Resistance Racing – Electrical

Battery Management System

Fall 2018 Technical Report

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Summary

System Description

The Battery Management System consists of an electrical circuit that has as main functionality to monitor the state of a battery pack. This is achieved through the constant measuring of a variety of parameters such as battery cell voltage, current, temperature, state of charge, etc. The use of a Battery Management System for our team is required since we are competing in Shell Eco-Marathon in the category of Prototype in the division of Electric Vehicle, which means that the main source of power for our vehicle comes from a battery pack. The type of battery established by the competition's rules is Lithium Polymer, which can be very dangerous if operating unsafely. This is why it is absolutely necessary to use a BMS when manipulating this kind of batteries.

Terminology

IC: Integrated Circuit. A device designed for mounting on a PCB or in a breadboard, usually in a small black package, which performs some specific functionality (opamp, microcontroller)

PCB: Printed Circuit Board. A board of copper and fiberglass used for wiring small IC's and passives in a compact manner.

Cell/Battery: Battery refers to the battery pack of 12 battery cells

Passive Device: electric device with linear IV relationship: resistor, capacitor, inductor.

Joulemeter: Device which measures current and voltage to determine the amount of instantaneous power consumption.

MC: Motor Controller. Delivers signals to the motor to control when and how fast it accelerates the vehicle. We are using a brushless DC motor and therefore a BLDC motor controller.

BMS: Battery Management System

DAQ: Data Acquisition System. Collects data and will provide visualization and analysis.

Microcontroller (μC): Small computer integrated in an integrated circuit. It includes the processor and also peripherals.

I2C: Serial communication protocol that consists in two main lines: clock and data signals. It accepts multiple masters and multiple slaves.

SPI: 4-wire serial communication protocol. It accepts both single- and multi-masters with multiple slaves. It includes CLK (clock), MISO (master in slave out), MOSI (master out slave in) and CS (control signal).

DC-DC Converter: Electronic device used to step down the voltage from 48 V to either 3.3 or 5 V.

Research and Requirements

Background Research

For the reader to fully understand this report, he or she must have a previous understanding of electric circuits and basic concepts such as RC circuits, filters, etc (ECE 2100). It will also help if the reader has a basic understanding of how transistors work, which is a content covered in ECE 3150 course. On top of that, it will be recommended to have some knowledge about microcontrollers and communication protocols, but it is not absolutely necessary; however, I would suggest to take the Design with Microcontrollers class (ECE 4760) if the reader is interested in further his or her knowledge about these topics. Lastly, I would recommend the user to take a look to this report which covers the basics of Battery Management Design:

https://www.electronicdesign.com/power/look-inside-battery-management-systems

Design Requirements

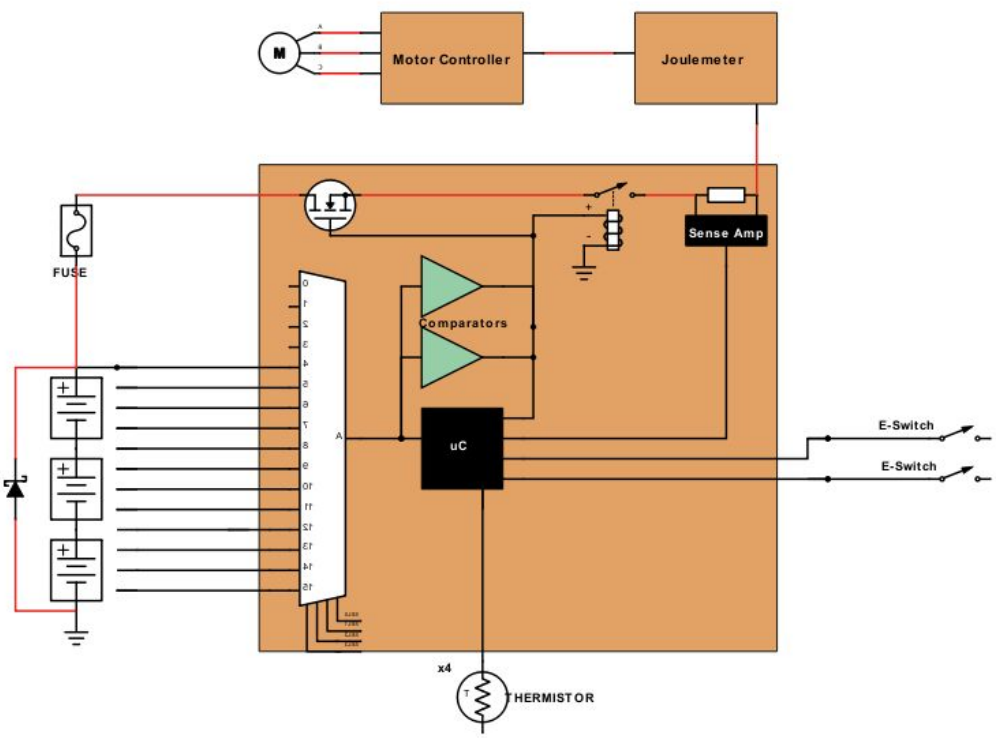
Shell establishes a group of requirements for the Battery Management System. It does not explicitly require the custom design of a BMS, but it is definitely a good design practice. The BMS used must be tailored for LiPo batteries of maximum voltage of 60 V and nominal of 48 V for a maximum capacity of 1000 Wh. The system must be able to detect short and open circuits, over and under voltage, over current, over temperature, and isolate the battery pack from the rest of the electrical system in case of any of these faults. For the isolation, it is recommended the use of a Normally Open relay. In addition, the system must be isolated from the driver, so it must be installed in a separate compartment in the car. The BMS is an intermediate between the battery pack and the rest of the electrical system, so in reality no other device is directly connected to the battery pack. Shell establishes the use of only one battery pack in each vehicle (in our case, the propulsion battery), so we must use other devices such as Buck converters in order to power the different electronics.

