REVO Electric Racing, Olin College of Engineering

Electrical System Form FSAE-E 2016
Car E218

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List of Abbreviations

- MSD- Manual Service Disconnect
- CONN- Main accumulator connector
- NDA - Non Disclosure Agreement
- SDB- Shutdown Button

Any other abbreviations used in this document are those used in the 2016 Formula SAE Rules and those used in the FSAE ESF template document.

1 System Overview

The system will support all requirements for vehicular movement while guaranteeing driver and maintenance safety. There will be two primary electrical systems, galvanically isolated from each other: a 98.4V high power tractive system (maximum) and a 12V low power sense and communication system.

The low power system will include a shutdown circuit, a series of sensors and switches that ensures the vehicle is safe to drive before engaging the tractive system. A 12V lead acid battery powers the GLV and shutdown system. The shutdown circuit will monitor the vehicle for dangerous conditions, such as a collision or ground fault in the tractive system, and will disengage the tractive system in case of emergency. Finally, the low power system will power a CAN communication network using ATmega16M1 microcontrollers that will be used to operate several rules required functions, such as the ready to drive sound, and will also serve as a debugging tool for both electrical systems.

The tractive system consists of a custom accumulator container, two Sevcon motor controllers, and two Zero Motorcycles brushless DC motors. The accumulator comprises 12 Nissan Leaf battery modules. The motors are configured for rear wheel drive with independent control over the left and right wheels. Communication to the motor controllers is completed using an analog signal from the isolated CAN system.

See Figure 1 for an electrical block diagram.

Maximum Tractive system voltage	98.4V VDC
Nominal Tractive system voltage	90 VDC
Control-system voltage	13.5VDC & 12VDC
Accumulator configuration	2s2p in 12s
Total Accumulator capacity	65.0
Motor type	Brushless DC Motor
Number of motors	Total: 2
Maximum combined motor power in kW	65.7 kW

Table 1: General parameters

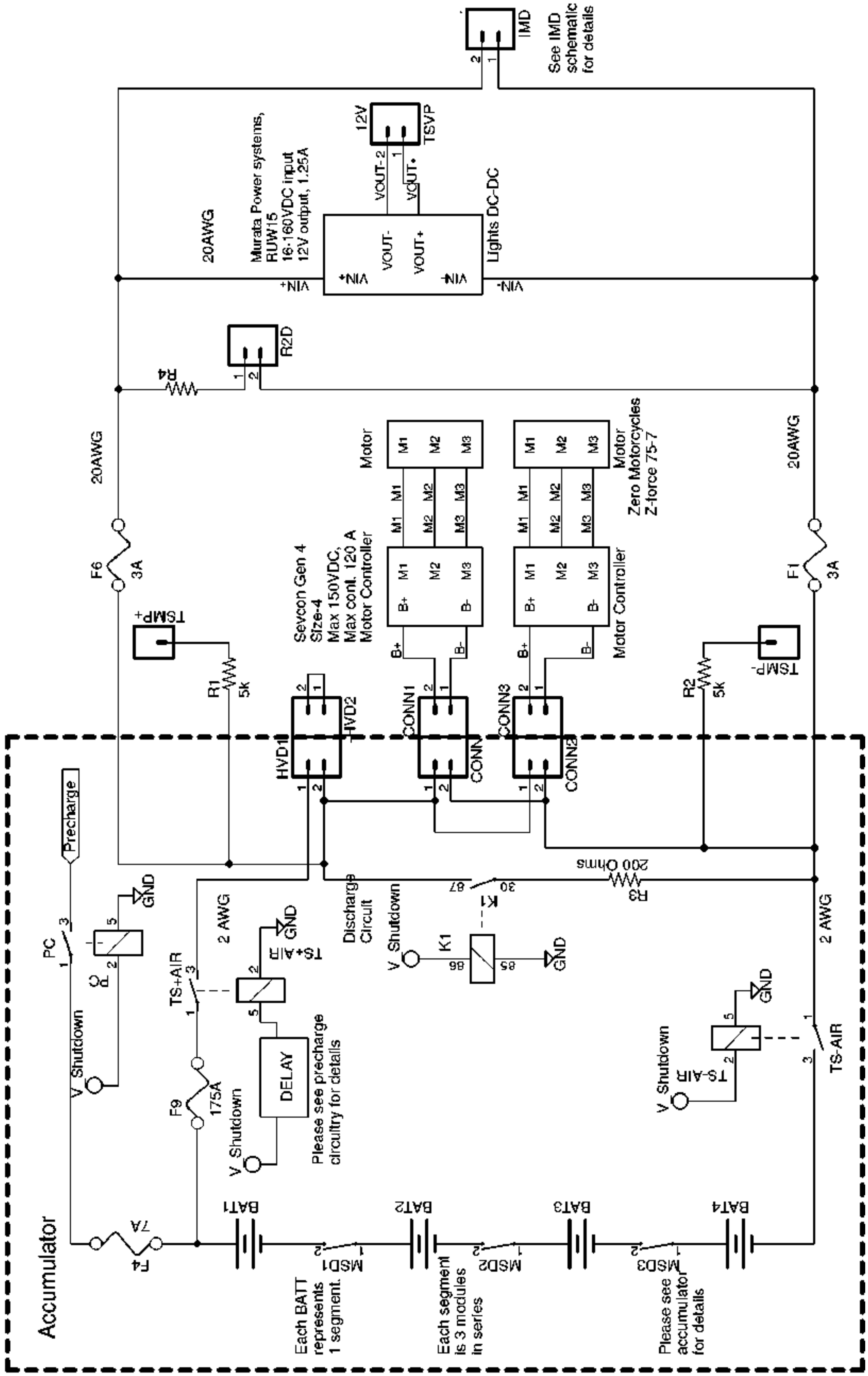


Figure 1: Tractive system block diagram. Please note that there is additional circuitry around the precharge relay, which is clarified in figure 13

2 Electrical Systems

2.1 Shutdown Circuit

2.1.1 Description/Concept

The shutdown circuit is the primary method for maintaining driver and maintenance electrical safety at all times. The shutdown circuit prevents high voltage from being present outside of the accumulator container before the vehicle is safe to drive and will shut down the tractive system during driving if it detects an unsafe or emergency condition. The shutdown circuitry directly controls the current going to the AIRs through a series of safety sensors and relays. Triggering the shutdown circuit opens the circuit and causes the AIRs to open. To power the system, we have a 12V lead acid battery.

The shutdown circuit consists of 10 major components

- The GLVMS controls all power to the GLV system. As a result, high voltage cannot be present when the low voltage system is not active.
- The TSMS is the last component in the shutdown circuit before the AIRs. This allows full testing of the GLV system without engaging the TS and only intentional use of the TS.
- The BOTS is used to detect a mechanical failure in the brake system. If the brake system fails, the TS is disabled to allow the vehicle to roll to a stop and ensure the safety of the driver.
- The SDBs are used for emergency shutdown of the TS. The cockpit SDB allows the driver to quickly shutdown the tractive system from the driver's seat. The left and right SDBs are intended for emergency shutdown in a crash or rollover scenario by first responders.
- The IMD is used to detect if the TS has lost isolation with the GLV system. This protects from lost isolation being live on the chassis, which acts as ground.
- The AMS monitors the state of the accumulator and triggers a TS shutdown if the modules enter a dangerous temperature or electrical condition.
- The inertia switch triggers a TS shutdown if it experiences an acceleration indicative of a collision. This ensures the vehicle is electrically safe in an emergency situation.
- Interlocks close the shutdown circuit when all high voltage connections are properly made. This ensures that high voltage is only present within the TS and disabled if connections are left open.
- The BSPD detects if the motor controllers are drawing significant current from the accumulator while the brakes are engaged. To protect the driver and the vehicle, this scenario triggers a TS shutdown.
- Finally, the shutdown circuit contains a CAN Watchdog to shut down the TS in the event of a CAN error. This functions as protection in the rare event of software failure.

Part	Function
Main Switch (GLVMS and TSMS)	Normally open
Brake over travel switch (BOTS)	Push-pull button
Shutdown buttons (SDB) (Left, right, cockpit)	Normally closed
Insulation Monitoring Device (IMD)	Normally open
Battery Management System (AMS) x4	Normally open
Inertia switch	Normally closed
Interlocks	Closed when circuits are connected
Brake System Plausibility Device (BSPD)	Normally Open
CAN Watchdog	Normally closed

Table 2: List of switches in the shutdown circuit

2.1.2 Wiring/Additional Circuitry

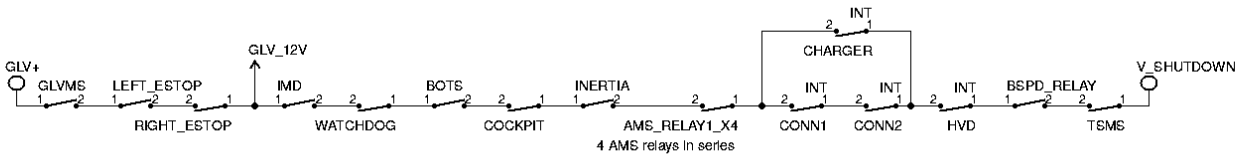


Figure 2: Shutdown Circuit Switches

Figure 2 shows only the switches in the shutdown circuit, and does not include the AIRs or the precharge and discharge systems. The tractive system can only be enabled when all switches are closed, allowing the AIRS to be closed. The point after the TSMS splits into power for the AIRs, which are in parallel, the keyswitch (trigger for the internal precharge system of the motor controller) and the discharge system. This schematic has been simplified to not include the circuitry around the coils that close these switches, but those schematics can be found in their respective sections.

Total Number of AIRs:	2
Current per AIR	3.8A until 150 ms passes, then 0.4 A
Additional parts consumption within the shutdown circuit:	3A
Total current:	8 A until 150 ms passes, then 4A
Cross sectional area of the wiring used:	0.00080384 in^2 (20 AWG)

Table 3: Wiring- Shutdown Circuit

The GLV system also has 12V and 5V supply lines in parallel to the shutdown circuit. It supplies the 555 timers, CAN nodes, coils and lights, which are all in parallel with the AIRs.

2.1.3 Position in Car

There are many shutdown components are in or mouonted to a housing called motor controller housing, which is a waterproof enclosure located at the rear of the chassis, behind the main hoop, underneath the motor controllers. This enclosure is bolted onto steel brackets which are welded to the main hoop. This enclosure consists of an Nylon panel where the TSMS, GLVMS, TSMPs, GLVMPs, AMS reset button, and IMD reset button will be mounted, and a 3D printed rear housing with integrated 23-pin TE connectivity Ampseal connector, as seen in figure 3. In addition to the buttons and measuring points, the housing also contains the IMD, IMD relay, a PCB (Side panel node, which includes the watchdog relay), and the GLV battery, as seen in figure 4. Mounted to the outside of the box includes the GLVMS and TSMS. The tractive system and low voltage systems are separated by at least two centimeters at all times, with certain wires wrapped in nomex tubing.

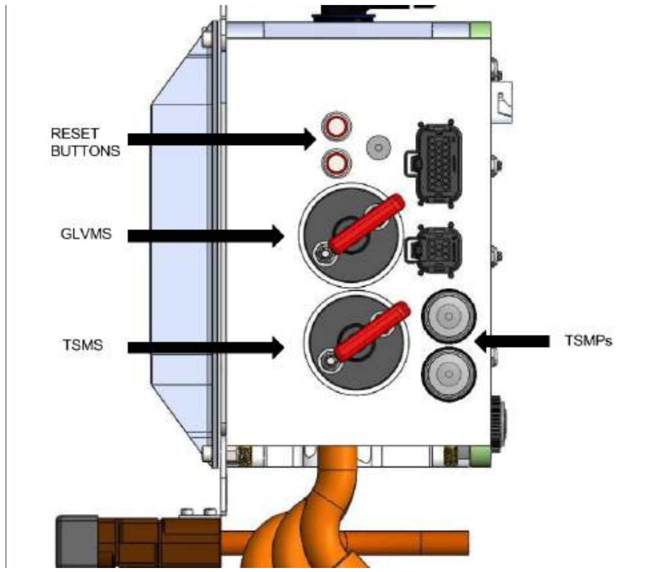


Figure 3: Outside view of the side panel housing, labelled

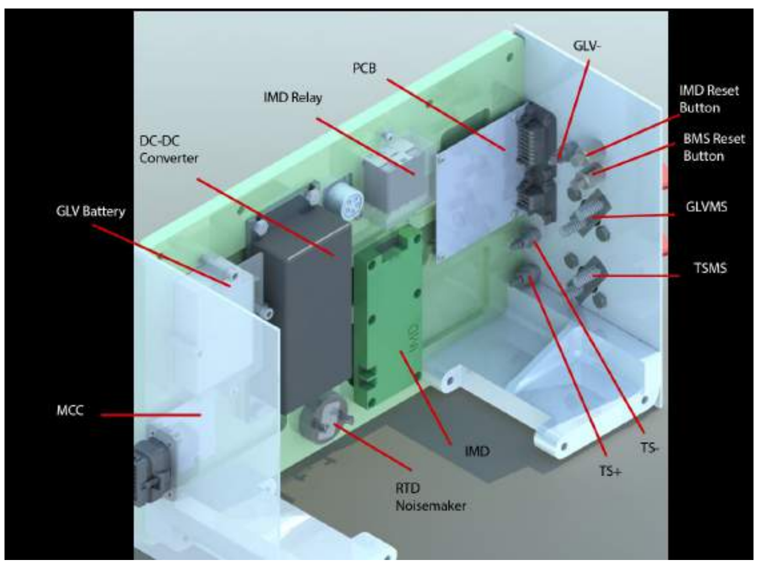


Figure 4: Inside view of the side panel housing. The DC-DC converter will actually not be placed here.

2.2 IMD

2.2.1 Description (Type, Operation Parameters)

The IMD used will be a Bender A-ISOMETER IR155-3204. The output is normally high and only low if it does not detect a ground fault. The output is then used in a 4PDT relay to close the switch in the shutdown circuit and activate the CAN system to not power the IMD light in the dashboard.

Supply voltage range:	10...36VDC
Supply voltage	12VDC
Environmental temperature range:	Unknown
Selftest interval:	Every 5 minutes
High voltage range:	0-1000 VDC
Set response value:	100 kΩ
Max. operation current:	150 mA
Approximate time to shut down at 50% of the response value:	$\leq$ 40 sec

Table 4: Parameters of the IMD

2.2.2 Wiring/Cables/Connectors

To fit the connectors and the low current draw of the IMD, the wires used for the IMD will be 22 AWG and 18 AWG. There is a fuse protecting the low current, high voltage wiring of the IMD and other components, and it is rated to 1A (details of the fuse are in the appendix, section 11). It is the same fuses (1A on both poles) that protect the other high voltage, low current devices.

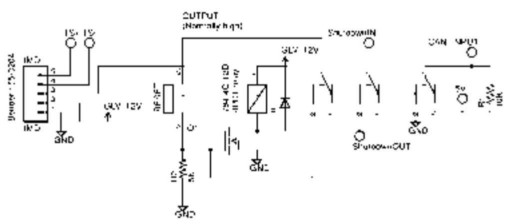


Figure 5: Schematic of the IMD and its connections

The IMD output powers a four pole double throw relay. However, for the relay to become powered, at the start of each driving/operable session (not when there is a fault in the shutdown system), a person must press the IMD reset button, which closes the circuit and allows the coil to power itself through the first pole. The other two poles close the shutdown circuit and the input pin to the CAN node. The fourth pole is not connected. The can input will inform the CAN system about the status of the IMD (pull up resistor ensures IMD CAN pole input is not left floating). The ATmega16M1 controls the IMD light in the cockpit through the CAN system. With the coil powered from the IMD's positive output, the shutdown circuit will close.
The connectors used for the IMD are the TYCO-MICRO MATE-N-LOK 1 x 2-1445088-8 and its mate. 18 AWG wire will be used to connect the low voltage connections between the IMD and side panel PCB. The 18 AWG wire used is rated for 300V, 90 °C.

2.2.3 Position in Car

As part of the shutdown circuit, the IMD will be located inside the enclosure shown in Figure 4. This is a convenient location for the IMD as high voltage sensing lines must already be present here for the TSMP's.

2.3 Inertia Switch

2.3.1 Description (Type, Operation Parameters)

The Sensata Resettable crash sensor (6-11g version) will trigger due to an impact that decelerates the vehicle at between 6-11g.

Inertia switch type	Sensata 6-11g crash sensor
Supply voltage range	12 VDC
Supply voltage	12VDC
Environmental temperature range	-10-120 °C
Maximum operational current	20A for max. duration 30sec, 10A max. continuous
Trigger charactersitics	Operate above 11g peak, 60ms duration Not operate below 6g peak, 60ms duration

Table 5: Parameters of the Inertia Switch

2.3.2 Wiring/Cables/Connectors

The Inertia switch will be wired to be normally closed and open the shutdown circuit in the case that there is a crash. The inertia switch is wired in-line with the shutdown circuit to be normally closed. Please see figure 2 for the position of the IMD in relative to the other shutdown system components.

2.3.3 Position in Car

The inertia switch will be located on the dashboard, in reach of the driver as to fit EV5.7.4. It is mounted properly (upwards), so it can be triggered and reset.

2.4 Brake Plausibility Device (BSPD)

2.4.1 Description/Additional Circuitry

The BSPD will constantly check if there is a substantial amount of current across the motor controllers and if the brakes are being pressed hard. If both are true, after 0.5 second of continuity, the relay will open the switch in the shutdown circuit. The circuitry consists of a series of op amps and logic gates which detect when the combined current going to both motors is greater than 50A and the brake sensor is being activated. The output of this result then powers a 555 timer which will output a high pulse to the reset pin of a SR-latch which allows for the circuit to be latching.
There are two Hall Effect current sensors monitoring the current draw of the two individual motor controllers. The measured current draw of both sensors is then summed in order to get the total current.

