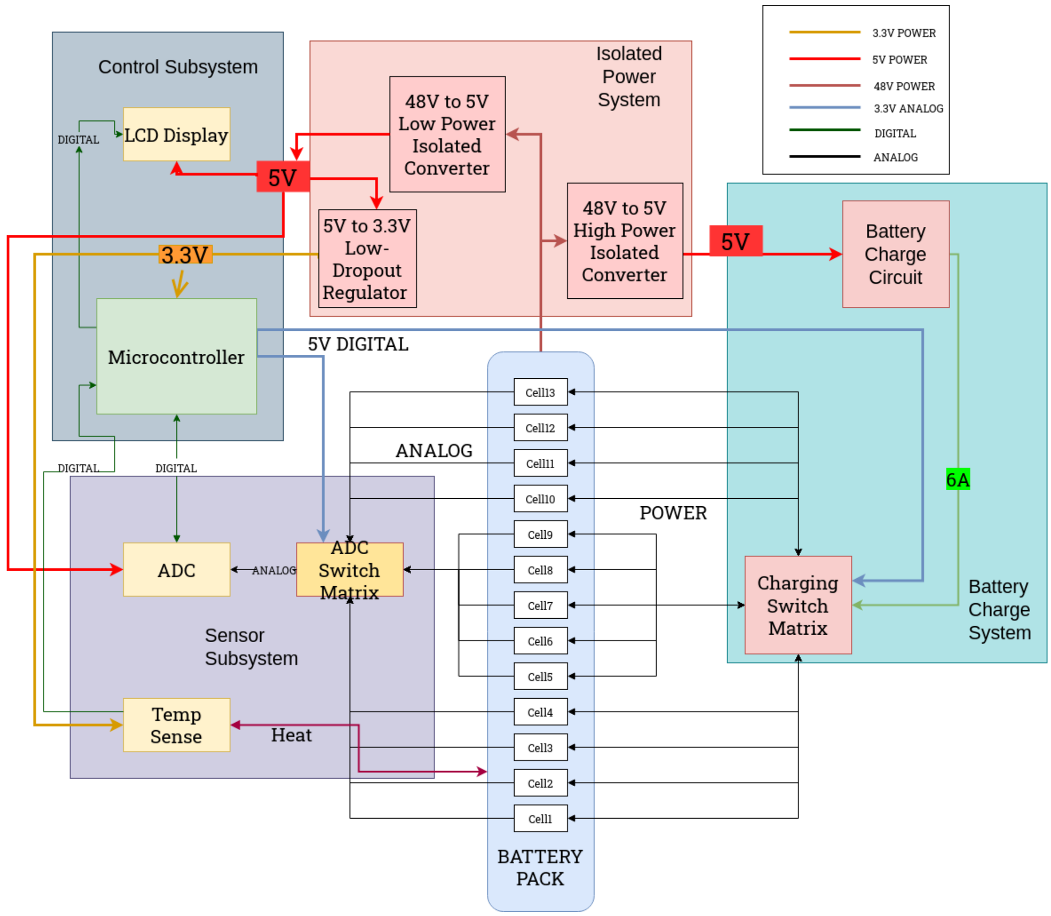

Figure 1: Active Balancing BMS

1 Introduction

In an era of growing popularity of electric vehicles, more efficient battery management systems are crucial for the longevity of battery life and vehicle range. The most efficient battery management systems provide active cell balancing, meaning that during charging or normal operation, all cells are maintained at he same state of charge. This prevents any cell from over-discharging and being damaged. Also, due to the COVID-19 pandemic, there has been a shortage of silicon and delays of production of integrated circuits that caused issues with the production of efficient battery packs. The goal of our project is intended to cover both of these issues. We will make an active balancing BMS using widely available chips at a low cost that can be easily substituted in the future design revisions.

Our BMS will have a central control system to monitor battery state of charge and temperature, as well as display this info on an LCD screen. It will be powered entirely from the battery pack, generate an appropriate charging power, and connect this charging current to an arbitrary cell within the pack in an isolated manner. This BMS will be a pack-to-cell style system. The cell with the lowest voltage will be charged until its voltage is equal to that of the average of the pack, using energy from the entirety of the pack. This system will require a dedicated micro-controller with multiplexed outputs, various isolated power supplies, an array of power MOSFETs, and a high efficiency battery charger. A high level block diagram of this system is in figure 1.

2 Design

There are 4 main components of our BMS that combine to provide safety protocols while providing a highly efficient active balancing system. These system interactions can be seen in the high level block diagram, figure 1.

The Control Subsystem is responsible for monitoring the signals that are coming from the Sensor Subsystem, i.e voltage and temperature of each cell, and then based on these conditions it is required to send 5V or 0V signals to the Charge Switch Matrix to properly charge the lowest charged battery cell inside of the pack. Also this system is responsible for outputting the information about the battery pack on an external LCD screen with an update rate of 1Hz for better user interface.

The Sensor Subsystem is responsible for measuring voltage in an isolated manner within 0.1V using a combination of ADC Switch Matrix with an ADC. The other component of this system is the Temperature Sensor which is responsible for reading the temperature within 2°C of the battery pack for extra security.

Isolated Power System is responsible for providing isolated power to all other subsystems. It consists of 48V to 5V Low Power Isolated Converter, 5V to 3.3V Low-Dropout Regulator and 48V to 5V High Power Isolated Converter. In this project isolation is really important due to the fact that the whole system is getting powered from the battery pack and it operates with each of the individual cells inside of the pack. By improper handling of the cell the whole battery pack can have internal shorts that will cause a fire hazard and will harm the battery cells.

The Battery Charge System is responsible for creating a way of charging individual cells inside of a battery pack in an isolated manner. This is accomplished by a Battery Charge circuit that is outputting 6A into the Charge Switch Matrix that later connects to a desired cell to charge it. 6A is chosen as a normal charging current for LG H2 batteries is 1.5A [1] and the battery pack provided has 4 battery cells in parallel.

2.1 Control Subsystem

The system is required to control the sensing and balancing systems and output information to a LCD screen

2.1.1 LCD

Design Decisions LCD display in this project is needed for better and easier way of providing information for an user. Display is mostly used for the demo, so it was not the priority to be the highest quality. Any alternative screen can substitute this display with some minor hardware and firmware modifications.

Design Details Main information that needs to be displayed is the number of the cell, its voltage, temperature and the status. LCD-20x4Y was chosen for this design as this display has 4 20-character lines, has a common I2C interface and has a good support online.