Key Parameters

The Battery Management System interfaces with multiple systems. The first parameter to take in consideration is the placement of the system in the vehicle. According to Shell's rules, the BMS along with the rest of the electronic devices must be isolated from the driver, so they should go in a separate compartment in the vehicle. The BMS should be placed as closed as possible to the battery pack since they will share various connections both high and low power; having them very close with respect to each other will guarantee a more elegant and effective design. Another important specification is the agreement with other systems in terms of the communication protocol used. Usually, when we talk about out of board communication, serial communication protocols are more effective. All systems should agree in the communication protocol they will use. It could also include wireless communication protocols such as Bluetooth or WiFi. In addition, there must be an agreement between the different systems in terms of connectors used. In general, another consideration for the BMS will be the power consumption, which is a key parameter for the competition.

System Diagram

In high level, the system should be able to detect if the battery pack is operating out of its safe operating area. It should monitor the voltage level of each battery cell (in the stack of 12 battery cells), measure the current drawn by the motor, and monitor the temperature of the battery pack; some of these parameters can also be used to calculate others such as the state of charge of the battery. There are multiple options to complete these different functionalities and a variety of reasons to choose one over the other as it will be analyzed in the next section. In general, the system will look something like the diagram below. There are multiple details about the system that will be fully understood in the Potential Designs sections, but in general we can notice the connections of each battery cell with the microcontroller through an analog mux, the use of comparators to check for voltage limits for each battery cell, the use of a fuse to control over current, the inclusion of both a power mosfet and a NO relay to isolate the battery pack from the rest of the system, the use of a current sensor to measure the value of the current and the inclusion of emergency switches and thermistors.

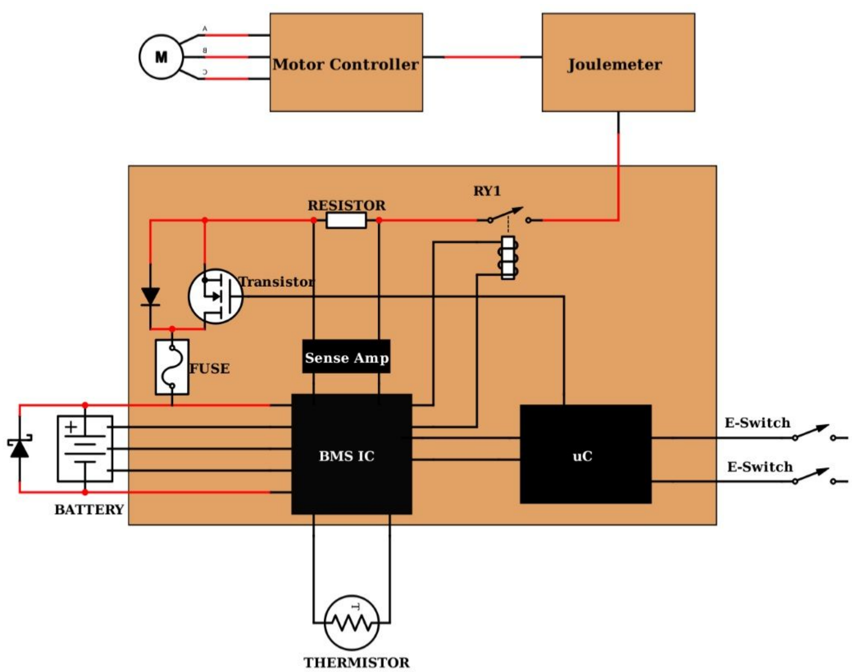


Potential Designs

As aforementioned, there exists multiple possible implementations for each of the subsystems that compose the Battery Management System. Here I try to describe the ones I took in consideration to make the final selection so you can understand the thought process behind. Also, for the selection of each design, we should take in consideration important aspects such as performance (specially in terms of power consumption), cost, feasibility, among others.

Battery Cells Voltage Monitoring

I believe it is valid to reference the BMS report from Fall 2017 and Spring 2018 to explain this part. The design used back then was the first Battery Management System designed for this type of competition and following Shell's rules. Back then, the design selected consisted of choosing a BMS IC (an integrated circuit that performs the specific functionality of a BMS) and building the circuit around it. This is in reality how most Battery Management Systems are designed in the industry. These ASICs (Application-Specific Integrated Circuit) have been subject to tons of research and are very reliable and accurate in measurement. However, they don't offer much flexibility to customize the design to our specific necessities. In addition to that, the IC orchestrates the collection of all data and then communicates it to a microcontroller through a communication protocol. It seems simple, but at the same time it can generate a lot of problems if the communication between these devices doesn't work properly. An issue of this type could cost multiple weeks of debugging without success. The ASIC ends up being a black box and you can't do anything to fix any problem it has.



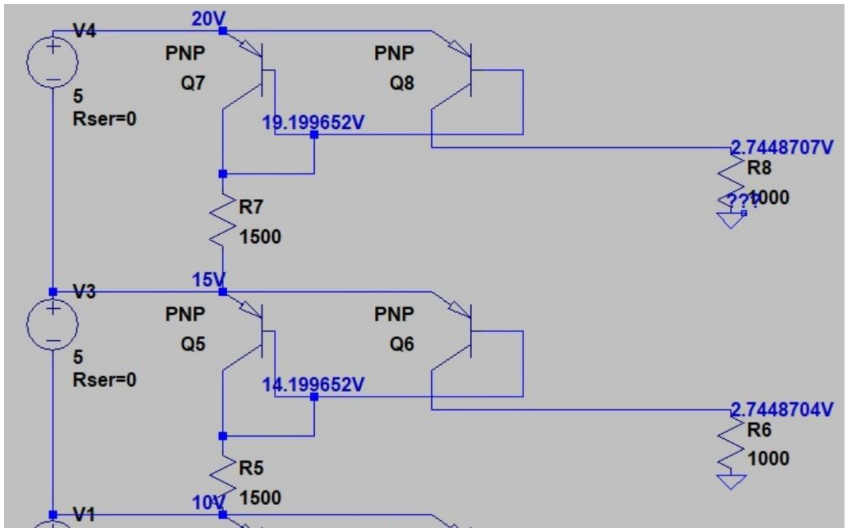
The diagram above illustrates the high-level design of the BMS back then where you can notice the BMS IC as the main device. This problematic experience that costed so much time to our peers has served as an incentive for a new design of the Battery Management System. After some analysis of how the BMS IC operates to achieve its multiple functionalities, we came up with the idea of developing ourselves the circuitry of the BMS, which means that we could get rid of this ASIC and all the communication faults that it could generate. The problem now was that, since most of the BMS in industry are designed using these ASICs, we would lack documentation for our new approach.

