# Formula SAE 2020
# Electrical Systems Form

Western University

Western Formula Racing

FSAE North Number: 204 FSAE Electric Number: 219

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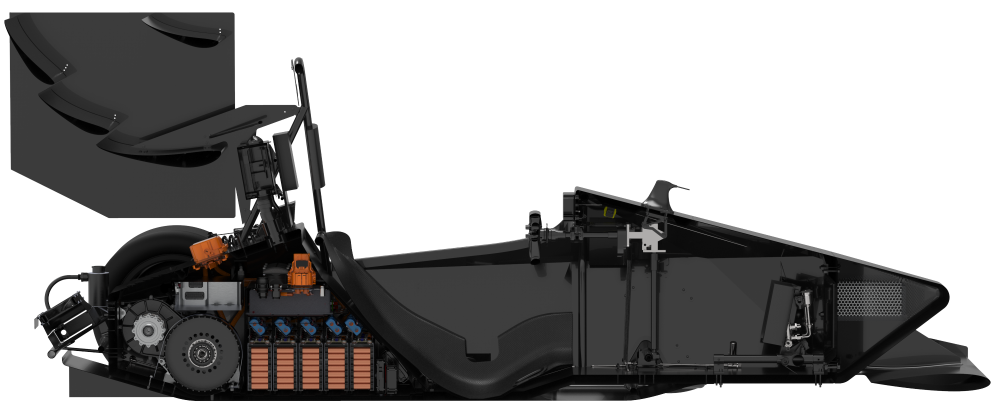

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**Abbreviations**

| Term | Expanded Term | Explanation |
|---|---|---|
| ACC | Accumulator | |
| AIR | Accumulator Isolation Relay | |
| AMS | Accumulator Monitoring System | |
| APPS | Accelerator Pedal Position Sensor | |
| BMS | Battery Monitoring System | |
| BOTS | Brake Over Travel Switch | |
| BSPD | Brake System Plausability Device | |
| DMZ | Demilitarized Zone | Spacing between HV and LV on Printed Circuit Boards |
| GLV, LV | Grounded Low Voltage | |
| GLVMP | Grounded Low Voltage Measurement Point | |
| HV | High Voltage | |
| IMD | Insulation Monitoring Device | |
| TS | Tractive System | |
| TSAL | Tractive System Active Light | |
| TSMP | Tractive System Measurement Point | |
| HVIB | High Voltage Interlock Board | |
| HVD | High Voltage Disconnect | |
| MP | Maintenance Plug | |
| VCU | Vehicle Conrol Unit | |
| HVC | High Voltage Connector | Main Current Path on Accumulator |
| LVC | Low Voltage Connector | LV Controls Connector on Accumulator |
| HV AUX | High Voltage Auxiliary Connector | HV Auxiliary Connector on Accumulator |
| INT | Internal Reset Loop | Driver Resetable |
| EXT | External Reset Loop | Not Driver Resetable |
| RST | Reset | |

# 1 System Overview

The vehicle has a single EMRAX 228 MV LC motor driving the rear axle via a differential and a step-down gearbox. The motor is powered by a Rinehart PM100DXR inverter running on a 400VDC bus. The inverter is acting as a CAN-bus slave to a Motec M150 ECU. The M150 is running on custom firmware developed by the team and handles all non-hardware safety functions as well as torque commands and data logging. All low voltage components on the vehicle run on either 12VDC or 5VDC.

Table 1.1: High Level Specifications

| | |
|---|---|
| Maximum Tractive System Voltage: | 399VDC |
| Nominal Tractive System Voltage: | 342VDC |
| Grounded Low Voltage System Voltage: | 5VDC, 12VDC |
| Number of Accumulator Containers: | 1 |
| Total Accumulator Capacity: | 7.182kWhr |
| Motor Type: | Synchronous Permanent Magnet, Axial Flux |
| Number of Motors: | 1 |
| Maximum Combined Motor Power: | 40kW (Software and Fusing limited) |

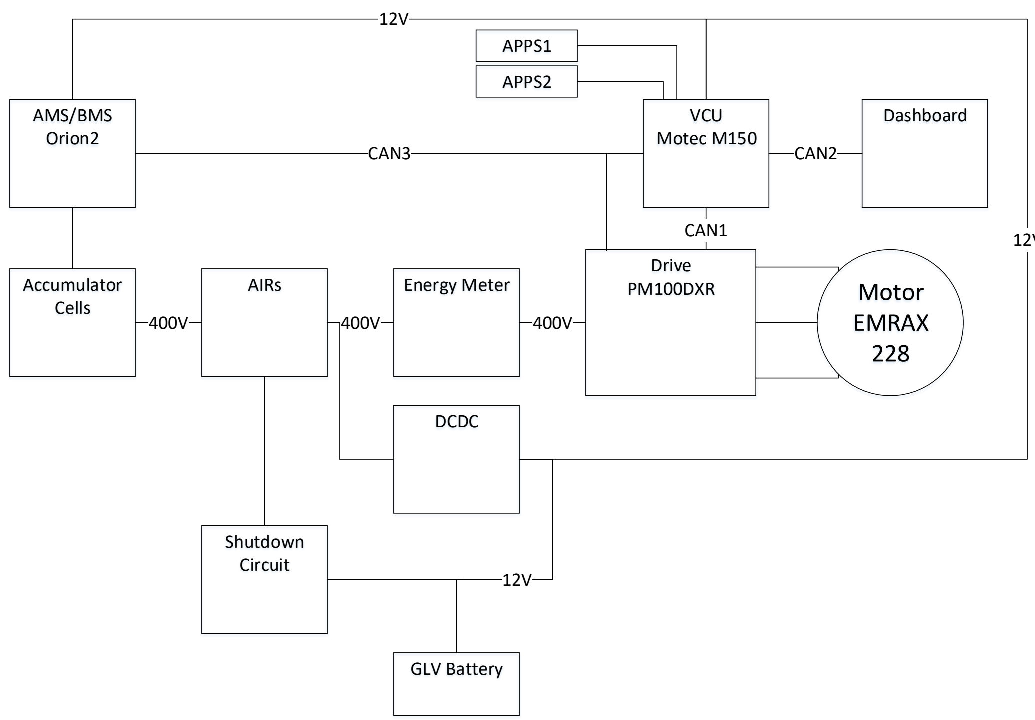


Figure 1.1: High Level System Block Diagram

# 2 Tractive System Schematics

## 2.1 Tractive System Schematic (Power Electronics)

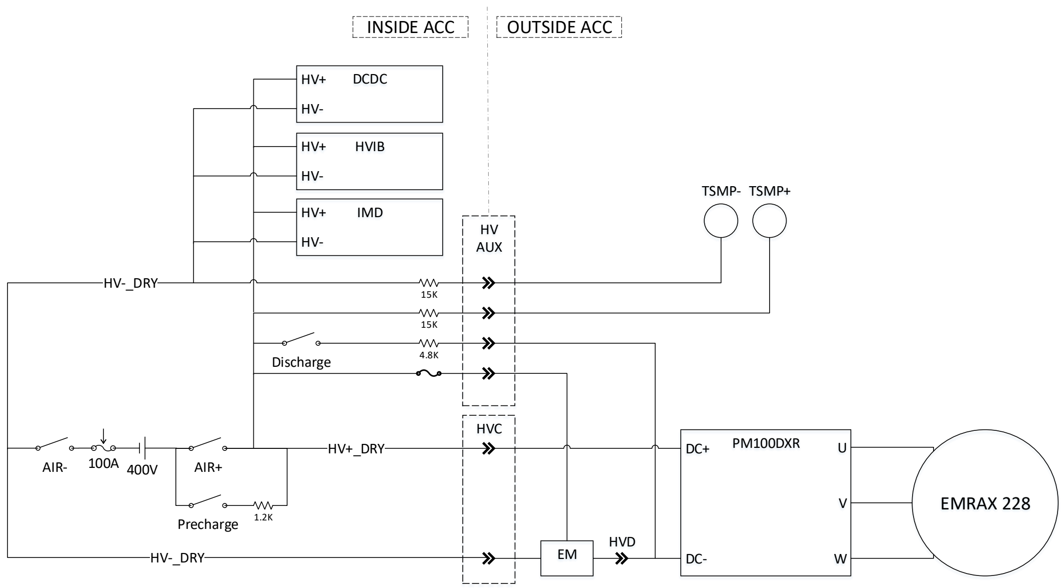


Figure 2.1: Tractive System HV Schematic

## 2.2 Fusing Diagram

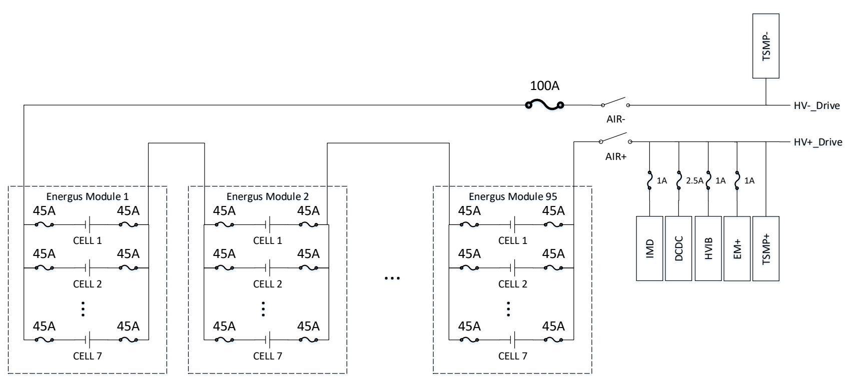


Figure 2.2: Fuse Diagram

Table 2.1: Fuse Specifications

| Fuse Location | Current Rating | Voltage Rating | Interrupt Rating | Datasheet |
|---|---|---|---|---|
| Main Fuse, Littlefuse L50S100 | 100A | 450 V | 20KA | Datasheet |
| Charger output | 30A | 500V | 20kA@500VDC | Datasheet |
| Cell Fuses – Energus Modules | 45A | N/A | N/A | See Figure 5.5 |
| IMD, HIVB, EM | 1A | 500 V | 100A | Datasheet |
| DCDC | 2.5A | 500 V | 100A | Datasheet |

# 3 Shutdown System

## 3.1 Shutdown Circuit Schematic

*Note: The diagram is vector graphics: zoom in as much as needed.*

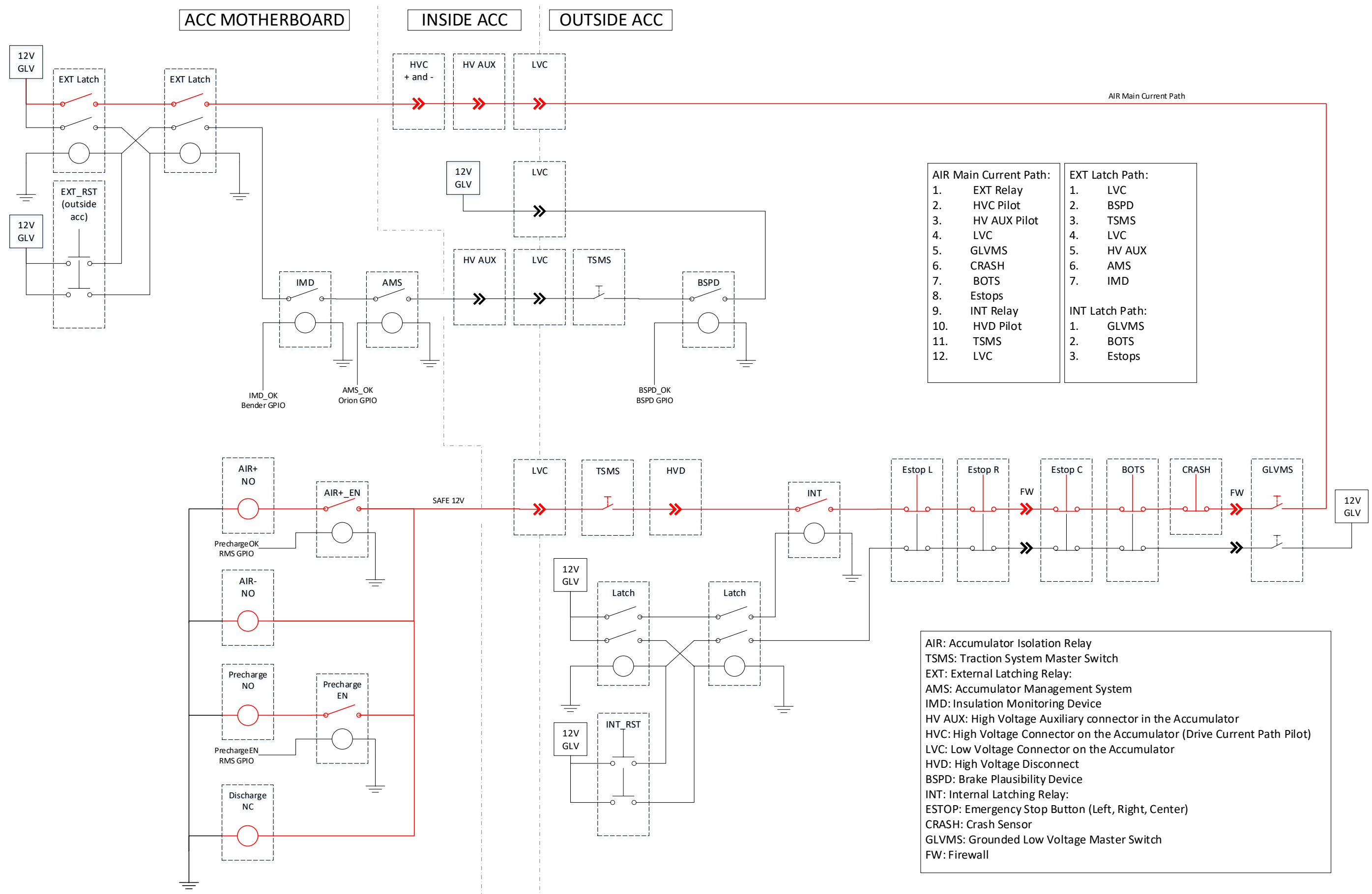


Figure 3.1: Shutdown Schematic

## 3.2 Wiring

Table 3.1: Conductor Specifications

| Conductor Location | Size | Voltage Rating | Ampacity | Fuse Rating | Temperature Rating | Datasheet |
|---|---|---|---|---|---|---|
| Cell Busbars | $44.45mm^2$ | NA | 205A | See Section 2.2 | NA | Team Manufactured |
| Tractive System DC and Phase Wire | $35mm^2$ | 1000V | 158A | See Section 2.2 | -45C to 150C | Datasheet |
| Accumulator Wire | $35mm^2$ | 600V | 158A | See Section 2.2 | -70C to 150C | Datasheet |
| TSMP, EM+, Motherboard | 16AWG | 600V | 13A | See Section 2.2 | -68C to 150C | Datasheet |

Table 3.2: Connector Specifications

| Connector | Ampacity | V Rating | HVIL | Wire Gauge | Datasheet |
|---|---|---|---|---|---|
| Accumulator Main Receptacle | 250A | 1000V | Yes | 2 AWG | Datasheet |
| Accumulator Main Plug | 150A | 1000V | Yes | $35mm^2$ | Datasheet |
| High Voltage Disconnect | 200A | 1500V | Yes | $35mm^2$ | Datasheet |
| Accumulator Aux Receptacle | 13A | 600V | Yes | 18 AWG | Datasheet MPN: 796272-1 |
| Accumulator Aux Plug | 13A | 600V | Yes | 18 AWG | Datasheet MPN: 796271-1 |
| Motherboard: Board to Board | 9A | 600V | N/A | N/A | Datasheet F, Datasheet M |
| Motherboard: Board to Cable | 9A | 600V | N/A | 18 AWG | Datasheet |

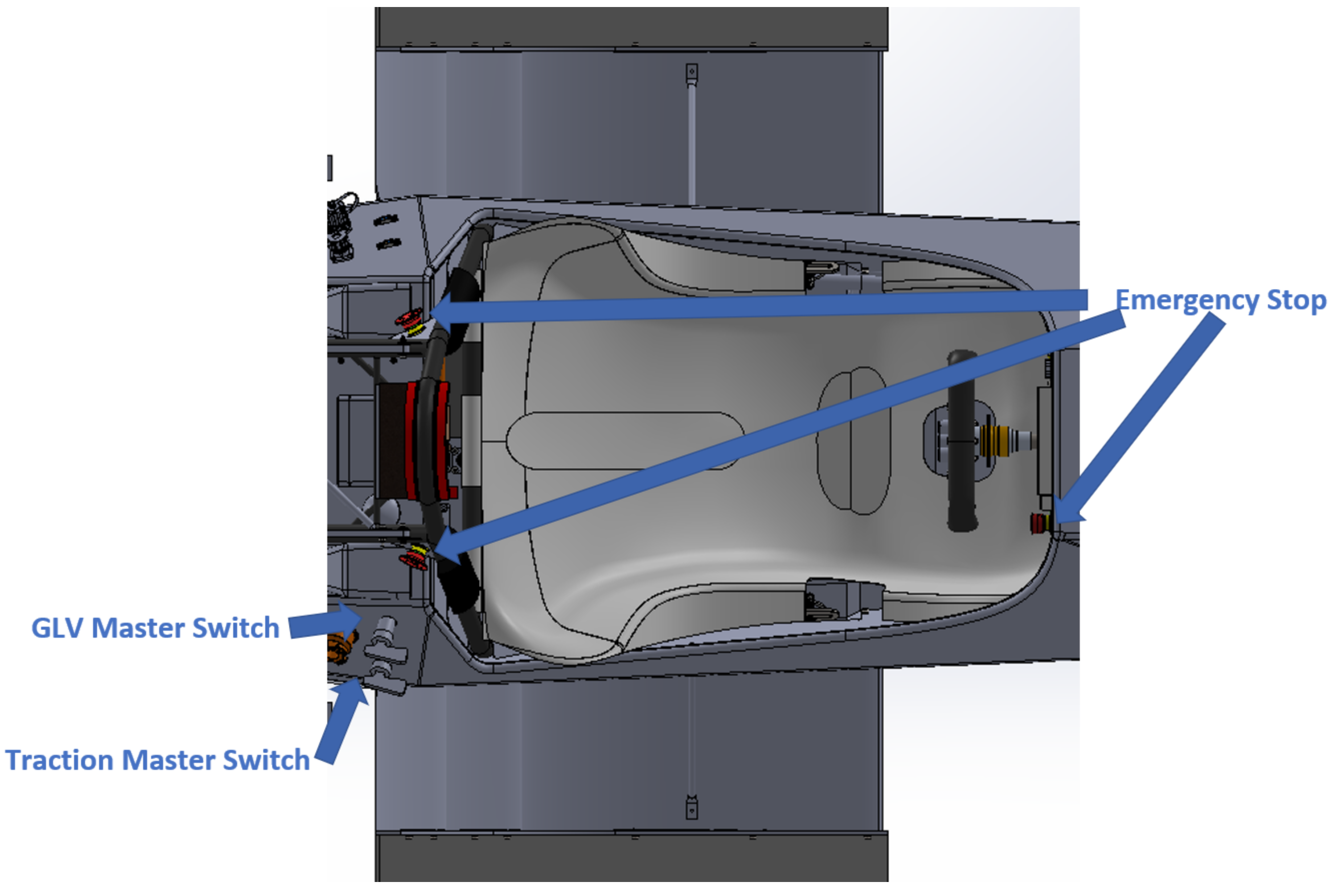


Figure 3.2: Shutdown Switch Locations

Table 3.3: Shutdown Circuit Loads

| | |
|---|---|
| Total Number of AIR's: | 2 |
| Current per AIR: | 0.23A (holding), 3.9A (inrush) |
| Additional parts consumption within the shutdown circuit: | 0.17A (Discharge relay holding current) |
| Total current: | 0.63A |

## 3.3 IMD

Table 3.4: IMD Specifications

| | |
|---|---|
| Make / Model | Bender IR155-3203 |
| Supply voltage | 12VDC |
| Environmental temperature range: | -40..+105C |
| Self-test interval: | Every 5 minutes |
| High voltage range: | DC 0..1000V |
| Set response value: | 200k (500/Volt) |
| Max. operation current: | 150mA |
| Approximate time to shut down at 50% of the response value: | 40s |
| Datasheet | Datasheet |

### 3.3.1 IMD Fault Latching

Latching for all devices in the safety circuit is accomplished using a relay configuration with two channels. The relays used for each channel are interlocked with each other so that each will not turn on without the other being on as well. Once there is a fault (i.e. one or both channels goes low), neither relay will be able to turn on unless the reset button is pushed.

There are two such dual-channel relay configurations in the vehicle. These are shown in a simplified manner in the Shutdown System Schematic as "Ext." (External) and "Int." (Internal). The IMD is part of the circuit controlling the "Ext." relay module.

The IMD has a high-side output to control its associated NO relay. If the output is floating, it will not be able to close the relay. See Figure for how the IMD's relay connects to the safety circuit.