2.1.2 Microcontroller

Design Decisions For this BMS design the control unit needs to have 32 pins of I/O for controlling both the Sensor Subsystem and Charge Matrix and extra 2 for ADC measurements as a part of sensor system and 2 more for I2C communication with the LCD display chosen. To multiply the amount of I/O 8 analog

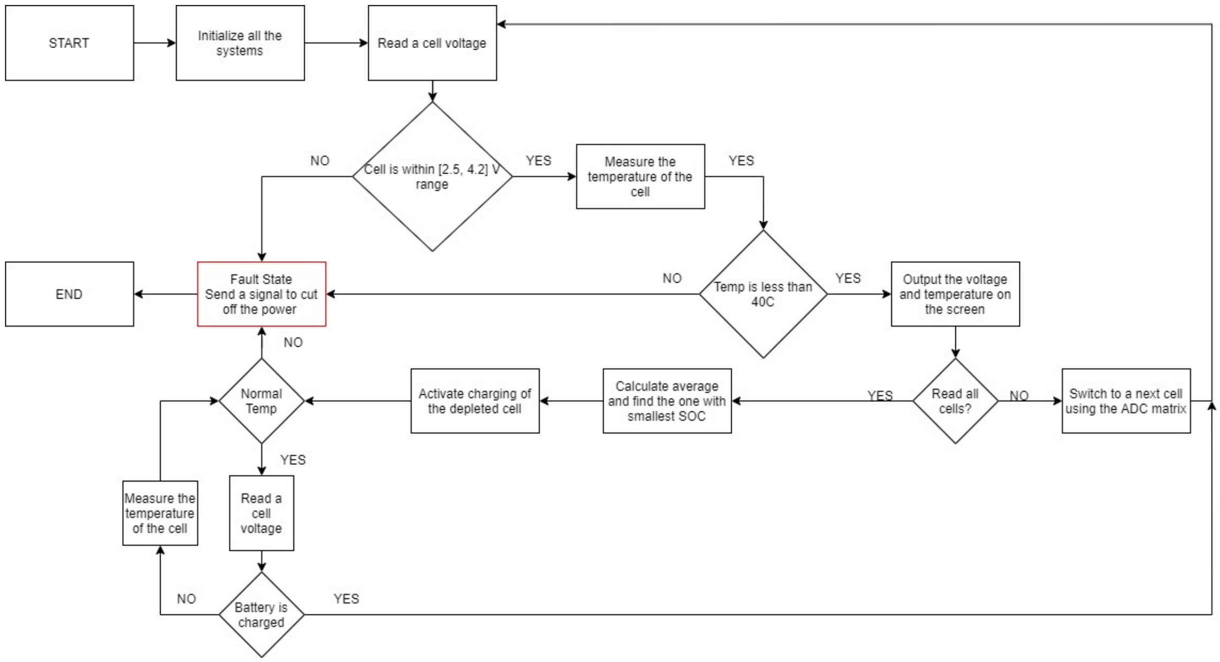

Figure 2: Software Flow of the BMS

8 to 1 MUXes were used. Any microcontroller that supports I2C communication and ADC measurements can be used instead.

Design Details For this particular design STM32F446 was chosen due to 48 pin package, fast clock and great functionality provided by firmware STM32CubeIDE such as ability to use breakpoints and debugging mode. TMUX1308 was chosen for the analog MUXes due to its low cost and high availability on the market. 4 MUXes are connected to a 3.3V rail and send signals to the Sensor Board and 4 MUXes are used for the Charge Switch Matrix, that requires 5V digital input. The microcontroller runs the code that is represented on Figure 2. In short, microcontroller collects data about each of the cells such as voltage and temperature, outputs it to the screen, finds the lowest charged cell and charges it to the average level of all other cells. In case of overtemperature, undervoltage or overvoltage conditions, the charging, voltage and temperature measurements stop and the microcontroller goes into an error state about which user is notified by a message on the screen. Currently the IC we have chosen is not available on the market anymore, the whole project can be easily migrated to another microcontroller from STM32 family or any other microcontroller with changes specific to software environment of the new IC. On the last stage of integration between boards a problem has been discovered that the isolated gate drivers for Polarity Switcher in Charging System 12 are not 3.3V logic tolerable and, based on our experiment, in fact work with 4V signals. To mitigate that a level shifter from 3.3V to 5V was used shown on the Figure 3 from the book [2] This circuit was providing us with 4.5V which was sufficient for proper control the Polarity Switcher.

2.2 Sensor Subsystem

The system is required to safely measure the voltages and temperature of each cell. These sensor measurements are key to accurate balancing and ensuring the battery cells remain in a safe operating range.

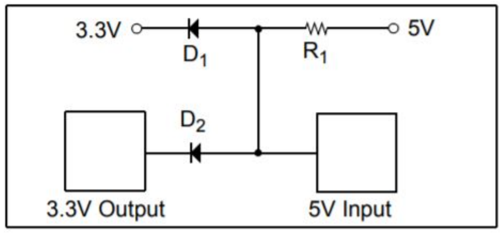

Figure 3: 3.3V to 5V Level Shifter

2.2.1 Voltage Measurement Subsystem (ADC and ADC Switch Matrix)

Design Decisions In order to measure the voltages of cells safely a proper isolation should be used to make sure that no cells are sharing the same connection at the same moment. Due to high cost and limited stock of differential isolated Analogue-to-Digital Converters (ADCs), a combination of isolating matrix and usual ADC is used. Isolation matrix connects to the top and bottom of a desired cell and then shares a connection between the Sensor Subsystem ground and bottom of the cell. With that reference ADC measures the voltage between top of the cell and ground and passes the information to the Control Board. The correctness of polarity is ensured by a polarity switcher matrix inside of the isolation matrix as it is crucial to prevent inverse polarity.

For the isolating matrix optocouplers were chosen due to an easy isolated control, low cost of the parts and easy scalability of the matrix for battery packs of different sizes. Optocouplers, basically, work as switch that can be controlled without a connection to either of the terminals on the output. Optocouplers could be substituted by relays in an alternative design, but it will require slightly different system of the control. Another approach to this design can be implemented by using 13 different ADCs, however, it would be much more costly.

Design Details The design consists in 3 main components: matrix that was connected to the cells, a polarity switcher that ensured always positive output as bottom of one cell can be top of another and an ADC to precisely (within 0.1V) measure voltages up to 4.2V and digitally communicate the results to the Control Board. On the figure 4 a block connected to the cells, polarity switcher and ADC is shown.

For the optocouplers VOM617A were chosen due to a compact footprint and 80V maximum collector emitter voltage [3] which gives more than 30V headroom for safety. It also means that they can be used on a higher voltage battery packs as well. A 1K resistor on the anode of the optocoupler was chosen to limit the current to $3.3V/1000\Omega = 3.3mA$, according to the datasheet [3] the maximum DC forward current is 60mA. For every every connection between cell and common rail and from the common rails and ADC input optocouplers are connected bidirectionally, meaning that 2 optocouplers share the same control signal and one connected in opposite polarity on the output to the first one. This allows current to flow bidirectionally. When testing the setup with only one optocoupler connected to the bottom of the cell, the voltage drop between emmiter and collector would change non-linearly depending on the cell voltage making it impossible to provide consistent and precise measurements. Having the bidirectional configuration seen on the figure 4 allows for isolated measurements within 0.1V.

After having problems with implementing external ADC an internal ADC of STM32F446 from Control Subsystem 2 is used with a voltage divider. As the maximum voltage needed to be measured will not exceed 4.3V and STM32F446 ADC can measure up to 3.3V, a voltage divider with 10KΩ and 33KΩ is used, so the input of 4.2V will result to $4.2 * 3.3/4.3$ V measurement.