The first challenge generated after our decision of eliminating the use of the BMS IC was that the microcontroller's pins were not rated to high values of voltage. This means that we could not directly connect the signal from each battery cell to the microcontroller's pins. We needed a circuitry to massage the signal so we could convert it to something plausible. Since each signal won't work with reference to GND, we then took a different approach, working on referencing each cell with respect to its adjacent cell (its predecessor counting from GND to the top cell). This is known as voltage difference, so the signal from each battery cell will have the voltage of its adjacent cell as reference. Since each LiPo battery cell should operate in the range of 2.5 to 4.2 V, this range of voltage worked fine for the pins of the microcontroller. Now the question was how we could obtain this voltage difference.

The simpler way to obtain different levels of voltage is through voltage division by the use of two series resistors per cell and manipulating their values to obtain voltages in the required region. The main problem with this approach is its efficiency; this type of circuitry consumes a lot of static power (P = IV), which hurts our system in the most important parameter for the competition. This design is also not very effective since the values of voltage obtained will depend on the amount of current passing through each leg of resistors, so it could vary a lot.

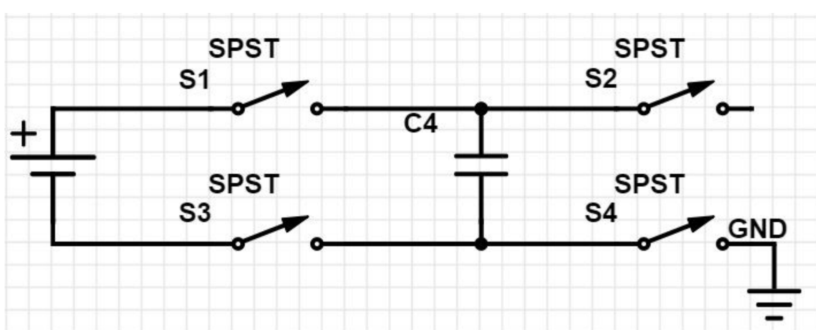
Another option was to use operational amplifiers using the difference amplifier topology, but the problem with this is that the two input signals will be much higher than Vdd (5 V) taking GND as reference, so this will break the amplifier.

Another interesting solution was the use of current mirrors, a concept that is covered in the Microelectronics class (ECE 3150). In high-level, it consists of a topology that uses transistors and resistors where two legs (connection from Vdd to GND) are connected with each other via the gates (in the case of mosfets) or base (in the case of bjt) of the transistors which produces the same current in both legs. This current could be manipulated by the selection of the value of the resistors. The transistor of the first leg must be diode-connected to guarantee its saturation and it is the one that will mark the amount of current; the second leg will draw the same amount of current than the first one if the transistor is physically identical to the first one and, by using a resistor, we could manipulate the amount of voltage across this resistor, which we could use to measure a voltage proportional to the voltage of the battery cell. The topology described would look something like this:

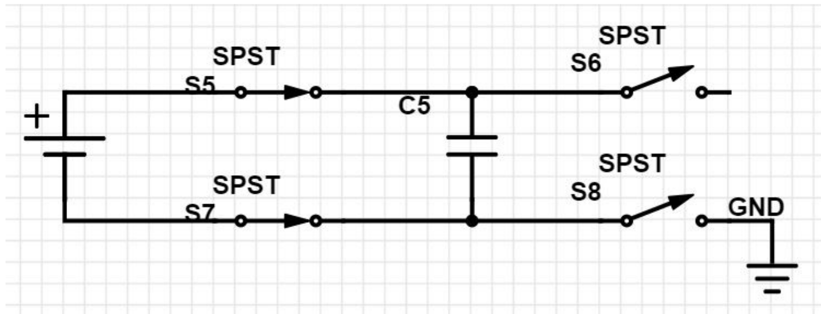


Theoretically, this seems that will work, even though we will have a static power that is being dissipated through the first leg from the top cell to ground which is not trivial. On top of this, we must take in consideration the sensitivity of both BJTs and resistors to temperature variations. The temperature in Sonoma CA, the place where the competition will happen, varies from 40 to 100 degrees, which will definitely affect the parameters of our circuit. Therefore, this design is not plausible for our purposes.

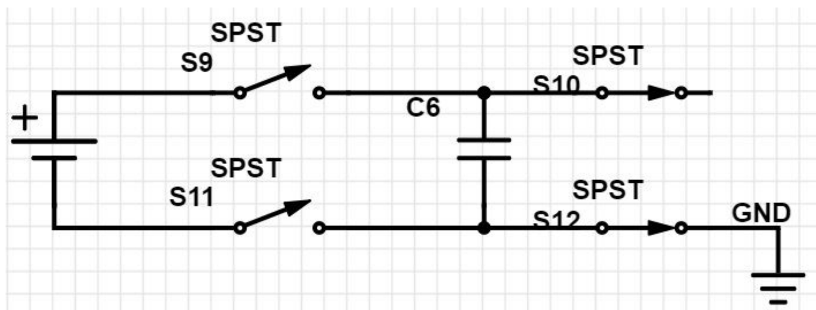
The final design we came up with was the use of what is called switched capacitor. It consists of the connection of a capacitor in parallel to a specific battery cell in order to charge it up to the same voltage of the cell and later isolate the capacitor and measure the voltage value with respect to ground. Since the safe operation region for each cell is from 2.5 to 4.2 V, the voltage measured in the microcontroller will be within the rating values for its pins. The switching effect of the system will be completed by the use of transistors. For the selection of the transistors, it makes sense to use PFETs as high-side switches and NFETs as low-side switches; this means that PFETs will connect and disconnect the battery cell with the capacitor and the NFETs will connect and disconnect the capacitor from the microcontroller pins. The following constitutes a conceptual diagram of the circuit:



High-Level Design of Switched Capacitor



Charging of the capacitor

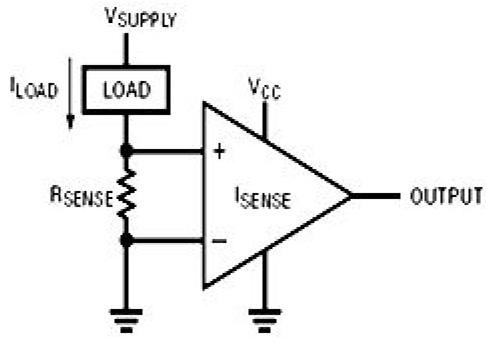


Measurement of the voltage across the capacitor

The real design will substitute the conceptual switches by transistors including all the necessary circuitry to bias them. Also, it will include a transistor from the top of the capacitor to ground in order to completely discharge it and current-limiting resistors. In terms of efficiency, this design is more effective since the power consumption is dynamic (there is supposedly not static power consumption) and it depends on the capacitance and the switching frequency which can be both manipulated.