Brake sensor used:	Pegasus Brake Light switch, part 3601
Torque encoder used:	Active Sensors MHR5621
Supply voltages:	5V
Maximum supply currents:	15 mA
Operating temperature:	-55 to 150 °C
Output used to control AIRs:	TE Connectivity Relay, part PB766-ND

Table 6: Torque Encoder Data

2.4.2 Wiring

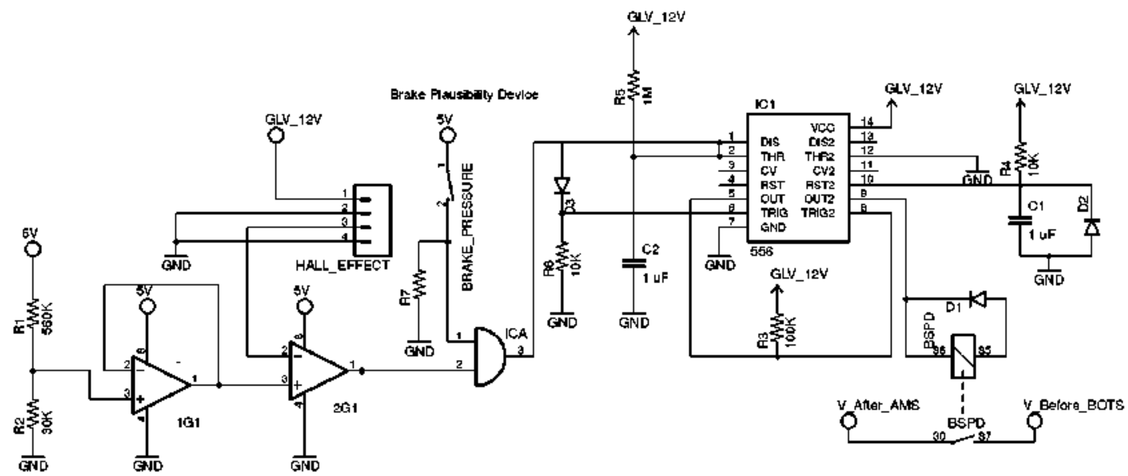


Figure 6: Schematic of the BSPD

Two hall effect current sensors, each wired around the power lines of the motor controllers, will send a proportional signal to a comparator. If the (summed) current is above 50 Amps, the output will be positive, and a positive signal will be sent to the AND gate. If the brakes are actuated, a positive signal will come from the brake pressure switch, causing the AND gate to return positive. This output powers a 555 timer, which if it remains powered for 0.5 seconds will send out a high pulse to the reset pin of an RS-latch. The normally open relay will be opened because of the reset state of the RS-latch, shutting down the current to the AIRs. The BSPD can be reset through CAN which will send a high pulse to the set pin of the RS-latch. This is a failure mode that is possible, however it is also possible for the AMS reset. In either case, being reset is the safer mode to fail. Microcontroller failure will be caught by watchdog and the shutdown system will open anyway. BSPD reset button has been moved to the back side panel, sharing the same button as the AMS reset. If the AMS system is not having any issues (as seen through CAN), then the BSPD will reset.

2.4.3 Position in Car/Mechanical Fastening/Mechanical Connection

The brake sensor is Pegasus Racing P/N 3601 pressure switch that activates between 60 and 120psi. It is attached to the brake line using a -3 AN T-fitting. The brake system is composed of a combination of hard and flexible brake line and will use a combination of SAE flare connections and AN fittings.

The circuit board controlling the BSPD is located near the motor controllers, on a board called motor controller controller. The input line from the brake will be fed from the front bulkhead of the vehicle. The board will be positively retained using standard hardware and stand-offs, all external connections will be made using Ampseal connectors and all internal enclosure connections will be made using Molex PCB connectors. Figures 7 and 8 show how the brake sensor will be mounted and where it will be located.

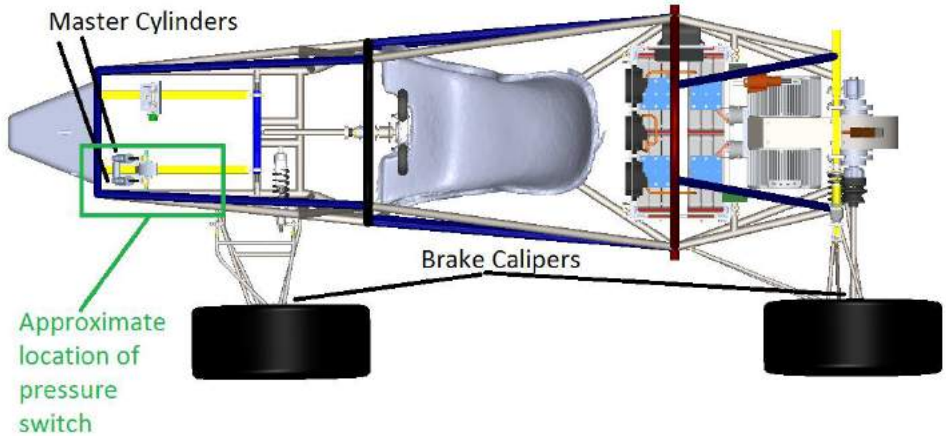


Figure 7: View of BSPD Pressure Switch and T-Fitting

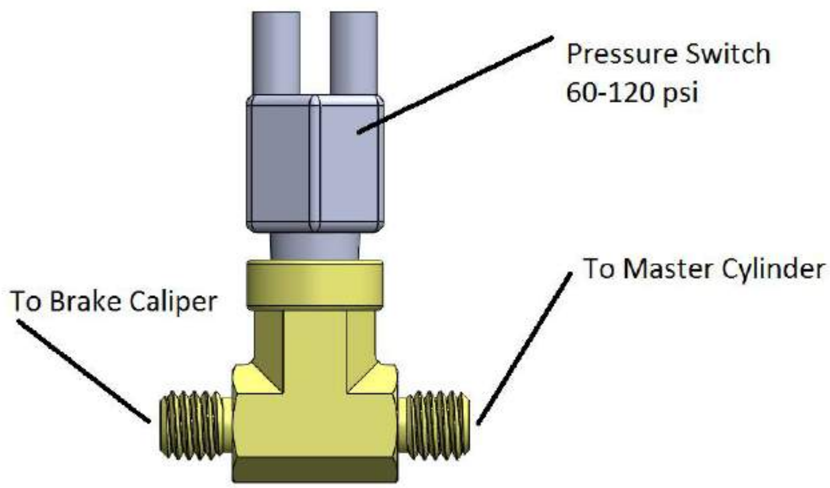


Figure 8: Approximate Location of BSPD Pressure Switch in Vehicle

2.5 Reset/Latching for IMD and BMS

2.5.1 Description/Circuitry

If the AMS detects a fault, it opens the shutdown circuit, and latches into that state. When the AMS reset button is pressed, the nearby CAN node passes a CAN message to the AMS boards. If the accumulator is within safe electrical and temperature operating limits the AMS closes the shutdown circuit.

To reset the IMD an operator other than the driver must push the IMD reset button located on the outside of the car on a panel next to the TSMPs, master switches and E-stops. If the output of the IMD is high because there is no ground fault, the reset button will activate the coil and close the shutdown circuit.

2.5.2 Wiring/Cables/Connectors

The IMD's output, as seen in figure 5, continuously closes the shutdown circuit as long as its output is high. The reset button closes the circuit to the coil to then allow the coil to power itself for as long as the output is high. Once low, the coil will open its four poles, thereby allowing power to the CAN node input, thereby activating the IMD light or the switch in the shutdown circuit. The 4PDT relay is specified for 15A, while the GLV system it controls is fused for 5A. The wire gauge to the IMD relay is 20AWG.

The BMS reset button is a button that connects 5V to a CAN input pin on the side panel node later mentioned in section 8.3. When the CAN node receives a high signal it sends a message to the rest of the system, including the AMS nodes, and if the AMS detects the accumulator is safe, the AMS relay will close the shutdown circuit and allow normal operation. All wire gauges will be 20 AWG except for PCB traces.

2.5.3 Position in Car

The IMD and BMS reset buttons will be panel mounted to the enclosure shown in Figure 4. The AMS will be within the accumulator container.

2.6 Shutdown System Interlocks

2.6.1 Description/Circuitry

Interlocks are low voltage mechanically activated switches that close when a high voltage connection is made or a system is closed. In the shutdown circuit, the main accumulator connectors, and the HVD have interlocks. The shutdown circuit will be open when any of these TS connections are opened. There is also an interlock on the charger connector which bypasses the main battery connector interlocks.

2.6.2 Wiring/Cables/Connectors

Interlock wires are mechanically integrated with HV connectors such that they are simultaneously disconnected with the removal of a connector. The removal of a connector therefore breaks shutdown circuit continuity. The interlock wires will be 20 or 22 AWG and be fused from the shutdown GLV fuse (2A).

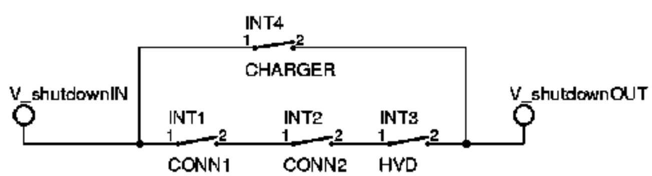


Figure 9: Interlocks contained in the shutdown circuit

2.6.3 Position in Car

Interlocks are contained within the main accumulator two-pole HV connector (labeled CONN) and the HVD. Both connections are out of the accumulator, and located in the back of the car. Please see section 2.11 for details.
There is a charger interlock that overrides (in parallel with) the main connection interlocks. This interlock is only used during charging.

2.7 Tractive system Active Light

2.7.1 Description/Circuitry

The TSAL illuminates when the tractive system is active, which is defined as the tractive system voltage being over 60V or the AIRs being closed.

Supply voltage:	12V
Max. operational current:	0.04A
Lamp type	LEDs
Power consumption:	0.48 W
Brightness	Unknown
Frequency:	Manual with 555 timer, 3.1
Size (length x height x width):	103x27x51 mm

Table 7: Parameters of the TSAL

2.7.2 Wiring/Cables/Connectors

The circuitry designed has two optocouplers with the mosfet sides in parallel. If either optocoupler is powered, the TSAL will be powered. On the TS-controlled optocoupler, when the TS is over 60V, zener diodes with a breakdown voltage of 56V and 3.6V respectably power one side of an optocoupler when the TS voltage is over 60V. On the GLV-controlled optocoupler, the optocoupler is powered when there is shutdown voltage before the AIRs. In this way, the light will be powered when the tractive system is over 60V or the AIRs are closed. The TS input to the zener diode circuitry is after the same 1A fuses as previously mentioned for the IMD and R2D. The power line for the TSAL is also interrupted by a mosfet that has its gate controlled by a 555 timer to allow it to blink at a rate of 3.1 Hz.

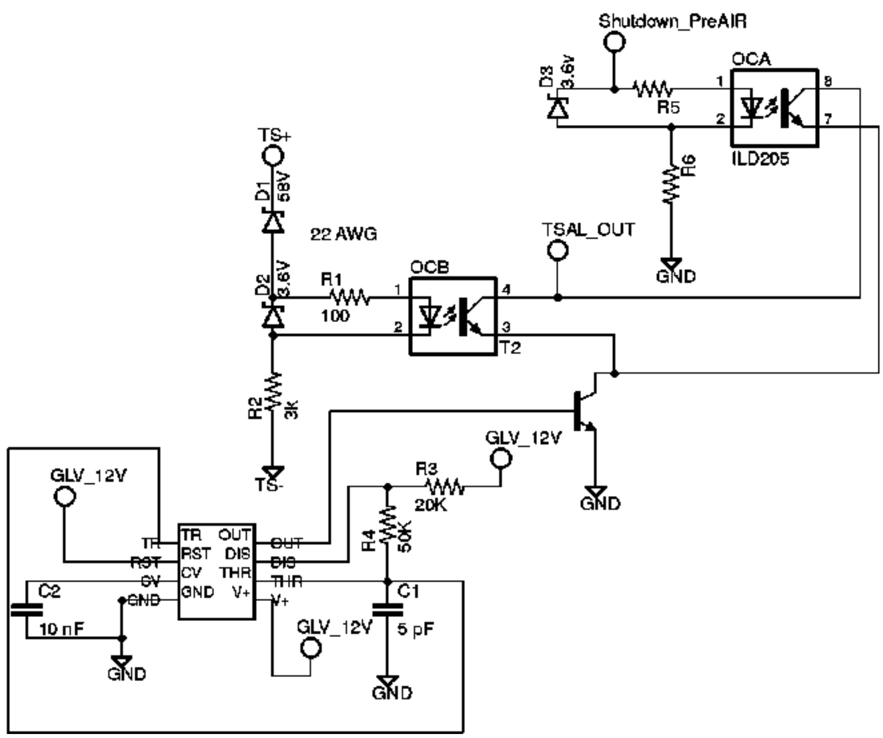


Figure 10: Schematic for the TSAL

All connections made by wires will be 20 AWG rated for 600V, 125 ˚C and 7A, while all PCB traces will be a minimum of 12 mil, but nominally 20 mil in width. The TS voltage will have been fused to 1A on both the positive and negative TS poles, with the same fuses that protects the TSMPs, IMD and R2D sound (fuses located on the AIR control board PCB). The fuse has a 125V rating and 300 A @ 125VDC interrupt rating. It only protects the DC-DC converter for the TSAL circuitry and TSAL TS input, IMD, accumulator indicator and R2D sound. It used to protect a GLV DC-DC but that has been removed. It is within the low current TS voltage harness, which connects to the 8-pin Ampseal on the side panel PCB.

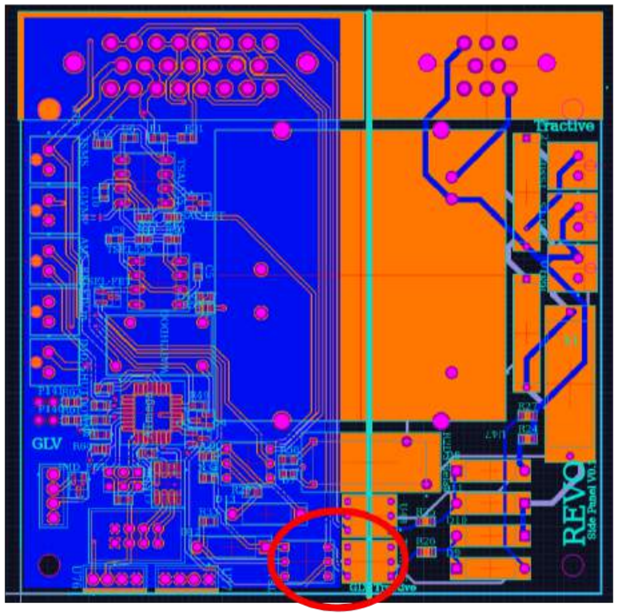


Figure 11: PCB for the TSAL circuitry, located on the side panel PCB. The circled photorelay mosfets control the tsal circuitry

2.7.3 Position in Car

The TSAL will be mounted to the underside of the highest point of the main roll hoop, per EV 4.12.4, using a mounting point of a small metal tab on the frame. The PCB will be located in the side panel enclosure, also known as the motor controller housing.

2.8 Measurement Points

2.8.1 Description

The TSMPs and GLVS ground measuring points are housed in a non-conductive, well-marked housing that can be opened without tools. It will be protected from people touching it by shrouded banana jack connectors and multimeter probe covers. The measuring points allow for safe measurement of the tractive system voltage and for manual detection of ground faults. The TSMPs will be in the same housing as the side panel CAN node and PCB.

2.8.2 Wiring, Connectors, Cables

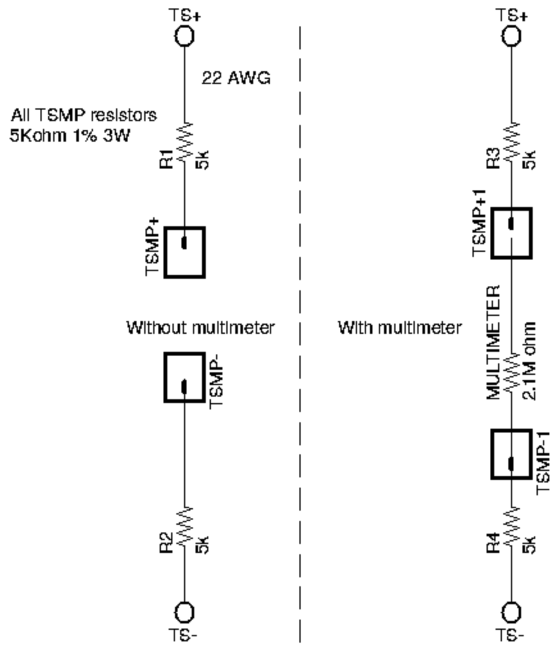


Figure 12: Tractive System Measuring Points

Figure 12 shows the TSMP schematic. Left shows the schematic including the banana jacks. Right shows the multimeter measuring the tractive system, with the multimeter's expected resistance and the same resistors as before the TSMP's on the left side.

There will be three measuring points: TS+, TS-,and GLV-. The TSMP connections will be secured with 5 kΩcurrent limiting resistors. The worst case scenario for the TSMPs occurs when there is a short between the TS+ and TS- banana jacks. This could occur as a result of operator error when measuring the TS voltage and create a voltage over a human operator's hands. The current limiting resistors ensure that the current draw in this scenario will not harm a human. There is no fuse before the TSMP resistors and probe points.

$$V = I * R \tag{1}$$
$$100V = I * 10,000\Omega \tag{2}$$
$$I = 0.01A \tag{3}$$

$$P = I * V \tag{4}$$
$$P = 0.01I * 100VV \tag{5}$$
$$P = 1W \tag{6}$$

Therefore, a 1W, 5kΩresistor will be placed before each TSMP banana jack. The resistor will be on the side panel PCB, which contains all of the low current TS circuitry and certain shutdown components.