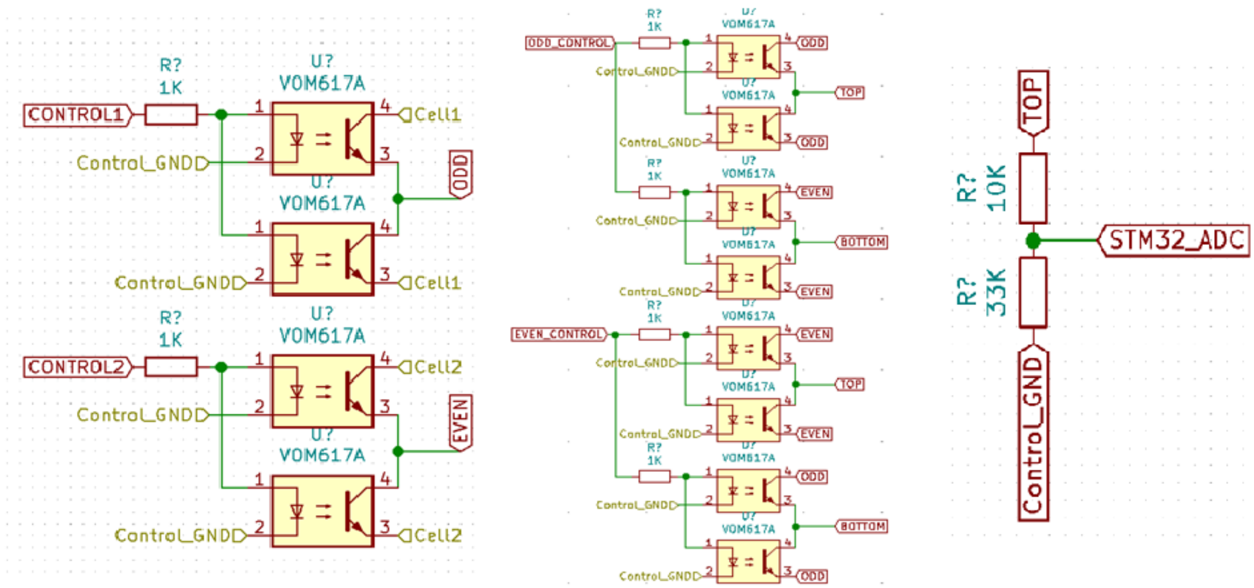

Figure 4: Design of Voltage Measurement Subsystem

2.2.2 Temperature Measurement Subsystem

Design Decisions Temperature measurements are important due the fact that overheating of the batteries can cause faster degradation of the cells and fire hazard in extreme cases. However, in our design we are planning to charge the battery cell at normal current and room temperature, batteries need to be within a range of -5 50°C For that precision of 2°C would be enough. With such precision a sensor doesn't need to be complicated and thermistor should perform perfect for the requirements. As an alternative to thermistor, thermocouples can be used, or a special thermo-measuring IC that can be placed on the pads of the battery pack.

Design Details In current design MF52A2103J3470 thermistor is used. It's a 10K nominal resistance thermistor [4], hence 10K resistor is used to create a voltage divider. Internal to STM32 12-bit ADC is used to measure the change of voltage and then it is converted to temperature using the B equation variation of Steinhart–Hart equation: $\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln \frac{R}{R_0}$, [5]. Analog MUX, TMUX1308, is used to connect 8 different thermistors to one pin of STM32, minimizing the amount of I/O used on the microcontroller.

2.3 Isolated Power Subsystem

Design Decisions The Isolated Power System is required to provide power for other subsystems of the BMS. The Isolated Power system consists of multiple power supplies that are isolated from the main battery pack. They must be isolated to prevent shorts in the battery pack in the case of faults in other subsystems.

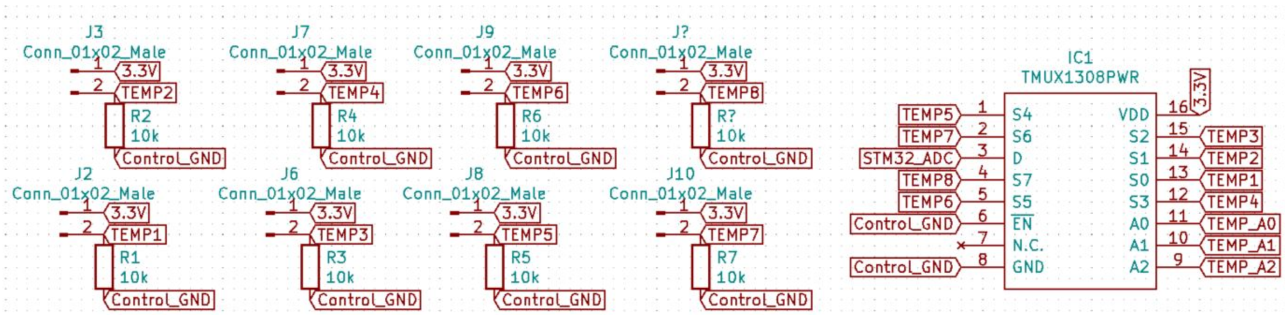

Figure 5: Design of Temperature Measurement Subsystem

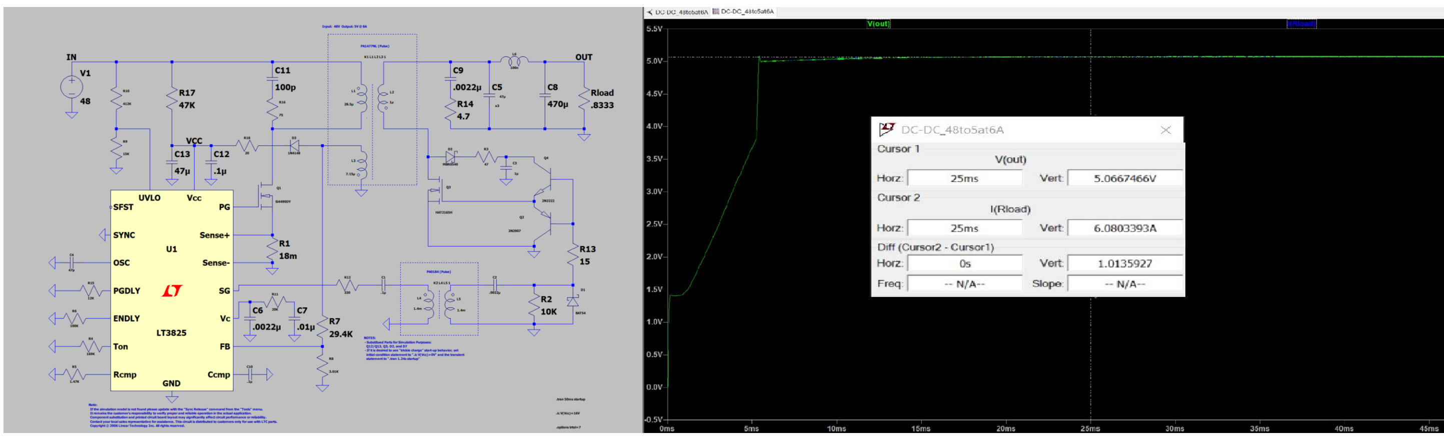

Figure 6: Simulation and Results of 48V to 5V Flyback Converter

There are 3 main components of the isolated power supply: a 48 V to 5V at 6A Isolated Flyback Converter, a 48V to 5V at 1A Isolated DC-DC Converter, and a 5V to 3.3V Low-Dropout Regulator(LDO). The 48V to 5V at 1A converter was used for ADC and LCD power. It also went to a 5V to 3.3V LDO, which ultimately went to the microcontroller and thermistors.