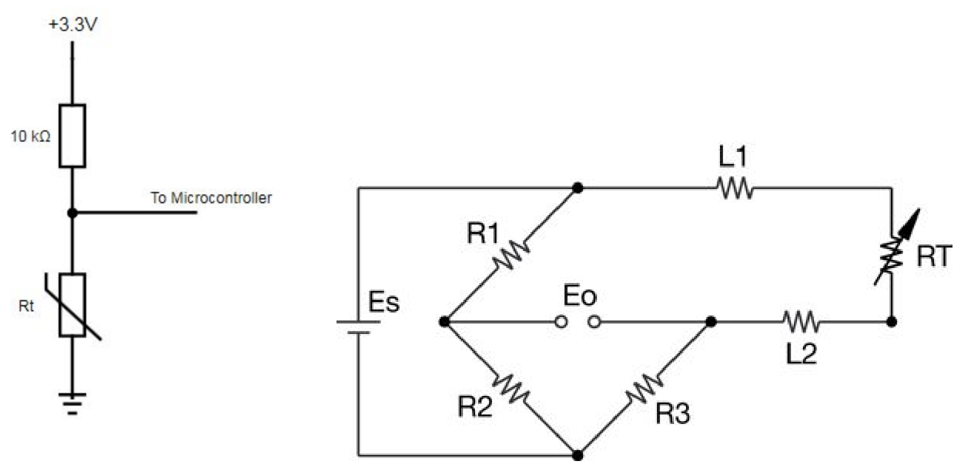
Current measurement

For the design of the circuitry able to measure the current drawn by the system (mostly by the motor) in the high power connection, we can use a current sensor, which is the most used technique in this case. The current sensor will be a very small resistor that, given its resistance and measuring the voltage across it, we could calculate the amount of current. This resistor is placed in series in the high power line that goes from the BMS to the Joulemeter and its value is very small so the voltage drop is insignificant. Since the voltage drop will be very small, we need to measure this value using an amplification device. The output will be connected to an ADC (analog to digital converter) in the microcontroller to measure the value. We could also add comparators so the detection of extreme conditions does not rely on the microcontroller.



Temperature measurement

In the case of the temperature, the most straightforward methodology we can apply is the use of thermistors in voltage divider topologies. This will not be super accurate but it will be sufficient to establish a threshold temperature. Another option is to use wheatstone bridge to improve accuracy but this will imply the incorporation of multiple resistors and we do not really need that level of precision. Both topologies are included below:



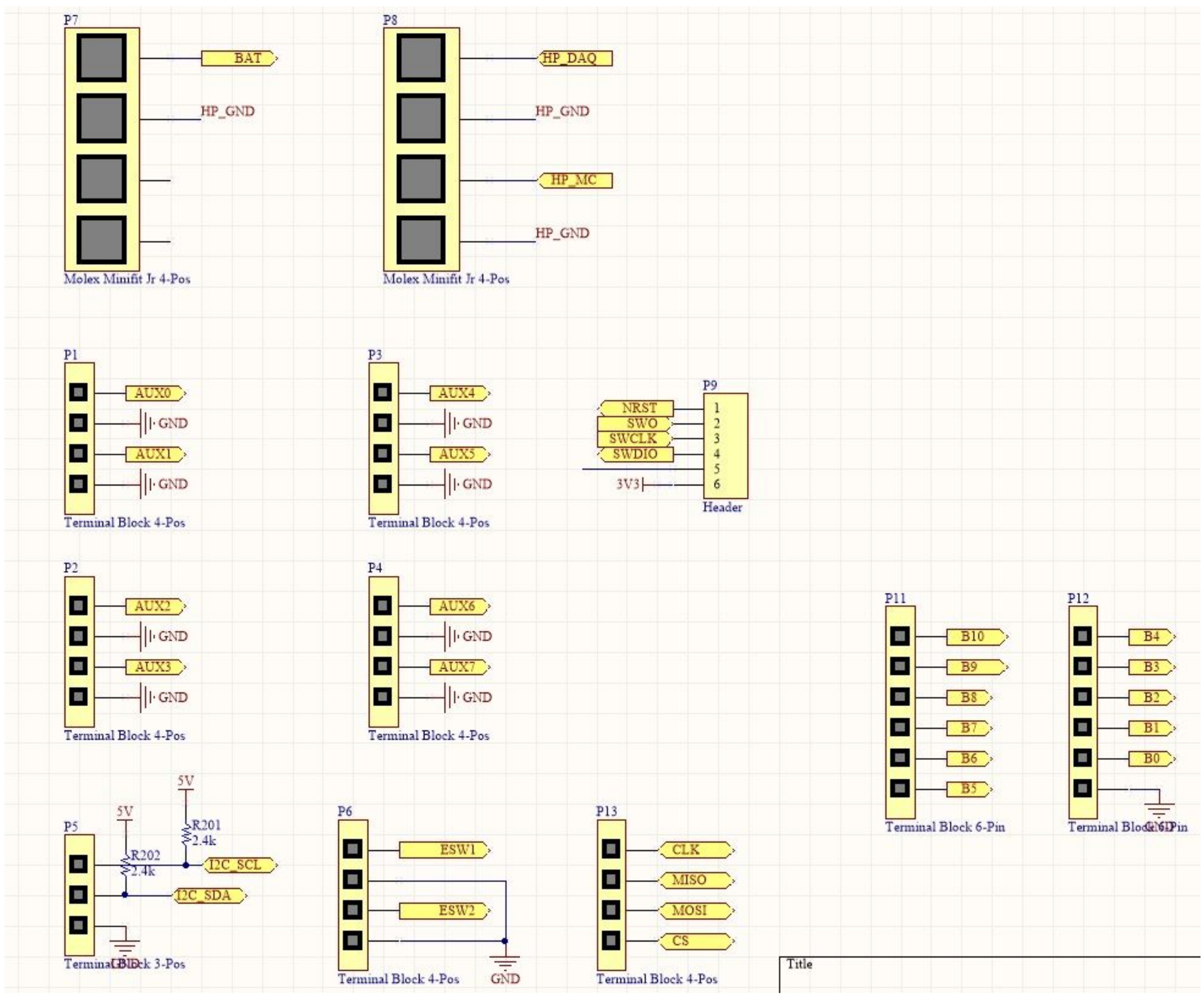
Thermistor in a voltage divider topology (left) vs thermistor in a wheatstone bridge (right)