Another worst case scenario that could occur at the measuring points is a short between the TS and GLV systems over the banana jacks, again by operator error. In this scenario, the IMD will open the shutdown circuit.

The TSMP banana jacks are 72930-2 and 72930-0 Pomona Electronics 4 mm banana jacks (red and black, respectively). The TSMP resistors are Vishay Dale, ALSR035K000FE12 (manufacturer's part number), rated for 122V and part of the ALSR series. The datasheets for both the banana jacks and the resistors can be found in section 11.

2.8.3 Position in Car

The TSMP's will be located in the enclosure shown in Figures 3 and 4 along with the side panel circuitry. Body panel removal will not be required for access. The enclosure itself is bolted together using 1/4" hardware.

2.9 Pre-Charge Circuitry

2.9.1 Description

In order to prevent damage to the motor controllers, AIRs, and ultimately the driver, it is important to ramp the tractive system up to full operating voltage rather than instantaneously jump from 0V to 100V. One consequence of an immediate transition to high voltage can be arcing across the AIRs. This can cause pitting in the relay contacts over time and ultimately cause the system to fail. Pre-charging reduces the difference in potential on each side of the relay to prevent arcing and ensure the integrity of the electrical system over many uses.

2.9.2 Wiring, Cables, Current Calculations, Connectors

. Once the shutdown circuit is closed, it will immediately power the coils of the normally closed discharge relay, the normally open precharge relay, and the normally open TS- AIR. This opens the discharge relay, and closes the precharge relay and TS- AIR. Instead of connecting Batt+ to TS+ through a current limiting resistor, the precharge relay connects B+ to the key switch terminal on each of the Sevcon motor controllers. When powered by their key switch terminals, the motor controllers charge their internal capacitors up to around 50V for 0.5 seconds, then up to 90V (or another specified voltage) for 0.1 seconds. The CAN system clocks this process with a timer in software, and then considers precharge to be finished and sends a CAN message. This CAN message causes a node in the accumulator to allow the shutdown circuit to close the TS+ AIR.
Please note the schematic in figure 13.

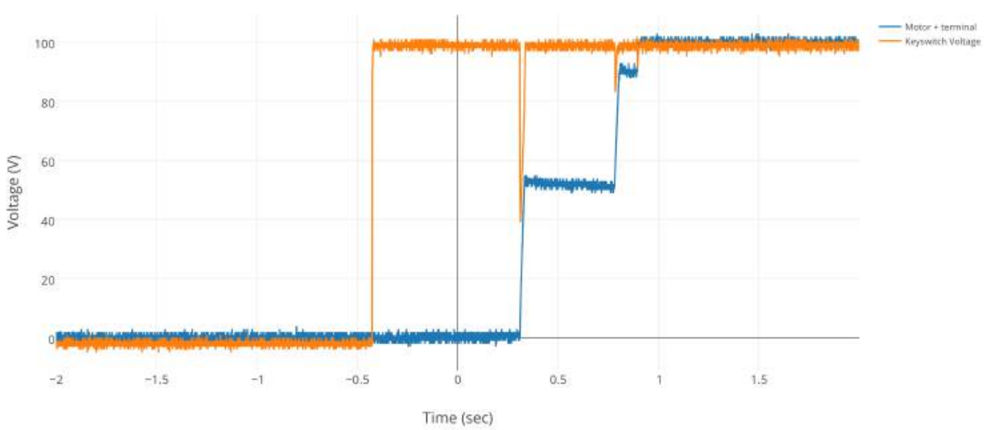


Figure 14: Voltage vs time, measured in a test setup.

In figure 14, the voltage of a test setup of the pre-charge system internal to the motor controller was measured. Because there is no resistor other than the motor controller, the current could not be calculated

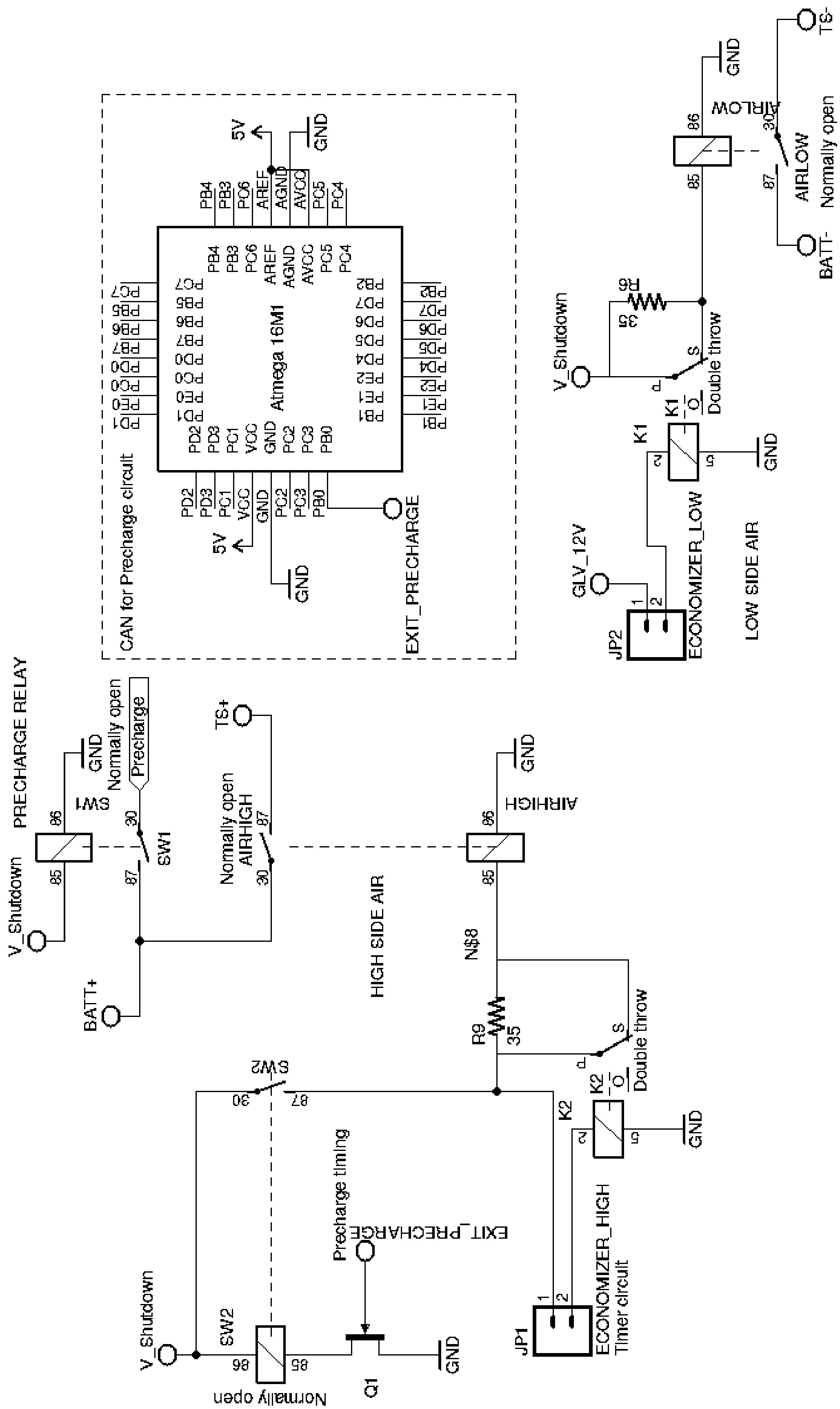


Figure 13: Precharge system schematic, including the AIR economizers

and/or graphed. This was discussed in rules clarification ticket 4487. As discussed above, the function describing the pre-charge is stepwise.

Resistor type	N/A
Resistance	N/A
Continous power rating	N/A
Overload power rating	N/A
Voltage rating	150 VDC
Cross-sectional area of wire used	0.001275 inˆ2 (18 AWG)

Table 8: General data of pre-charge resistor

Relay type	Omron Electronics, G5CA series, part no. G5LE-14-DC12
Contact arrangement	SPDT
Continous DC current	10A
Voltage rating	125VDC
Cross-sectional area of wire used	0.001275 in^2 (18 AWG)

Table 9: General data of the pre-charge relay

2.9.3 Position in Car

The pre-charge circuit is located internal to the Sevcon motor controllers. The position of the controllers in the vehicle is discussed at length in section 5.1.3 and first shown in figure 54.

2.10 Discharge Circuitry

2.10.1 Description

When the car shuts down, there are still reserves of energy in the tractive system that can be harmful to the driver or team members conducting maintenance. The discharge circuit dissipates the capacitance found in the vehicle after TS shutdown. When the shutdown circuit is opened, the normally closed discharge relay will close a switch and discharge the tractive system with a 220Ωpower resistor.

2.10.2 Wiring, Cables, Current Calculations, Connectors

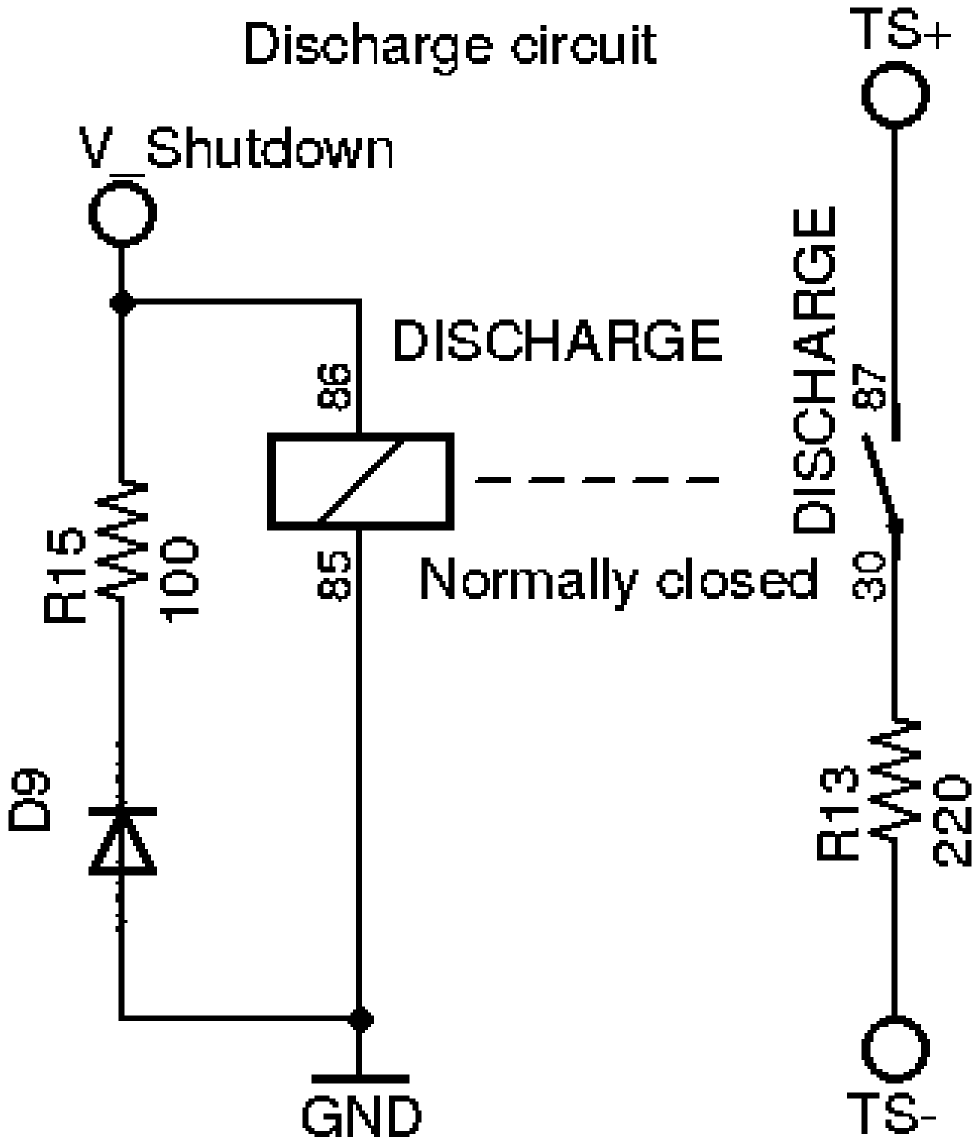


Figure 15: Schematic of the discharge system

Since the internal capacitance of our motor controllers was unknown, it was determined by the team experimentally.

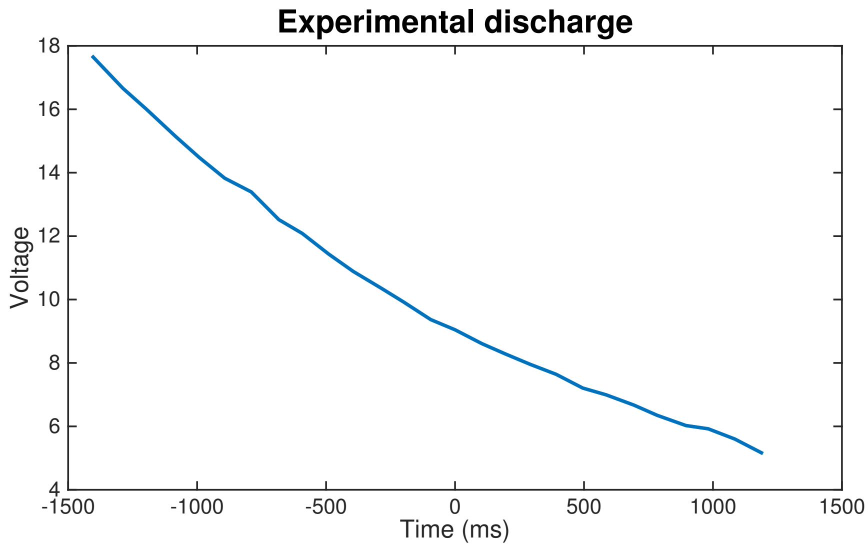


Figure 16: A single motor controller being discharged across a known resistor.

That experimental discharge in figure 16 starts at 17.65 volts at a time of -1403 milliseconds. Given that this is an RC parallel circuit, we expect to loose 63% of the charge in the first RC time constant. The graph hits $17.56V * 0.37 = 6.53V$ at 773.5 milliseconds, or in 2.1765 seconds. Given that we know we were discharging with an 846Ω resistor, we can calculate the internal capacitance of the motor controller.

$$RC = 2.1765s \tag{7}$$

$$C = \frac{2.1765s}{846\Omega} \tag{8}$$

$$C = 2.57mF \tag{9}$$

With that calculation, we can estimate that our two motor controllers will have a combined capacitance of $5.14mF$ that the discharge circuit needs to handle.
With a 220Ω discharge resistor, we can calculate how the discharge will progress over time using the natural response of an RC circuit,

$$V(t) = V_0 * e^{-t/RC} \tag{10}$$

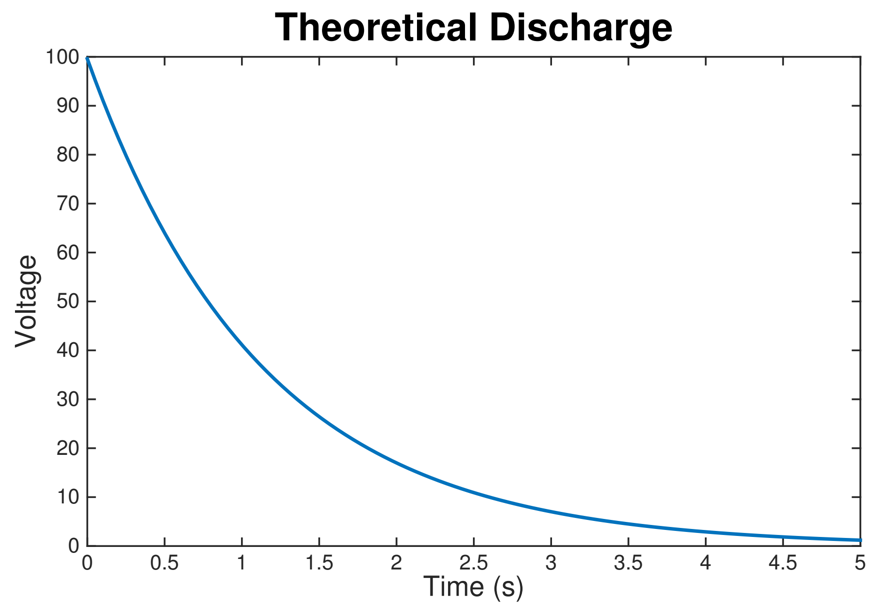


Figure 17: The theoretical discharge of both motor controllers across the resistor specified in table 10. This calculation shows that we should able to discharge to well under 60V DC in 5 seconds.

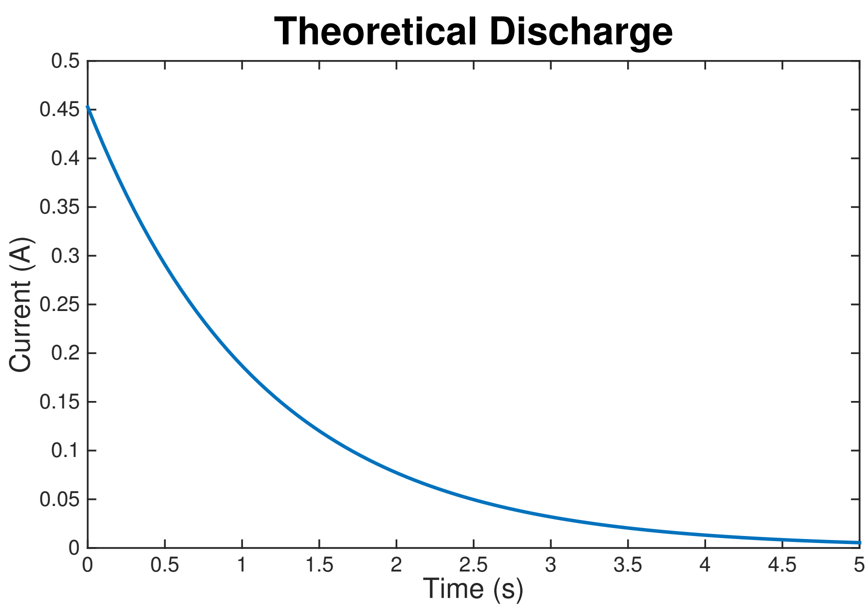


Figure 18: The current of the theoretical discharge.