Design Details We chose to use a common Murata MYBSP01201ABF 48V to 5V at 1A Isolated DC-DC Converter for our low power application. The LDO we had used was a TLV2217 from TI, which was perfect for our low 1.7V dropout voltage requirement. The Isolated Flyback Converter needed to power the Battery Charge Circuit, which requires 5V at up to 6A. To achieve this, we used an LT3825EFE from Analog Devices. This IC can control flyback circuits rated up to 40W, supporting 8A at 5V. The design is adapted from the reference design provided in the datasheet and as can be seen on the simulation Figure 6 achieve our requirements. The final design required optimizing the PCB layout of the Flyback Converter from the first revision, since there was significant noise at the output, seen through an oscilloscope. The Isolated Power Supply had issues when connected to the Constant Current Source, namely we were not getting a constant 6A output due to the noisy output of the flyback converter. To solve this, high current paths had to be shortened greatly, in order to reduce capacitance and noise pickup. We also moved the current sense resistor closer to the IC to reduce the overall noise in the system [6].

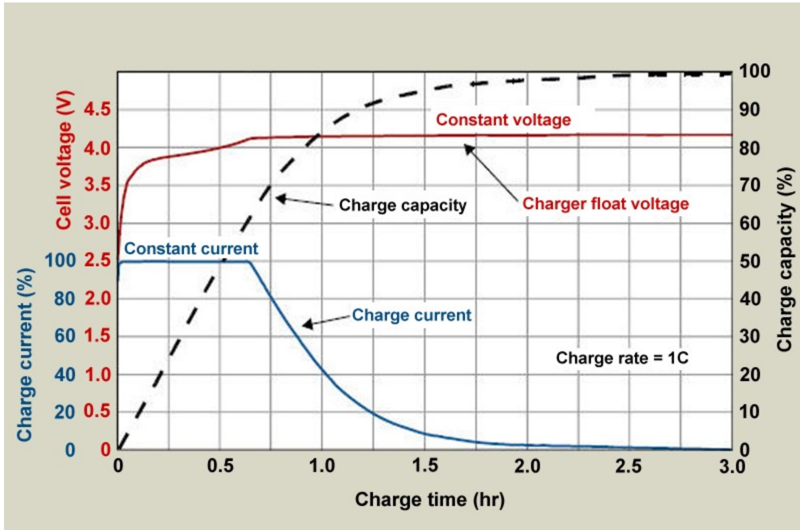

Figure 7: Charging Cycle of a Lithium-Ion Battery [7]

2.4 Battery Charge Subsystem

The battery charge subsystem is responsible for charging up a specific cell based on digital inputs from the Control Subsystem. This requires generating the proper charging power and connecting it to an arbitrary cell in the battery pack.

To charge a lithium-ion battery, a special charging procedure must be followed, Figure 7. Because our BMS only operates while the pack is in use, it will never need to be able to charge a cell to max voltage. This means we only need the constant current (CC) portion of the charging cycle. This will be on it's own PCB to better accommodate a modular system. To connect the charging current to a specific battery, an array of switches will be used, the charge switch matrix. Each battery within the pack has a 12Ah capacity, so for balancing the pack a 6A charging current is desired, see [8].

2.4.1 Constant Current Source

Design Decisions The constant current source must operate given a constant 5V input from the Isolated Power Subsystem, 2.2.2. Additionally, since battery voltage may range from 2.5V to 4.2V, it must be capable of 6A for all loads in this voltage range. To accomplish this, a N type MOSFET will be used in series on the sink side of our constant current supply. Since a MOSFET operates as a voltage to current amplifier when in saturation, it can be used to limit the current flow through the circuit. Alternatively, a BJT or P type MOSFET could have been used; however, N-MOSFETs are more common and more familiar to our team. Our current source also needs to be adjustable during testing/building, to permit testing on batteries of different capacity.

Design Details Although a n-channel MOSFET provides constant current for a given gate voltage, the gain depends on the $V_D S$, which will vary based on battery charge. To solve this, a op-amp and current shunt will be used to provide closed loop control of the current flow. We chose the LM358 opamp as it is able to operate on a single 5V supply. A 0.04Ω current shunt was chosen to minimize power loses that would occur if using a standard resistor. The op-amp will compare the voltage across the current shunt, to

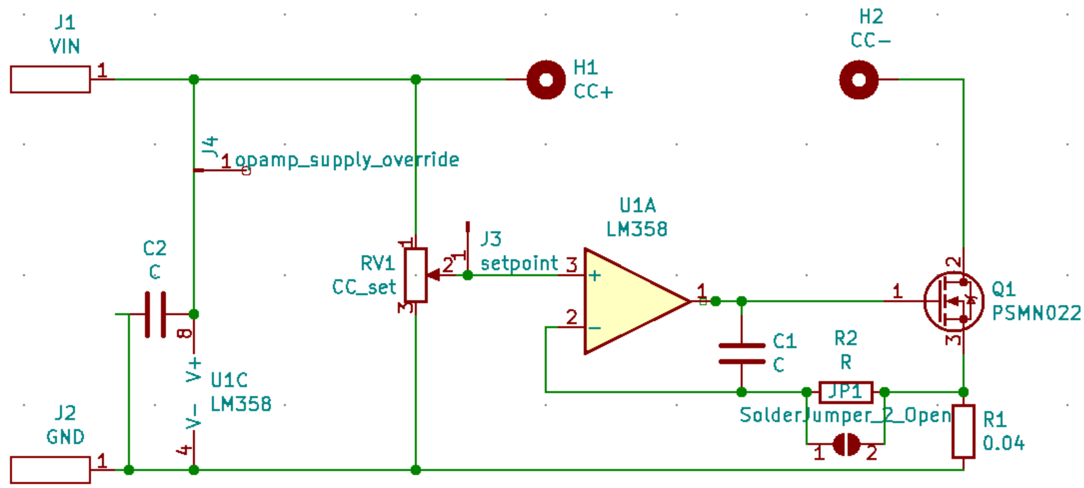

Figure 8: Constant Current Source Schematic

the current set point on a potentiometer, and adjust to $V_G S$ of the MOSFET accordingly. This circuit is in figure 8. The schematic also has space for a RC filter on the op-amp input to limit any oscillations that may occur with the MOSFET. This may be required depending on noise in the system.

2.4.2 Charge Switch Matrix

Design Decisions The charge switch matrix must operate based on digital inputs from the Control Subsystem, 2. Since the switch matrix will be connected directly into the battery pack, these inputs must be isolated from the rest of the switch matrix. The switch matrix must be able to handle bidirectional flow since a battery cell connection may be the low side for one cell, but the high side for another. This means that each switch must support current flow in both directions, as well as adding an additional polarity switcher since the constant current source has a fixed polarity. Each switch must also support the 6A produced by the constant current circuit.
Each cell tap will have 1 switch on it to connect it to the charge system, or isolate the cell when not being charged. One option for the individual switches is a relay. While they easily support bidirectional current flow and high currents, their mechanical nature makes them not ideal. For a solid state solution, MOSFETs were chosen. One issue with this is that they have a body diode, allowing them to always conduct source to drain. A source-source bidirectional configuration is needed to prevent this, see figure 10.