Selected Design and Justification

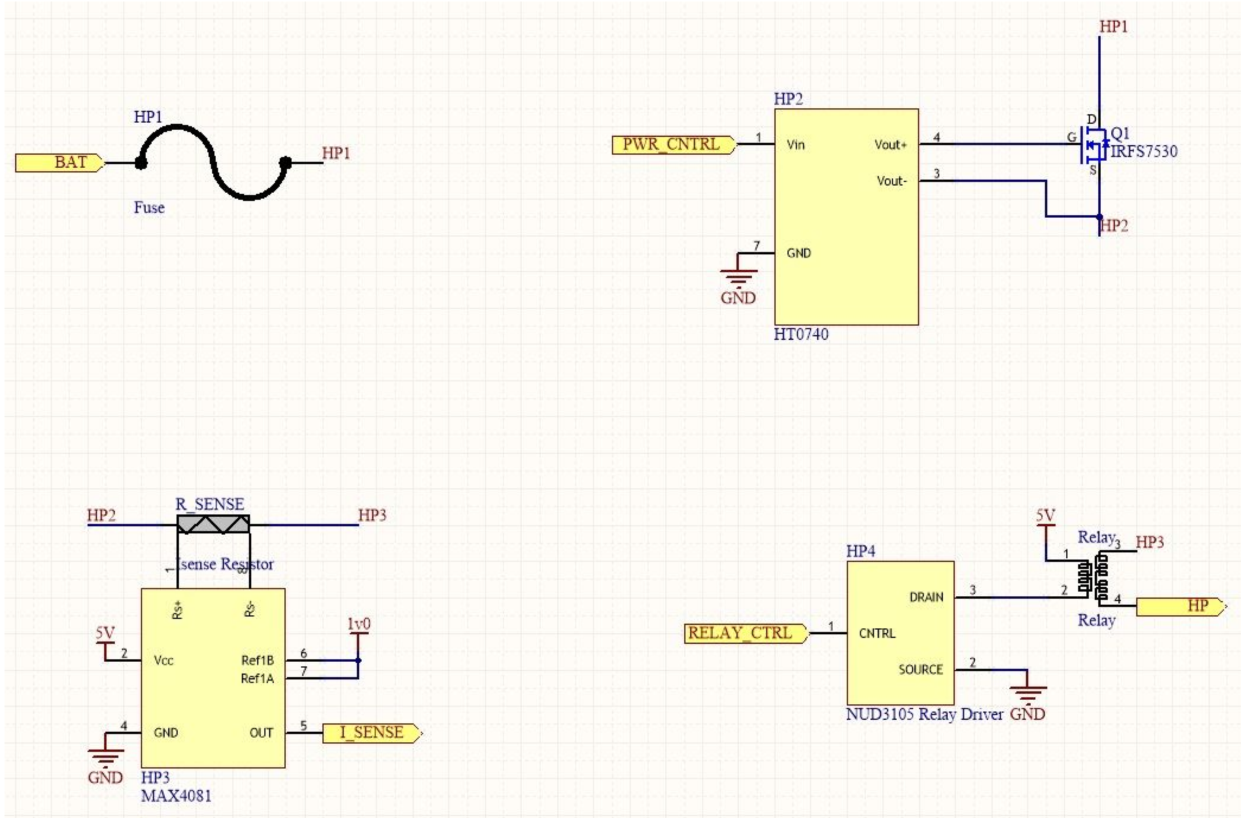
From the designs discussed in the previous section, we selected the switched capacitor topology for the voltage measurement, current sensor for the current measurement and thermistor in voltage divider for the temperature measurement. The justification for each of them was well explained in the previous section when comparing them to their homologues. The effectiveness of some of these designs, specially the switched capacitor, was properly simulated using LTSpice. The next step will be the actual test using a test board.

Detailed Design (Schematic)