Resistor type	WH Series, part no. WH50-220RJI
Resistance	220 Ω
Continuous power rating	50W
Overload power rating	See figure in appendix
Maximum expected current	0.45 A
Average current	0.1 A
Cross-sectional area of the wire used	0.0005065 in^2 (22 AWG)

Table 10: General data of the discharge circuit

At peak power, the discharge resistor should be dissipating 44.82 W. The power rating of the resistor is higher than the peak power it will see. Further resistor and relay information can be found in section 11.

2.10.3 Position in Car

The circuit board containing the discharge circuit called the AIR control board will be housed inside the accumulator, above and isolated from the battery cells.

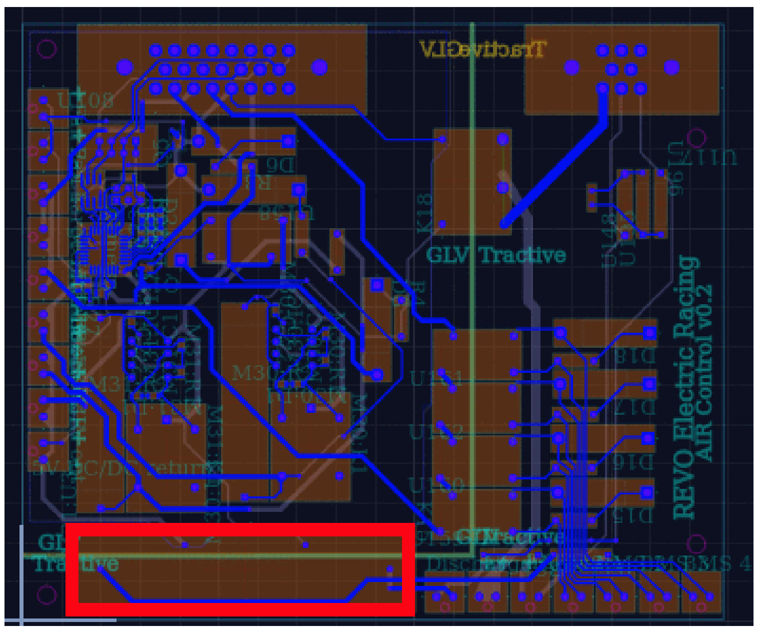


Figure 19: The discharge relay is pointed out in the red box, on the PCB containing most of the accumulator wiring (called AIR control board). The resistor will be located right next to the PCB, at the same height of the accumulator.

2.11 HV Disconnect (HVD)

2.11.1 Description

We will be using an Anderson Power Products SB Smart VEH-G12 HVD (P/N 115158G12 Vehicle Side and P/N 115158G11 Outboard Side) as our high voltage disconnect, provided by Zero Motorcycles. The part we have in-hand also has a rubber grip on the outboard side of the HVD, which gives the user a greater purchase on the HVD, as shown in Figure 20.

2.11.2 Wiring, Cables, Current Calculations, Connectors

Figure 20: Anderson Power Products SB Smart VEH-G12 HVD

The connector is rated for 600V and 230.0A on the primary contacts. Because the HVD has an interlock connection with the shutdown circuit, when it is opened it shuts down the TS system by opening the shutdown circuit.]The HVD has a cover to seal off the lead connections from any possible water, etc, which can be seen in figures 21 and 22.

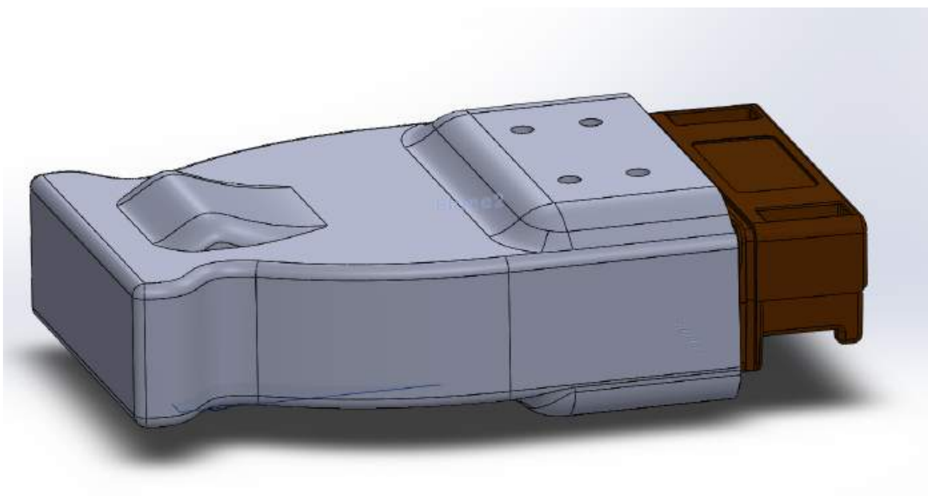


Figure 21: The connector with its cover as seen in CAD

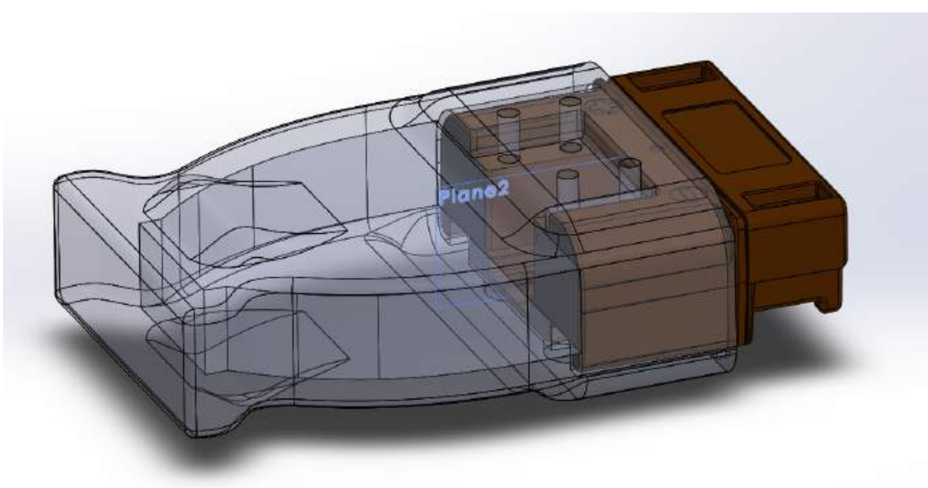


Figure 22: The connector with the cover set as transparent as to see the other side of the connector

2.11.3 Position in Car

The HVD comes out of the accumulator, as it is in-line with the tractive system high side wire. In figure 23, it is the only non-shaded part, with the view being from the back right of the vehicle. The HVD is attached to the motor controller mounting brackets, which are made of 1/8" and 1/16" steel. The HVD will be clearly indicated and located higher than 350mm from the ground, as per EV 4.7.1.

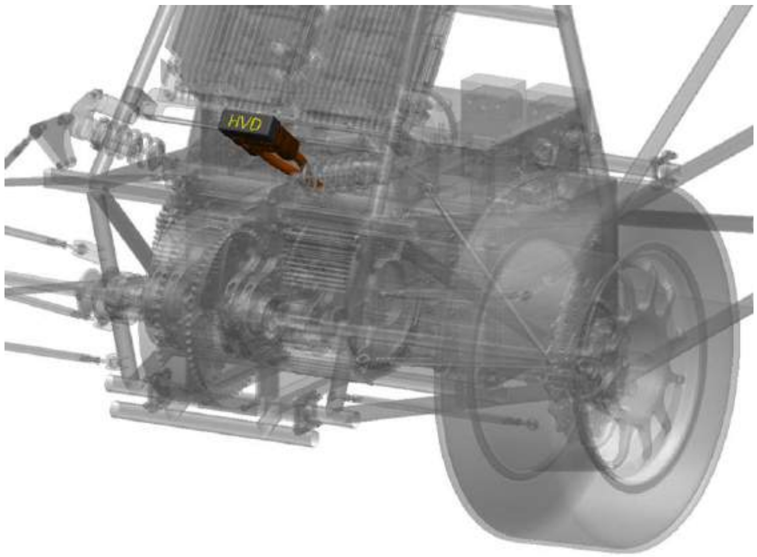


Figure 23: Position of the HVD in the vehicle. It is located in line with TS+, and is attached to the motor controller housing in the back of the vehicle.

2.12 Ready To Drive Sound (RTDS)

2.12.1 Description

The Ready to Drive sound includes a buzzer (Mallory Sonalert Products Inc. SC648ANR), a CAN node, and a relay. The buzzer automatically makes a noise when given power, with the loudness proportional to the voltage. The last step in the startup up sequence will notify the CAN system it is time for the ready to drive sound. Then the corresponding node on the buzzer will close a relay between TS+, after a 2.6 kOhm resistor (5 Watts), and the buzzer for two seconds. The resistor limits the voltage over the buzzer to 48V and the current to 20 mA. The SC648ANR is rated to be 95 dB(A) at 2 ft.

2.12.2 Wiring, Cables, Current Calculations, Connectors

When the shutdown circuit closes and activates the AIRs and the start button has been pushed (while the driver's foot is on the brake), the car is in ready to drive mode. As soon as the car is in this mode, the CAN system will activate the ready to drive sound node to send a positive output that powers the relay for 2 seconds, thus letting the buzzer sound for 2 seconds. This CAN node (called side panel) is also connected to the IMD, and the full schematic can be found in figure 70. The resistor will be current-limiting and act in the place of a fuse.

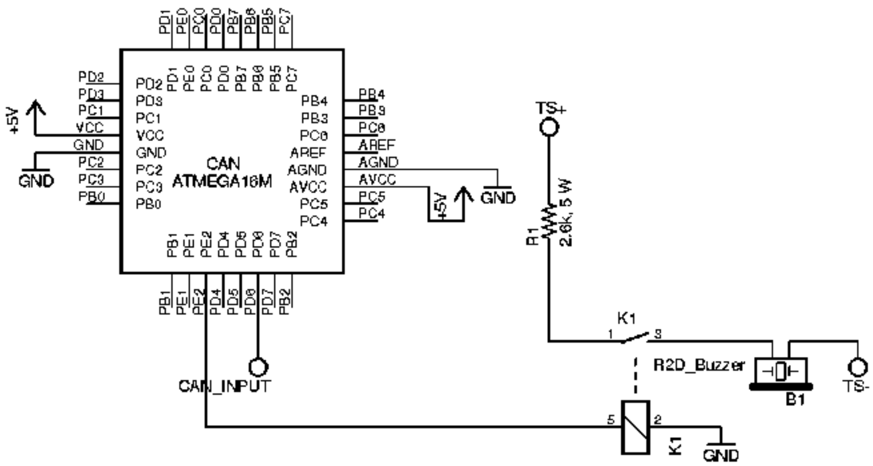


Figure 24: Schematic for the Ready to Drive Sound Buzzer

$$V = I * R \tag{11}$$
$$100 - 48V = 0.021A * R \tag{12}$$
$$R = 2285\Omega \tag{13}$$

$$P = I * V \tag{14}$$
$$P = 0.021A * 52V \tag{15}$$
$$P = 1.09W \tag{16}$$

According to these calculations, a 2.6kΩ 5W resistor will function as a current limiting resistor.

2.12.3 Position in Car

The ready to drive sound will be located in the enclosure shown in Figure 4. The buzzer will be mounted to the exterior and bottom of this enclosure. It must be contained outside of the box so that the buzzer is loud enough.

3 Accumulator

3.1 Accumulator Pack 1

3.1.1 Overview/Description/Parameters

The accumulator comprises 12 Nissan Leaf battery modules, wired in series. Each module comprises four LiMnO2 pouch cells, in a 2S-2P configuration as shown in Figure 26. Each cell has a shutdown separator and a nominal voltage of 3.75V, resulting in 7.5V per module and 90V total. The modules have alternating positive and negative terminal locations to make bus bar routing more efficient.
The Olin REVO team is under NDA with Nissan surrounding the information of the Nissan Leaf cells. We are allowed to share module capacity (at 2C), nominal voltage, size, weight and energy density. The rest of the numbers given in the following sections will either come from measurements or limits that the team imposes on the batteries, and we have the knowledge that they are safe for our cells.

Maximum Voltage	97.34
Nominal Voltage	90 VDC
Minimum Voltage	72 VDC
Maximum output current	Unknown
Maximum nominal current	NDA
Maximum charging current	NDA
Total number of cells	48
Cell configuration	12 2s2p in series
Total capacity	65 Ah at 2C rate, 25 ˚C
Number of cell stacks	4

Table 11: Main accumulator parameters

The maximum voltage for our cells has been limited to 4.056 V per cell by our charger, which creates a 97V maximum of the battery pack.

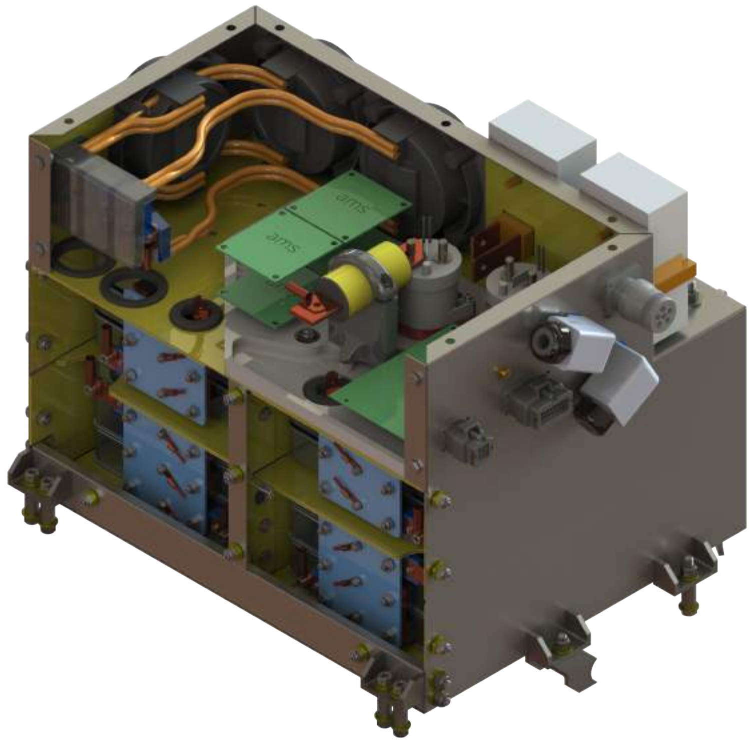


Figure 25: Locations of all major parts within the accumulator.

3.1.2 Cell Description

The cells used are Automotive Energy E5 lithium ion (pouch type) cells, and they were fabricated into modules by Nissan for their Nissan Leaf electric vehicle. Their datasheets are not included because of our team's NDA with Nissan. We are working to be able to share the necessary information, but the cell values noted are from our testing of the cells and other sources like the US Department of Energy (Link to source and located in the appendix.) Through their advanced testing, they note the maximum cell voltage at 4.2V and the minimum cell voltage at 2.5V, which aligns with our own research on other cells with lithium-manganese chemistry (Link to source), which says that they should stay over 3V for battery safety and the safety of the drivers and/or operators. Experimentally, an error of 100 mV was found in the battery management system reading the voltage, so precautions were set and the maximum voltage is conservatively set to 4V.

Cell Manufacturer and Type	Automotive Energy Supply Corporation Model E5
Cell nominal capacity	32.5 Ah
Maximum Voltage	4.056V
Nominal Voltage	3.75V
Minimum Voltage	3V
Maximum output current	Unknown
Maximum nominal output current	NDA
Maximum charging current	NDA
Maximum Cell Temperature (discharging)	58 °C
Maximum Cell Temperature (charging)	50 °C
Cell Chemistry	Lithium-ion - Laminate type Cathode/Anode Material: LiMn2O4 with LiNiO2/Graphite

Table 12: Main cell specification

3.1.3 Cell Configuration

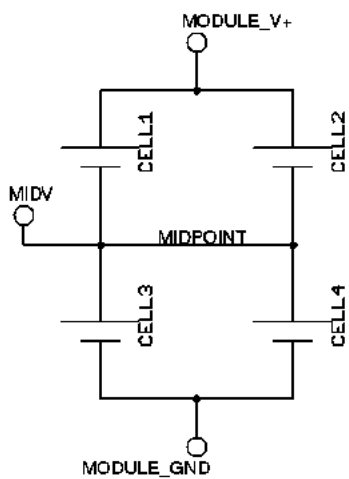


Figure 26: Schematic of a Nissan Leaf Battery Module

As stated in Section 3.1.1, there are 12 modules in series. Each module holds 4 cells which are in a 2s-2p configuration. The white terminal marked in white in Figure 27 references the point between the two parallel cell strings, as shown in figure 26 and labeled as MIDV.
The modules, each have a string of 2 cells in parallel, as seen in Figure 26. In the middle of each cell there is a shutdown separator, which acts as a fuse in over-current conditions. These modules are commercially sold in Nissan Leaf vehicles without issue, so we are referencing their safety to prove ours.