Design Details We chose a PMPB20EN MOSFET for its exceptionally small package and 10.4A current limit, see the datasheet [9]. Due to the relativly large gate charge, a dedicated gate driver will be needed to switch the FET on. The 1EDB7275F isolated gate driver was chosen primarily for its isolation capabilities. Based on the gate driver data sheets [10], it should be able to operate on the 5V logic signal from the control system, as well as provide plenty of current to switch the MOSFET. Our bidirectional switch schematic is in figure 9. 2 optocouplers are also used to disconnect the switch from power when not in use. This is important to prevent shorts through the MOSFET body diode as we discovered during our initial testing.

This bidirectional switch unit will be used on each cell tap. Due to the nature of the switch, the GND input gets connected to the source of the MOSFETs, and thus the battery cell when switched on. When charging a cell, 2 switches will be enabled, this means each of the enables switches must be operating on

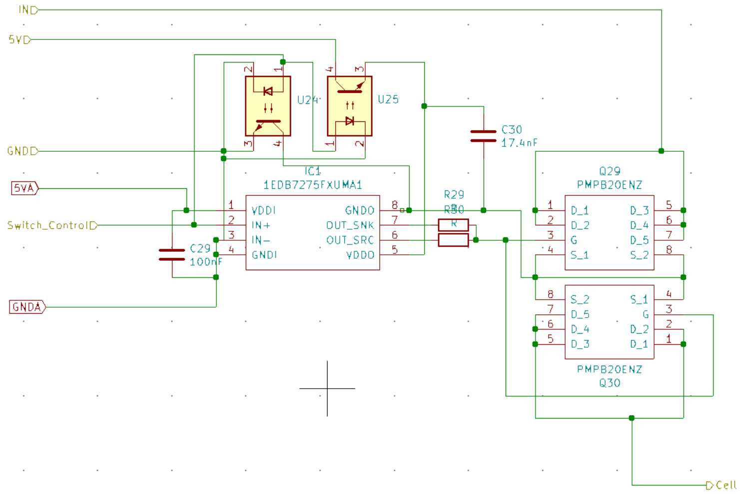

Figure 9: Bidirectional Switch Schematic

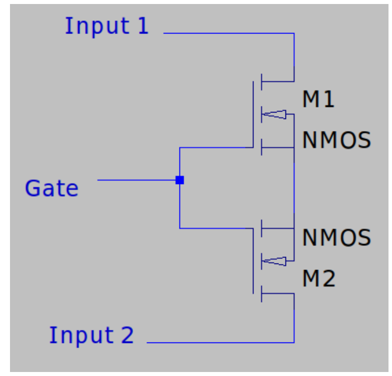

Figure 10: Source to Source Bidirectional nMOSFET

different isolated power supplies. To accommodate this, every other cell tap shares a isolated power supply. Each switch will connect the cell to either the EVEN or ODD rail. This will allow the polarity switcher the connect the top cell tap to the high side of the constant current circuit, based on the cell position. The cell tap switches are in figure 11. The polarity switcher is 4 of the switch units arranged in a full bridge configuration and is seen in figure 12. You can see the schematic for the full charge switch matrix in the Appendix, figure 16.

2.5 Subsystem Integration

Due to the large nature of the design, it is important to give specific engineering consideration to how all the subsystems will interact with each other. The full system can be seen in figure 13.

2.5.1 Physical Design

Our design has few distinct components which makes it optimal to build on multiple PCBs to aid in testing and modularity. The control and sensor subsystems were placed together on one PCB because of the heavy interactions and difficulty testing one without the other. The high power isolated supply was also on its own PCB with it being a clear unit within the system and needed lots of testing before interacting with other components to prevent damage. Initially the battery charge subsystem was all on one PCB, but there were difficulties testing the constant current source and the charge switch matrix without the other interacting with the system. For this reason, during the second revision, the constant current circuit was broken out to an individual PCB. This greatly eased the testing process.

2.5.2 Electrical Connections

With each subsytem on a separate PCB, connectors needed to be chosen to carry signals and power between them. 2 connectors were chosen for the system. The first is the high current connector, used for charging current throughout the system. This is a screw terminal and ring connector capable of over 15A. This was chosen for the robustness, low cost, and ease of use. Many other connectors are expensive, require special pins and crimping tools, and do not easily scale with different pin counts. This screw terminal was used in