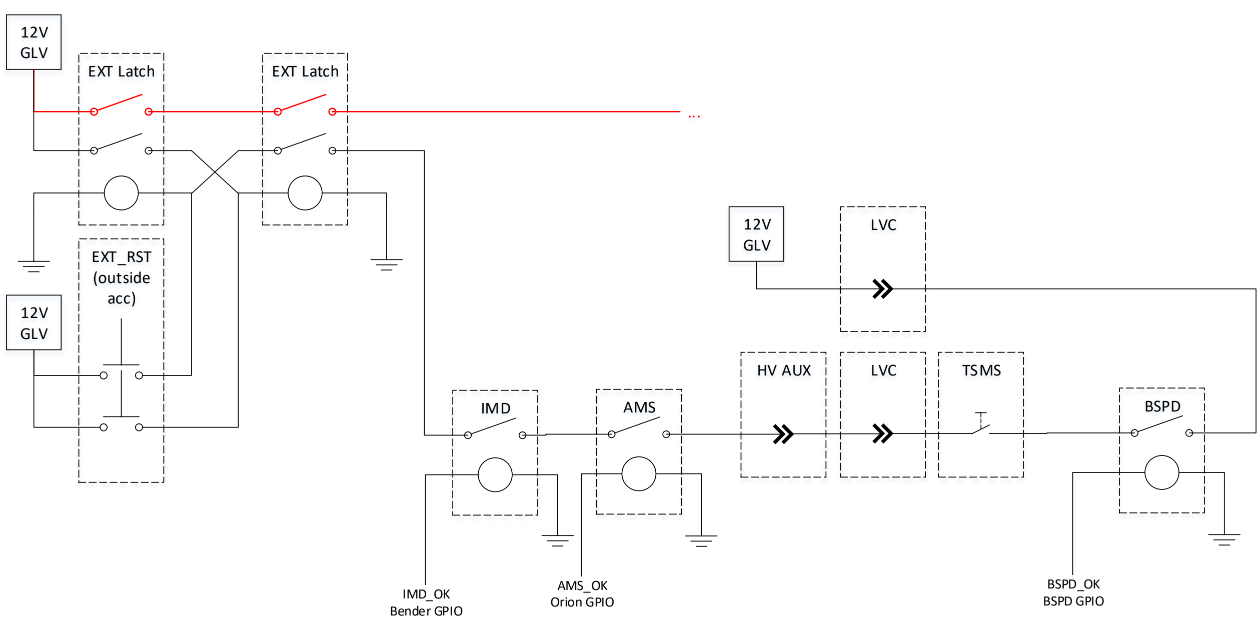


Figure 3.3: EXT Latch Schematic

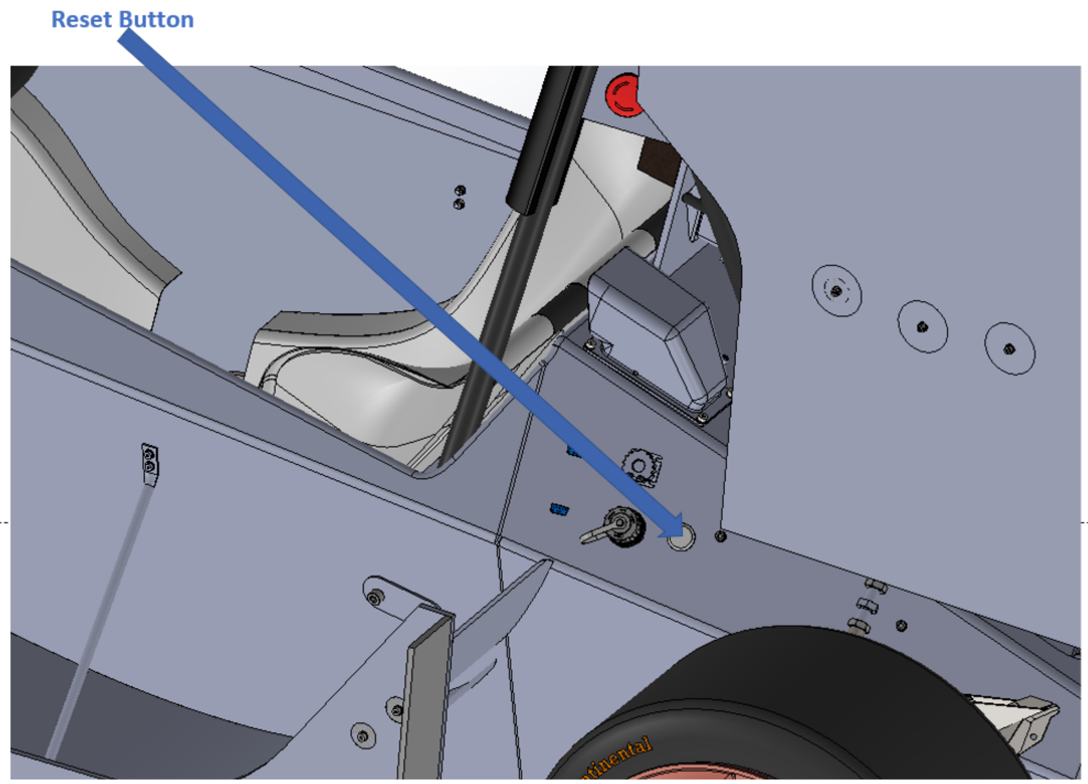


Figure 3.4: EXT Reset Location

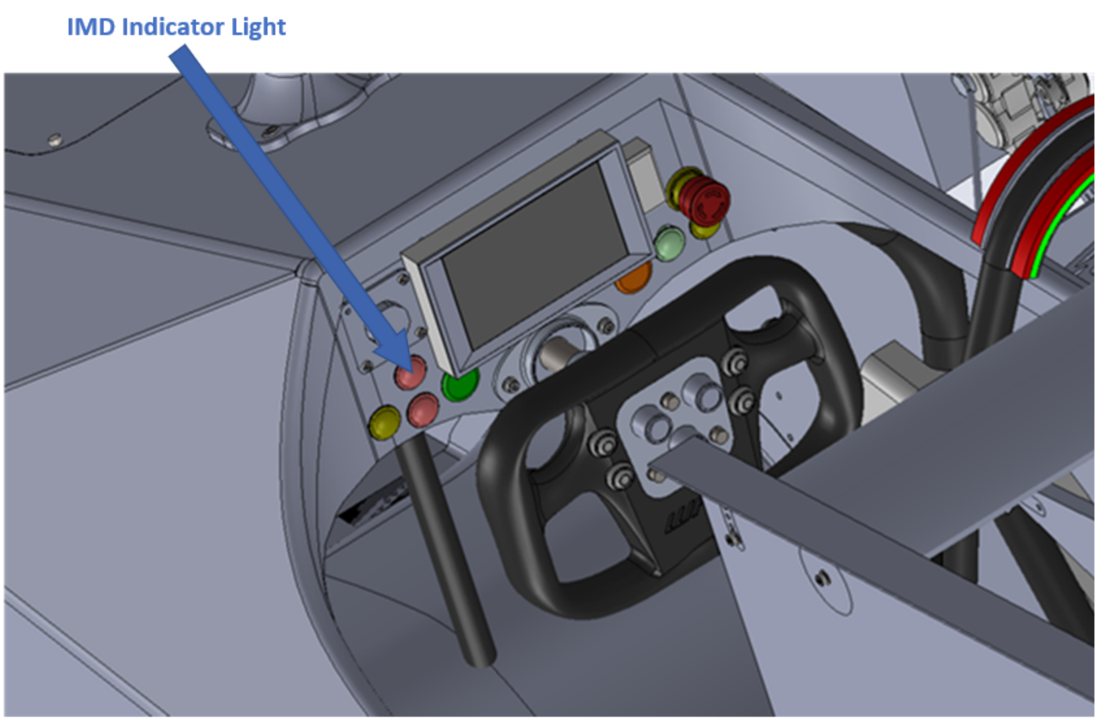


Figure 3.5: IMD Light Location

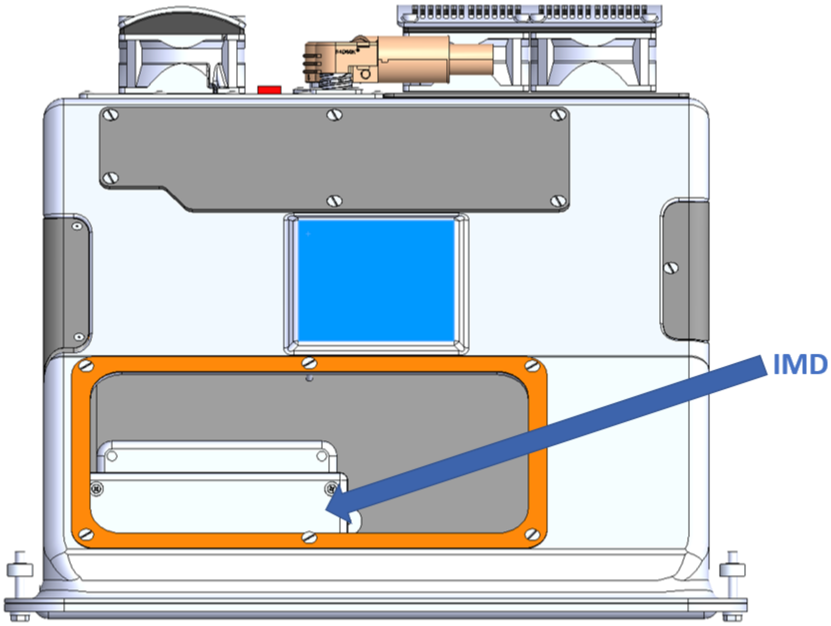


Figure 3.6: IMD Location

### 3.3.2 IMD Demonstration

1. Power on tractive system using the Tractive System Master Switch
2. Connect one end of a 50k resistor (50% of 250V/ as per rule IN.4.4.2) to the negative TSMP measuring point. The resistor is a through hole resistor soldered to a lead.
3. Choose a grounded location on the vehicle and connect the other side of the resistor to that location using an alligator clip.
4. Wait up to 30 seconds to observe the IMD shut down the tractive system
5. Turn the TSMS to the off position
6. Remove the resistor from the negative TSMP and disconnect the grounded location.
7. Turn the TSMS to the on position.
8. Reset the safety system using the external reset button located on the side of the vehicle behind the driver.
9. Repeat steps 2 through 8 to test other vehicle locations

## 3.4 Brake System Plausibility Device

### 3.4.1 BSPD Current Sensor

Table 3.5: BSPD Current Sensor

| | |
|---|---|
| Make / Model: | LEM / DHAB S/124 |
| Current input range: | +/- 75A Ch1, +/- 500A Ch2 |
| Output range: | 0.25-4.75V |
| Datasheet: | Datasheet |

### 3.4.2 BSPD Setpoint

Table 3.6: BSPD Operation

| | |
|---|---|
| Trip Current | 12.5A |
| Current sensor output @Trip Current | 2.83V |
| Delay time | 4.05ms |

### 3.4.3 BSPD Schematic

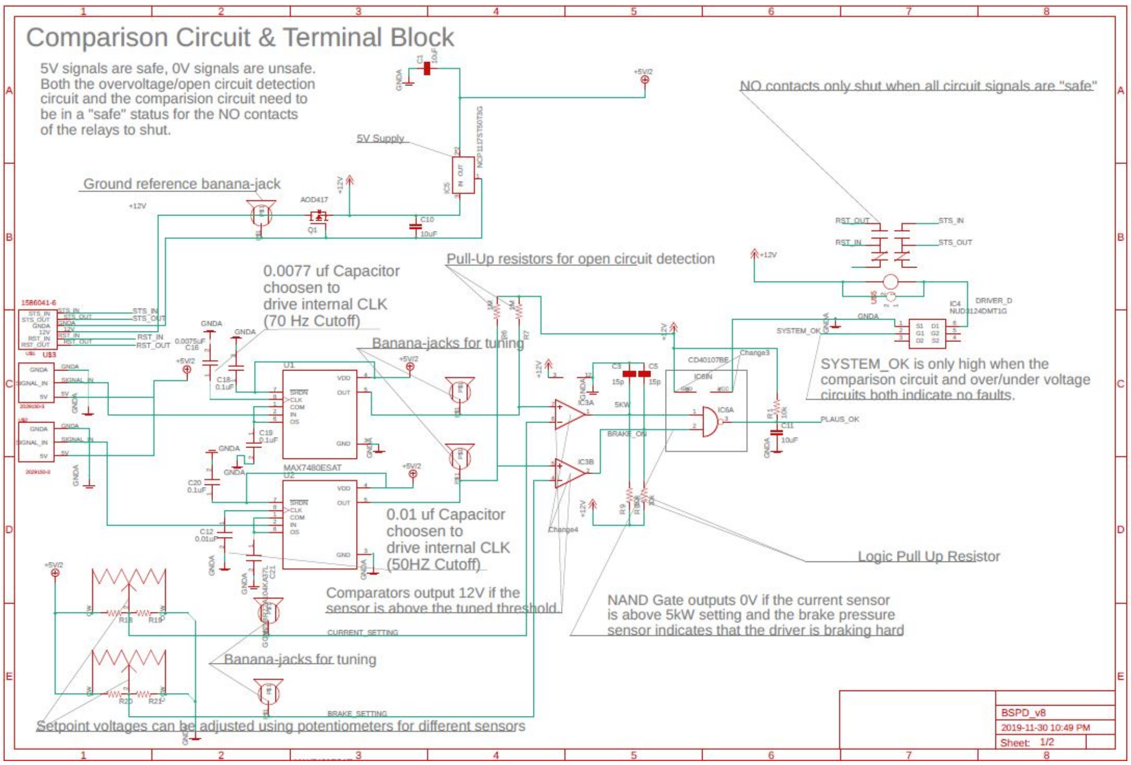


Figure 3.7: BSPD Schematic 1

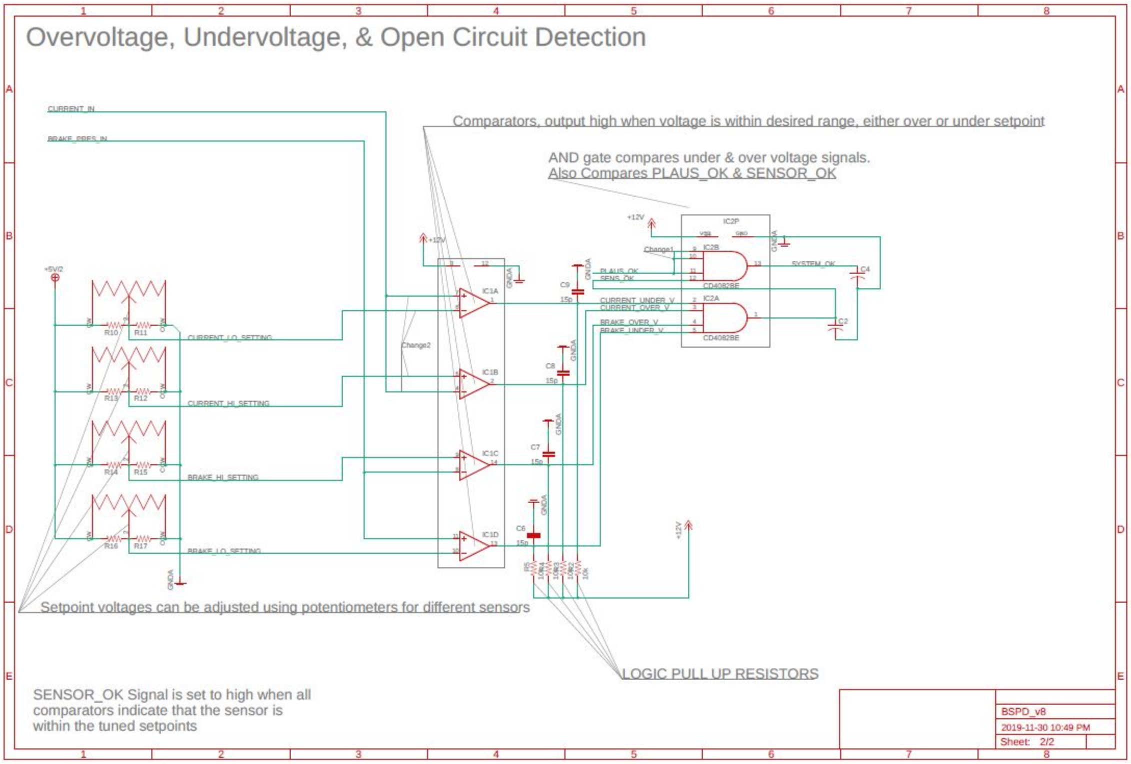


Figure 3.8: BSPD Schematic 2

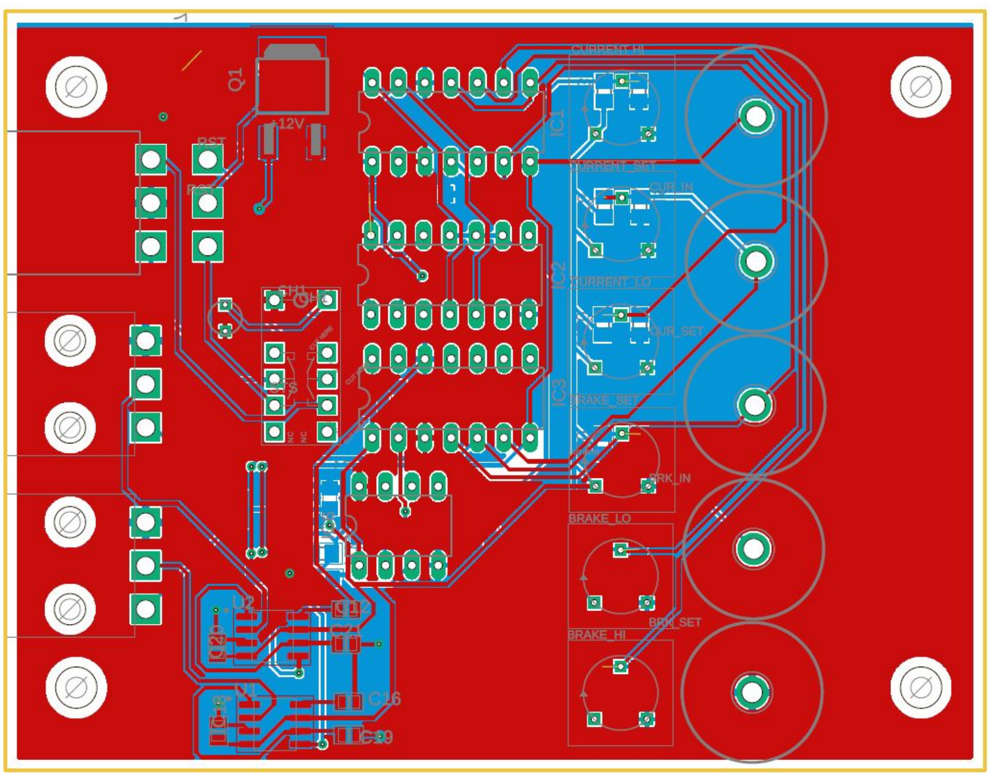

Figure 3.9: BSPD Layout

### 3.4.4 BSPD Location

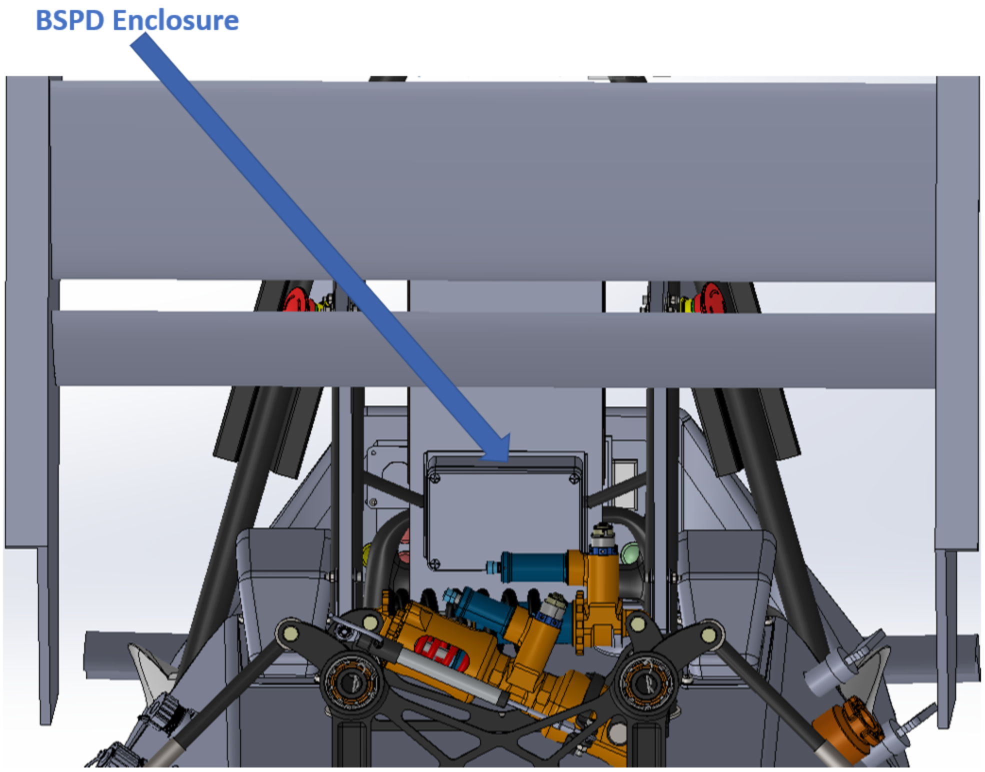


Figure 3.10: BSPD Location

### 3.4.5 BSPD Demonstration

The BSPD demonstration is performed as follows:

1. Connect power supply to the test resistor, and the testing points located in the rear of the car
2. Go through the car start up procedures to place it in ready to drive mode
3. Ensure that TSAL indicates HV is present and that the accumulator indicator light is on
4. Adjust current output from the power supply until it reads 12.5A. The brake pedal should also be depressed
5. Observe TSAL or Accumulator Light to determine if the BSPD de-activated the tractive system
6. Turn off test current
7. Reset both safety circuits. The internal reset should not Enable HV. Confirm this by making sure the TSAL is GREEN
8. Power down the vehicle by moving the TSMS and GLVMS to the off position.
9. Unscrew the +12V lead of the BSPD
10. Turn on GLVMS and TSMS.
11. Reset both safety circuits. The internal reset should not Enable HV. Confirm this by making sure the TSAL is GREEN
12. Power down the vehicle by moving the TSMS and GLVMS to the off position.