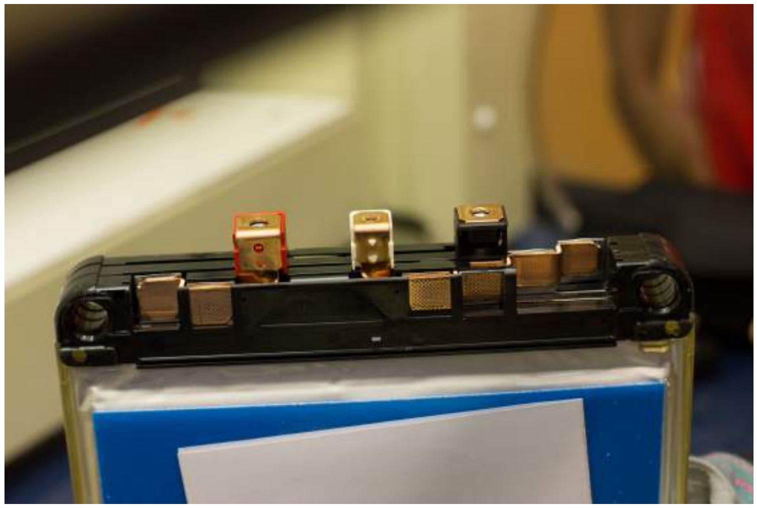


Figure 27: Inside view of a module

Busbars connect the modules in series, as shown in Figure 28. The busbars connecting module to module are copper with a cross-section of $60.5mm^2$, which has a higher ampacity than the tractive system lines (2 gauge). The blue squares seen in figure 28 are the cell top boards.

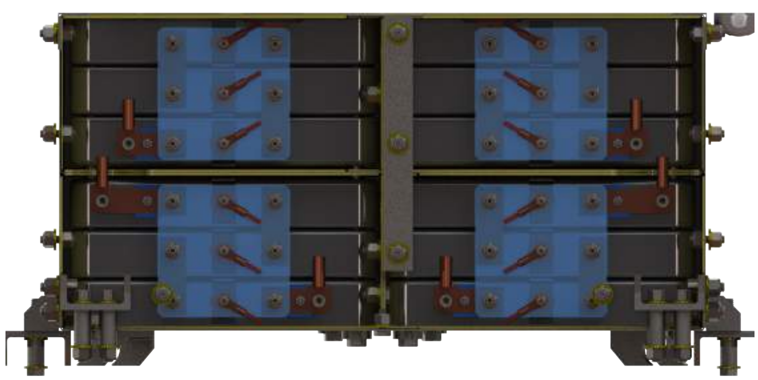


Figure 28: Front view of the accumulator, showing the busbars and thermistors.

There are 3 maintenance plugs, separating the segments to be less than 6 MJ each. Figure 40 points out the maintenance plugs, shortened as SMD or MSD. They are from Lear Corporation. Manual Disconnect used in Volt Gen 2 HV battery pack. 350Vdc bladed fuse, with integrated interlock and 2 step removal. The calculation verifying the segment energy is seen below.

$$\text{Seg Energy} = V_{nom} * \text{Number of Cells} * \text{Cell Ah (2C rate)} * 3.6\text{kJ} \quad (17)$$
$$\text{Seg Energy} = (7.5 * 3) * 65 * 3.6 \quad (18)$$
$$\text{Seg Energy} = 5265\text{kJ} \quad (19)$$
$$\text{Seg Energy} = 5.265\text{MJ} \quad (20)$$

3.1.4 Cell Temperature Monitoring

The temperature of the cells is monitored using 10KΩ ring terminal thermistors attached to the middle pole. The middle pole of each module is considered the negative terminal of two cells. Each module's midpoint is measured and one out of three module grounds is measured per accumulator segment. The thermistors are used to form three voltage dividers. When the temperature of the cells increases, the resistance decreases, resulting in less voltage drop across the thermistor. Three analog to digital converters attached to each of the voltage dividers is then used by the ATmega16M1 used in the CAN system to determine whether the temperature is too high or low. If the temperature is out of range, the shutdown system activates. There is a pull up resistor that pushes the output voltage to 5V if the ADC is a past a certain threshold and 0V otherwise. Because we are monitoring the negative terminals of half of the cells in each module, we are monitoring 50% of the total cells. The mounting of the thermistors can be seen in figure 28. They are on top of the cell top boards, which is bolted directly onto the module terminals through the busbars.

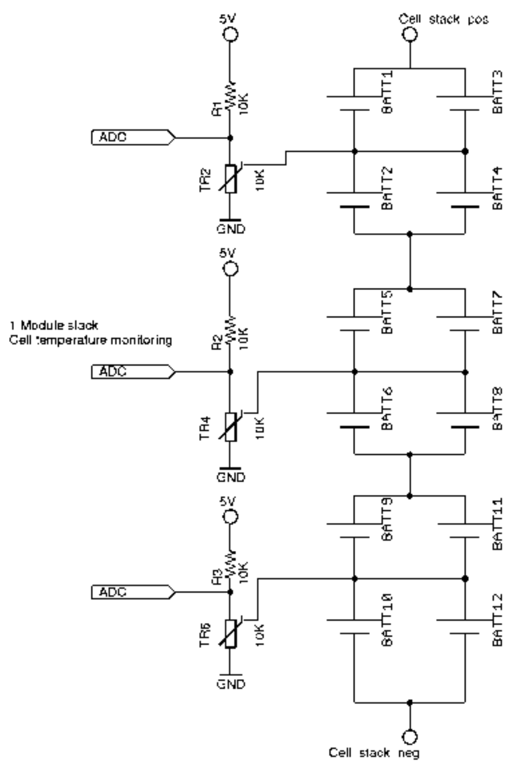


Figure 29: Schematic, (1) Module Cell Temperature Monitoring

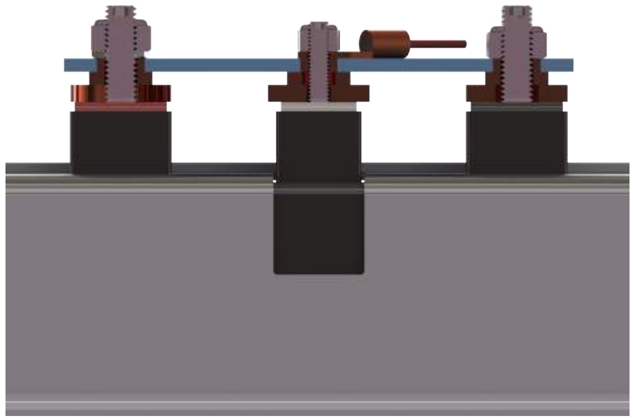


Figure 30: Section view of the thermistor mounted on the busbars

The distance between the bottom of the PCB and the top of the busbar is 3.2 mm (0.126 in.), while the distance from thermistor to terminal is 0.32 in. Because the cells are arranged within the module by the manufacturer, the distance from the busbar to the actual cell terminals (instead of the module terminals) is unknown.

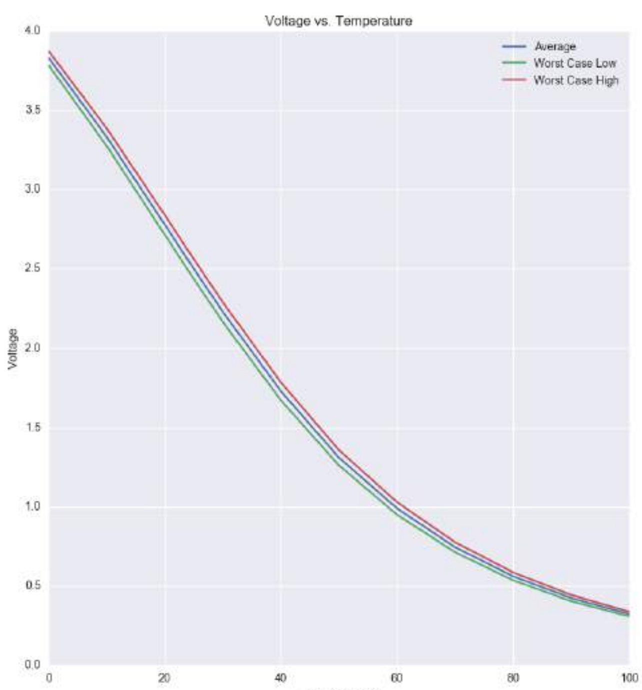


Figure 31: Voltage measured at BMS vs. temperature the cell is at.

Figure 31 shows the voltage that will be read by the BMS at different temperature readings. The BMS has an ADC with 10 bit resolution meaning that voltage differences of less than 0.005V can be detected. As seen in Figure 32 the worst case scenario for over-temperature sensing is when the temperature is at 62 ˚C. For this reason we will choose to be safe and raise an error when the temperature is at 58 ˚C which has a worse case reading of 60 ˚C.

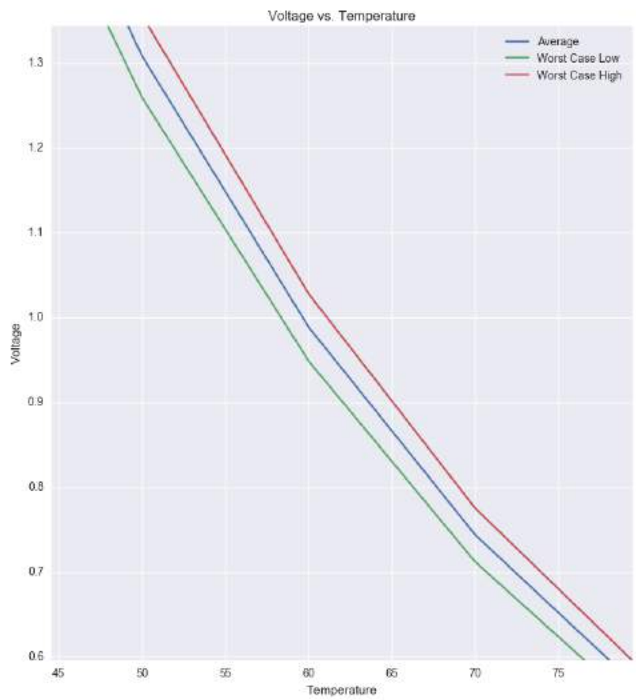


Figure 32: Voltage measured at BMS vs. temperature the cell is at. This just shows the voltage difference at different temperatures around 60 ˚C

3.1.5 Battery Management System

There are 4 AMS modules, and each AMS monitors 6 groups of cells in series. Each module contains 4 cells, 2 series x 2 parallel, so each AMS monitors 3 modules, or 12 cells (6 series x 2 parallel). There are 4 AMS boards. Each AMS board is coupled to a cell breakout board, which includes 3 thermistors and bolts to the power terminals of three modules, as shown in Figure 28 (blue circuit boards). The purpose of the cell breakout boards is to help manage wiring inside the accumulator. The cell breakout boards will have compression limiting copper pads at the terminal bolts and will be spaced above the bus bars using copper washers.

The AMS is able to shunt 3A when the cell voltage gets above 4.1 V. The AMS opens a relay in line with the shutdown circuit if any cell drops below 3V or 4.1V. The AMS opens a relay in line with the shutdown circuit if any cell gets above 58 ˚C. The power to each of the AMS relays is through a CAN output, and the CAN system does monitor all of the voltage and temperature.

CAN communication from the board is isolated via a TI ISO1050DUBR (isolated CAN transceiver). Only CAN communication is used to have the information from each AMS relayed to the rest of the system, and the boards are otherwise independent of each other. Each board has an electrical connection with a normally-open relay on the AIR control board (i.e. there are four AMS relays), and the ATmega16M1 of each CAN node can open its own relay. On each cell-top board, there are 7 surface mount Bel C1Q 3A fuses. (Lowest voltage reference and top voltage of each of 6 cells.) The relays which allow the AMS to control the shutdown circuit provide isolation between the AMS and the GLV system, as well as the isolated CAN transceivers. Please see Figure 78 for the schematic of one of the battery management system boards (AMS).

Figure 33 shows the CAD of one AMS PCB. The AMS boards only communicate through the CAN system. Close ups of this PCB in the appendix (section 11) show measurements of all spacings.

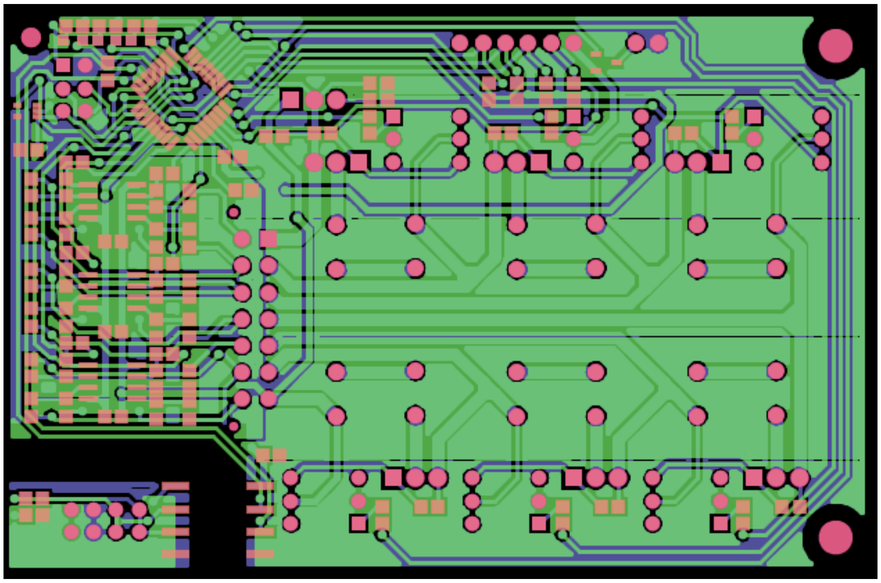


Figure 33: CAD of 1 AMS board (all identical). Spacing in the lower left was to separate TS and GLV.

Captures of the BMS separation are located in the appendix, to prove the compliance with a minimum over surface spacing (6.4 mm or 1/4" spacing) requirement.
Voltage and temperature data is relayed to the AMS by the cell breakout boards discussed earlier in this section. The cell top boards are electrically identical, but have mirrored layouts to accomodate which side of the accumulator they are on. There is a left hand side, figure 35 and right hand side, figure 36. The cell breakout board contains fuses on all sensing lines, detailed in Figures 34 - 35.

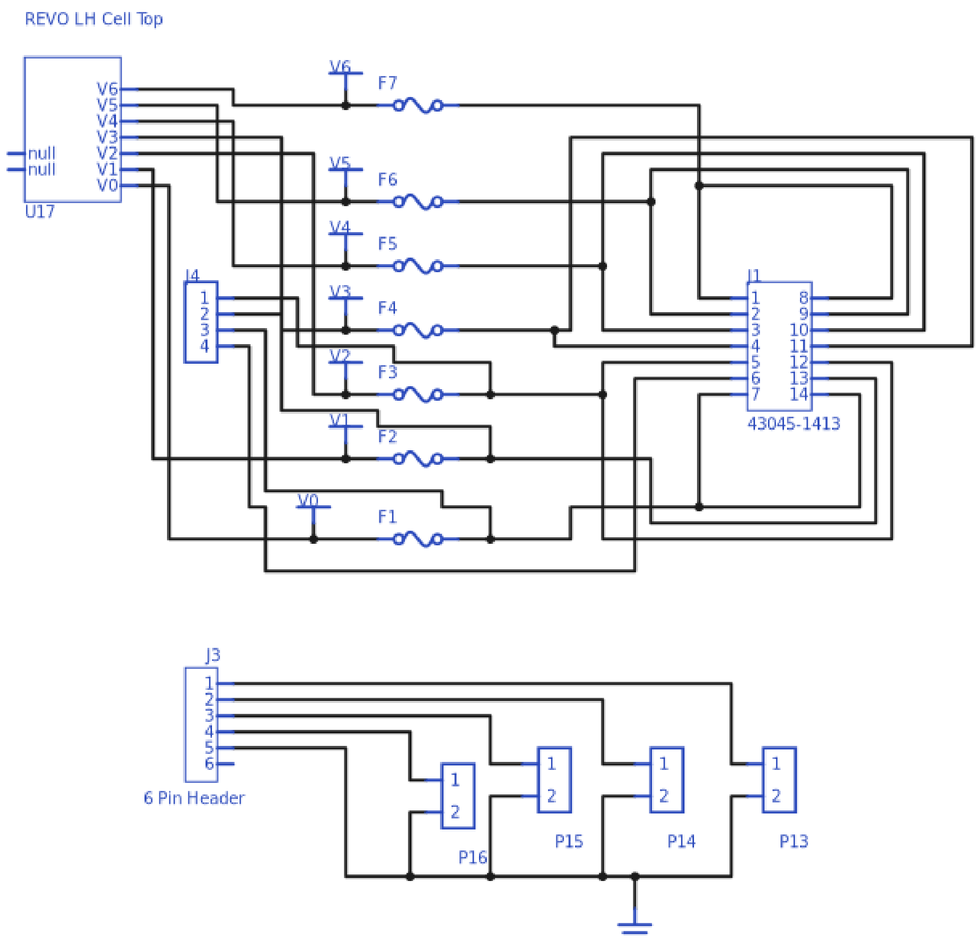


Figure 34: Schematic of Cell Breakout Board Connecting to the AMS

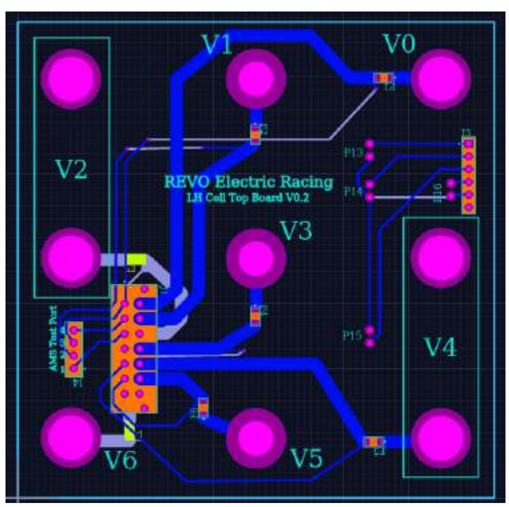


Figure 35: Cell Breakout Board PCB Layout for the left hand side Note the fuses labeled with F and then a number. There is only TS voltage on this PCB.