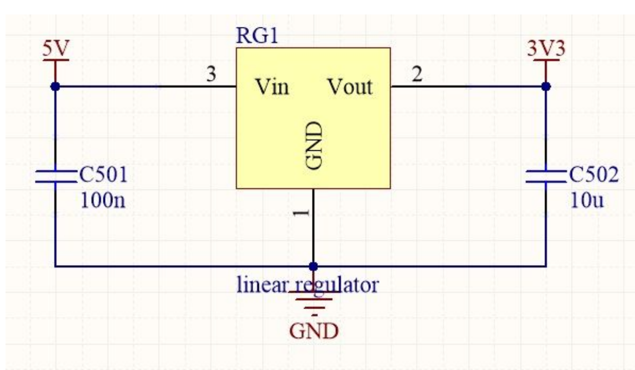
Design Overview



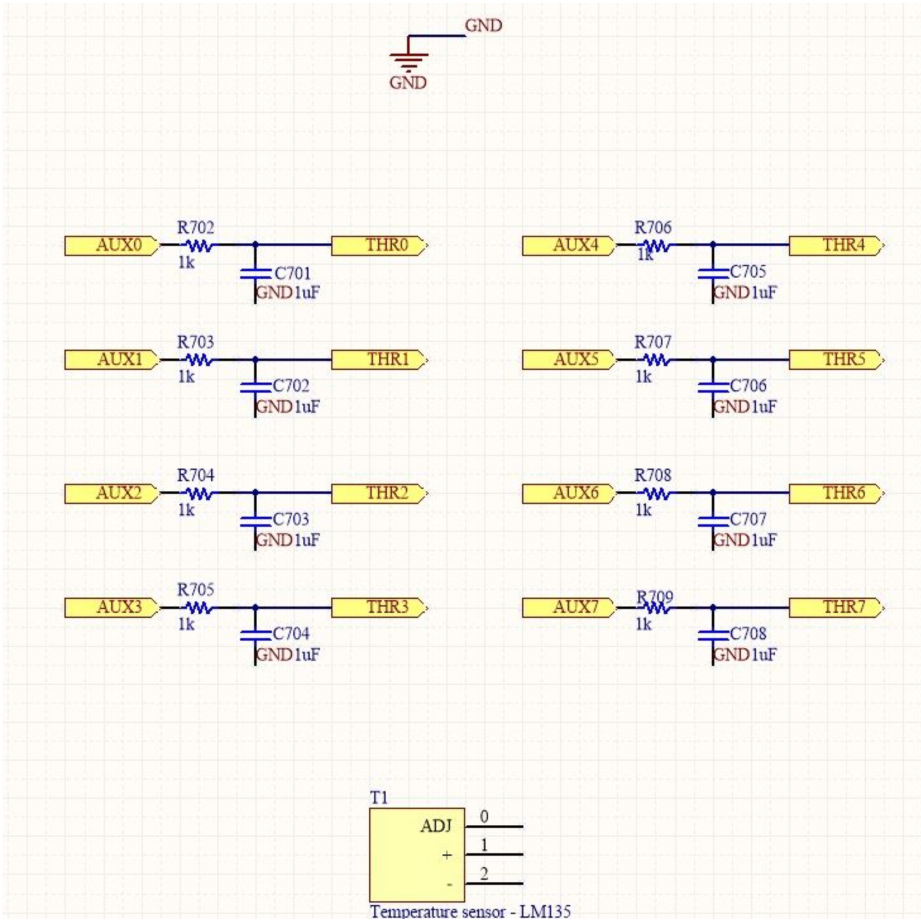
These are the headers or the connections of the BMS with other electronic devices. The top two are used for the high power connection and will probably be MiniFit Jr connectors. In the case of P11 and P12, which correspond to the low power battery connections, they will correspond to JST-XH. The battery pack will consist of 12 cells. For the rest of the connectors, there will definitely be pin headers and will be used for several purposes such as I2C and SPI communication protocols and the connections to thermistors and emergency switches.



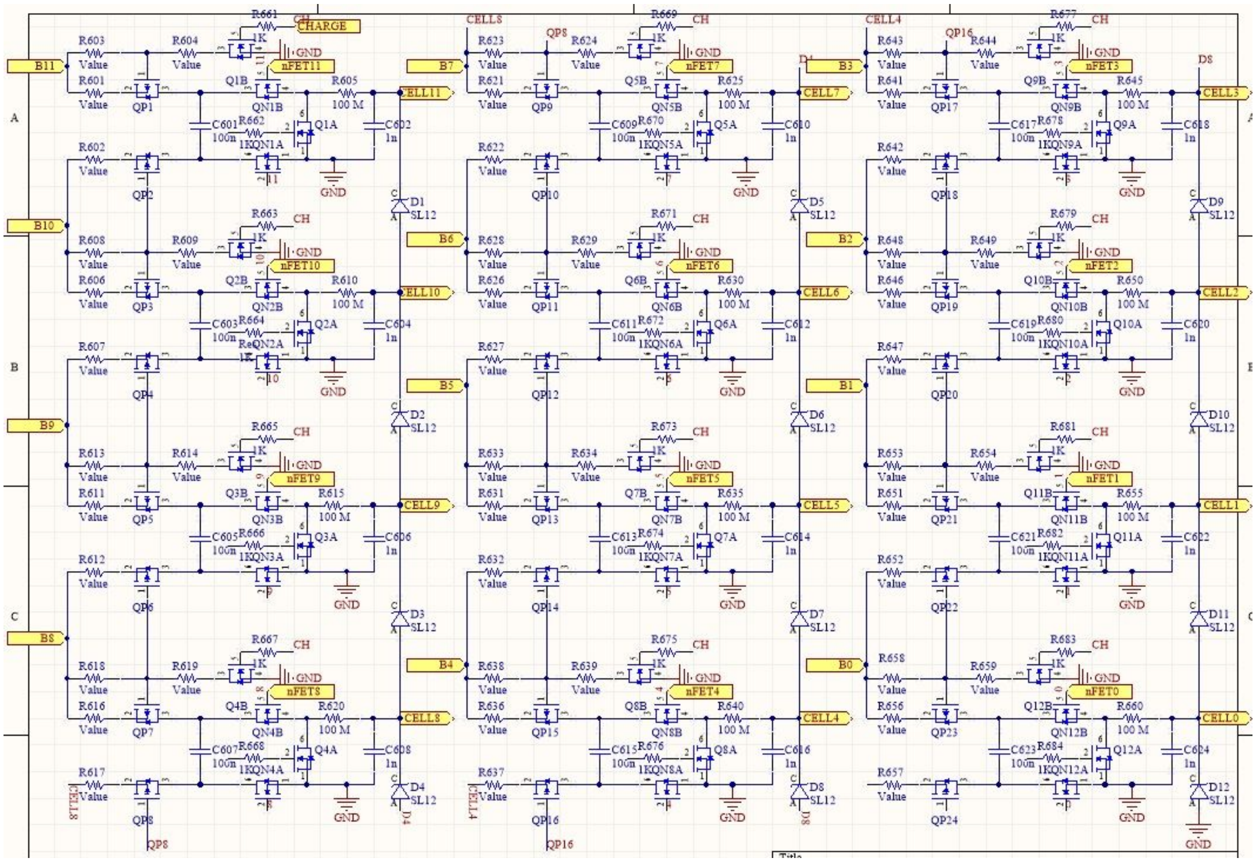
These elements correspond to the high power connection of the system. This is the path of the high power before going from the BMS to the Joulemeter and then to the Motor Controller and Motor. The top cell of the battery pack will be connected to the fuse which will be rated up to 30 A (this is the maximum value we have established for the current). From the fuse, the connection goes to a power mosfet which is driven by a MOSFET driver (HP2). The connection continues from the source of the power mosfet to the current sensor; it can be seen how the current sense amplifier measures the voltage across this resistor, value that is later used by the microcontroller to calculate the current value. From the sense resistor, the connection continues to the high side of the relay, which is controlled on the low side by a relay driver (HP4). As it can be seen, this design contains a lot of redundancies in terms of protection, which makes it safer.