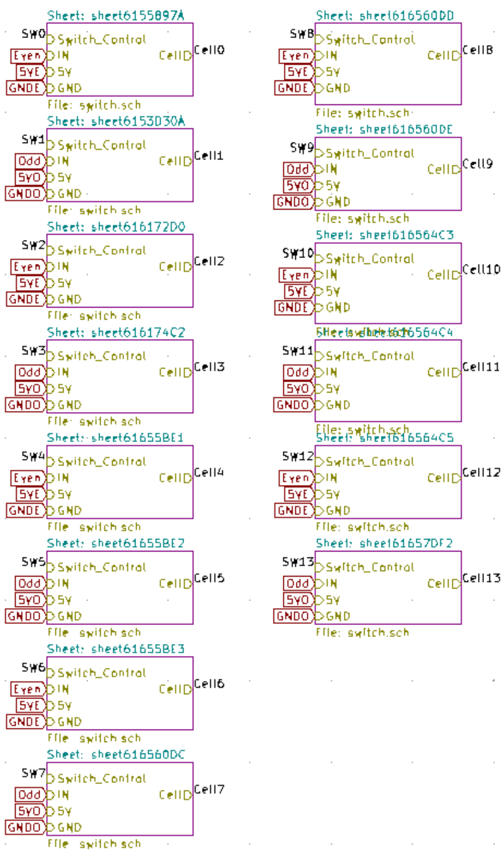

Figure 11: Cell Tap Switches

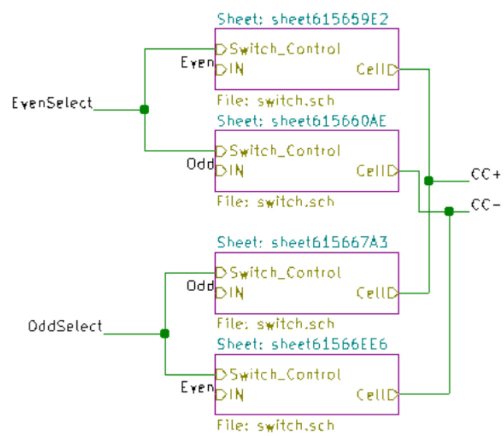

Figure 12: Polarity Switcher for Charging System

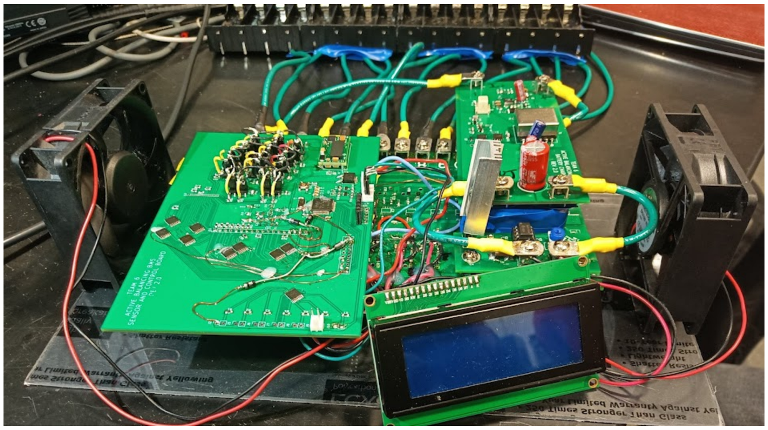

Figure 13: Full System Assembled

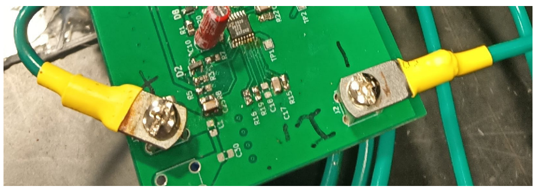

Figure 14: Connection Between Isolated High Power and Battery Pack

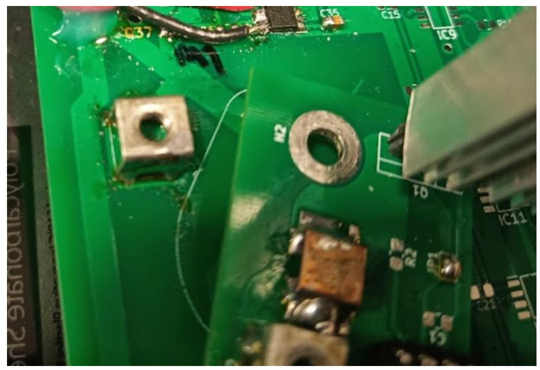

Figure 15: Connection Between Constant Current Source and Charge Switch Matrix

combination with ring terminals to connect the high power isolated supply to the constant current and to connect the charge switch matrix to the battery cells. This arrangement can be seen in figure 14. This screw terminal was also paired with a plated through hole to allow the small constant current circuit to stack on the charge switch matrix, figure 15.

The control and sensor subsystems also needed to connect to the charge switch matrix. They used 2.54mm pin headers since only logic signals needed to be connected. They also provided a convenient way to stack the PCBs.

3 Design Verification

All of the subsystems full requirements and verification tables can be found in the Appendix. Here a quick overview of key test will be provided, along with any issues discovered.

3.1 Control Subsystem

The control subsystem is pretty self-explanatory. Testing of it required procedural checking of each of the outputs of 16 signals for the Switch Matrix control, 16 signals for Voltage Measurement System, and 3 signals for the MUX for Temperature Measurement System. Using voltmeter to probe each of the outputs for Switch Matrix we verified that proper 2 cell taps and one respective polarity switcher were 5V at the same time, while all the other pins were 0V. The test was passed successfully. The same procedure was done for the Sensor Matrix, however the output voltage required there is 3.3V instead of 5V. The output on LCD display was verified by connecting the display to the system and by outputting "Hello World" on the screen.

3.2 Sensor Subsystem

The testing of this subsystem was broken down to several steps. For Voltage measurement system firstly, the isolation matrix is tested. To test the system signals needed to be sent from the Control subsystem to "connect" a proper cell to the ADC input. The first test required DMM in continuity mode to check that only desired optocouplers are conducting and conducting in a proper direction, current should flow from the top of the cell to the ADC and from the ADC to the bottom of the cell. Second test checked that isolation matrix with application of the voltage to simulate a battery cell. The system worked flawlessly, always providing the positive output, however, a constant voltage drop of 0.25V was discovered. Quick fix was implemented for it in software and kept the desirable precision. For ADC testing, the ADC pin of STM32 will be connected to a power supply. By using both debug mode on STM32CubeIDE to check the result of ADC conversion and by using a script that outputs values read by ADC on LCD screen, we verify that the read voltage value received corresponds to the voltage sent to the ADC within 0.1V over the range from [2.5, 4.2]. For Temperature Measurement System verification, we used an infared thermometer for reference and compared the values displayed on the LCD. They were consistent within 2C.

3.3 Isolated Power Subsystem

The Isolated Power system consists of 3 separate DC-DC converters, each of which can be tested similarly. The 48V to 5V Isolated Converter from Murata was tested by connecting a DC power supply set to 48V to the input and measuring the output using a digital multimeter to be 5V. A similar procedure was used to test the LDO, but the input voltage was set to 5V, and output was measured to be 3.3V. For the high power Isolated Flyback Converter, the first test performed was connecting a 48V DC supply at the input and ensuring the output voltage was 5V(+/-0.3V). The output voltage was also monitored on an oscilloscope to ensure minimal noise, via the ripple. In our final design, the ripple was only 0.2V, which was a big improvement from the almost 1V ripple present in the earlier board due to excessive noise. The second test of done to ensure the functionality of the Isolated Flyback Converter was using an Electronic Load in Constant Current Mode at 6A. The input voltage was set to 48V and output voltage was measured to ensure 5V when a load is connected. With this, all requirements for this subsystem were met.

3.4 Battery Charge Subsystem

3.4.1 Constant Current Source

The constant current source is a relatively simple circuit in terms or requirements, needing only to output 6A at 2.5V to 4.2V, given a 5V input. This was tested using a DC power supply set to 5V and a DC electronic load set to 2.5V. The 5V supply was connected to the input side of the constant current circuit and the electronic load connected to the output. While varying the voltage on the load from 2.5V to 4.2V, the current flow was monitored. Throughout the range the current flow remain constant at 5.9A. This current does not indicate the maximum of the circuit, just what it was configured for with its on-board potentiometer. This is considered passing and shows the circuit works to its full design specs.

3.4.2 Charge Switch Matrix

The charge switch matrix has 16 digital inputs, 2 power inputs, and 14 power outputs. The digital signals where the 2 inputs get connected to the output. To replicate the constant current circuit on the input, a DC supply was set to 5V with a 6A current threshold. The digital inputs normally come from the control and sensor PCB, but were instead wired into a breadboard using jumpers. Each input could then manually be pulled either high or low.

For the actual testing, it was performed in the pairs used for a single cell. Digital inputs were given to select cell 1, cell tap 0, cell tap1, and oddselect. Then the voltage was monitored across cell 1 output. If there was 5V, and 0 volts on all the other cell taps, this was a success. Then the DC Electronic Load set at 3.5V is connected to the cell, it should draw a full 6A, hitting the DC Supply current threshold, and dropping the voltage to 3.5. This is considered a success. If the circuit is not able to flow current, something is wrong. We often had this problem and it was due to dead MOSFETs or the gate driver not turning the MOSFETs all the way on.

4 Cost

Our design cost $176 in materials directly. While this is over the standard ECE 445 budget, when compared to commercial solutions, it is a order of magnitude cheaper. The TIDA-817 is a comparable BMS development board from TI, which cost $2500 [11]. With this in mind, our board has met our threshold for low-cost, and still has room for part simplification to further reduce cost. Whilst the labor cost were high compared to part cost, we would only have to manufacture 10 boards to reach a final board cost of $2000. This is still much better than the development board, while being easily avaliable when speciality IC are out of stock.