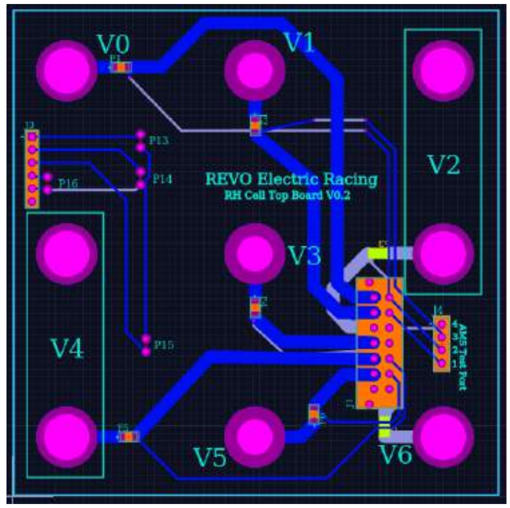


Figure 36: Cell Breakout Board PCB Layout for the right hand side Note the fuses labeled with F and then a number. There is only TS voltage on this PCB.

3.1.6 Accumulator Indicator

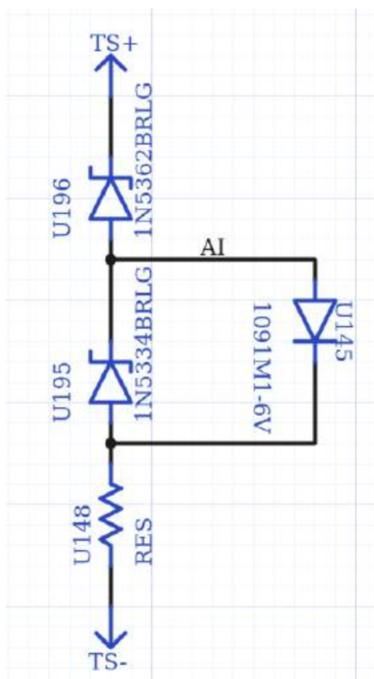


Figure 37: Accumulator Indicator schematic

As shown in the figure above, the zener diode allows TS voltage to pass through the accumulator indicator LED and a resistor after TS voltage is over 60 VDC. U148 is a 220 Ohm resistor to limit current. The calculations are as follows, assuming a forward voltage drop of the LED to be 2V:

$$100 - 2V = I * 220\Omega \quad (21)$$
$$I = 45mA \quad (22)$$

The accumulator indicator is located on the AIR control board PCB, and has traces of 20 mil, which are rated for 1.4A. The accumulator indicator is behind the 1A fuses protecting the high voltage low current harness - the same as the TSAL and IMD.

3.1.7 Wiring, Cables, Current Calculations, Connectors

There are 4 cells (in a 2s2p configuration) in each module, and there are 12 modules in series. Nissan Leaf cells are arranged within the their factory enclosures to be in modules. Within the modules, there is an internal shutdown separator, reacts to excessive thermal or overpressure events. Addition of inter-cell fusing may compromise this safety system's design, so our team considers to submit design lacking fuse inclusion as an error on cautious side. The accumulator has them separated into 4 stacks of 3 to comply with the segment energy limit. Between 3 out of 4 segments, there are MSDs for safely separating the segments while working on the accumulator. After the fourth section, there is an HVD in series with the positive pole, coming out of the accumulator. There will be two main connectors to the accumulator, each having connections of TS+ and TS-. This is so each motor controller can be individually connected to. Before the HVD and main connectors, there is an AIR on both the positive and negative poles of TS.
The high current (motor, motor controller) wires used for the tractive system will be as described in table 24 and 23. The low current (IMD, Lights DC-DC,and ready to drive sound) TS connections will be made with the wire described in table 13.

Wire type	CnC Tech, 20 AWG
Current rating	7A
Cross sectional area	0.326 mmˆ2
Maximum voltage	600V
Temperature rating	120 ˚C
Wire connects the following components:	TS V to IMD HV input, TS V to ready to drive sound buzzer

Table 13: Wire data of the company: CnC Tech, 0.326 mm^2

We will use OEM maintenance plugs provided by General Motors. As shown in Figure 38, these maintenance plugs, known internally as Manual Service Disconnects (MSD's), comprise a panel-mounted plastic housing (black) and a plastic plug (orange). The plug must be twisted and then pulled in two distinct steps, which disengages the copper bus-bar, contained in the orange plug, from spring-loaded contacts contained in the black housing. There is a fuse located in . General Motors will also be crimping custom length leads onto these MSD's for our vehicle. The leads are 40 mm^2 in cross-section, not including insulation. Each MSD also contains a two-pin interlock, as described in Section 2.6. To the best of our knowledge, these MSD's comply with EV 3.3.3. Additionally, the spring-loaded contacts located in the black housing are encapsulated in plastic, providing protection from shorting and accidental contact.

Figure 38: Manual Service Disconnect (Maintenance Plug)

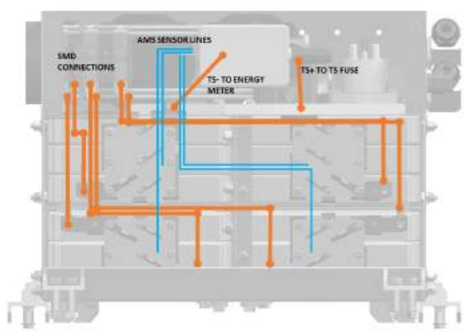


Figure 39: Diagram for the accumulator tractive system wiring front view

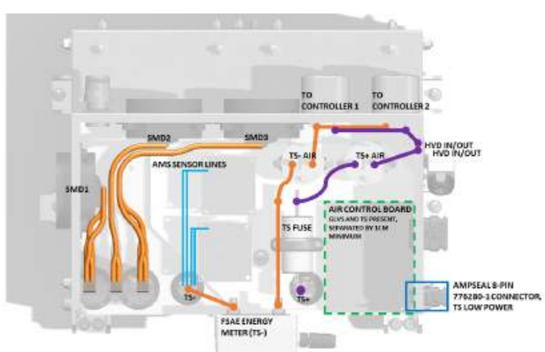


Figure 40: Diagram for the accumulator tractive system wiring top view

Figures 39 and 40 show the electrical connections and connectors of the accumulator.

3.1.8 Accumulator Insulation Relays (AIR)

We will use Kilovac EV200 relays as accumulator insulation relays. They will be paired with economizer circuits to draw less current during normal usage. The relay requires a 12 V control signal, and is rated for 500 A. Figure 13 shows the schematic location of the economizers and the AIR's.

Relay Type:	Normally Open
Contact arrangement	SPST-NO-DM
Continuous DC current rating	500A
Overload DC current rating	2000A
Maximum operation voltage	900VDC
Nominal coil voltage	12VDC
Normal Load switching	See figure
Maximum Load switching	See figure

Table 14: Basic AIR Data

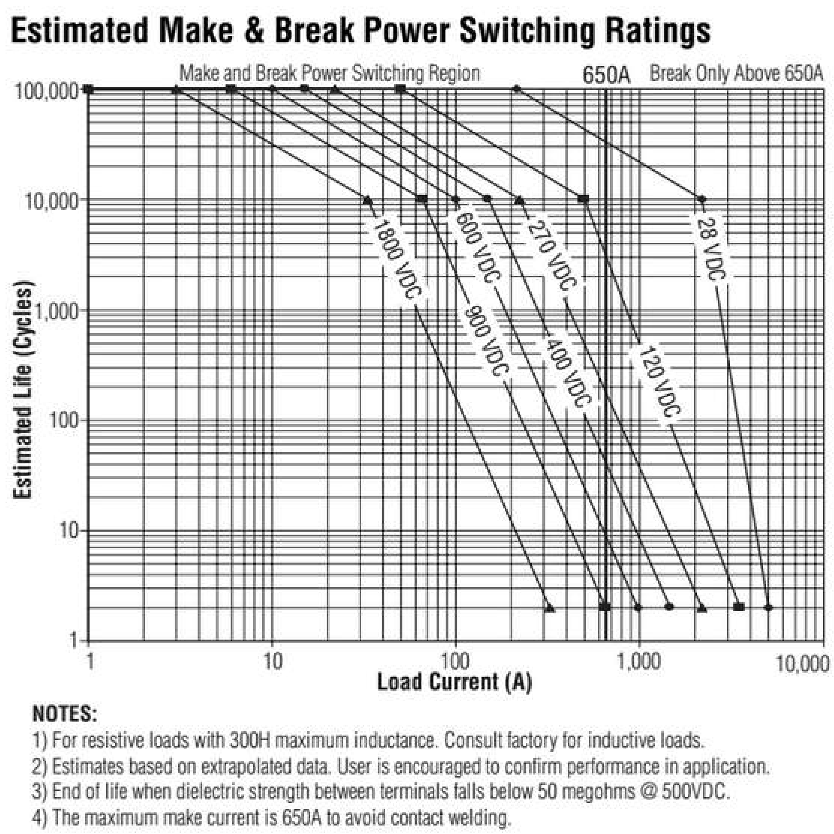


Figure 41: Load Switching detail from Accumulator Indicator Relay datasheet

The AIRs and main fuse are in a separate compartment of the accumulator separated by two layers of insulating G10/FR4 fiberglass and a single layer of 0.035 in 301 stainless steel, as shown in 25.

3.1.9 Fusing

Fuse manufacturer and type	Littelfuse, 251/253 Series
Continuous current rating	1 A
Maximum operating voltage	125V
Type of fuse	Fast acting
I2T rating	0.405 A2s
Interrupt Current (max.,current at which the fuse can interrupt the circuit)	30A at 125VDC

Table 15: Fuse to the IMD, TSMPs and light DC-DC converter, 251/253 Series

Fuse manufacturer and type	Ferraz Shawmut, Semiconductor AC series (A15QS)
Continuous current rating	7A
Maximum operating voltage	150VDC
Type of fuse	Fast acting
I2T rating	0.011 at 150 VDC and 10ms
Interrupt Current (max.,current at which the fuse can interrupt the circuit)	100kA

Table 16: Fuse to the precharge keyswitch v+

Fuse manufacturer and type:	Bussmann, LPJ type
Continuous current rating	175A
Maximum operating voltage	600 V
Type of fuse	Time delay
I2t rating	None listed, see figure 42
Interrupt Current (max. current at which the fuse can interrupt the circuit)	300 kA

Table 17: Tractive system main fuse, LPJ type

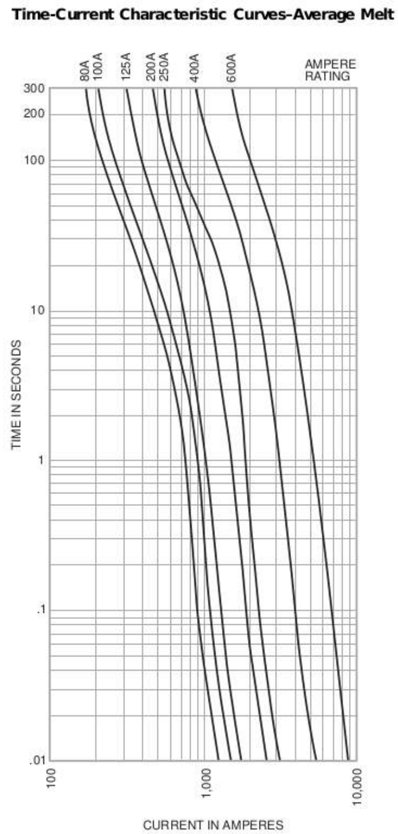


Figure 42: TS main fuse (175A) Time-Current information

The TS fuse mounting can be seen in figure 50. All wire ampacity ratings are according to the Power Stream's Wire Gauge chart, located in the appendix, figure 96.

Location	Wire Size	Wire Ampacity	Fuse type	Fuse rating
TS Main fuse (before HVD, on pos pole)	2 AWG	181A	LPJ type	175A
TS+ to GLV DC-DC converter	20 AWG	7A	251/253 series	1A
TS+ to IMD, TSMPs, TSAL's DC-DC converter	22 AWG	7A	251/253 series fuse	1A
GLV 12V to 5V regulator (CAN system)	22 AWG	7A	251/253 series fuse	1A
HV+ sense lead to Energy Meter	22 AWG	7A	251/253 series fuse	3A
Keyswitch, in parallel with TS voltage	18 AWG	16A	AC fuse	7A
Cell to BMS x28	PCB trace	Trace ampacity: 7.6 A (open air)	CIQ Fuse x28	3A

Table 18: Fuse Protection Table

3.1.10 Charging

Charger Type:	Delta Q Technologies QioQ 1000 Series
Maximum charging power	34.476 W
Maximum charging voltage	4.056 V (per cell)
Maximum charging current	8.5A
Interface with accumulator	CAN-Bus
Input voltage	125VAC or 250VAC
Input current	13A@125VAC or 10A@250VAC

Table 19: General Charger data

Figure 43: DeltaQ 96V QUIQ ICON charger

This UL-recognized charger supplies constant current at 8.5A until cell voltages reach 4.056V. Then, constant voltage is supplied at 4.056V per cell, summing to 97.34V, until the current tapers to 2.0 A. The charging power lines will be fused to 20A to protect the 12 AWG wiring. The fuse will be located on the accumulator side of the wiring, to protect the 12 AWG wire from a potential short in the accumulator (the charging current is inherently controlled).

The charger will indicate complete on its LED display when the battery voltage reaches 4.056V per cell, however it will continue charging until it finishes both stages.

The accumulator will only be charged on the charging cart, shown in figure 46. It will be able to support the full weight of the accumulator and only move when a dead man's switch is activated.

The accumulator cart will contain a specialized shutdown circuit that allows the accumulator to be charged through the main pack connector. The AMS will be active during charging and have the ability to open the AIRs and stop charging in the event of dangerous battery conditions. This shutdown circuit will contain a separate IMD, an emergency stop, and an interlocking connection between the charger and accumulator. The interlock will be in the two smaller pins found in the Deutsch connector (6 pin). The separate IMD used is also the IR155-3204 from Bender, the same model of IMD used on the car. The IMD will be mounted to the cart along with the PCB holding the shutdown circuitry that controls circuitry and the TSEL.

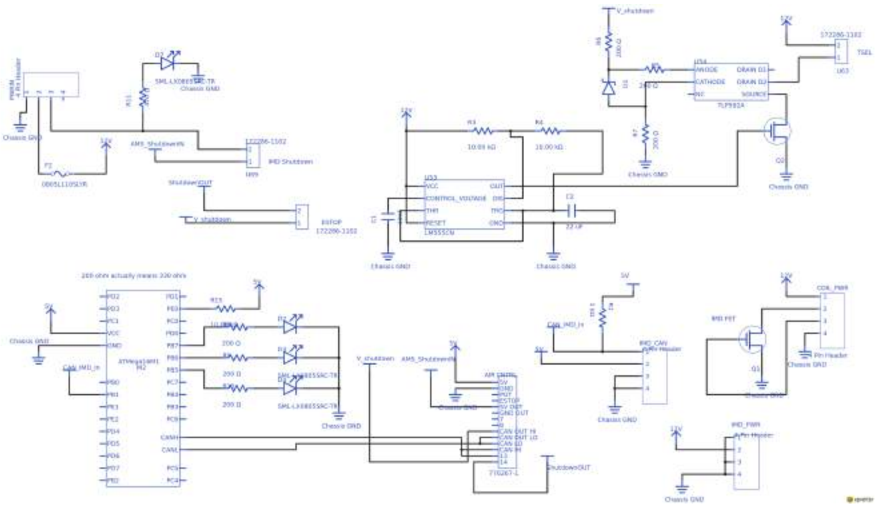


Figure 44: Schematic of the PCB controlling charging, while interfacing with the AMS relays and the AIRs, located on the AIR control board

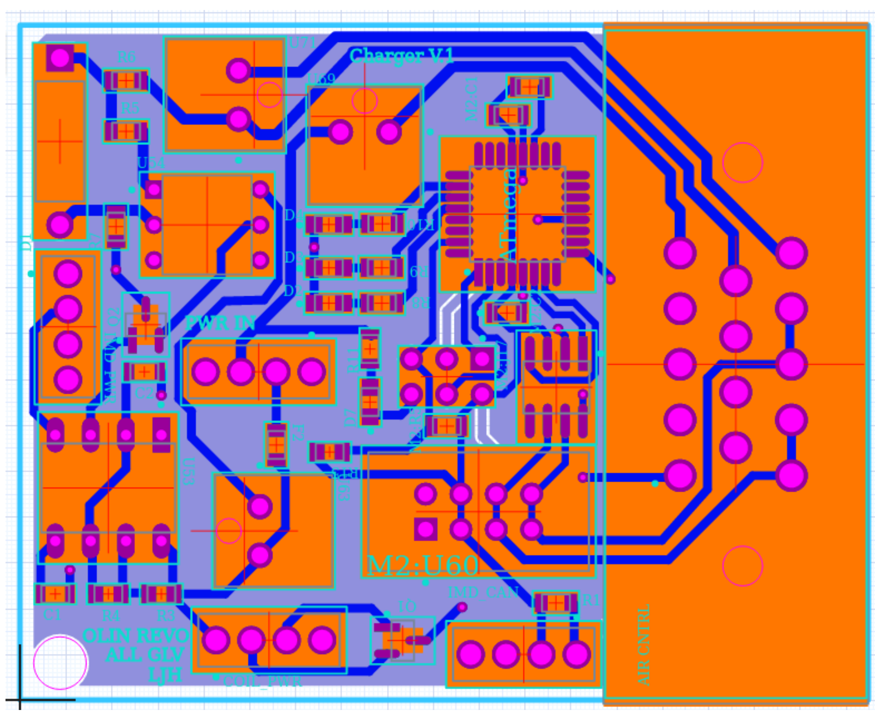


Figure 45: The charging PCB, which contains the charging system's shutdown circuitry and is all low voltage

The charging shutdown PCB will find 12V power from a wall wart (12VDC, 4A out) and include the components listed above. There will be a CAN node located on the PCB, which will be able to communicate with the AMS CAN nodes. Between the charging shutdown circuit, the AIR control board and the AMS boards (the later two being installed permanently in the accumulator), the charging sequence will be monitored for safety.