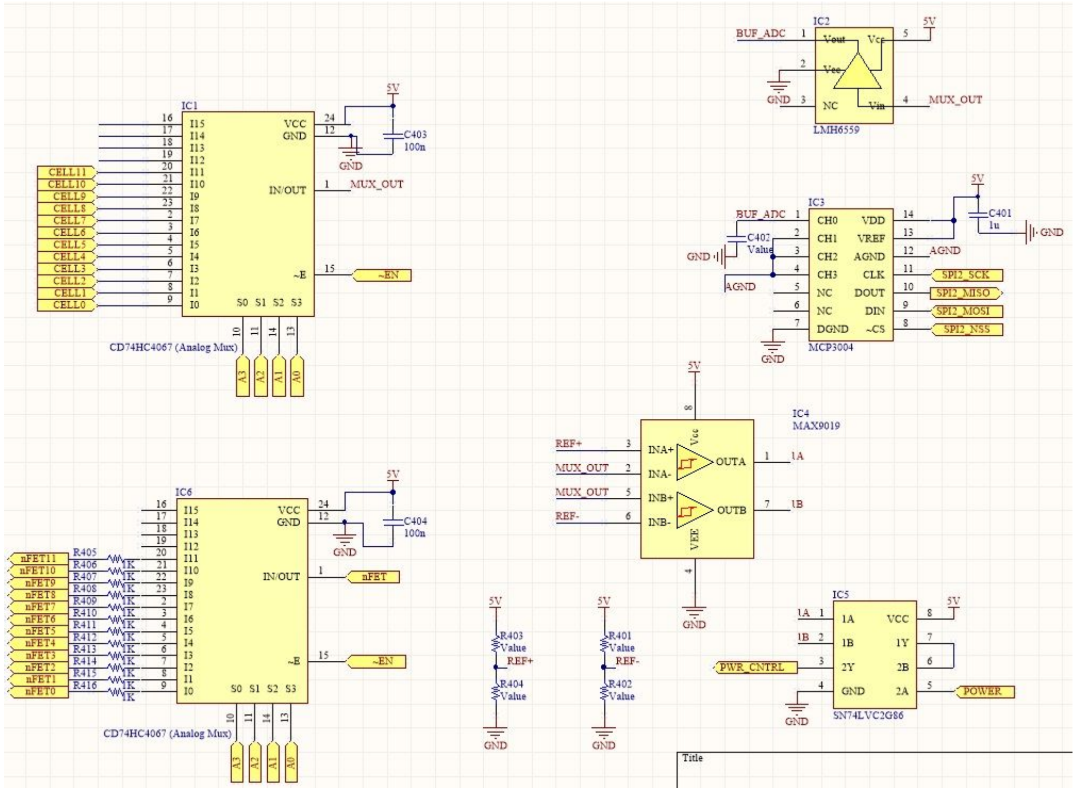
Since Shell establishes the use of only one battery pack, which in our case corresponds to the propulsion battery, we must step down the high voltage to either 3.3 or 5 V to power the electronic devices. For the transition from 48 to 5 V, we will use switching converters which promise to be one of the most efficient options. In the case of transitioning from 5 to 3.3 V, we could use linear regulators as the one included in the schematic above.



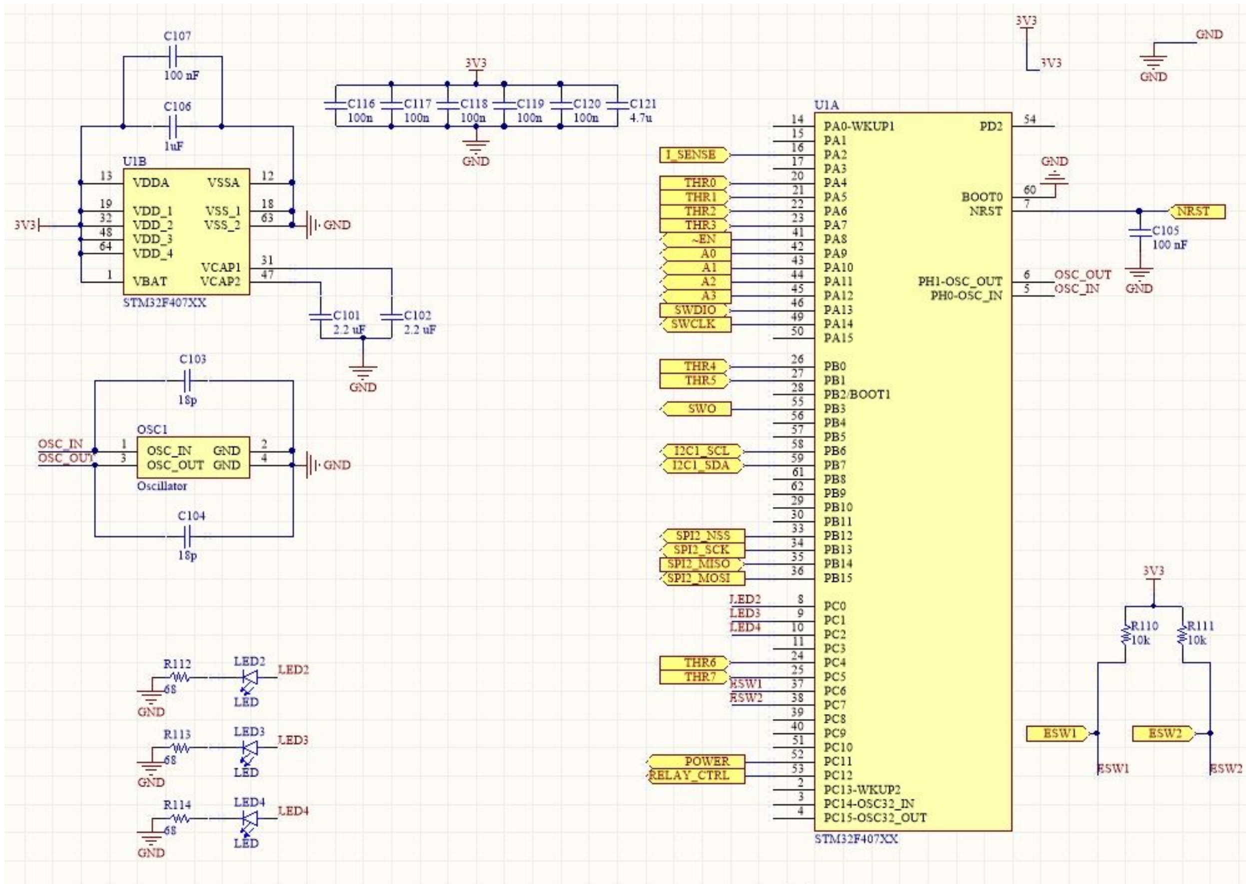
As aforementioned, we use thermistors to measure the temperature at different spots in the system (mostly in the battery pack and the printed circuit board). In order to do this, we use thermistors in a voltage divider topology and a temperature sensor (LM135) to measure the board temperature. The previous schematic shows these components, and we can notice the use of passive components to filter out high frequency noise.