4.1 Parts

Table 1: Parts Costs

Part	Manufacturer	Quantity	Bulk Purchase Cost ($)	Total Cost ($)
TPW2900ENH	Toshiba	1	$2.46	$2.46
TLV2217	Texas Instruments	1	$1.22	$1.22
SUS01	MEAN WELL	2	$4.73	$9.46
LT3825EFE	Analog Devices	1	$7.44	$7.44
PA1735NL	Pulse Electronics	1	$5.55	$5.55
PA0184NLT	Pulse Electronics	1	$3.36	$3.36
FMMT718	Diodes Incorporated	1	$0.47	$0.47
ZXT11N20DFTA	Diodes Incorporated	1	$0.64	$0.64
BAT54	Vishay	1	$0.29	$0.29
BAT760-7	Diodes Incorporated	1	$0.58	$0.58
B0540W	Taiwan Semiconductor Corporation	1	$0.40	$0.40
BSC011N03	Infineon	1	$1.92	$1.92
BAV23QAZ	nexperia	1	$0.42	$0.42
Si7336ADP	Vishay	1	$1.63	$1.63
BAS21LT3G	onsemi	1	$0.17	$0.17
860020472006	Wurth Electronics	3	$0.10	$0.30
860020778021	Wurth Electronics	1	$0.10	$0.10
MYBSP00502ABF	Murata	1	$13.55	$13.55
TPW2900ENH	Toshiba	1	$2.46	$2.46
PA4340.101NLT	Pulse Electronics	1	$0.88	$0.88
CRCW0805412KFKTA	Vishay	1	$0.15	$0.15
CRCW080529K4FKTA	Vishay	1	$0.15	$0.15
CRCW08053K01FKTA	Vishay	1	$0.15	$0.15
RC0805FR-07169KL	Yageo	1	$0.10	$0.10
CR0805-FX-1471ELF	Bourns	1	$0.10	$0.10
PSMN022	Nexperia	1	$1.27	$1.27

Continued on next page

Table 1 – continued from previous page

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
LM358	Texas Instruments	1	$1.60	$1.60
3386F-1-103TLF	Bourns	1	$2.48	$2.48
CSS4J-4026R-L500FE	Bourns	1	$1.78	$1.78
7768	Keystone	16	$0.58	$9.25
1EDB7275F	Infineon	18	$1.69	$30.42
PMPB20EN,115	nexperia	36	$0.42	$15.08
VOM617A-X001T	Vishay	72	$0.27	$19.44
0685T8000-01	Bel Fuse	1	$0.27	$0.27
CL21B223KBANFNC	Samsung	18	$0.02	$0.41
CL21B104KBFWPJE	Samsung	18	$0.28	$5.04
MF52A2103J3470	Cantherm	8	$0.45	$3.60
STM32F446RET6TR	STM32	1	$11.57	$11.57
LCD-20x4Y	Gravitech	1	$14.59	$14.59
TMUX1308PWR	Texas Instruments	9	$0.42	$3.78
M20-9771846	Harwin	2	$0.55	$1.10
M20-9991445	Harwin	2	$0.53	$1.06
Total				$176.59

4.2 Labor

A graduate from ECE makes an average of $92,227 per year [12]. There are 2080 work hours per year. This comes out to $44.3/hr.

Each member spent around 150 hours total throughout the semester.

Total Labor Cost = 3 * 150 hr * $44.3/hr = $19,953

5 Conclusion

5.1 Accomplishments

We were able to get each of the system working: the sensor system was properly measuring voltages and temperature of each cell, the control system was able to control the charge switch matrix, and the battery charge system was functional. We think that the project was a success and with some extra time the whole system would've been working flawlessly. We are planning on continuing improving this project to get it ready to deploy on a car.

5.2 Uncertainties

One of the major uncertainties is the complete functioning of the project since we were not able to get the whole system working. We were able to get each subsystem to work independently; however, when combined together there were a few problems. The first of these problems was improper work of the Voltage Sensing System when used in tandem with the Switch Matrix PCB. When connected, Sensor Board reads 0V, with a battery pack populated with batteries. However, the Sensor board works when the voltage is supplied using a bench DC power supply. We also had problems when testing with a full battery pack. When powered through a 48V DC supply with a single cell connected, the charging system worked as expected. However, when powered through the battery pack, we were not able to charge a cell within the pack. We think this may have to do with intermittent workings of the charge switch matrix. A large number of modifications were wired on top of the PCB to improve functionality, and this patchwork was not entirely reliable. There was not enough time to fully diagnose the issue, but believe with a more complete PCB the problem will be easily discovered.

5.3 Ethical considerations

Since our project deals with batteries, high currents, and high voltages, safety was extremely important when building our project. We chose to isolate subsystems as much as possible from the main battery pack, keeping possible shorts from affecting the cells and not putting us or the user at risk. Another important safety measure taken was to monitor the temperature and voltage of the cells through thermistor and ADC readings respectively. If the temperature or voltage fell outside the range of safe operation, we disconnected the system from the battery pack and stopped cell balancing. This follows the IEEE code of ethics, which states: "to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices" [13]

5.4 Future work

To improve the project a couple of things could be done. First of all, our boards have a lot of design changes that we implemented while testing, and these changes are proven to be working, now they just needed to be integrated into the schematic and PCB design for the new revision of boards. An improvement that can be implemented is using a MOSFET with lower Vgs_on voltage to improve max current flow, with minimal Ron. This will also allow us to charge the cells with higher current, which will make the charging process faster. Flyback Converter may need an additional noise filter to generate cleaner output voltage that will ensure safer and cleaner performance of the Constant Current source. Looking into power saving techniques for minimizing the idle power draw will be beneficial to make the BMS even more efficient.

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Appendix A Requirement and Verification Table

Table 2: Battery Charge Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Constant Current (a) Provide 6A constant within 0.1A (b) Take a 5V input	1. Setup DC power supply to 5V 2. Setup DC electronic load to 2.5V constant 3. Ensure current is constant and vary electronic load voltage from 2.5V to 4.2V	Yes
2. Connect arbitrary cell to constant current source (a) Only 1 cell should connect at a time (b) Carry 6A continuous	2. Setup DC Power Supply for 5V with 6A limit 3. Setup DC Electronic Load for 3.5V 4. Connect DC supply to constant current input 5. Connect a separate 5v supply for the digital inputs 6. Connect all digital inputs to low 7. Connect cell taps 0, tap 1, and odd-select to 5V 8. Connect DC load to cell taps 0 and 1. 9. Ensure 6A is flowing 10. Repeat from step 6 with increasing numbers, ex: 1 and 2, 2 and 3, etc. Choose evenselect or oddselect to align with the larger of the 2 numbers.	Yes