Figure 46: Charging cart. The wheels on the handleside have been replaced with wooden blocks. As the operator moving the cart stops actively picking up the side of the cart, the cart will stop, acting like a dead man's brake

The high voltage charger will be connected to the accumulator with 12 AWG wire and protected by a 20A fuse. The fuse and charger are both bolted to the charging cart.

Fuse manufacturer and type:	Bussman, SC type, Class G
Continuous current rating	20A
Maximum operating voltage	170 VDC
Type of fuse	Fast acting
I2t rating	None listed
Interrupt Current (max. current at which the fuse can interrupt the circuit)	10kA Vdc

Table 20: Charging fuse, Bussman SC Class G

3.1.11 Mechanical Configuration/Materials

The accumulator is comprised of flanged 403 stainless steel sheet metal panels, meeting the material and fastener requirements set by Formula SAE Electric rule EV 3.4.6. This rule specifies that the minimum sheet thickness for the floor is 0.049 in steel and 0.035 in steel for vertical and internal walls. The panels are fastened together using a minimum of three 1/4 in SAE Grade 5 at any joint, except at the intersection of internal walls. These intersections will be spot welded with weld area equivalent to a linear weld along the same length of joint. We will also be conducting a pull-test of test parts to ensure our spot welding settings are correct for full penetration. We have received a rules clarification 4795 stating that spot welding is regulation-compliant. The Nissan modules are additionally isolated by an additional layer of G10/FR4 Garolite, a fiberglass-cloth with a flame-retardant resin. G10/FR4 meets MIL-I-24768/27 and UL94-V0 for flame retardance (Mcmaster-Carr P/N 8667K55). These barriers do not create electrical insulation, which is performed internal to each module. We have insulation ratings between the Nissan module case and the cell terminals, but this information is under NDA.
In this design the Nissan/AESC battery modules are laid flat relative to the car, and broken up into segments containing less than 6MJ of total stored energy. The accumulator has two covers, both lined with FR4

insulating material. The cover revealing the battery modules also serves as a structural vertical wall, and great care was taken in the design to ensure compliance with EV 3.4.6.
The accumulator is mounted to the chassis using 10 SAE Grade 5 5/16 in bolts through welded, gusseted tabs.

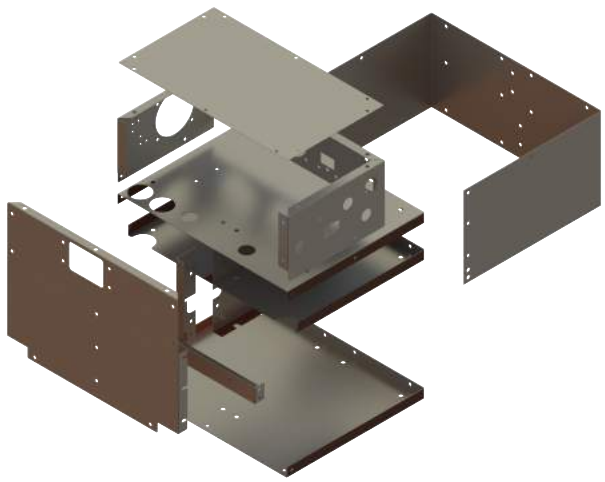


Figure 47: Exploded view of the sheet metal accumulator housing

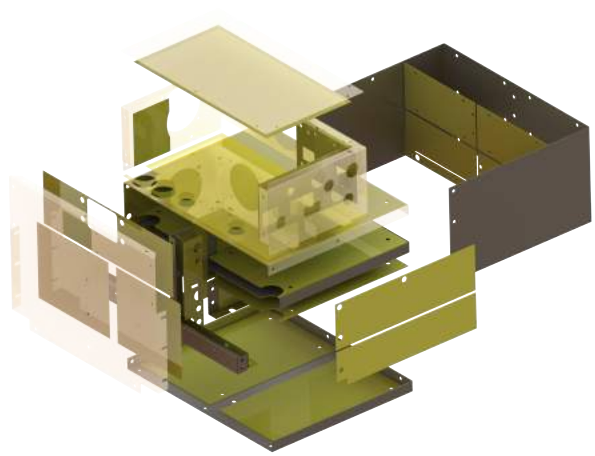


Figure 48: Exploded view of the sheet metal and insulation in the accumulator housing

3.1.12 Position in Car

The accumulator is located behind the driver, under the main roll hoop, and is entirely encapsulated by the primary frame structure.

3.2 Accumulator Pack 2

There will only be one accumulator for the vehicle, as described in Section 3.1

4 Energy Meter Mounting

4.1 Description

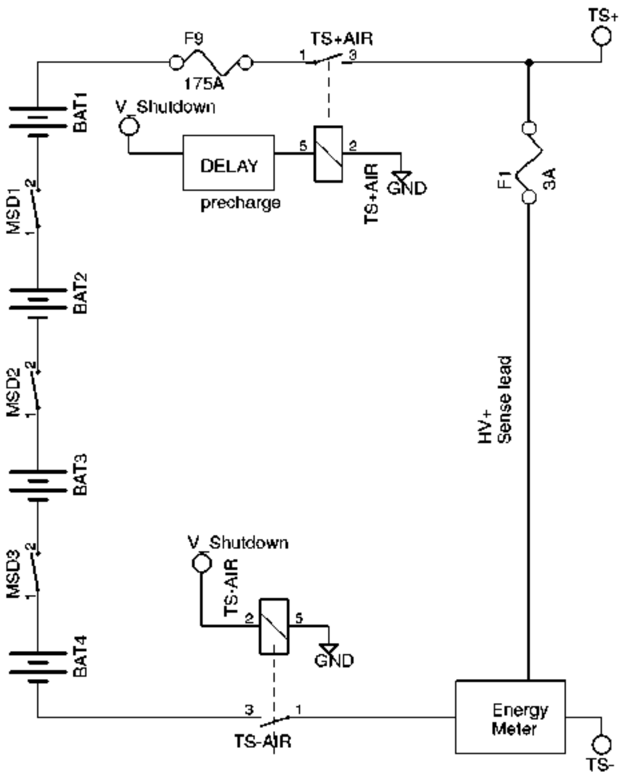


Figure 49: Electrical connections of the energy meter

The energy meter is a tool made by FSAE to calculate energy use during competition. The meter checks that the voltage is within the rule's ranges, the total power used is not over the maximum limit of 80 kW, and calculates the amount of energy used. The energy is calculated as the time integrated value of the measured voltage multiplied by the measured current logged by the Energy Meter, as per rule EV 4.9.

4.2 Wiring, Cables, Current Calculations, Connectors

The energy meter will measure current in the tractive system by being connected in series with the HV- line. It measures voltage in the system with a connection to HV+. The low power data collection systems inside of the Energy Meter are powered using the GLVS.
hlrA 3A 125V fuse will be on the HV+ sense line to protect the wiring.

Fuse manufacturer and type	Littelfuse, 251/253 Series
Continuous current rating	3A
Maximum operating voltage	125V
Type of fuse	Fast acting
I2T rating	0.405 A2s
Interrupt Current (max.,current at which the fuse can interrupt the circuit)	30A at 125VDC

Table 21: Fuse to the HV+ sense line to the energy meter, 251/253 Series

4.3 Position in Car

The energy meter is mounted to the accumulator using a plastic, waterproof enclosure that can be seen in figure 50. Its connections inside the accumulator can be seen in 40.

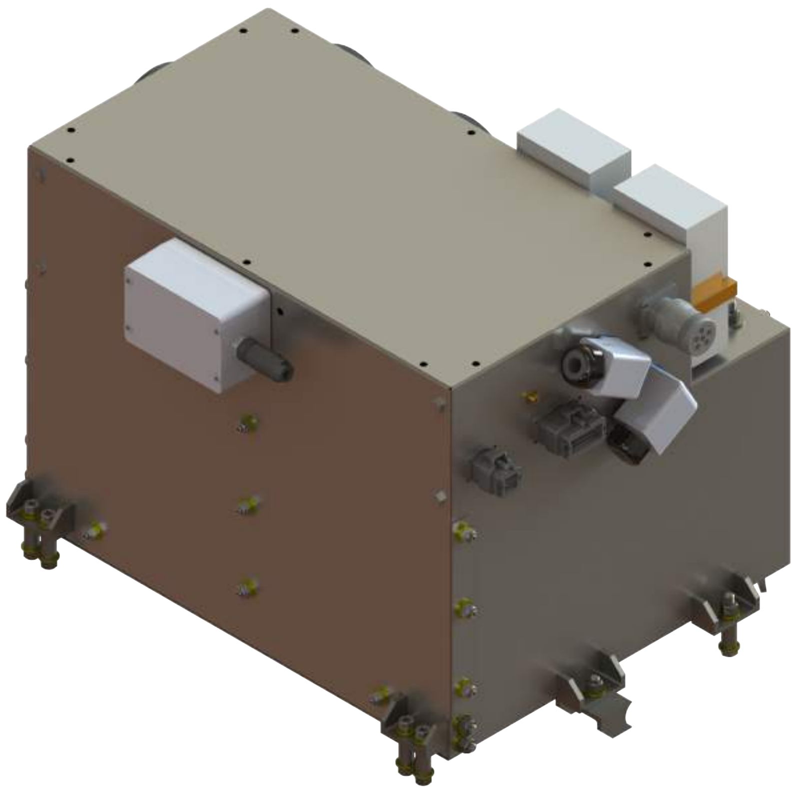


Figure 50: Isometric view of the accumulator, showing the energy meter

5 Motor Controller

5.1 Motor Controller 1

5.1.1 Description, Type, Operation Parameters

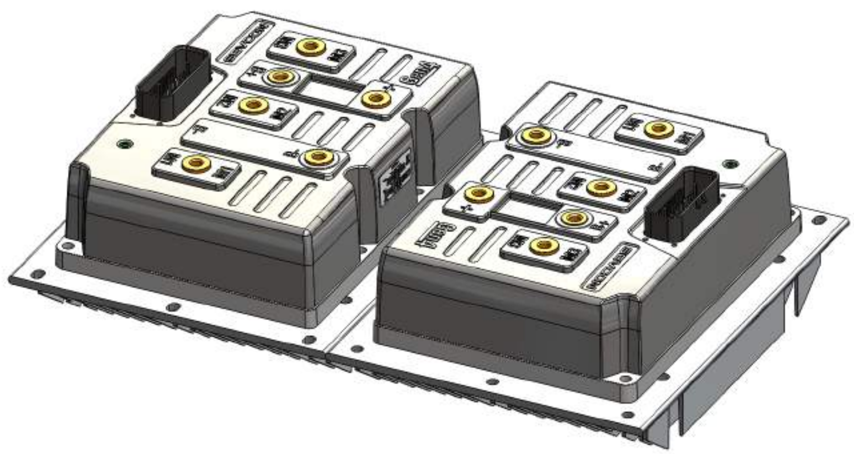


Figure 51: Sevcon Gen 4 Size 4 motor controllers

The two motor controllers used are both model Sevcon Gen 4 Size 4 motor controllers. These motor controllers are used commercially in the motorcycles of Zero Motorcycles, and they delegate power to the motors in response to the input of an analog signal. The motor controller comes with extra capabilities that will be used for other systems, like the precharge system. The motor controller does not provide isolation between its low and high voltage components, so all low voltage signals to the motor controller will be individually isolated. The motor controller controller (MCC) PCB will contain a CAN node that outputs the throttle information relayed from the Bulkhead (Throttle/Brake) CAN node. The analog output will be isolated through an optoisolator, as shown in figure 72.

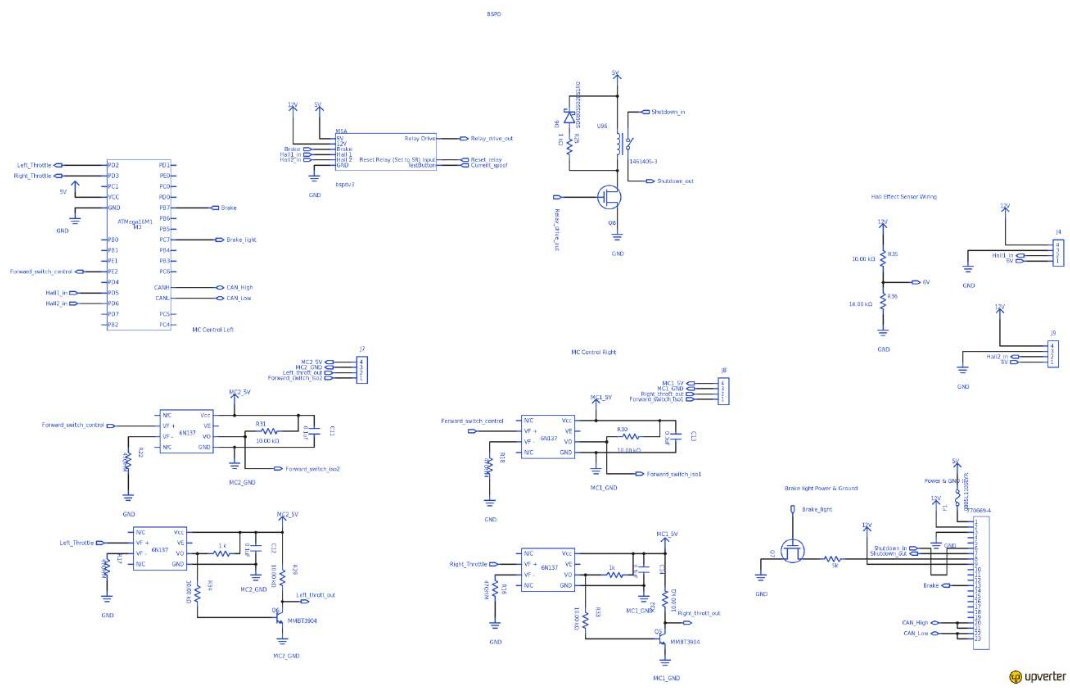


Figure 52: Motor controller schematic

Motor Controller type	Sevcon Gen 4 Size 4
Maximum continuous power	14.4 kW
Maximum peak power	54 kW
Maximum input voltage	150 VDC
Output voltage	Same as input voltage
Maximum continuous output current	120A
Maximum peak current	420A
Control method	messages through CAN system
Cooling method	Air
Auxiliary supply voltage	24VDC

Table 22: General Motor Controller data

5.1.2 Wiring, Cables, Current Calculations, Connectors

Wire type	2 AWG Cable
Current rating	181 A
Maximum operating voltage	8kVAC
Temperature rating	125 °C

Table 23: Wire data of the company: Prestolite, 0.052 in^2

Wire type	$35mm^2$ Cable
Current rating	181 A
Maximum operating voltage	600 V
Temperature rating	150 °C

Table 24: Wire data of the company: Delphi, 35 mm^2

The Prestolite is used in the 3 connections between the motor controllers and motors (each). The Delphi wire is used for the connections between the accumulator and motor controllers.

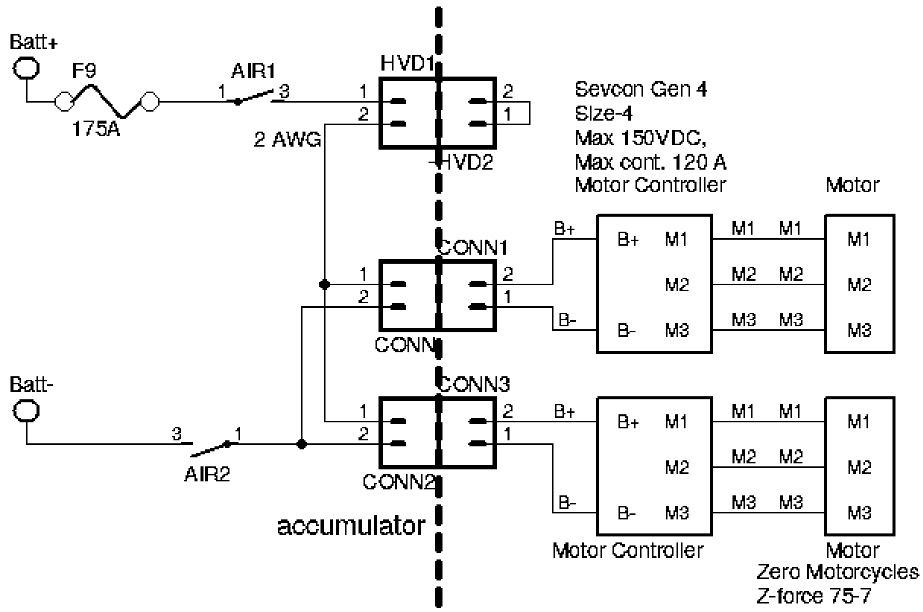


Figure 53: Schematic of the motor and motor controllers, in the tractive system

Both motors will follow the configuration in Figure 53, and are in parallel to the TS system. There is a 175A fuse located before the AIRs, which is smaller than the ampacity of 2 AWG wire according to appendix section 96 The connections from the accumulator to the motor controllers are shielded dual-insulated 35mm^2 stranded wire pigtails from a Delphi Shield-Pack HV2000 connector, which will be strain relieved at the motor controller using wire glands. There is also nomex tubing around the 2 AWG wiring to isolate it from the low voltage system. The information for this Delphi connector can be found in the appendix, section 11.

5.1.3 Position in Car

The motor controllers are located in the rear of the car, mounted to the main hoop bracing via steel brackets. This configuration is shown in Figures 54, 55, and 56. The controllers are entirely contained within the envelope of the chassis such that in any rollover attitude, the controllers will not make contact with the ground. The Sevcon Gen.4 controllers have no touch-protection from the TS terminals. Therefore, we will design a plastic enclosure with wire glands and conduit terminations where appropriate, which bolts to the rear of the motor controllers.