13. Reconnect the +12V lead
14. Unplug the brake pressure sensor
15. Turn on GLVMS and TSMS.
16. Reset both safety circuits. The internal reset should not Enable HV. Confirm this by making sure the TSAL is GREEN
17. Power down the vehicle by moving the TSMS and GLVMS to the off position.
18. Reconnect the brake pressure sensor.
19. Unplug the current sensor.
20. Turn on GLVMS and TSMS.
21. Reset both safety circuits. The internal reset should not Enable HV. Confirm this by making sure the TSAL is GREEN
22. Power down the vehicle by moving the TSMS and GLVMS to the off position.
23. Reconnect the brake pressure sensor
24. Reset both safety circuits. The internal reset should Enable HV. Confirm this by making sure the TSAL is RED.

Note that only the internal safety circuit can be reset from within the vehicle (faults that do not include the AMS, BSPD, or IMD). The external safety circuit has a reset button located on the side of the car which can be used to reset the AMS, BSPD, or IMD in order to comply with EV 7.2.6.

## 3.5 Battery Management System

### 3.5.1 BMS Faults

The following faults will cause the Orion BMS 2 to open the shutdown circuit: Over-voltage or cells above 4.2V Under-voltage of cells below 2.5V If the BMS is reading less than 20% of cell temperatures Cells are over 60C or under –20C If the Current draw from the cells is above the limit conditions determined by voltage, temperature, and state of charge. If the BMS determines there is a fault in any of its voltage tap connections If there is a fault in the current sensor

### 3.5.2 BMS Fault Latching

The BMS fault latching functionality is achieved through use of a dual-channel relay module as described in further detail in section 3.3.2. The BMS fault relay is part of the "Ext." relay circuit and, as such, requires the reset on the exterior of the vehicle to be depressed before the AIR's will close again.

### 3.5.3 BMS Demonstration

Perform the following:

1. Turn on the GLV system.
2. Connect to the Ewert CANdapter to the CAN network on the car (via connector outside the accumulator).
3. Open Orion BMS 2 Software Utility on a Windows PC and connect to the CANdapter.

4. View live parameters in the software.
   - View cell temperatures
   - View cell voltages
5. Within software utility show all conditions that will trigger opening of AIR
6. Manipulate fault conditions to trigger fault to occur.
   Example: lower max temp to ambient and watch fault open AIR's

Example: lower max temp to ambient and watch fault open AIR's Hit safety reset onside accumulator while fault is occurring to show fault latching Remove fault condition and hit safety reset to show reset works.

1. Turn the GLV System ON 2. Connect to the Sensor CAN Bus (BMS is on this bus) at 1000 kbit/s 3. Send CAN request to broadcast all cell voltages and temperatures 4. Display CAN Bus traffic with symbols database to show the voltages and temperatures of all the cells 5. Display code snippets for conditions to open the AIR'S

# 4 Safety Systems

## 4.1 Tractive System Active Light

Table 4.1: TSAL Specifications

| | |
|---|---|
| Make/Model: | Adafruit / 3860 |
| Color: | Red |
| Flash Rate: | 4Hz |
| Powered By: | GLV |
| Controlled By: | TS |
| TS Turn On Voltage: | 60V |
| TS Turn Off Voltage: | 60V |

See the Section 7.4.6 for the HVIB Schematic. The HVIB is the circuit which drives the TSAL.

### 4.1.1 TSAL Location

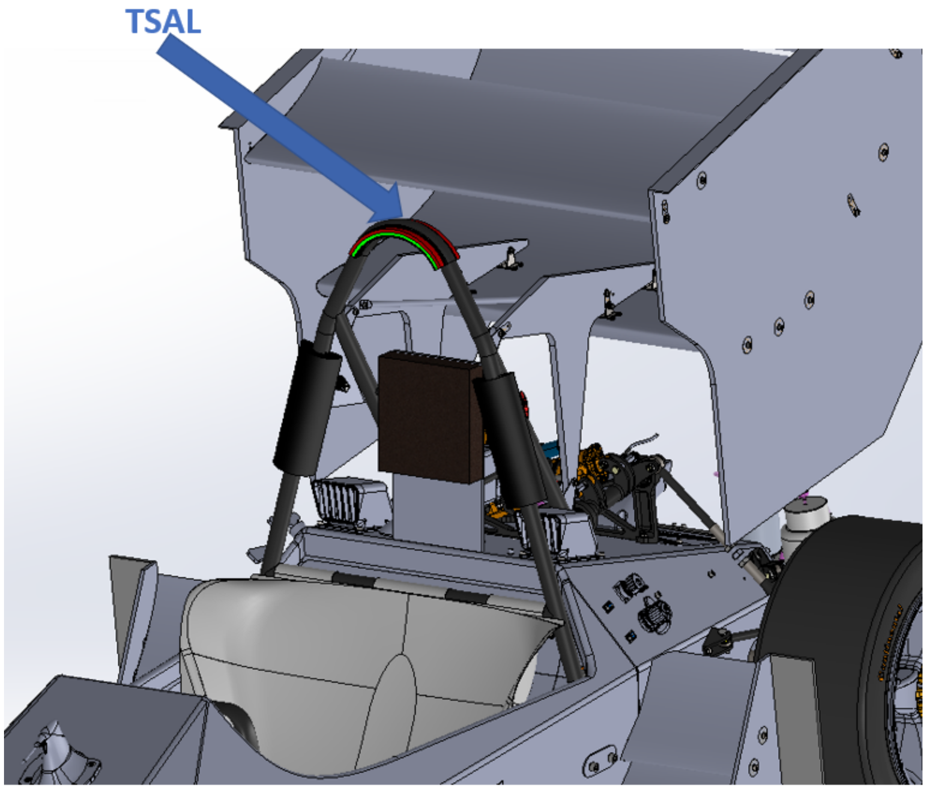


Figure 4.1: TSAL Location

The TSAL Light is located on the roll hoop and is mounted as shown in Figure.

## 4.2 Tractive System Measurement Points

### 4.2.1 TSMP Current Limiting Resistor Specifications

The TSMP protection resistor has been split into a chain of ten SMD 2512 resistors to achieve the required resistance and power dissipation.

Table 4.2: TSMP Resistor Specifications

| | |
|---|---|
| Make / Model: | Bourns / CRM2512-JW-152ELF |
| Resistance | 1.5 kOhm |
| Quantity | 10 |
| Power Dissipation / Power Rating | 1.067W / 2W |
| Configuration / Total Resistance | 10 in series / 15K |
| Maximum Overload Voltage | 600V |
| Working Voltage | 40V |
| Datasheet | Datasheet |

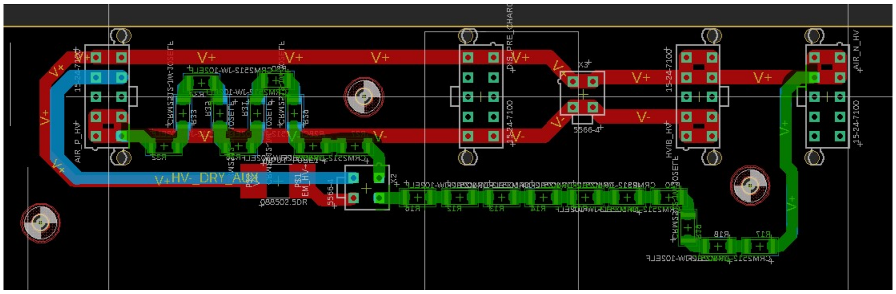


Figure 4.2: TSMP Resistors Location

TSMP Series resistor chains are Green in Figure 4.2. These resistor chains are located on the bottom of the accumulator motherboard. See the Accumulator Motherboard section.

The TSMP Resistors are not heatsunk. The 2W rating applies for continuous operation at ambient temperature without a heatsink. Each resistor is operated at 1.067W.

### 4.2.2 TSMP Receptacles

The backing of the TSMPs as well as the GLV measuring point Is protected by a 3D printed housing. It is designed in such a way that the through air requirements are met for the distance between HV+, HV-, and GLV. Additionally, walls are printed between each contact to ensure accidental touching between contacts or fingers does not occur. On the front of the TSMP's a cover has been 3D printed to ensure that accidental touching cannot occur and to prevent water ingress. Please see below for the front and back covers.

Table 4.3: TSMP Receptacle Specification

| | |
|---|---|
| Make / Model: | Tenma 76-1658 |
| Voltage Rating: | 600V |
| Datasheet: | Datasheet |

Figure 4.3: TSMP Receptacle Location

### 4.2.3 TSMP Demonstration

Discharge Resistance Value Power down tractive system using the TSMS Confirm that the TSAL is indicating that the AIR's are open Measure the resistance at the TSMP Subtract 25k

Current Limit Resistor Value Power down tractive system using the TSMS Confirm that the TSAL is indicating that the AIR's are open and that there is no HV present. Measure the resistance at the TSMP Subtract 2.2k and divide by 2 This will give the value of the TSMP resistors since they will be in series with the discharge resistor when the discharge circuit is active.

TS Voltage (Confirm Off) Turn off TSMS and GLVMS Confirm the TSAL is indicating that the AIR's are open Measure the voltage at the TSMP

TS Voltage (Confirm On) Turn on TSMS and GLVMS Confirm HVD is in place Press the traction system start button on the dash Confirm the TSAL is indicating that the AIR's are closed Measure the voltage at the TSM

## 4.3 High Voltage Disconnect

### 4.3.1 HVD Specification

Table 4.4: HVD Specifications

| | |
|---|---|
| Make / Model: | Hirose / EM30MSD |
| Ampacity: | 200A |
| Voltage rating: | 1500VDC |
| Datasheet: | Datasheet |

### 4.3.2 HVD Location

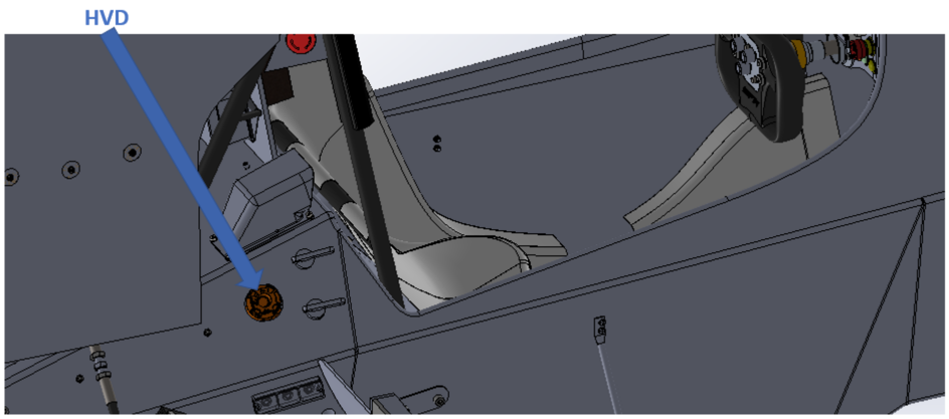


Figure 4.4: HVD Location

### 4.3.3 HVD Connections

The female receptacle of the HVD is connected via ring terminals and hex bolts. The HVD is mounted on the monocoque of the vehicle and not on any removable body work. Additionally, a 3D printed housing will be fastened to the back of the female receptacle to protect it from water ingress and being touched by anyone. The male receptacle is just a loop that passes the connection from one side of the female connection though a fuse and out the other. It comes pre-assembled and will completely protect from water ingress. Additionally, a pilot line through the connector will ensure that upon opening the circuit the AIR's are decoupled so that high voltage cannot be present at the connection when the HVD is removed.

### 4.3.4 HVD Demonstration

To remove the HVD Lift the two-stage lever assisted black latch on the HVD and pull on the connector. Replace the HVD with a dummy connector to ensure the prevention of water ingress and accidental touching.

Remove the HVD if performing maintenance on the following:

- Accumulator
- Inverter
- Any component containing high voltage in the vehicle
- IMD

- Manually pushing the vehicle
- During charging
- Before technical inspection at competition
- When leaving the vehicle unattended

## 4.4 Ready to Drive Sound

### 4.4.1 RTDS Device and Control

The ready to drive signal is controlled from a half bridge output of the VCU. It is sounded before the VCU enters the ready to drive state and allows torque output.

Table 4.5: RTDS Specifications

| | |
|---|---|
| Make / Model: | Mallory Sonalert Products / ZA016LDFP1 |
| Control Voltage: | 12V |
| SPL at 2m: | 98.98 dBA |
| Datasheet: | Datasheet |

### 4.4.2 RTDS Demonstration

Set TSMS and GLVMS to ready to on position Reset external circuit Enter vehicle Reset internal circuit Press brake pedal and hold start button Wait for ready to drive sound, observe light on dashboard Release start button

## 4.5 Discharge Circuit

### 4.5.1 Discharge Specifications

The discharge resistance consists of two TO-247 THT resistors in series.

Table 4.6: Discharge Resistor Specifications

| | |
|---|---|
| Make / Model: | Riedon / PF2473 |
| Resistance: | 2.2 kOhm |
| Voltage: | 700V |
| Power Heatsunk / Power Free Air: | 140W / 5W |
| Power @15sec: | 0W |
| Datasheet | Datasheet |

Table 4.7: Discharge Relay Specifications

| | |
|---|---|
| Make / Model: | Gigavac / G81C235 |
| Contact Current Rating: | 5A |
| Contact Voltage Rating: | 10 kVDC |
| Datasheet: | Datasheet |

Table 4.8: Discharge Heatsink Specifications

| | |
|---|---|
| Make / Model: | Ohmite / RA-T2X-25E |
| Thermal Resistance Free Air | 4.8 degC/W |
| Thermal Resistance @ 200 LFM | 1.5 degC/W |
| Datasheet | Datasheet |

The discharge resistor is rated to 140W with a heatsink and 5W without a heatsink. The power dissipated by each TO-247 THT resistor is 18.18W, thus a heatsink is required. The thermal resistance of the heatsink must be less than:

$$R_{\theta H} = \frac{T_{Max} - PR_{\theta R} - T_a}{P} = \frac{147.73 - (18.182)(0.9) - 30}{18.182} = 5.575°C/W$$

$T_{MAX}$ is obtained from the power derating curve in the resistors' datasheet. $R_{\theta R}$ is provided in the resistor's datasheet. $T_a$ is assumed to be $30°C$.

The specified heatsink has a natural thermal resistance of $4.80°C/W$ which is less than the maximum requirement given above. The DCDC's cooling fan and accumulator chassis fans are situated in the immediate vicinity of the discharge heatsink, thses fans will provide indirect airflow, thus we can assume that the true thermal resistance of the discharge heatsink is less than the natural specification.

### 4.5.2 Discharge Simulation

The motor drive has internal capacitance of 440 uF and the DC/DC converter has input capacitance of 0.8uF. The discharge voltage is shown above using the system voltage of 400V and the discharge resistance of 4400 Ohms. The system takes 3.6s to discharge to under 60V and 9.68s to fully discharge (5Tau).

Note that although the discharge circuit is in the accumulator, it has its negative end connected to the negative pole of the motor inverter directly, this will allow the capacitance in the motor controller to discharge fully even with the HVD removed. The capacitance in the DC/DC converter would be discharged through the HV detection circuit in this scenario.

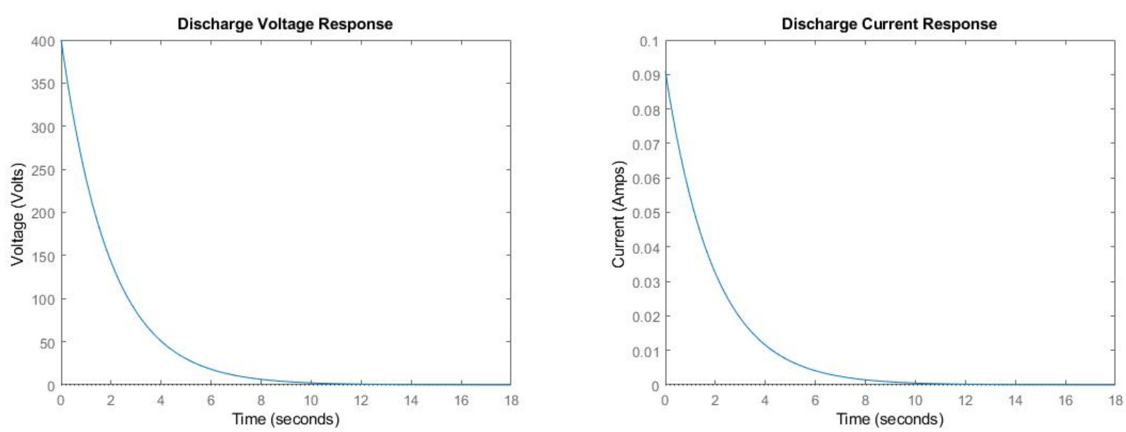


Figure 4.6: Discharge Simulations

```
    % Model as a series-RC circuit
R =4.4E3 %ohms,Discharge resistor size
C = 440E-6 %Farads, model of the RMS PM100DXR
Vacc = 400 %Volts, Accumulator voltage
t = 15 %s, rules sustained power for resistor
%Tmax = 100 %Maximum Resistor Temperature @ cont. power
Ta = 40 %Ambient Temperature inside Acc
Rtr = 1.9%degC/W, Thermal Resistance of Resistor. PN used: Riedon PF2473

Tau = R*C

Ppeak = Vacc^2/R;
Tmax = polyval(polyfit([100, 0],[25, 175], 1), Ppeak); %calculate power derating temp

s = tf('s')
Discharge = Vacc/(1+ R*C*s);
DischargeV = Vacc - Discharge;
DischargeI = DischargeV/R

h = stepplot(DischargeI);
hold on
title("Discharge Current Response")
ylabel("Current (Amps)")
hold off

ChargeTime = 5*R*C; %5Tau rule of thumb
HeatsinkRth = (Tmax - Ppeak*Rtr - Ta)/Ppeak;

SingleResistor = table(R, Ppeak, ChargeTime, HeatsinkRth, Tmax, Ta, Tau)

Ppeak = Ppeak/2;
Tmax = polyval(polyfit([100, 0],[25, 175], 1), Ppeak);
R = R/2;
HeatsinkRth = (Tmax - Ppeak*Rtr - Ta)/Ppeak;

DoubleResistor = table(R, Ppeak, ChargeTime, HeatsinkRth, Tmax, Ta, Tau)
```

Figure 4.5: Heatsink Calculation MATLAB Code

### 4.5.3 Discharge Circuit Location

The Discharge Circuit is located in the Accumulator Motherboard. See Section 7.4.1 and Section 7.4.4.

### 4.5.4 Discharge Control

The discharge is enabled any time the AIR's are open. The NC contact on the AIR's is connected to the coil of a second NC relay to invert the logic. Finally, from the second NC contact the discharge relay is energized when the AIR's are turned on to disable the discharge circuit, and de-energized when the AIR's are turned off, which enables the discharge circuit. The discharge is connected to the drive negative through the auxiliary connector such that it can still operate when the HVD is connected.

### 4.5.5 Discharge Circuit Demonstration

Power down vehicle using the Tractive System Master Switch Wait 5 seconds Measure voltage at Tractive System Measuring Point via the procedure in the TSMP section.