Appendix B Circuit Schematics

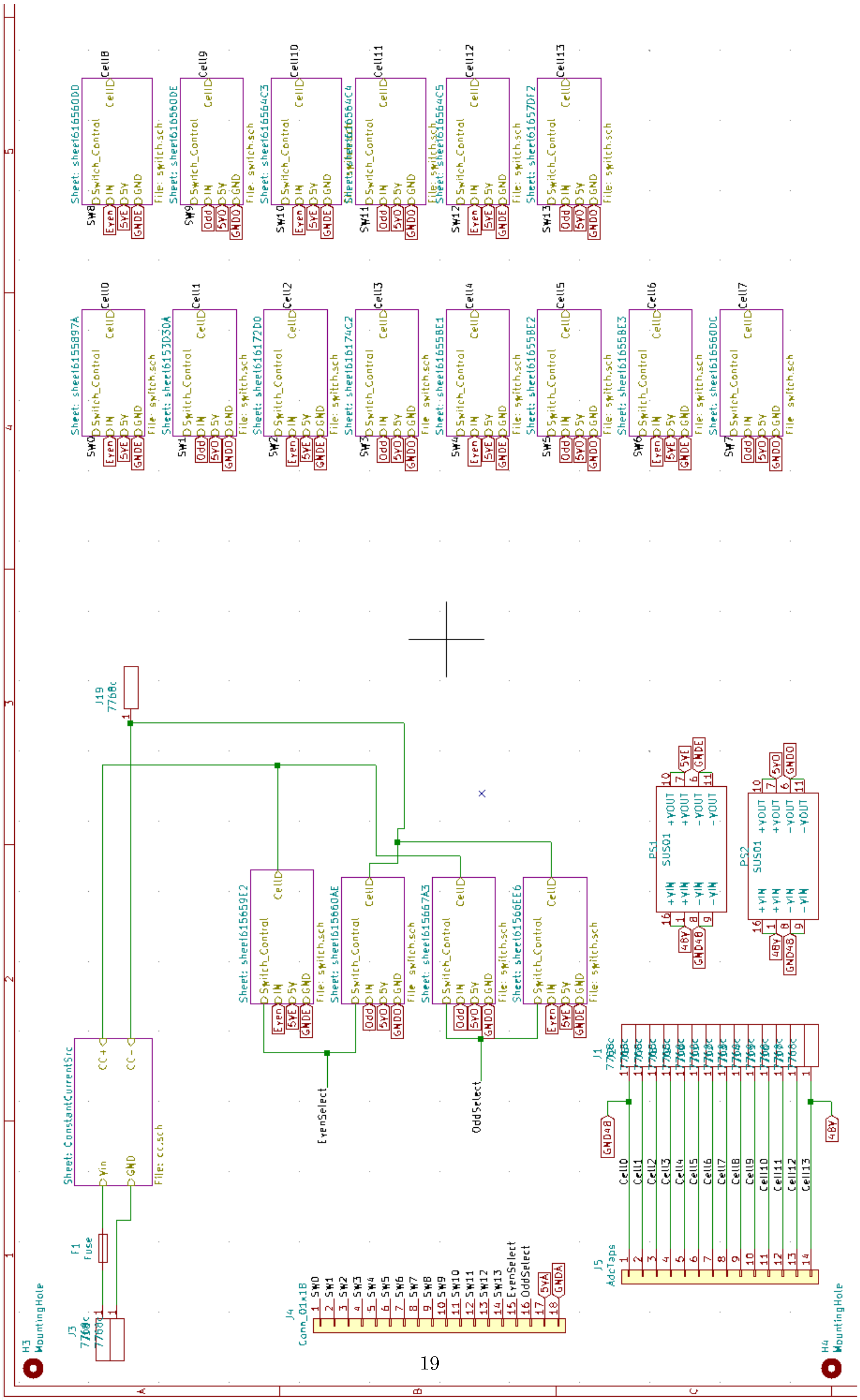

Figure 16: Full Schematic for the Charge Switch Matrix

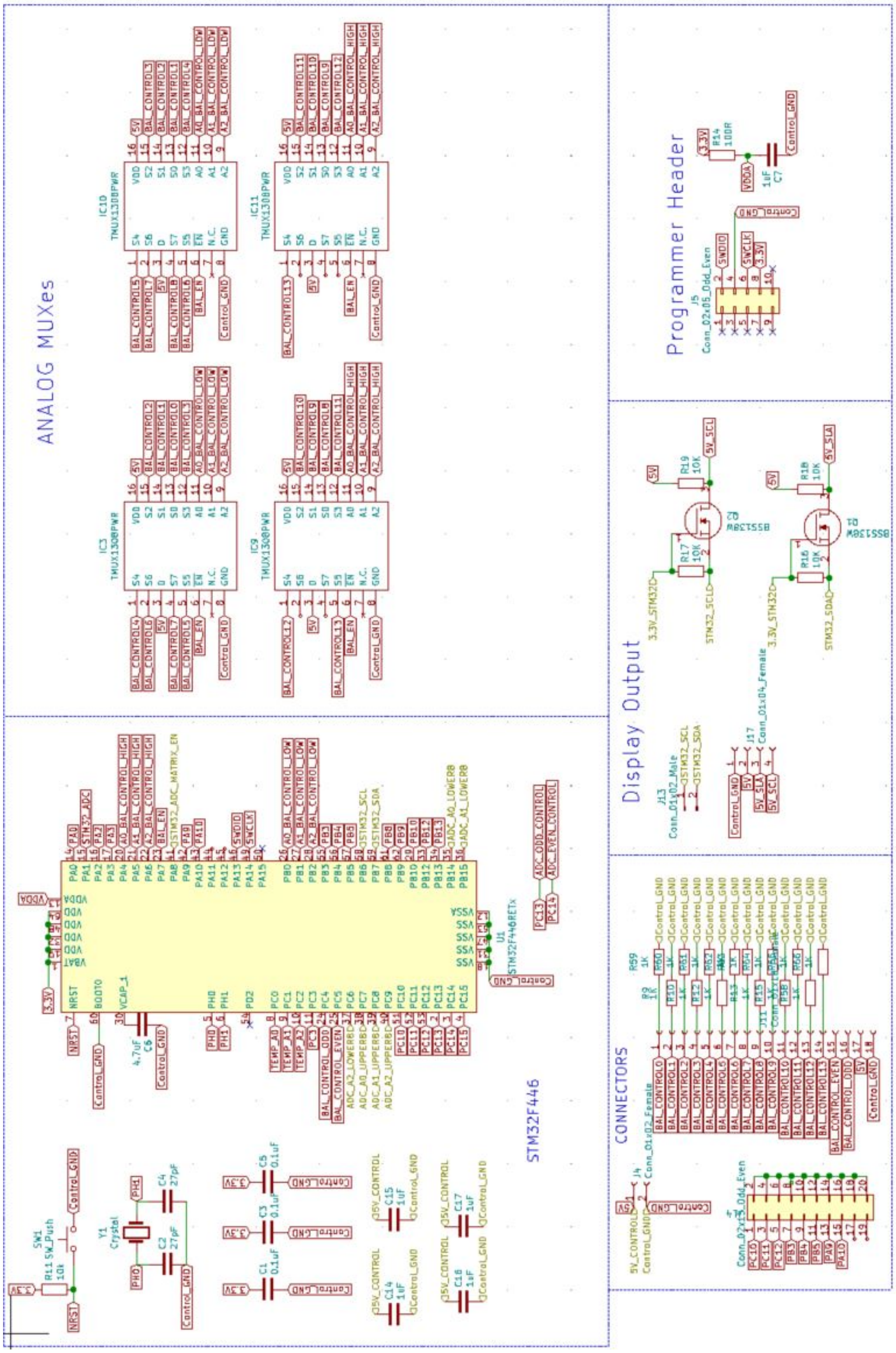

Figure 17: Full Schematic for the Control Subsystem