The previous schematic shows the cell connections in order to measure the signal from each cell. As it has been described, we are using a topology called switched capacitor where we use a capacitor to capture a snapshot of the voltage in a battery cell. We can notice the use of transistors here in substitution to the conceptual switches previously used. In our case, we are using PFETs as high-side switches and NFETs as low-side switches. This decision helps us not to have floating sources which can be problematic since this is the reference for the biasing of the transistors. We can also observe the inclusion of current-limiting resistors. In addition, we can see the use of zener diodes for protection purposes as it will clamp any value of voltage greater than expected. Notice that the PFETs gate signal is regulated by a voltage divider with an NFET as low-side switch. PFETs operate the opposite in comparison to NFETs: at high values of Vgs it turns off and at low values it turns on. The problem is that these PFETs are rated to gate-to-source voltage values of -20 V <= x <= +20 V; this means that in the case of the top cell for instance, taking the gate voltage all the way to GND will destroy the transistor. Therefore, we include a switching voltage divider so it could be turned on without getting all the way to GND.



The charging of the capacitors to measure the voltage difference between one battery cell and its adjacent will be done all in parallel for simplicity. This means that the same signal will be used to charge all these capacitors at the same time, which will be the signal biasing the NFET in the low-side of the voltage divider. In the case of the reading of the voltage from each capacitor, it cannot be done all in parallel so we need to create a sequence to read them all in the microcontroller. To read all these cells sequentially, we have decided to use an analog mux so the microcontroller generates the selector signals to choose the battery cell to read from. Similarly, we needed a way to generate alternating signals for the biasing of the NFETs of the low-side of the cell connection in order to read all those voltages. Since this has the opposite effect of the analog mux, we will use an analog demux, which will be basically the same component but used differently. To generate the signal for the capacitors to be discharged, we are still debating between generating an independent signal or using the same signal for the biasing of the NFETs with a delay element. After the signal is outputted by the analog mux, it passes through an analog buffer that basically lowers the output impedance to ensure signal integrity since the input impedance of the ADC is relatively low. After this, the signal bifurcates into three alternatives: the Analog-to-Digital Converter to measure the voltage and to a pair of comparators in order to keep the voltage values within the limits; if any battery cell measured is operating out of the safe area, the system will completely isolate the battery pack. The signal outputted by the comparators are later inputted into an 3-input AND gate that also receives the signal from the microcontroller that everything is operating fine. Any zero value that the AND gate receives, the system is shut down.



In terms of microcontroller, we started with the idea of using STM32 which is ARM based and it was the one used last year so we could reutilize the code. However, we then realized that this type of microcontroller was unable to provide 5 V through its pins which is the amount of voltage that we need in order to biasing the NFETs. The schematic included here corresponds to the specific pins of the STM32 but the schematic for the new selected microcontroller will be similar. The new microcontroller will be the PIC18(L)F67K40 which is very similar to the STM32 in terms of peripherals but can provide 5 V. In general, the microcontroller will receive all connections from the rest of the electrical system to digital, analog, I2C pins, among others. We can also see the inclusion of emergency switches and LEDs.

Component Selection

The components selected for this design are included in the Bill of Materials and justified in previous sections.

Mounting and Packaging

This board will be mounted probably using four M3 bolts and nuts as it was done last year. The mounting of the BMS onto the bulkhead will be done making sure it is as close as possible to the battery pack. We must also take into consideration possible vibrations that could affect the connection of the BMS with the DC-DC converter, so we must make sure the converter is correctly attached to it and with enough support to keep it fixed.

Analysis

Load Cases

As load cases for this system, we will have a maximum current of 30 A limited by the rating of the fuse utilized in the high power line. In terms of maximum voltage, it will be around 48 V which is provided by 12 LiPo battery cells in series. In the case of the temperature, the maximum value will be 170 degrees.

Bill of Materials

https://docs.google.com/spreadsheets/d/1ZTg53DmSDKfQUKK6yf-XeLRCCl8ZKExc2UZxPOTxljo/edit#gid=0

Testing Plan

The first part of the testing plan was to run several simulations of the design. These tests seem to work but this is something that we must confirm by creating a prototype and testing it properly. The plan will be doing this and then proceed to the fabrication and testing of the actual device. Later, it will come the programming part of it.

Project Reflection and Future Work

Making a design from scratch is a very exciting yet challenging project. It takes a lot of time to figure out a new design specially when there is no much helpful documentation out there. It can be very rewarding though because you learn a ton about design process of a device. For future work, I will suggest to contact people capable of helping. You do not have to do everything by yourself. There are many professors who are willing to help. Also, start earlier investigating, specially if your design is brand-new.

References

The main reference for the development of this project was the report from last year.