# 5 Accumulator

## 5.1 Accumulator Schematic

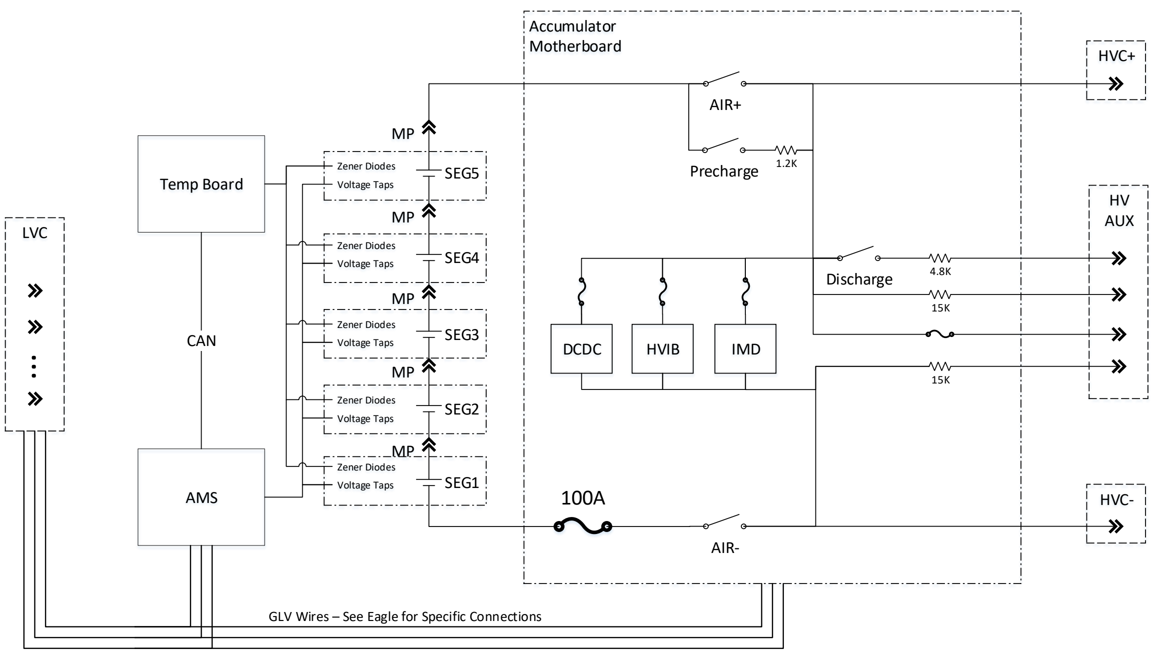


Figure 5.1: Accumulator Diagram 1

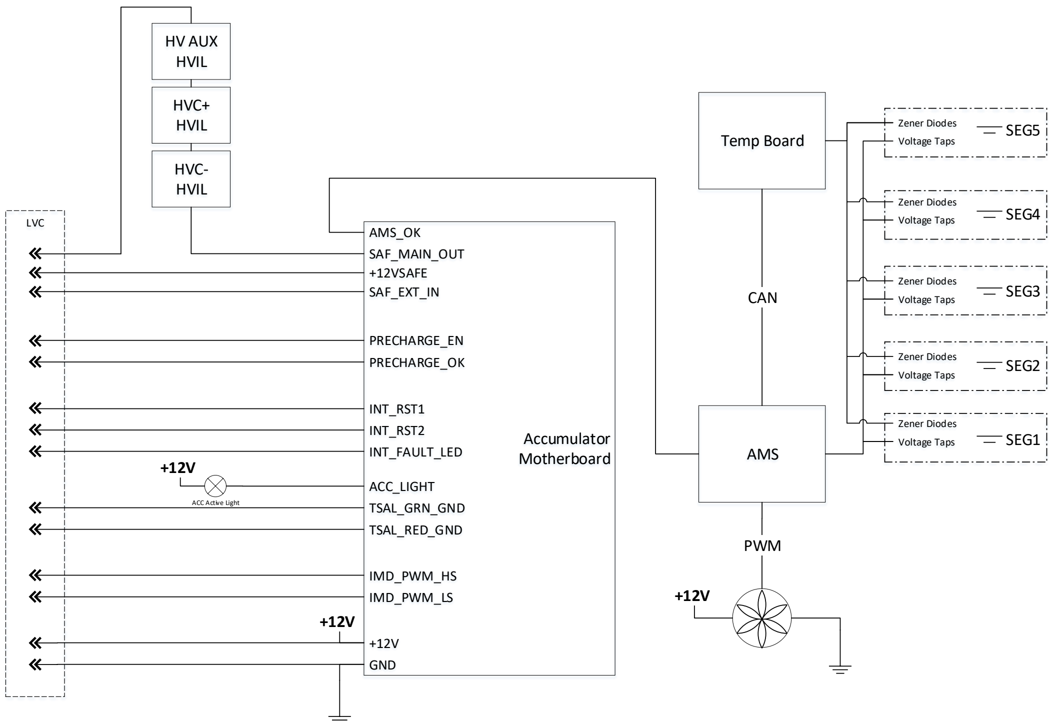


Figure 5.2: Accumulator Diagram 2

See Section 7.4.1 for an Accumulator Motherboard Schematic.

## 5.2 Cells

### 5.2.1 Cell Specifications

Table 5.1: Cell Specifications

| | |
|---|---|
| Cell Make / Model / Style: | LG HG2 - cylindrical |
| Cell nominal capacity: | 2.858Ah |
| Maximum Voltage: | 4.2 V |
| Nominal Voltage: | 3.6V |
| Minimum Voltage: | 2.5V |
| Maximum output current: | 95A for 0.5s |
| Maximum continuous output current: | 20A – Tested by LG for 30A without issue |
| Maximum charging current: | 4A |
| Maximum Cell Temperature (discharging) | 60C |
| Maximum Cell Temperature (charging) | 45C |
| Cell chemistry: | Li[NiMnCo]O2 (H-NMC) / Graphite + SiO |

### 5.2.2 Cell Electrical Configuration

The battery pack is arranged in a 7P95S configuration. The pack is broken into 5 segments of 7P19S connected in series. Each segment was created through use of 19 x 7P1S modules from Energus Power Solutions connected in series.

### 5.2.3 Cell Connections

The individual cells are packaged into modules by Energus Power Solutions. The specific connections between the Energus modules can be found below. The modules are connected using busbars with a cross sectional area of 44.45 mm2̂ and ampacity of 150 A. Positive locking is achieved using tab washers on the aluminum bolts as shown in the rendering. Once all bolts on each busbar are torqued down, the tabs are bent up around the bolt head to prevent rotation and ensure a retained connection between the cells and the busbar.

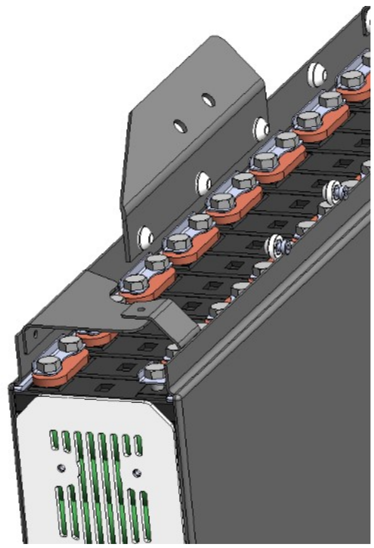

Figure 5.3: Cell Connections

### 5.2.4 Parallel cell Overcurrent Protection

Each cell in a parallel series is connected to its segment's bus bar in series as denoted in the cell configuration. Each one of the parallel segments represents one of the Energus 7P1S modules. The cells in the Energus modules are individually as shown below in the fuse blow time chart. Each cell is connected to a module busbar with a 45A fusible link as shown in Figure 6-4. This gives each parallel segment a continuous rating of 315A. A fast-acting LittleFuse L50S100 fuse will be present in line with the accumulator to blow before the Energus fuses are able to blow as shown below. For a representation of the blow time on the master fuse vs. the blow time of the Energus modules see the graph titled Blow Time vs Accumulator Current below.

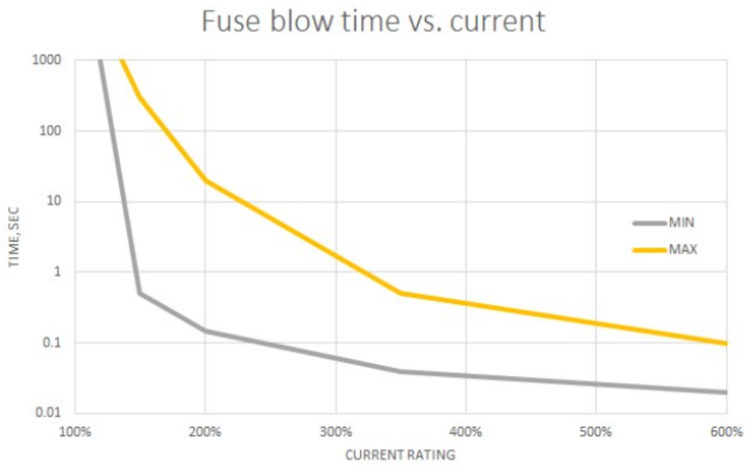


Figure 5.4: Fuse Blow Time vs. Current

Figure 5.5: Energus Cell Fuse

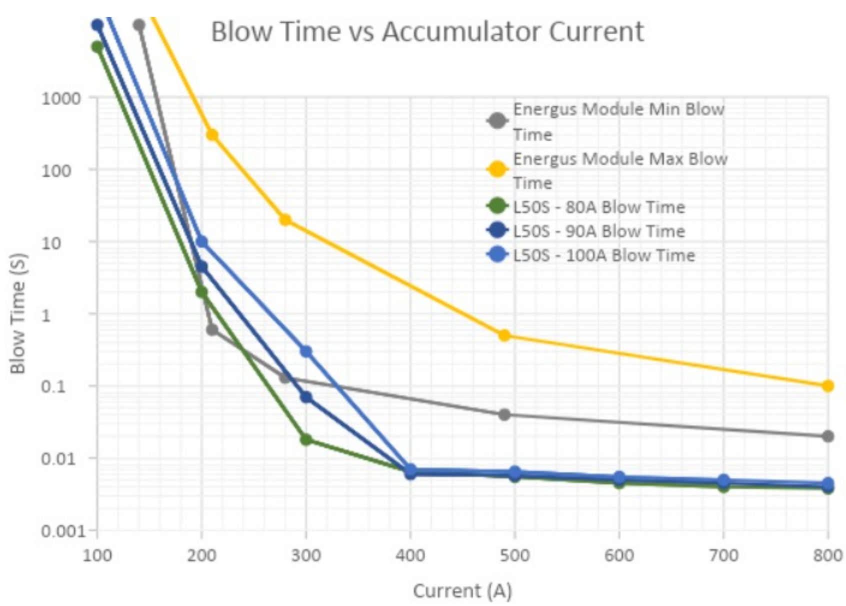


Figure 5.6: Fuse Blow Time vs Accumulator Current

### 5.2.5 Cell Mounting

The Energus battery modules come as a set of seven 18650 cells encased on the top and on the sides by a structural UL94-V0 plastic. This layer of structural plastic ensures that the cells do not contact the surrounding structure. The cell modules are placed vertically in segments and connected by bus bars. Each segment acts as a rail system which slides into the accumulator. Modules are retained to each segment using side walls and clamping force. A 3D printed, ABS plastic racking system is bonded to a glass and carbon fiber reinforced polymer tray (glass fiber is used for insulation). The racking system and walls of the tray retain the cells both vertically and laterally. Longitudinal retention is attained through clamping features, glass and carbon fiber reinforced polymer parts, fastened to the bottom corners and top center of the segment rail. A total of 10, M3 fasteners will be used. PEEK plastic fasteners will be used as they offer sufficient strength properties, and dielectric breakdown properties that are acceptable to the tractive system voltage, in the case of a falling fastener.

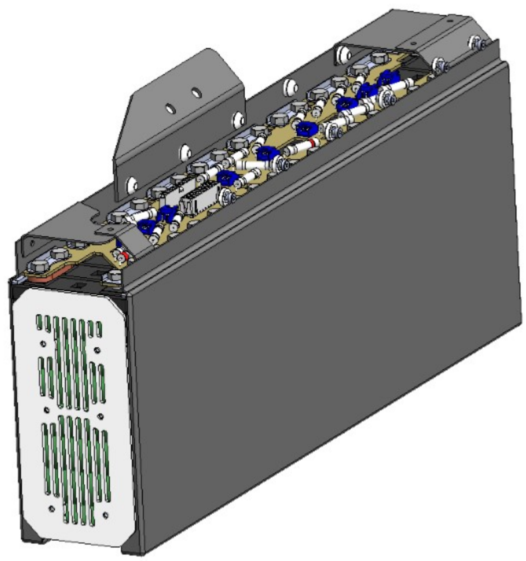

Figure 5.7: Cell Mounting in Accumulator

## 5.3 Segments

### 5.3.1 Segment Specifications

Table 5.2: Segment Specifications

| | |
|---|---|
| # of Segments: | 5 |
| Cells per segment: | 19 Energus Modules (133 Cells) |
| Cell configuration in segment: | 7P19S |
| Energy in segment: | 6.0MJ / 1.596KWh |
| | 5.03MJ / 1.40 kWh (integral) |

### 5.3.2 Segment Energy Calculation

$$(133\ cells)(4.2V)(3.000Ah)(3.6\frac{MJ}{kWh}) = 6.0MJ$$

Energy in a cell segment is equivalent to the integral of power vs time of each segment. Since voltage of the segment will drop as the cells become discharged the power output will drop over time. The voltage vs time graph for various currents of an LGHG2 cell is as follows:

The integral of this curve multiplied by current yields the area under the curve and hence energy in one cell. Each cell has $10499Wh$ of energy in it as measured by the $0.2A$ discharge curve (most conservative). Multiplying this value by the 133 cells in each segment yields $1.396kWh$ which is equivalent to $5.026MJ$ and under the competition limit.

An even more conservative calculation would use the maximum voltage of each cell multiplied by its nominal capacity of $2.858Ah$ (as shown in the graph above). This calculation is as follows:

$$(4.2V)(2.858Ah)(133cells) = 1.596KWh = 5.75MJ$$

which is also under the competition limit.

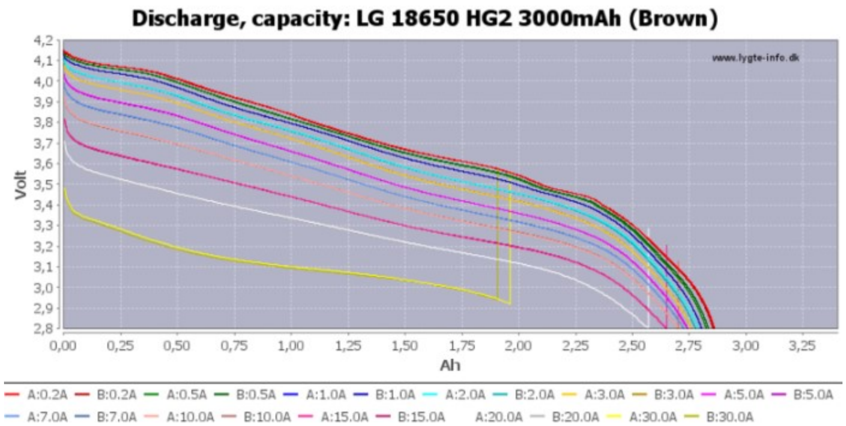


Figure 5.8: LGHG2 Discharge Energy

### 5.3.3 Segment Physical Isolation

The modules are packaged into five segments of 19 modules, separated by composite walls. Each composite wall is made of carbon fiber and is insulated with glass fiber. When packaged into their sections, the only visible surface of each battery is the sidewalls. The battery box is safe from dropped tools because it is completely enclosed except for cooling vents and access hatches, which are covered by filters with ¡3mm of space through which a tool tip could protrude. Furthermore, the battery modules are located under all GLV components and cooling fans, whose footprint completely cover the top projected area of the batteries, protecting from tools and has a fiberglass insulated barrier between the fans and GLV components. The top of the segments are covered by flanges made from glass fiber reinforced polymer.

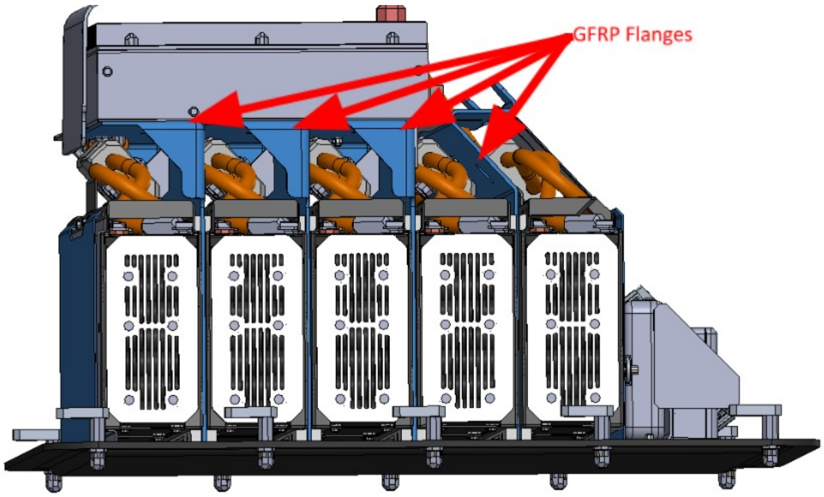


Figure 5.9: Accumulator CAD of Segments

### 5.3.4 Maintenance Plugs

Andersons Power SB175 were used as maintenance plugs in the accumulator. The maintenance plugs were given their own housing just above the fans in the accumulator container to so that a person cannot accidently touch the accumulator cells when disconnecting the maintenance plugs. The flange for the maintenance plug access hatch covers all other hatches so that a user is mechanically guided to disconnect the maintenance plugs before opening any other hatch on the accumulator. Each plug and receptacle receives its own channel above its segment so that it cannot be accidently plugged into an incorrect connector. As shown in the rendering below each maintenance plug acts on both the positive and negative lead of each segment in the accumulator to connect all segments in a series configuration.

Table 5.3: Maintenance Plug Specifications

| | |
|---|---|
| Make / Model: | Andersons Power SB175 |
| Ampacity: | 175A |
| Voltage: | 600V |
| Datasheet: | Datasheet |

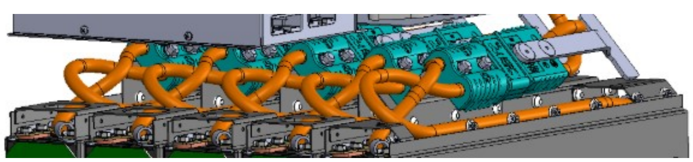

Figure 5.10: Accumulator CAD MP

### 5.3.5 Maintenance Plug Positive Locking

Andersons Power SB175 connectors satisfy the positive locking requirement through their contact retention force rating of 300lbf as clarified by a rules question.

### 5.3.6 Maintenance Plug Unique Configuration

As shown below the maintenance plugs are designed in such a way that there is a maintenance hatch that must be removed to access the maintenance plugs. Once the hatch is removed four channels will be exposed. Each connector gets its own channel except for the front most segment in the accumulator. This channel will be shared with the segment next to it and the connectors in this channel will be specifically keyed to ensure that they cannot be inserted into the incorrect receptacle.

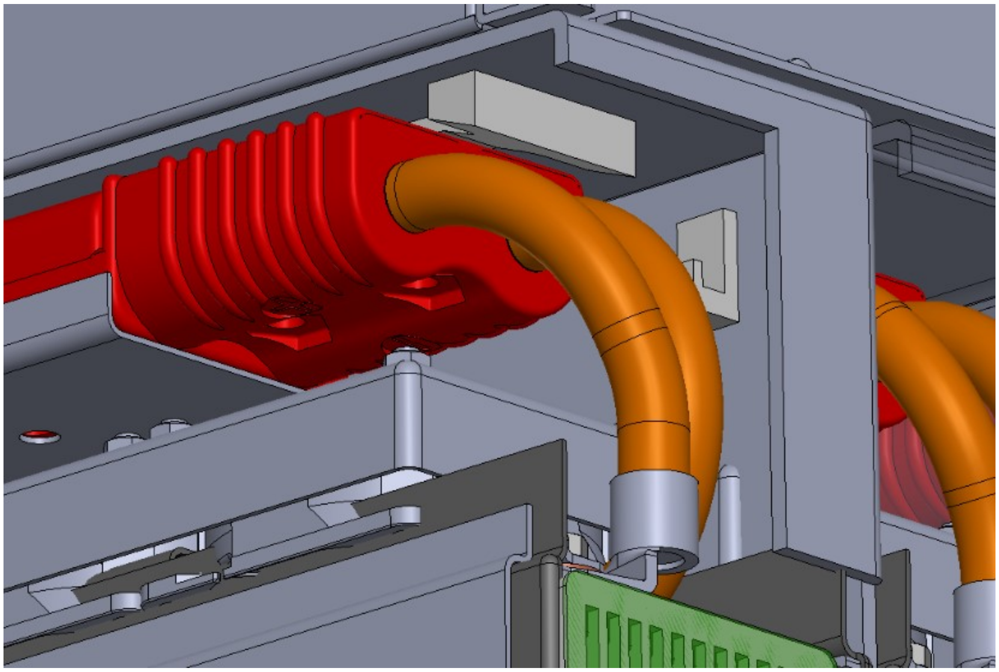

Figure 5.11: MP CAD

### 5.3.7 Maintenance Plug Demonstration

Maintenance plugs can only be accessed by removing the maintenance plug hatch of the accumulator. When disconnecting the maintenance plugs, high voltage gloves, safety glasses, and insulated tools will be used. Remove the Maintenance plug access panels Remove the five smaller BMS plugs Disconnect the left most connector Latch the connector into its disconnected position to ensure no accidental contact Repeat steps 2 and 3 for all connectors Reattach the maintenance plug access panel

## 5.4 Precharge Circuit

### 5.4.1 Precharge Circuit Specifications

The precharge circuit is included in the Accumulator Motherboard. See the dedicated section. The precharge resistance consists of two TO-247 THT resistors in series.

Table 5.4: Precharge Resistor Specifications

| | |
|---|---|
| Make / Model: | Rideon/ PF2473 |
| Resistance: | 620 |
| Voltage: | 700V |
| Power: | 100W |
| Power @15sec: | 0W |
| Datasheet | Datasheet |

Table 5.5: Precharge Relay Specifications

| | |
|---|---|
| Make / Model: | Gigavac / G81C235 |
| Contact Current Rating: | 5A |
| Contact Voltage Rating: | 10000 VDC |
| Datasheet: | Datasheet |

Table 5.6: Precharge Heatsink Specifications

| | |
|---|---|
| Make / Model: | Ohmite / RA-T2X-25E |
| Thermal Resistance Free Air | 4.8 degC/W |
| Thermal Resistance @ 200 LFM | 1.5 degC/W |
| Datasheet | Datasheet |

### 5.4.2 Precharge Schematic

The Precharge Circuit is located in the Accumulator Motherboard. See Section 7.4.3.

### 5.4.3 Precharge Controls and Simulation

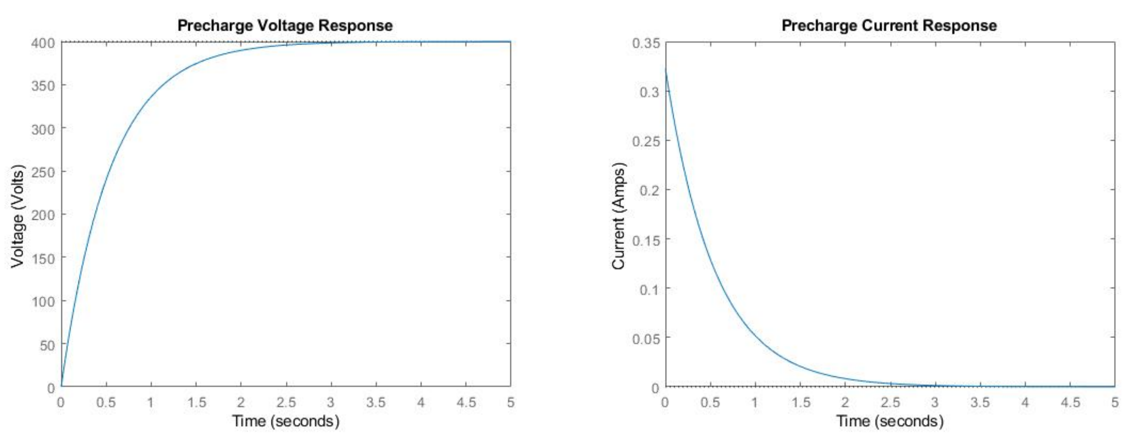


Figure 5.12: Precharge Simulations

The precharge relay is controlled by pin J2 – 21 on the inverter, with the coil power supplied from the TSMS. When the drive receives a start request over can bus the pre-charge relay is actuated to begin charging the inverter. The internal capacitance of the PM100DXR is approximately 500uF, and the precharge resistor is 1240ohms. This gives a time constant of 0.5456 seconds, assuming the inverter will be charged to 95% within three-time constants, this gives a pre charge time of 1.64 seconds.

The system can determine if the vehicle is done pre-charging with the vehicle state machine of the PM100DXR. Charge completion is determined from the following set of steps taken from page 49 of the PM100DXR manual. See Appendix for the relevant section of the PM100DXR Manual.

## 5.5 BMS

### 5.5.1 BMS Specifications

The Orion BMS 2 has been selected for use as a BMS. The Orion BMS 2 is a pre-packaged solution that offers galvanic isolation between the GLV and TS busses. The Orion BMS 2 datasheet can be found here.

The Orion BMS 2 has the following Isolation features: Cell taps isolated from input power supply, chassis and I/O 2.5kV isolation between each connector of cell taps Isolation allows for use of in-pack safety disconnects and fuses High voltage isolation fault detection circuit to monitor the breakdown of wire insulation

In addition to the isolation provided by the unit, five connectors which are bonded to the top of the cell segments are used to provide isolation in addition to the maintenance plugs. These connectors are unplugged before disconnecting the maintenance plugs. A picture of the five sets of connectors is shown below:

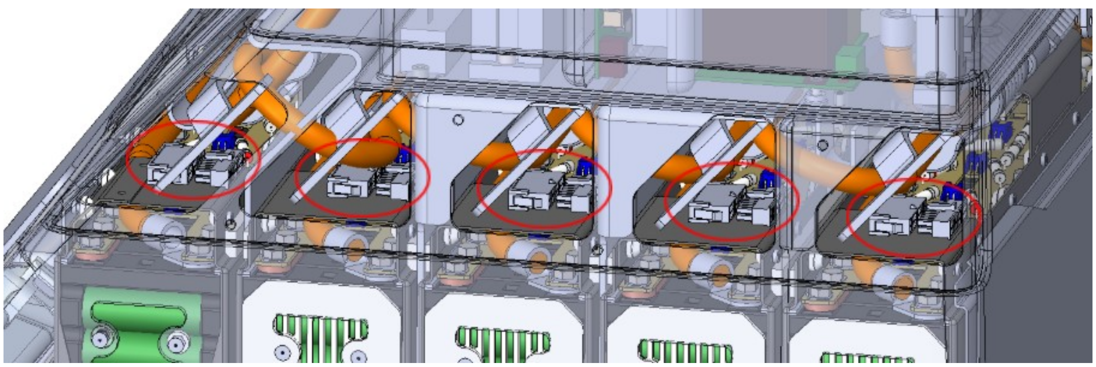

Figure 5.13: Voltage Taps

The make and model of these plugs are listed below:

Table 5.7: Voltage Tap Connector Specifications

| | |
|---|---|
| Make / Model: | Molex / 430202000 |
| Ampacity: | 8A (CSA) |
| Voltage: | 600V (CSA) |
| Datasheet: | Datasheet |

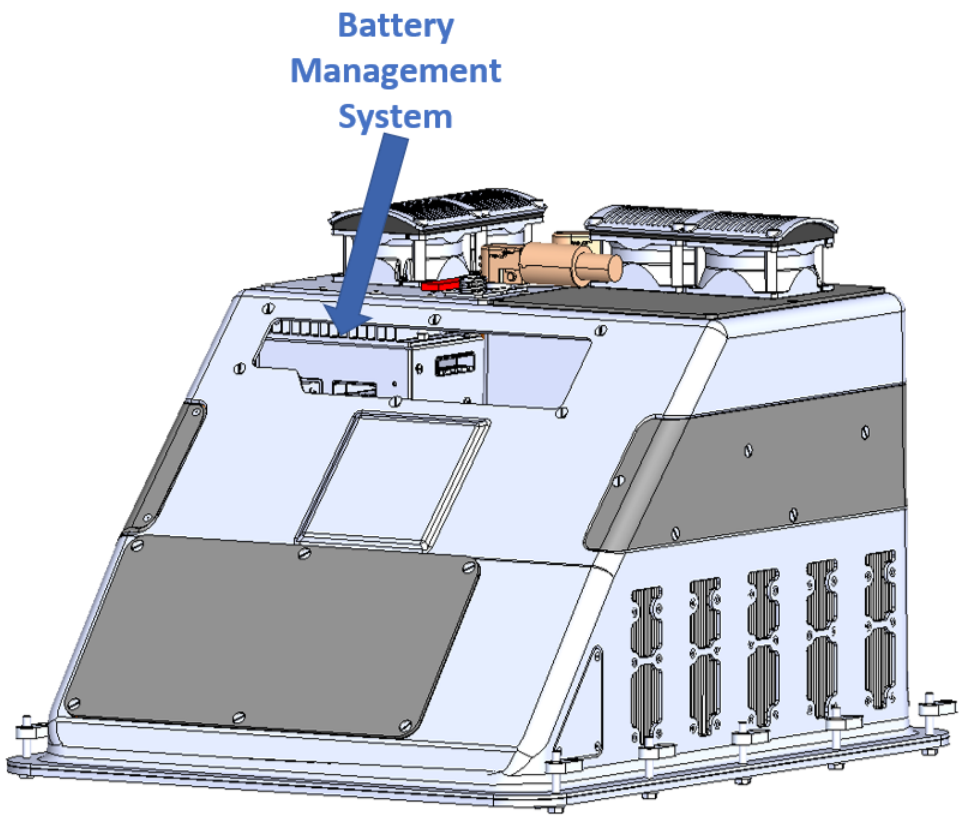


Figure 5.14: BMS Location

### 5.5.2 Temperature Sensors

Table 5.8: Temperature Sensor Specifications

| | |
|---|---|
| Make / Model: | Texas Instruments LM 135 |
| Accuracy of sensor: | 1C when in operating range of –20C to 60C |
| Datasheet: | Datasheet |
| # of sensors: | 40 |
| % of cells sensed: | 42% |

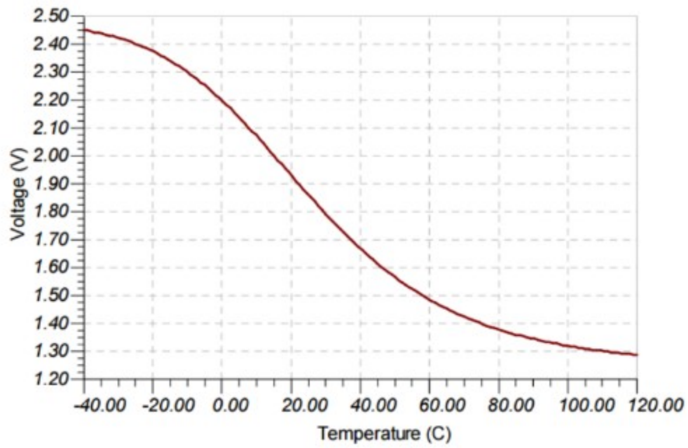


Figure 5.15: Temperature Sensor Output Curve

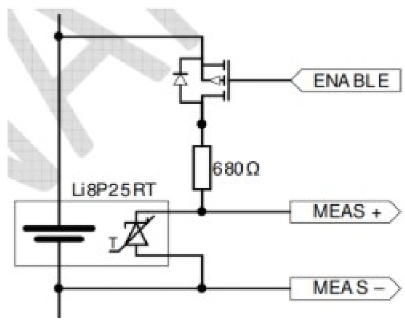


Figure 5.16: Temperature Sensor Schematic

### 5.5.3 Temperature Sensor Locations

The temperature sensors are directly built into the modules purchased from Energus. The temperature sensors are directly mounted to the negative terminals of each cell and are OR'd together to provide the highest temperature via to analog pins on the outside of each module. An image outlining this connection is shown below which is representative of the connection type, but not our specific modules.

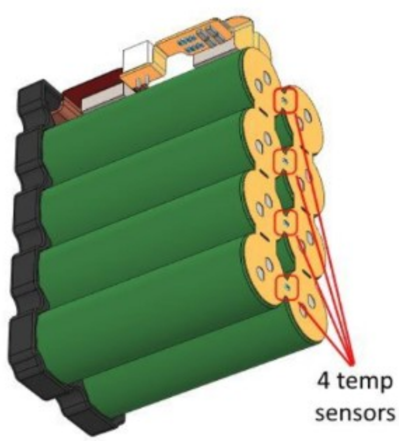


Figure 5.17: Temperature Sensor Location

### 5.5.4 BMS Voltage Sens Leads

The voltage sense leads are attached to the cells via a M5 bolt placed on top of the busbar connection to each parallel string of cells. The M5 bolt will clamp the busbar and voltage sense lead together and be positively retained via a tab washer. See below for a view of this connection.

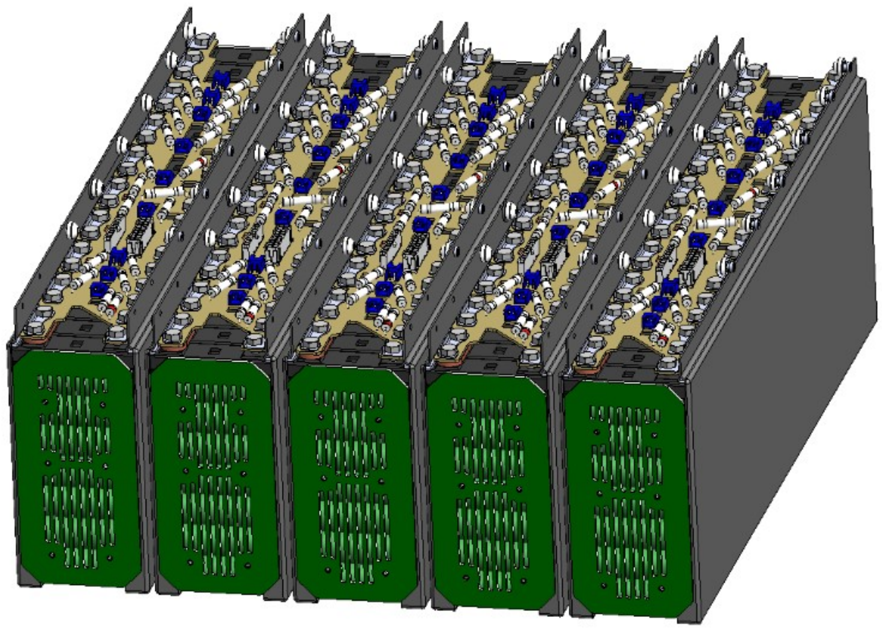

Figure 5.18: Voltage Sense Leads

### 5.5.5 BMS Voltage Sense Lead Overcurrent Protection

The Voltage Sense leads are over current protected by an in-line axial fuse (TR2-S505H-V-3.15-R). The fuses are placed on the cell segment boards above the cells which make direct connections to each of the cell modules below it. The sense leads that run to the AMS are size 16AWG wire with an ampacity of 13 amps. To protect the sense lead the mentioned 3.15 amp fuse was used. It is rated for 400VDC and 600VAC.

### 5.5.6 BMS Limits

Table 5.9: BMS Setpoints

| | |
|---|---|
| Max Cell Voltage: | 4.2V - 0.1mV (for error) – 0.2mV (for FOS) |
| Min Cell Voltage: | 2.5V - 0.1mV (for error) + 0.2mV (for FOS) |
| Max Temperature: | 59C (for discharge) 49C (for charging) |
| Min Temperature: | -19C (for discharge) 1C (for charging) |

## 5.6 AIR

An AIR holdup circuit is used to hold the AIRs closed for an additional 250ms after the AIR coil power has been removed. See the AIR holdup circuit schematic in Figures 7.10 and 7.12. As no SPICE model exists for the Gigavac Contactor, the capacitance has been determined by trial and error during the previous design season.

### 5.6.1 AIR Specifications

Table 5.10: AIR Specifications

| | |
|---|---|
| Make / Model: | Gigavac / GV245BPB |
| Contact Current: | 400A |
| Contact Voltage: | 800V |
| Datasheet: | Datasheet |

## 5.7 Accumulator Indicator

### 5.7.1 HVIB Schematic

The accumulator light output comes from the ACC light terminals located on the HVIB. It is activated by the same sensing lines that turn on the TSAL when the accumulator is connected to the vehicle. The HVIB is powered directly from a fused line on the DC/DC converter and will have power whenever the AIR's on the vehicle are closed and hense the Accumulator Indicator will illuminate. Further documentation on the HVIB is located at the end of the document in section.

The accumulator indicator is driven by the same circuit as the TSAL circuit. Instead of driving a clock signal however, it is driven by a single MOSFET which turns on an LED on the accumulator container.

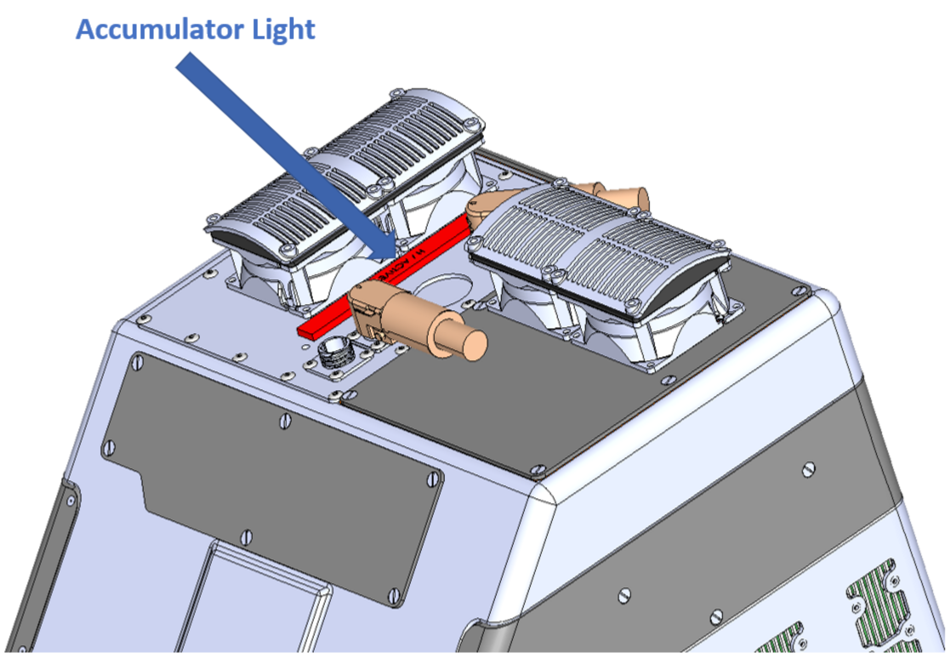


Figure 5.19: Accumulator Light Location

## 5.8 Mechanical

### 5.8.1 Accumulator Enclosure

Each cell module is insulated from the accumulator container by means of a structural UL94 V-0 plastic that encases the cells.

The accumulator container, including all internal vertical walls, is made of sheets of carbon and glass fiber reinforced polymer. Each sheet contains some number of carbon fiber plies such that structural requirements are met as per the Structural Equivalency rules for the HV Enclosure. Each sheet also contains glass fiber plies such that it is insulated and rated to a dielectric breakdown greater than the voltage of the traction system. See below for insulation calculations:

Dielectric strength of fiberglass: 13.5MV/m (datasheet)

Critical thickness = 400V/13.5MV/m = 0.00002962962m = 0.002mm

Finishing glass fabric has thickness between 0.1-0.2mm, meaning panels will be insulated with a factor of safety of 100-200 for dielectric breakdown.

Each sheet is infused with CELLOBOND Phenolic J2027X-1 , a phenolic resin provided to the team by Hexion (Three Data Sheets: datasheet 1, datasheet 2, datasheet 3), in order to be flame retardant to FAR25. Phenolic resin is not electrically conductive. Furthermore, the extremely fine weave of the glass plies combined with the fact that it is encased in the resin means that panel will remain insulated even if it is scratched or otherwise damaged.

### 5.8.2 AIR and Fuse Separation

Each Energus battery module is a set of seven 18650 cells encased on the top and on the sides by a structural UL94-V0 plastic. This layer of structural plastic ensures that the cells do not come into contact with the accumulator container, and also create separation between the cells and the AIR and/or fuses.

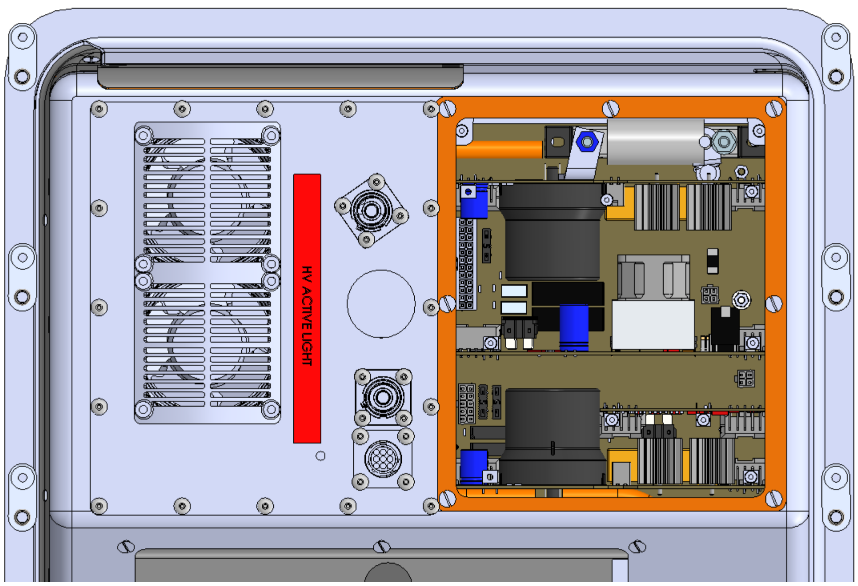


Figure 5.20: AIR and Fuse Separation

## 5.9 Charging

### 5.9.1 Charger Specifications

Table 5.11: Charger Specifications

| | |
|---|---|
| Make / Model: | Siemens Valeo - EV250035 |
| Power: | 3.5KW |
| Output Voltage: | 430V |
| Output Current: | 12A |
| Input Voltage: | 85 – 275VAC (single phase) |
| Input Current: | 16A |
| Datasheet: | Datasheet |

### 5.9.2 Charging Shutdown Circuit

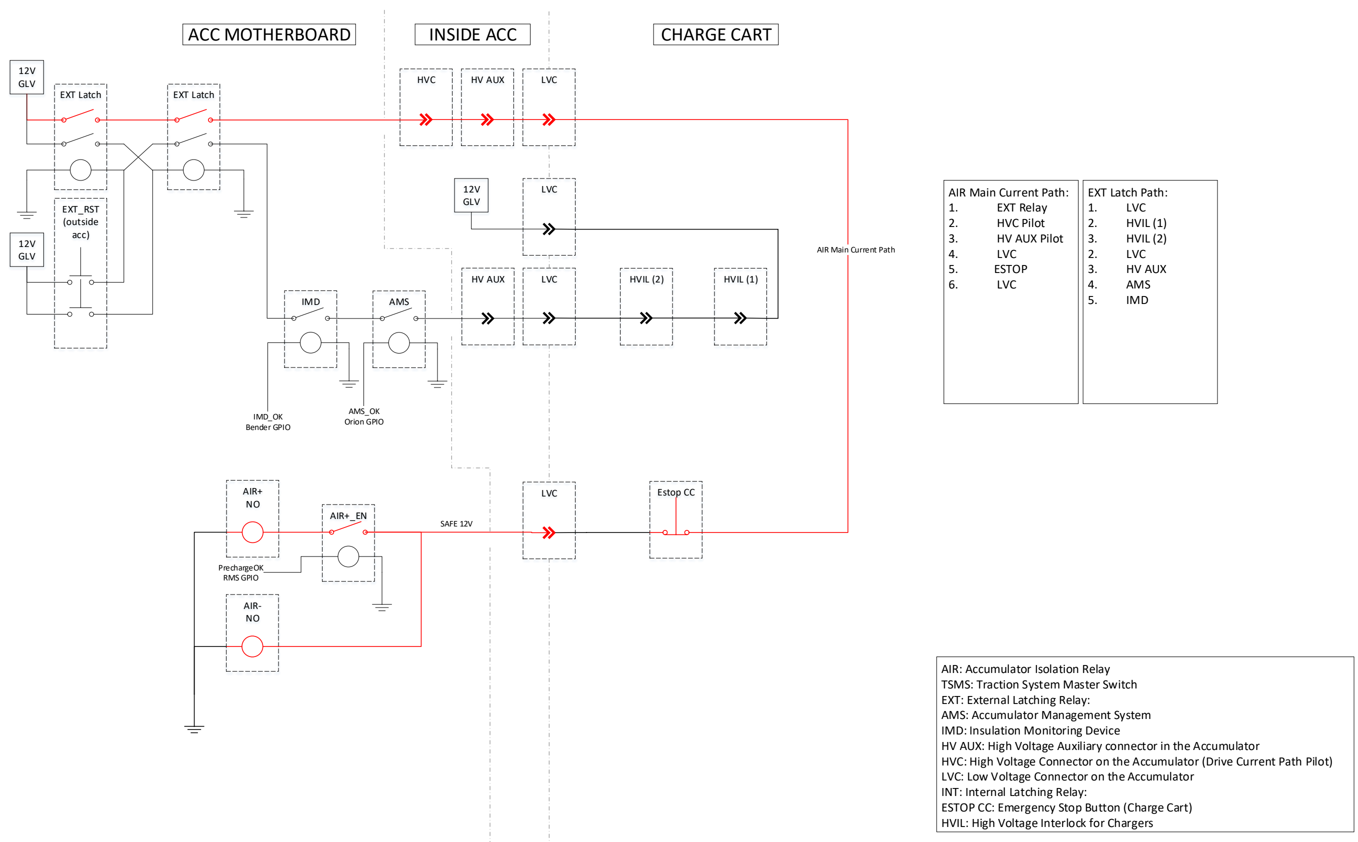


Figure 5.21: Charging Shutdown Circuit

### 5.9.3 Charging TS Circuit

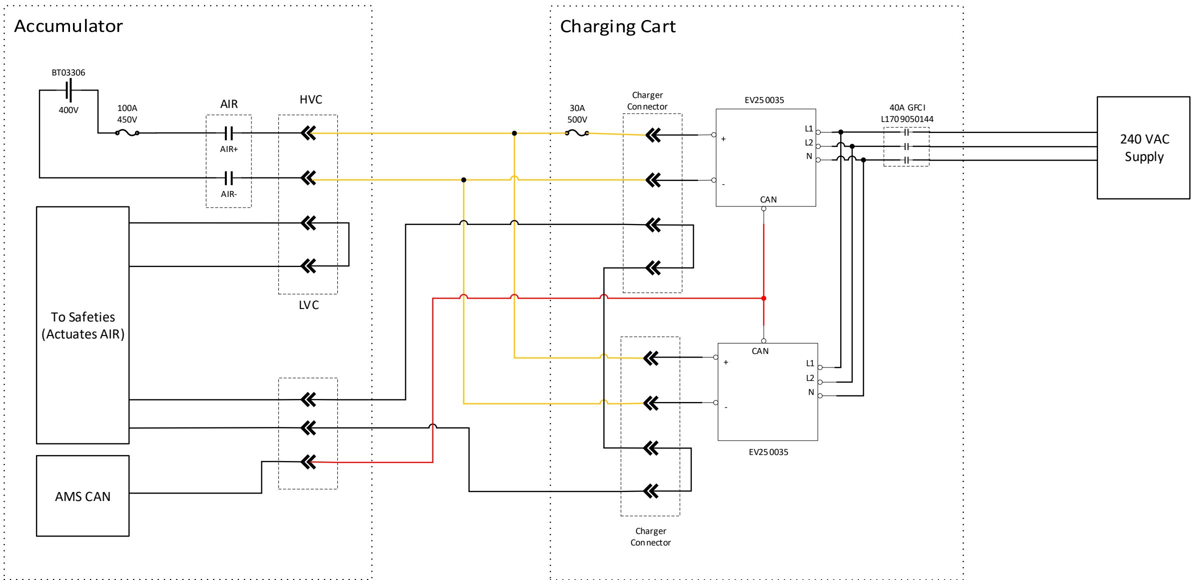


Figure 5.22: Charging TS Circuit

### 5.9.4 Charging Connection Interlock

The main TS connector for our accumulator has a pilot line interlock integrated into it. If this pilot line is broken or any other safety faults occur, the AIR's are opened. If the AIR's are open the DC/DC loses power and the charger is put into standby move (no power output).

### 5.9.5 Charger Control

Once the low voltage connector is plugged into the accumulator from the charging cart, the BMS will boot up in charging mode. While in charging mode the accumulator has an interlock connection the charger, which will shut the charger off in the event of the following conditions:

- Overcurrent
- Over-temperature
- Under-temperature
- Over-voltage
- Under-voltage
- General fault

If the AMS detects any of the previous faults, it will output an unsafe status signal to the charger which will shut it off.

### 5.9.6 Charger Demonstration

1. Ensure the charger is disconnected from AC power.
2. Ensure service cap is installed on the accumulator's TSMP connector.

3. Connect low voltage connector to the charger harness.
4. Connect high voltage connector to the charger harness.

Ensure that the accumulator indicator light is red to indicate that the AIR's are shut. Once the charger is connected properly it will have output current displayed on an LCD screen located on the front of the charger.

# 6 Motor Controller

## 6.1 Control Architecture and Torque Security

Table 6.1: APPS Specifications

| | |
|---|---|
| Make / Model: | BEI Sensors / 93600903 |
| Electrical Travel: | 90 degrees |
| Angular Travel Utilized: | 35 degrees |
| Sensor Type: | Hall-Effect |
| Input Voltage: | 5 VDC |
| Datasheet: | Datasheet |

Our apps sensor provides two isolated sensor outputs which are measured by the VCU. The VCU then compares the two signals which are scaled against a chart that is tuned by the team. If the two signals deviate by more than 10% of their scaled values, then the VCU signals an implausibility fault and sets the output torque of the motor controller to 0. If the signal is determined to be plausible then the requested torque is determined based on a scaled value from zero to 125 Nm.

In a short circuit scenario, the ECU will read more than 10% difference between the two sensors and signal a plausibility fault. The plausibility fault will set the torque command to 0 Nm. In an open circuit scenario, there is a pull up resistor connected to the negative slope line and a pull down resistor connected to the positive slope line that will pull both lines to a voltage corresponding to 0% throttle.

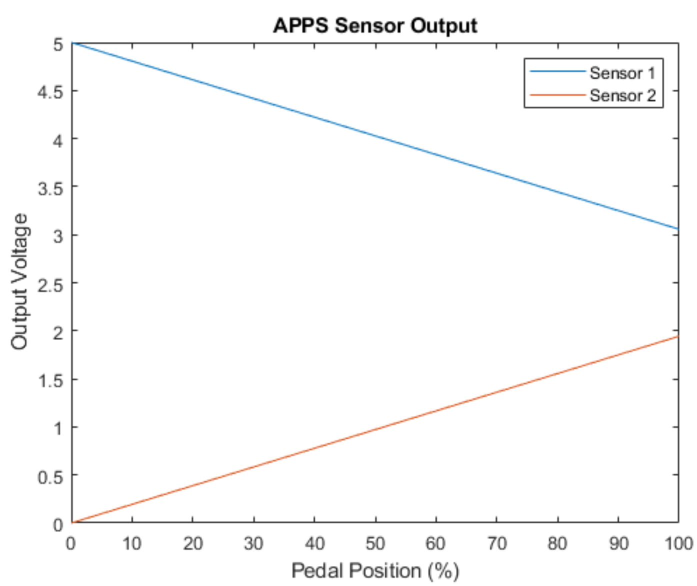


Figure 6.1: APPS Sensor Output

If the vehicle detects wheel slippage than compensation torque is applied to reduce the output torque of the motor. Compensation torque can only be negative, meaning that it can only reduce the requested torque from the motor, not increase it.

The signal path for the torque command is shown in the figure below, highlighted by the red square.

The torque signal from the APPS input is internally pulled up by the VCU, and the CAN-BUS transmission from the VCU to the PM100DXR is verified by a heartbeat signal. If the heartbeat signal is lost between the VCU and the PM100DXR the output torque of the motor is set to zero.

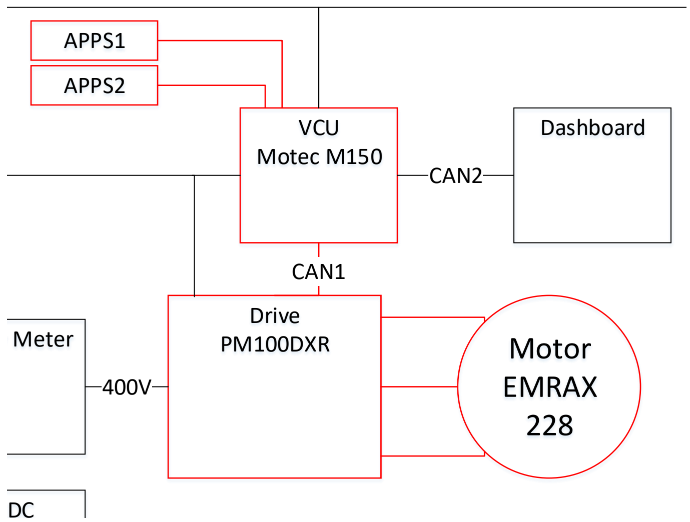


Figure 6.2: APPS Sensor Connection

## 6.2 Galvanic Isolation

The RMS PM100DXR HV system is isolated from the 12V power input.

# 7 Other Items

## 7.1 Energy Meter

### 7.1.1 Energy Meter Location

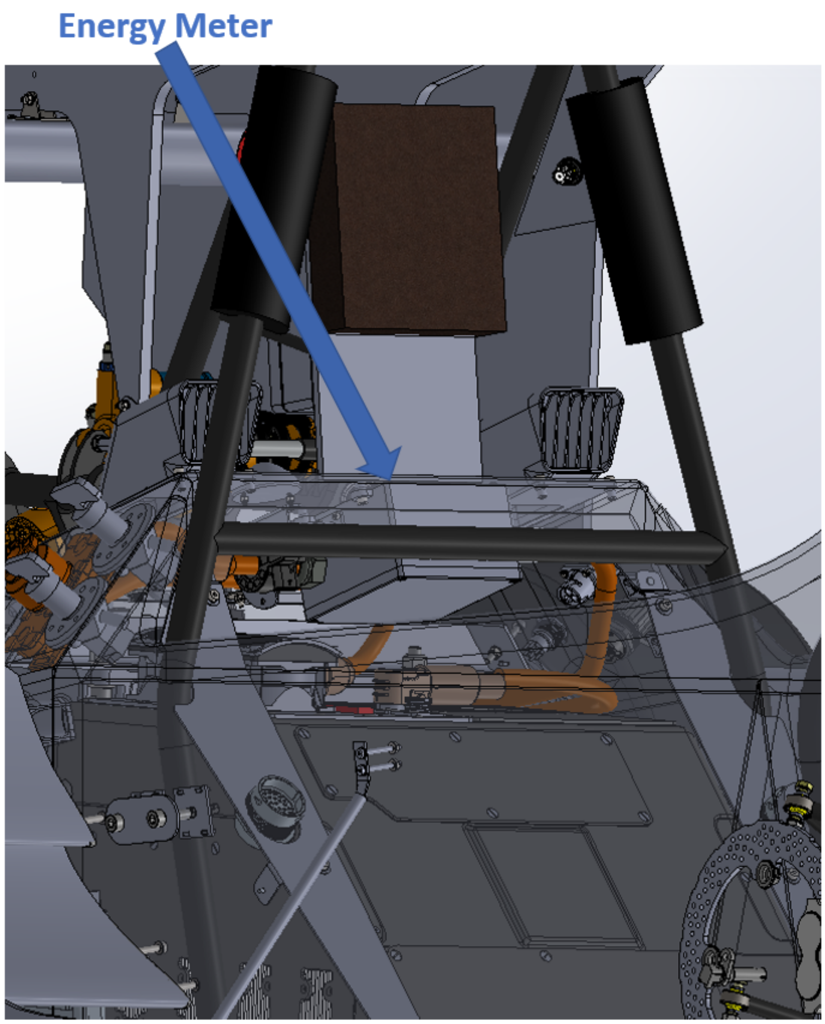


Figure 7.1: Energy Meter Location

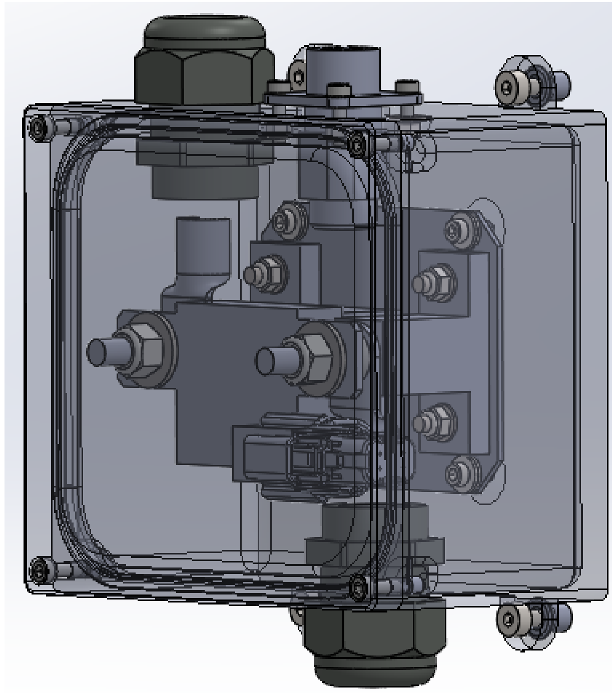

Figure 7.2: Energy Meter Box

### 7.1.2 Energy Meter GLV Supply

Energy meter GLV power is supplied via the LV power distribution module (PDM) located outside of the accumulator.

### 7.1.3 Energy Meter HV Sense

The accumulator voltage is sensed by the energy meter by using the voltage sense line coming from the auxiliary connector of the accumulator. The voltage sense line exits via the auxiliary connector, and then enters the energy meter enclosure via a wire gland. The line is fused by HVIB terminal 14 located within the accumulator.

## 7.2 Firewall

### 7.2.1 Firewall Layer Thickness

Table 7.1: Firewall Specifications

| | |
|---|---|
| Aluminum layer thickness: | 0.64mm |
| Insulating layer thickness: | 1mm |
| Insulating Material Make / Model: | Fiberglass fabric with Phenolic J2027X-1 Cellobond resin. |
| Insulating Material Datasheet: | Datasheet 1 |
| | Datasheet 2 |
| | Datasheet 3 |
| Insulating layer side: | Driver Side (as per rules) |

### 7.2.2 Firewall Location

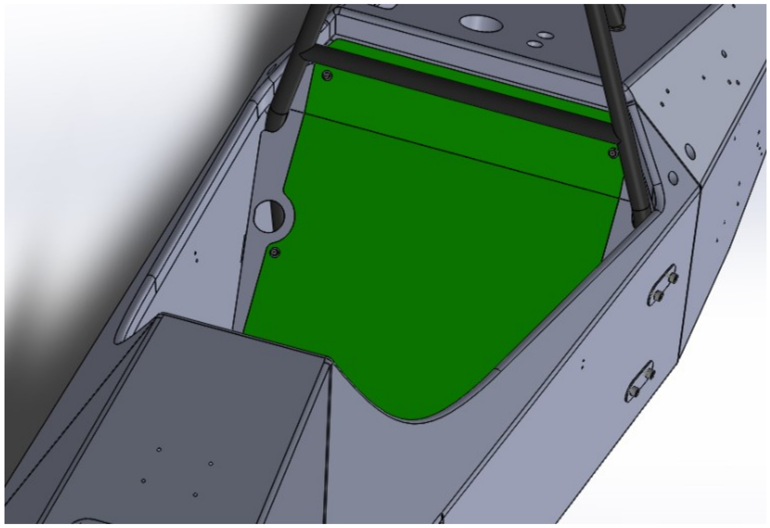

Figure 7.3: Firewall Location

Firewall shown in red in render above. The plate it is directly resting on, the firewall bracket, can also be considered part of the firewall. Two Grounded Low Voltage (GLV) bulkhead connections are placed on this bracket.

## 7.3 Grounding

All composites will be grounded using a highly conductive spray-on Nickel coating. This coating is offered by MG Chemicals and was tested by the team to confirm conductivity (Datasheet).

Product number: MG Chemicals Super Shield Nickel Epoxy Conductive Coating 841ER.

## 7.4 Other Components

### 7.4.1 Accumulator Motherboard

The Accumulator Motherboard houses the following components:

- HVIB / TSAL Driver
- DCDC Converter
- AIRs
- Precharge Circuit
- Discharge Circuit
- IMD
- External Reset Latching and Monitor Circuitry
- TSMP Current limiting resistors and EM+ Fusing

The Motherboard is a selection of Printed Circuit Boards. There is a Main Board and Several Daughter Boards. The Daughter Cards mount into the Main Board via Board-to-board power connectors.

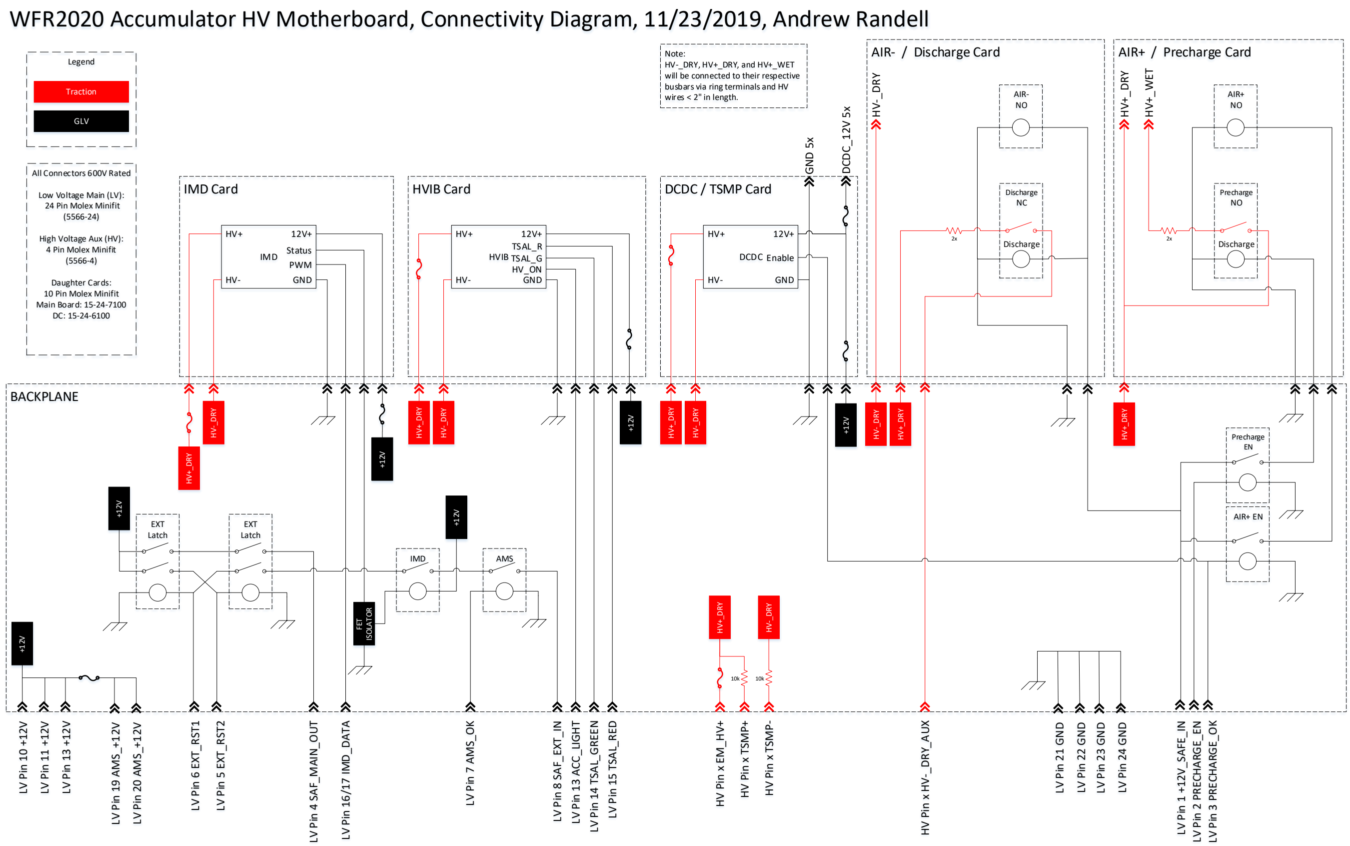


Figure 7.4: Motherboard Block Diagram

Table 7.2: Motherboard Specifications

| | |
|---|---|
| PCB Material | FR4 |
| PCB Coating | MG Chemical 4223-312G Datasheet |
| Copper Weight | 2 oz |
| HV Trace Spacing | 1.5mm minimum |
| HV Trace Width | 1.27mm minimum |
| HV Trace Ampacity | 4.02A minimum |
| DMZ Spacing | 4mm minimum |
| LV Trace Spacing | 0.2mm minimum |
| LV Trace Width | 0.2mm minimum |
| LV Trace Ampacity | 0.65A minimum |

The PCB Specifications listed in Table 7.2 are common across all PCBs used on the vehicle. Note: All spacing is rated for $600V$, See Figure A.3.

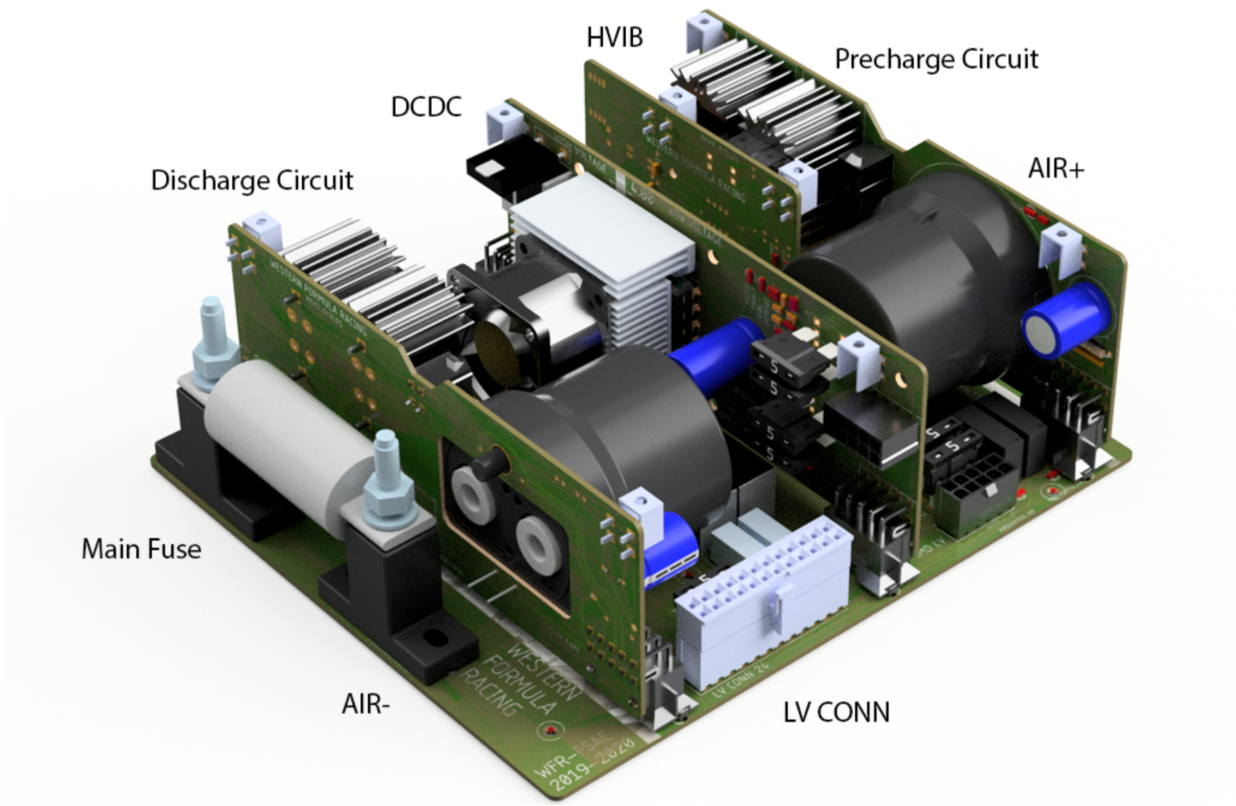


Figure 7.5: Motherboard Render

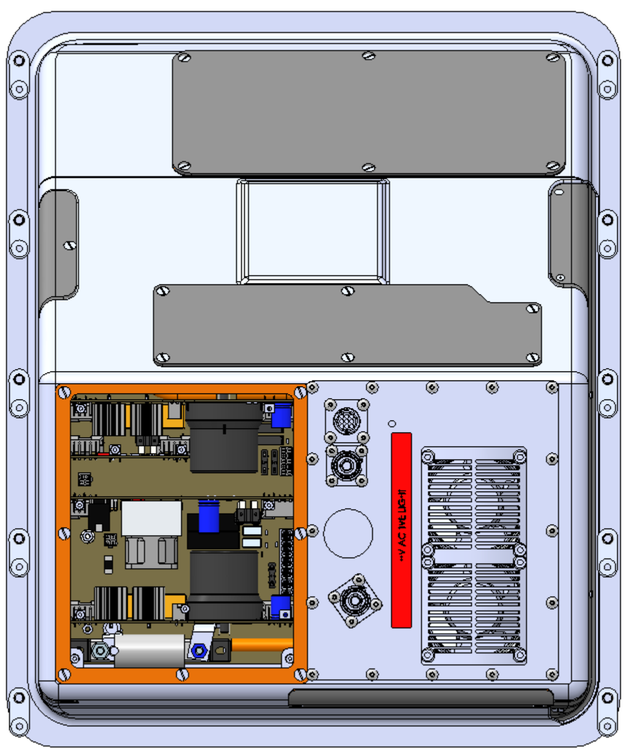

Figure 7.6: Motherboard Location

### 7.4.2 Backplane

The backplane connects all the daughter cards.

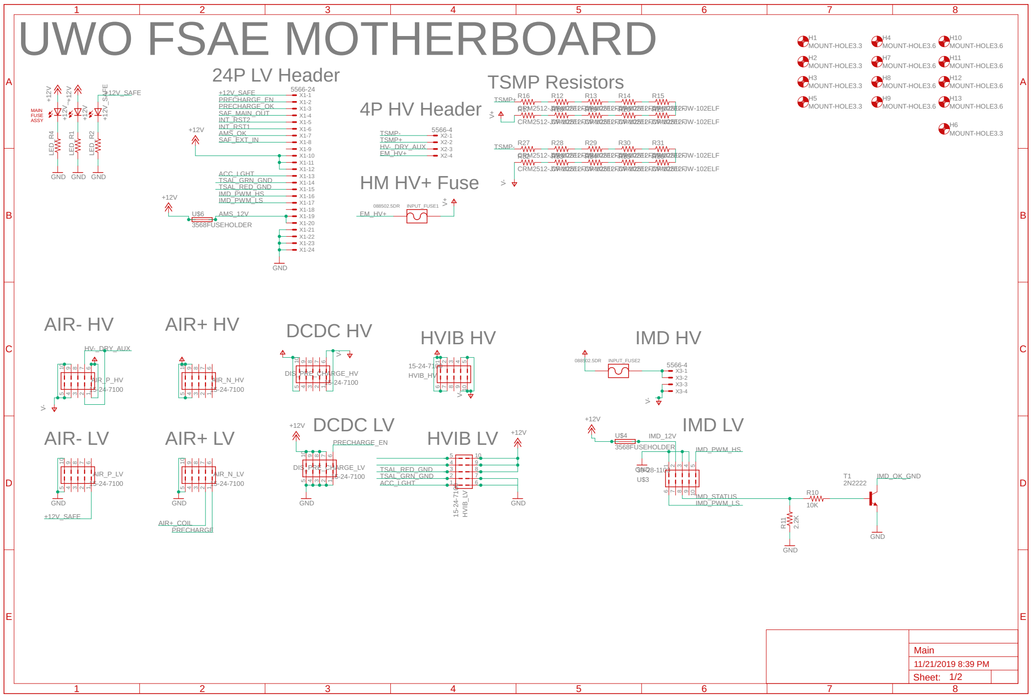


Figure 7.7: Backplane Schemaic Page 1

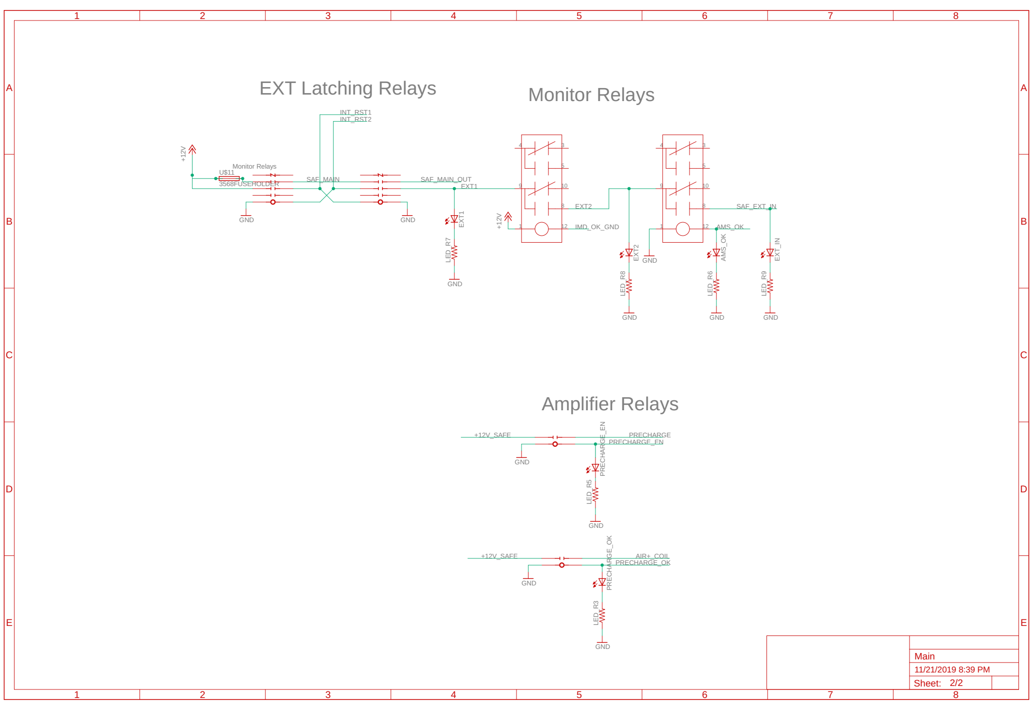


Figure 7.8: Backplane Schemaic Page 2

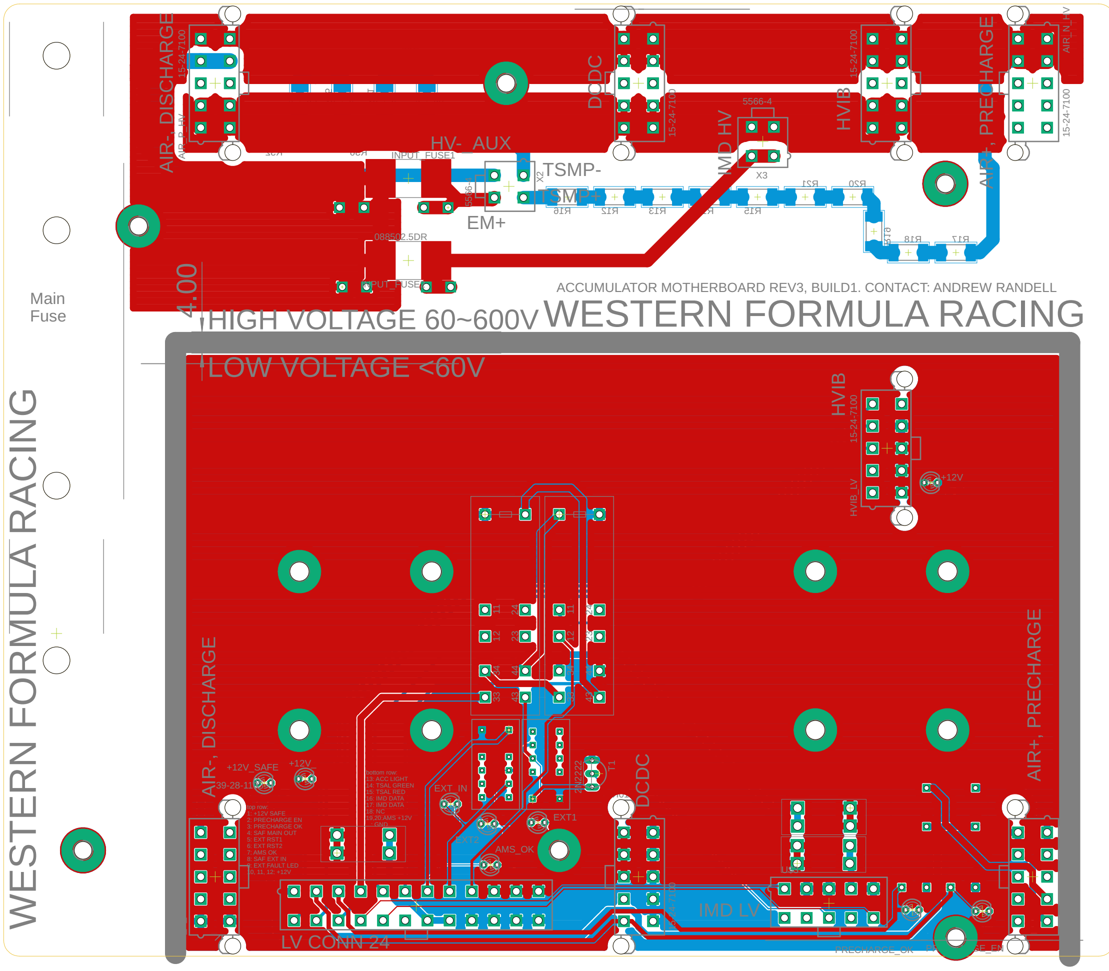


Figure 7.9: Backplane Layout

### 7.4.3 AIR + and Precharge Circuit

The Positive AIR and Precharge Circuit live on a daughter card within the motherboard. HV is landed to the PCB via a HV wire and ring terminals mounted to the AIR terminals. These HV wires are less than 3 inches in length.

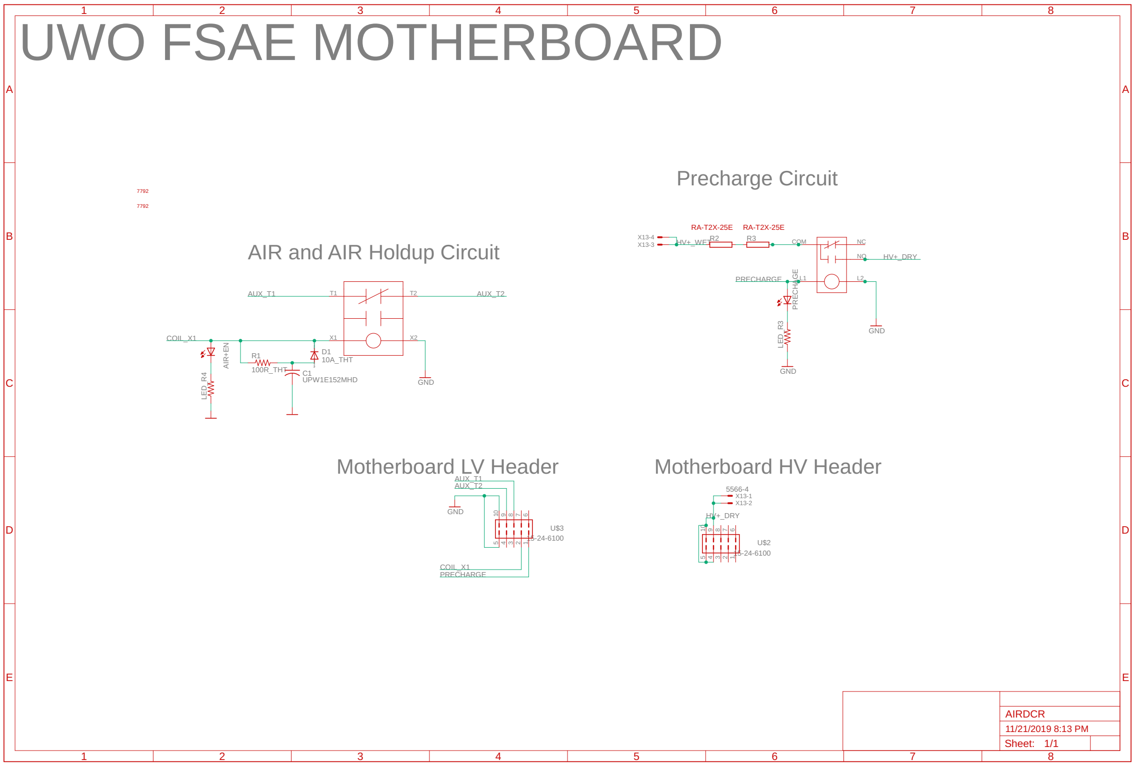


Figure 7.10: AIR+ and Precharge Schematic

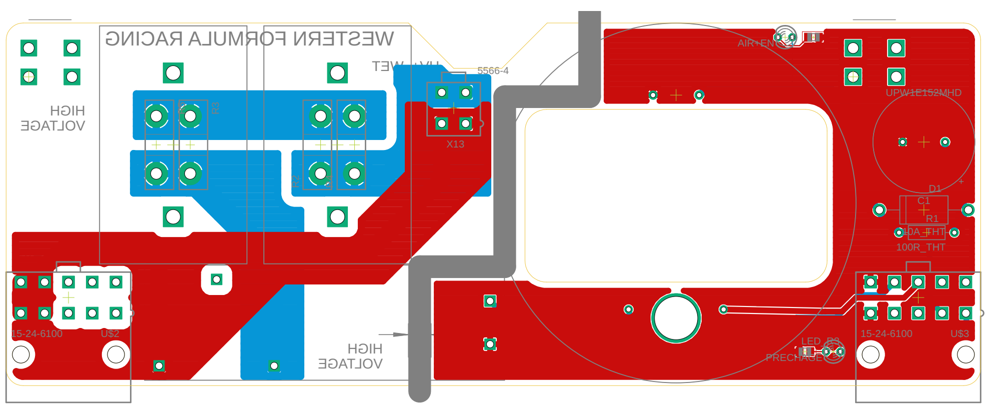


Figure 7.11: AIR+ and Precharge Layout

### 7.4.4 AIR - and Discharge Circuit

The Negative AIR and Discharge Circuit live on a daughter card within the motherboard. HV is landed to the PCB via a HV wire and ring terminals mounted to the AIR terminals. These HV wires are less than 3 inches in length.

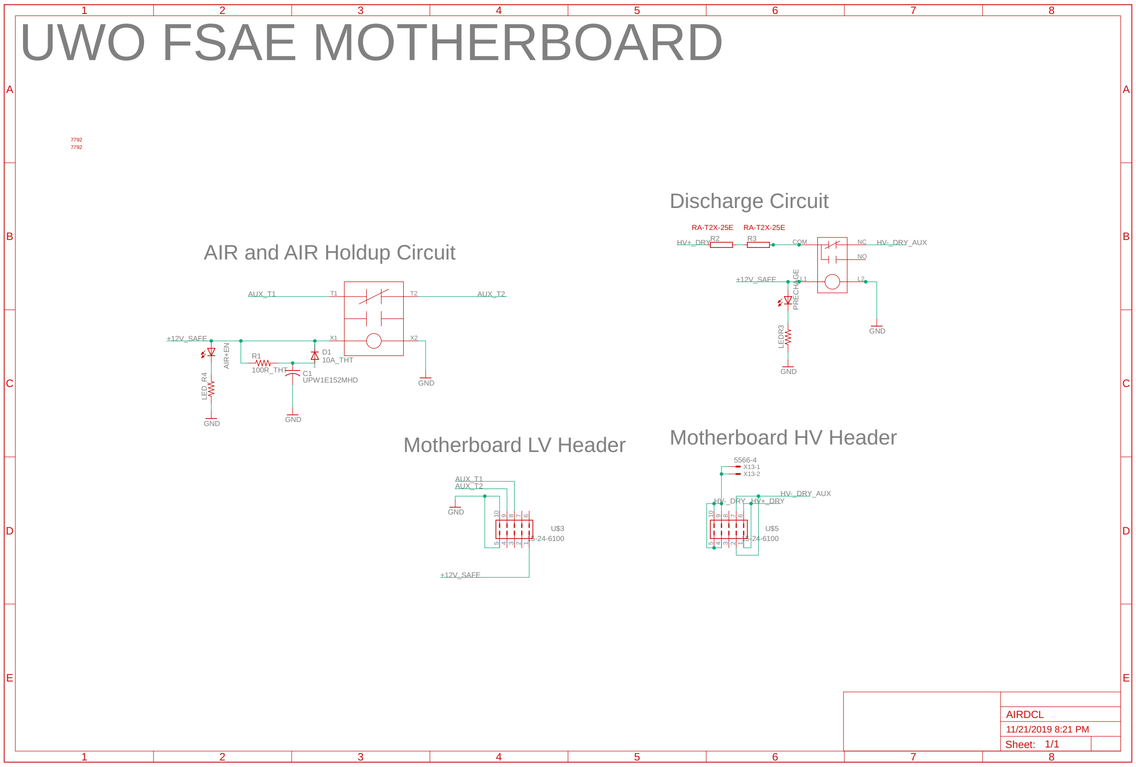


Figure 7.12: AIR- and Discharge Schematic

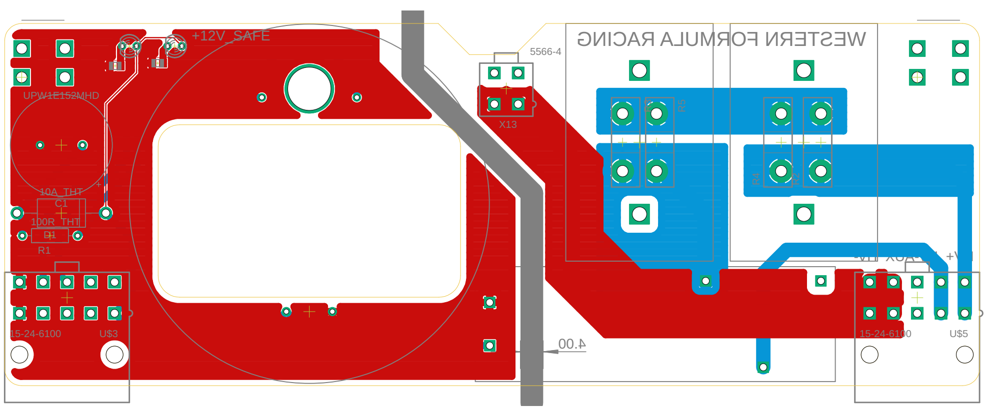


Figure 7.13: AIR- and Discharge Layout

### 7.4.5 DCDC Converter

The DC/DC converter is a daughter board located in the accumulator Motherboard. It is fused using at 2.5A. It is de-activated during the pre-charge sequence using a set of p-channel mosfets so that the DC/DC converter does not draw current while the vehicle is in a pre charge sequence. The DC/DC converter is supplied from the motor controller (dry) side of the AIR's.

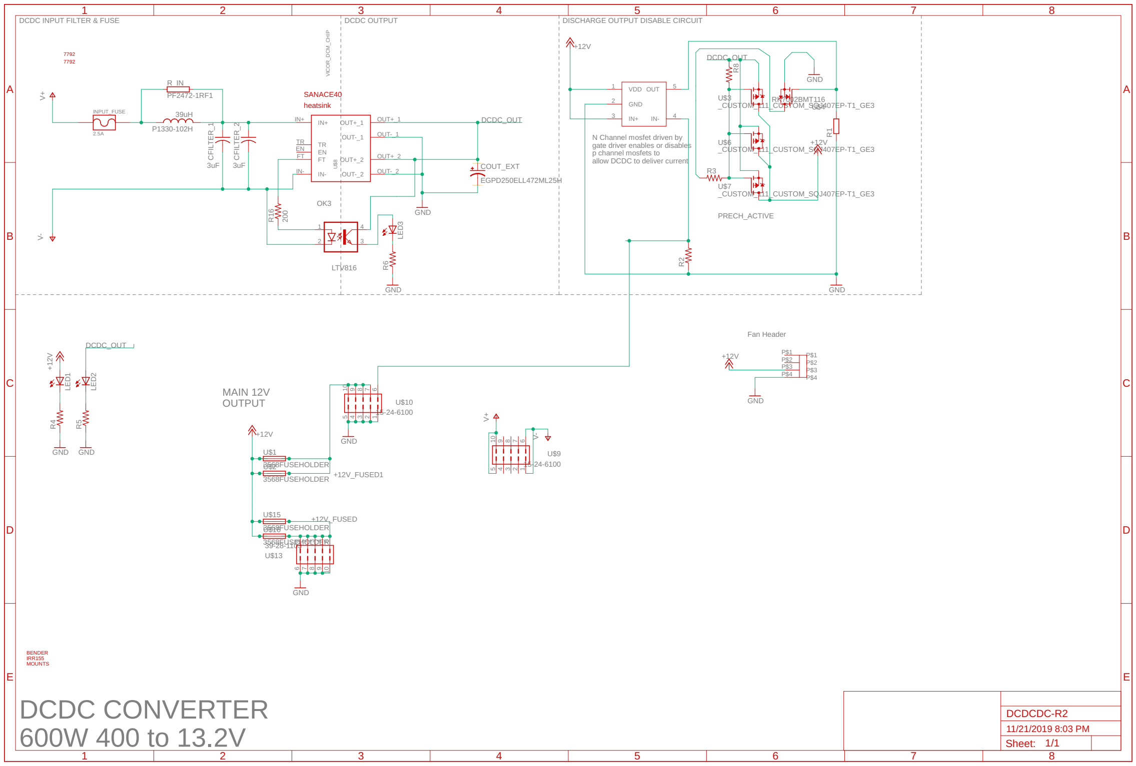


Figure 7.14: DCDC Schematic

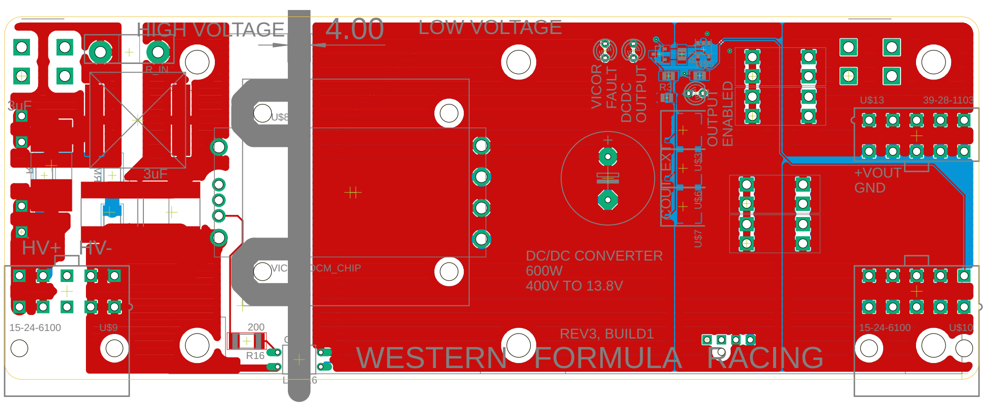


Figure 7.15: DCDC Layout

The DCDC converter contains a 400k passive discharge resistor. This is designed to discharge the 6uF input capacitance to less than 60V in less than 5 seconds.

### 7.4.6 HVIB

The HVIB is a daughter board located in the accumulator Motherboard. The High Voltage Interlock Board is designed to accomplish the following tasks

- Sense the presence of voltage on the dry poles of the AIRs'
- Drive the TSAL
- Drive the Accumulator Indicator Light

The HVIB detects the presence of voltage on the dry poles of the AIRs'. Based on that, the circuit provides a switched ground output for the accumulator indicator light, the TSAL green and red lights.

The HV detection circuit works by means of the Zener Diode with a 60V reverse breakdown voltage on the HV side of the HVIB board. When TS greater than 60V, the Zener Diode will conduct feeding the current regulator which is coupled to an opto isolator which transmits the signal to the LV side of the board. These sensing circuits have their sense leads attached on both poles of the AIR's and measure between HV+ Dry and HV- Dry (dry pole sense).

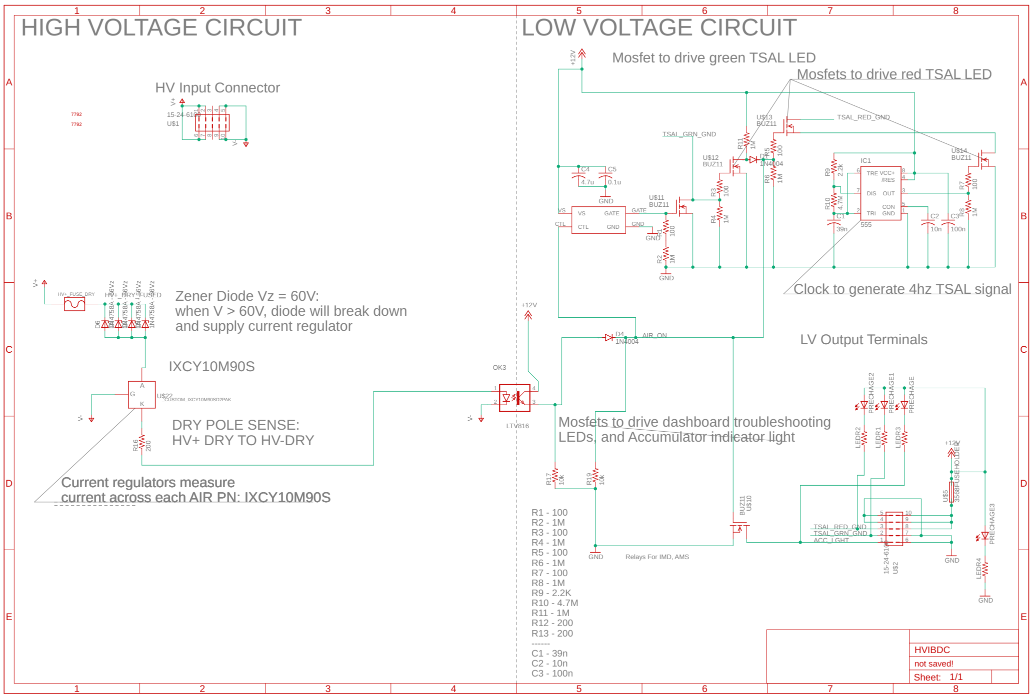


Figure 7.16: HVIB Schematic

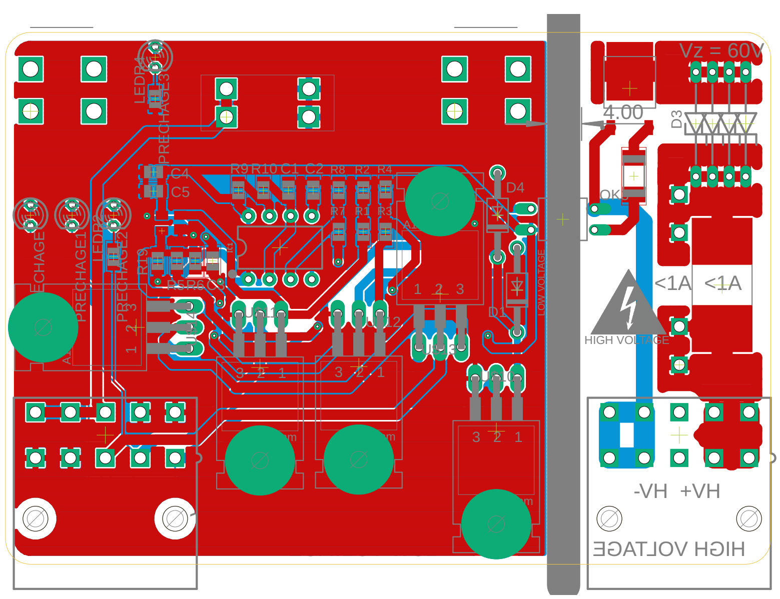


Figure 7.17: HVIB Layout

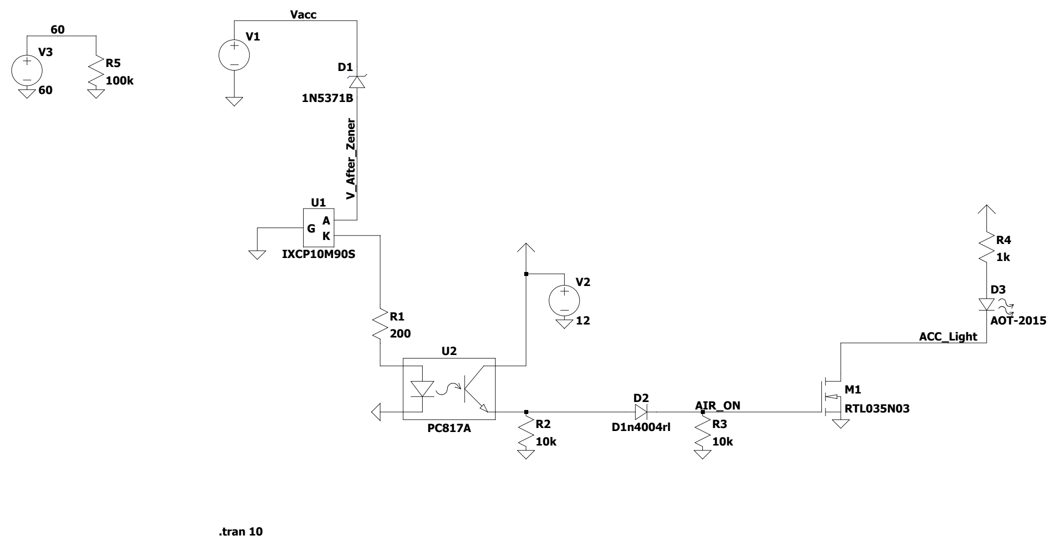


Figure 7.18: HVIB Spice Model Schematic

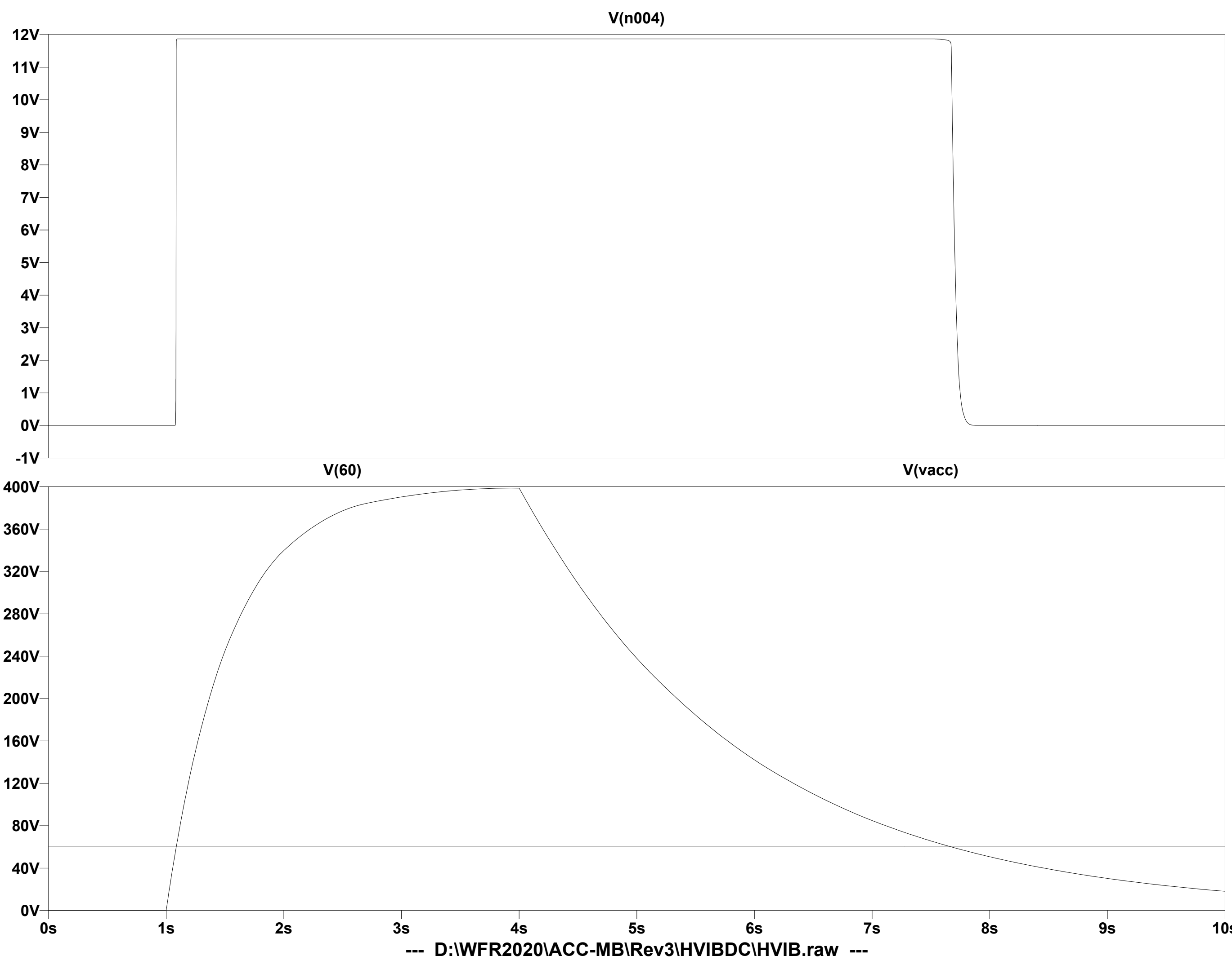


Figure 7.19: HVIB Spice Simulation Results

# A Appendix

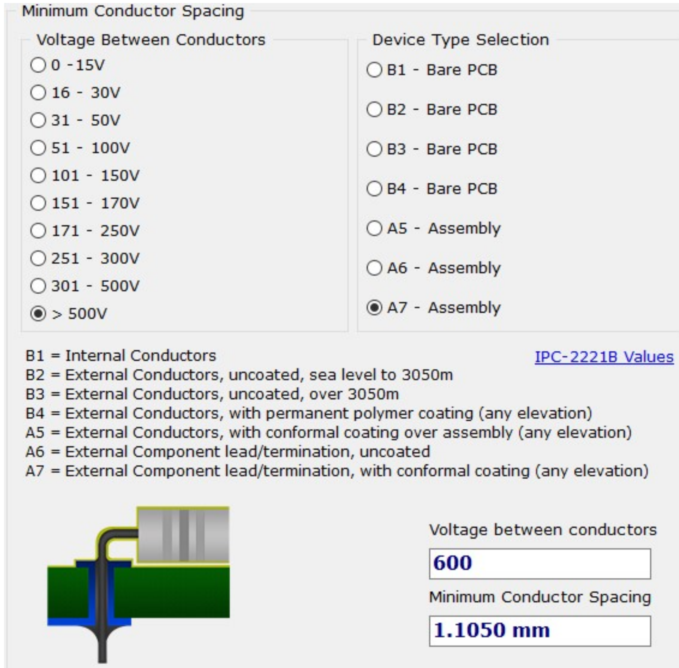


Figure A.1: IPC Spacing Requirement for all PCBs

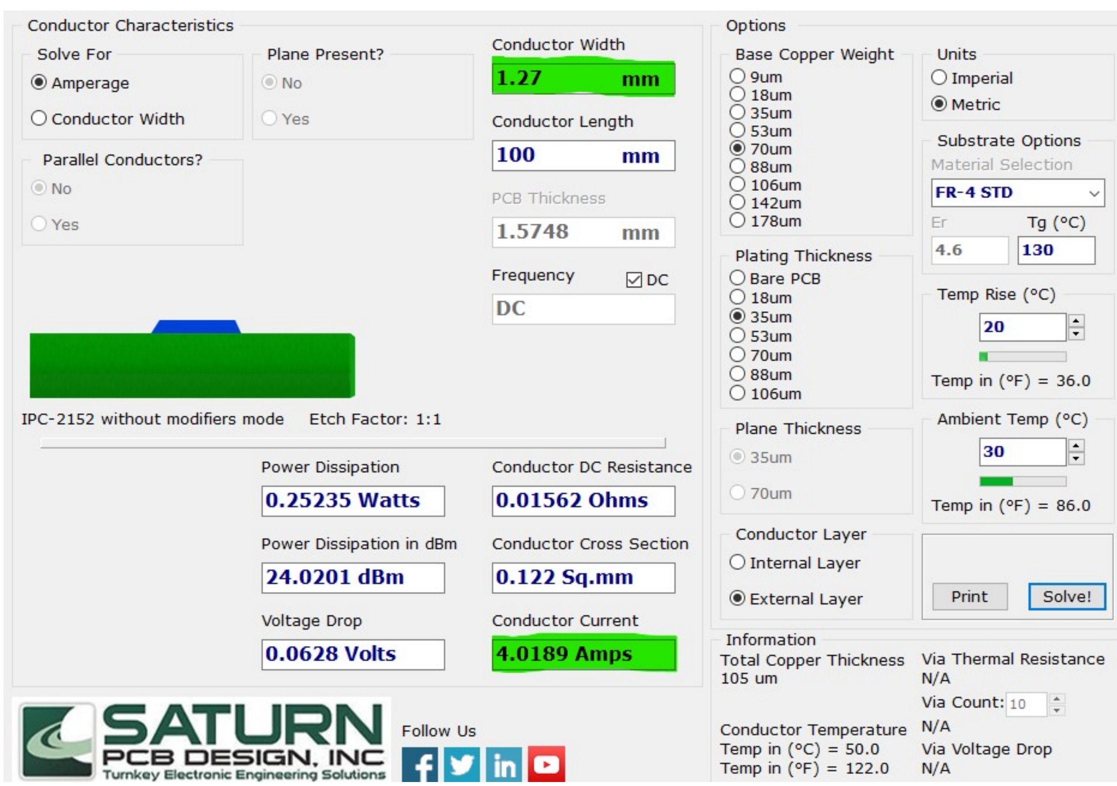


Figure A.2: HV Trace Width Minimum

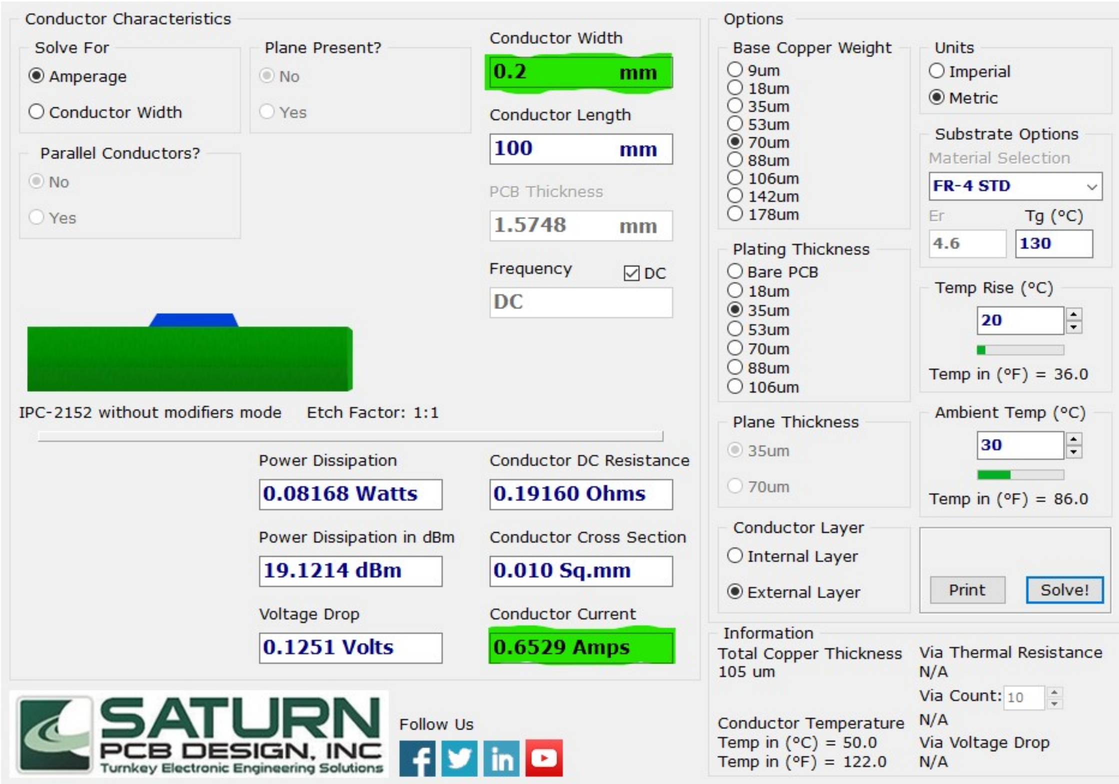


Figure A.3: LV Trace Width Minimum