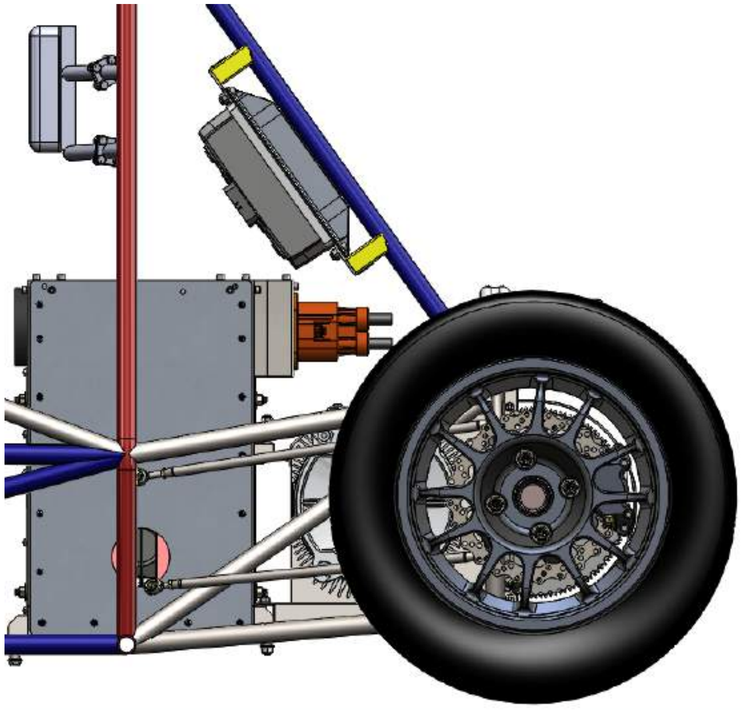


Figure 54: Side view of the motor controllers, mounted

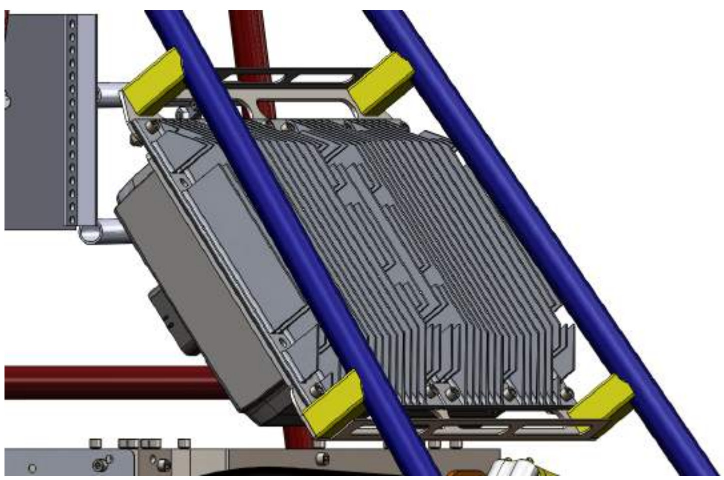


Figure 55: Isometric view of the motor controllers, mounted

Figure 56: Rear view of the motor controllers, mounted

5.2 Motor Controller 2

The second motor controller used will be exactly identical to that described in the section 5.1. Its wiring is shown in Figure 53.

6 Motors

6.1 Motor 1

6.1.1 Description, Type, Operating Parameters

Figure 57: Isometric view of the 75-5 Z-force motor

We will use Zero Motorcycles Z-force BLDC Motors (75-5 Size), shown in Figure 57. They are 3-phase DC brushless motors, compatible with the motor controllers used and described in Section 5.1.

Motor Manufacturer and Type:	Zero Motorcycles, Model # 30-0534
Motor principle	DC Brushless
Maximum continuous power	24.9 kW per motor
Peak Power	41.8 kW per motor
Input voltage	99.6V
Nominal current	250 A
Peak current	420 A
Maximum torque	85 ft-lb
Nominal torque	75 ft-lb
Cooling method	Air

Table 25: General motor data

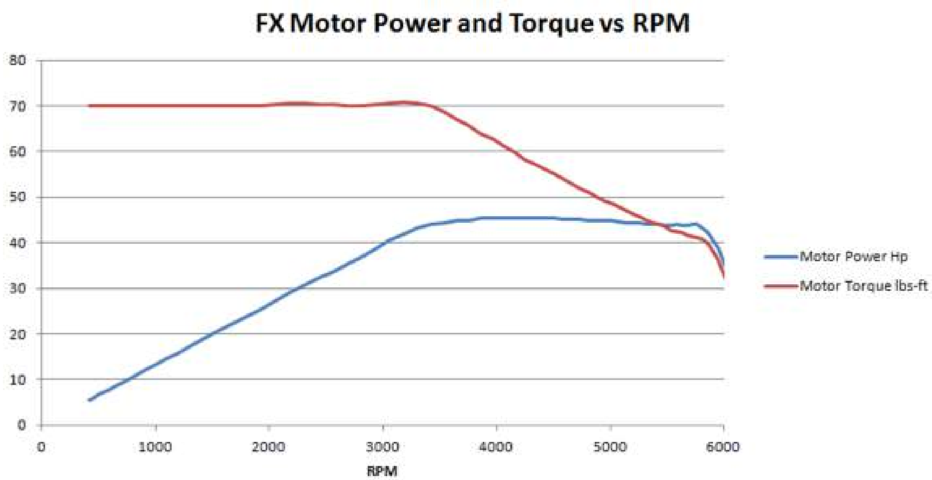


Figure 58

The motor's maximum power and torque were measured by Zero Motorcycles and graphed in figure 58. The accumulator used in the motorcycle for this motor has a lower operating voltage. Assuming a linear relationship between voltage and current, and a linear relationship between current and torque, approximately 85-ft-lbs of peak torque in the flat linear range (0-3000 RPM) is expected.

6.1.2 Wiring, Cables, Current Calculations, Connectors

The wiring from the motor controllers will simply connect the M1, M2 and M3 outputs of the motor controllers to the motors' inputs. Refer to Figure 53 for the schematic of motor 1 and motor 2. All power wires will be 2 AWG, described in Section 5.1.2. Connections from the motors to motor controllers will be encased in UL-listed conduit, which will be properly terminated at each end to provide proper strain relief. The shielding will be properly grounded at the motor controller side using industry standard practices. The conduit will be tightly wrapped in orange fabric so that the high voltage leads are orange.

6.1.3 Position in Car

The motors will be located behind the driver and accumulator, as shown in figures 60- 61. It is mounted to a steel face plate and a single stage chain transmission.

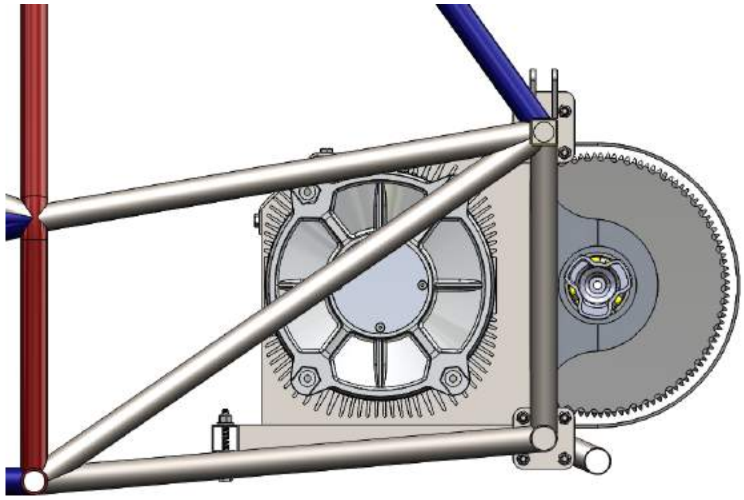


Figure 59: Side view of the motor mount

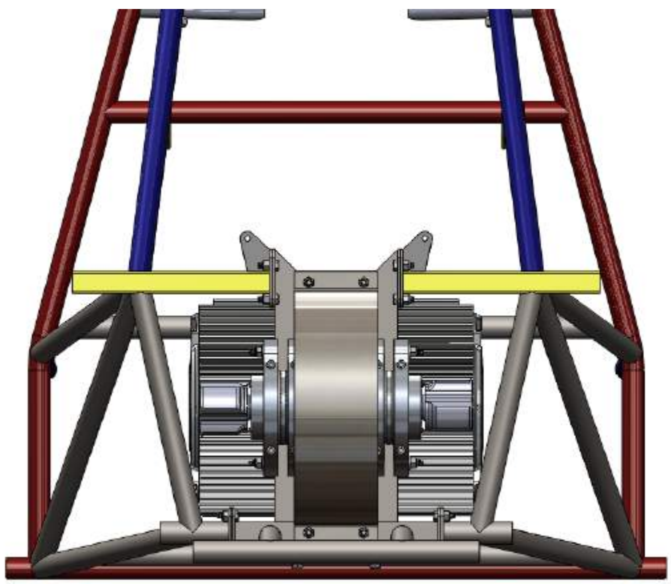


Figure 60: Rear view of the motor mount

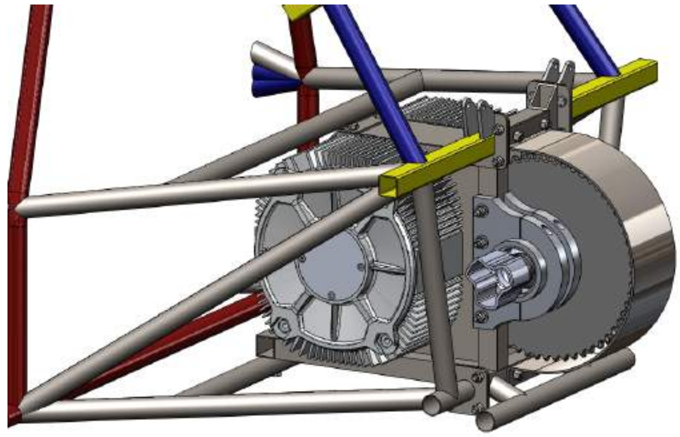


Figure 61: Isometric view of the motor mount

6.2 Motor 2

The second motor used will be exactly identical to that described in section 6.1 and its wiring is also shown in figure 53.

7 Torque Encoder

7.1 Description/Additional Circuitry

Two rotary potentiometers are mechanically housed in one unit from Active Sensors (P/N MHR5621) and mounted to the rotating shaft of the throttle pedal assembly. The use of a single housing eliminates concerns regarding mechanical backlash and misalignment. The output of the potentiometers are read by a CAN bus connected ATmega16M1. Software will compare the outputs to ensure that they are within 10% of each other and will then send a torque request to the CAN node that controls the motor controllers.

Torque encoder manufacturer and type:	MHR5621 from Active Sensors
Torque encoder principle	Potentiometer
Supply voltage	5V
Maximum supply current	15 mA
Operating temperature	-55 to 150 ˚C
Used output	0-5V

Table 26: Torque Encoder data

7.2 Torque Encoder Plausibility Check

Two potentiometers are mounted on the torque pedal. A CAN node probes the voltage dividers. The ATmega will compare the two independent voltages and will only send non-zero torque commands if the sensors read a voltage within 10% of each other. If a short circuit or wiring failure with either potentiometer occurs, the input will be outside the normal operating range due to an internal pull-up resistor in the ATmega read pin, and the motor controllers will not be sent torque requests. The node will log the error in the CAN bus.

There will also be a Pegasus Brake light pressure switch (part number 3601, recommended by Formula Hybrid) on the brakes, wired to a CAN node with 22 gauge wire. If the pressure switch indicates actuation of the brake and the potentiometers measure more than 25% pedal travel the CAN node will not send any torque requests to the motor controller until the torque pedal goes to less than 5% travel.

7.3 Wiring

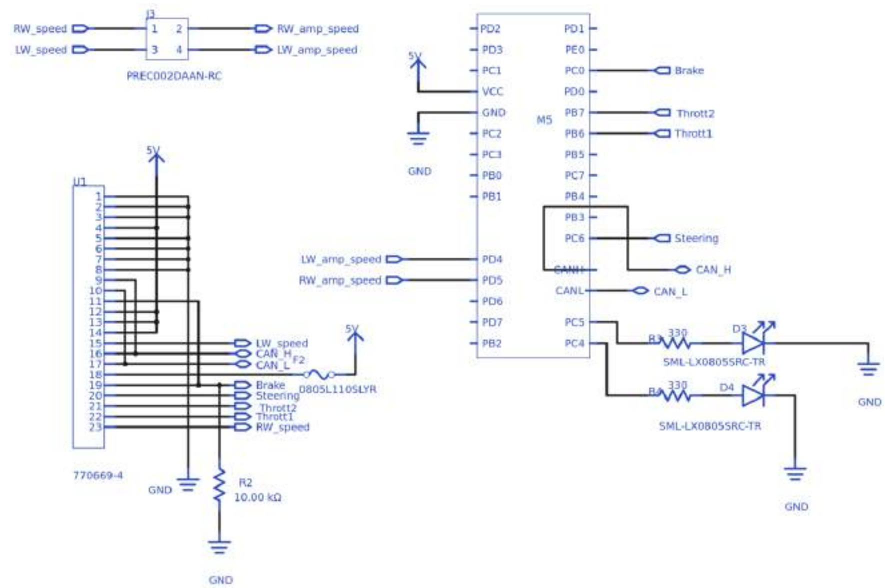


Figure 62: Schematic of the bulkhead, which has inputs for both linear potentiometer torque encoders

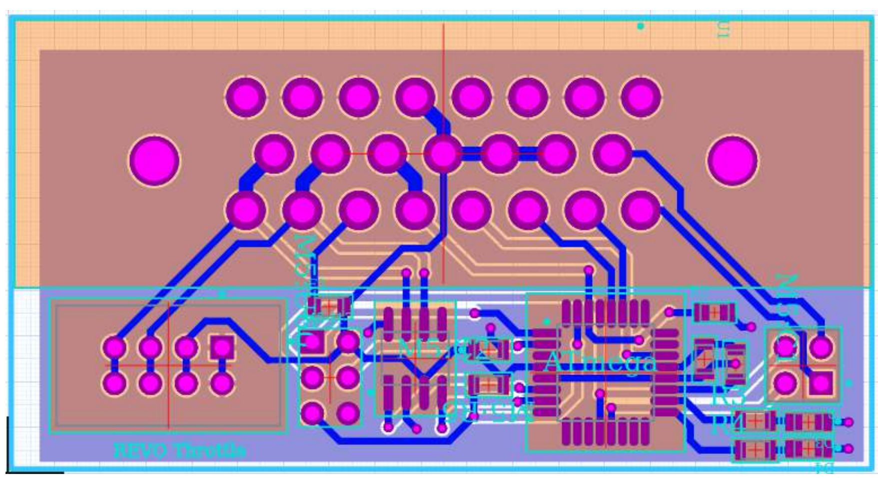


Figure 63: PCB cad of the bulkhead, which has inputs for both linear potentiometer torque encoders

Two potentiometers are wired with their output to the microcontroller analog input pins which have internal pull-up resistors. The potentiometers are given separate power lines of 5V, parallel, to the supply power of the CAN node itself. The brake switch is positioned to trip at a level of hard braking and when triggered will deliver 5V to the microcontroller input pin.

The CAN system is highly resilient and is programmed with error handling as the highest priority. The CAN protocol itself specifies a cyclic redundancy check which ensures that the messages are not corrupted in transmission. Both the Throttle node and MCC node will check the throttle values to ensure that they are in a valid range. If the MCC node does not receive a throttle CAN message for a tenth of a second it will tell the motor controllers to have 0 throttle.

7.4 Position in Car/Mechanical Fastening/Mechanical Connection

The torque encoder is bolted to the accelerator pedal assembly with 4x $\frac{1}{4}$"-20 bolts. The bolts are safety-wired to prevent loosening. The torque encoder is manufactured with a D-shaft. This is rotationally fixed to the accelerator pedal axle by a 4-40 set screw. The set screw is bonded with Loctite Purple to prevent loosening. This allows the torque encoder to measure the angular position of the accelerator pedal axle. The accelerator pedal axle is prevented from moving axially by retaining rings. The mounting of the torque encoder does not affect the relative plausibility check. The sensor used contains two independent encoders, each measuring the position of the single shaft.

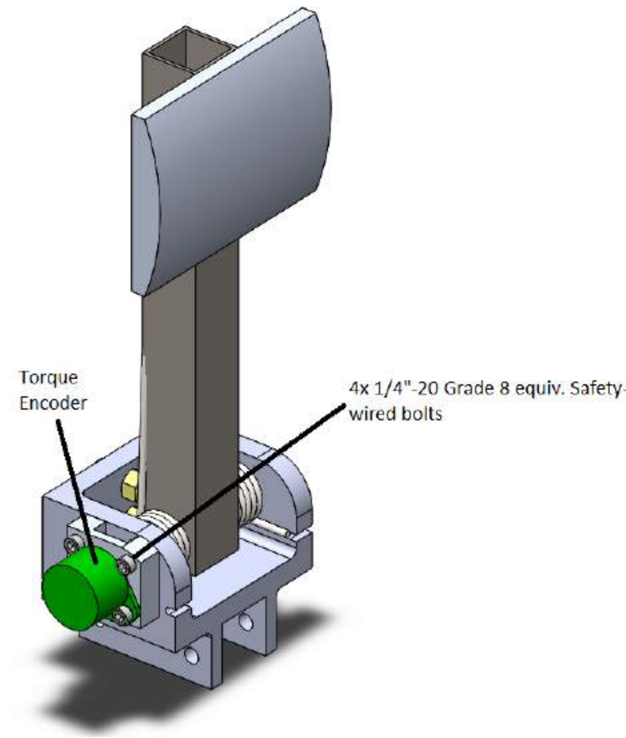


Figure 64: Mechanical fastening and connection to the throttle pedal. Note that the torque encoders are two encoders housed in one package

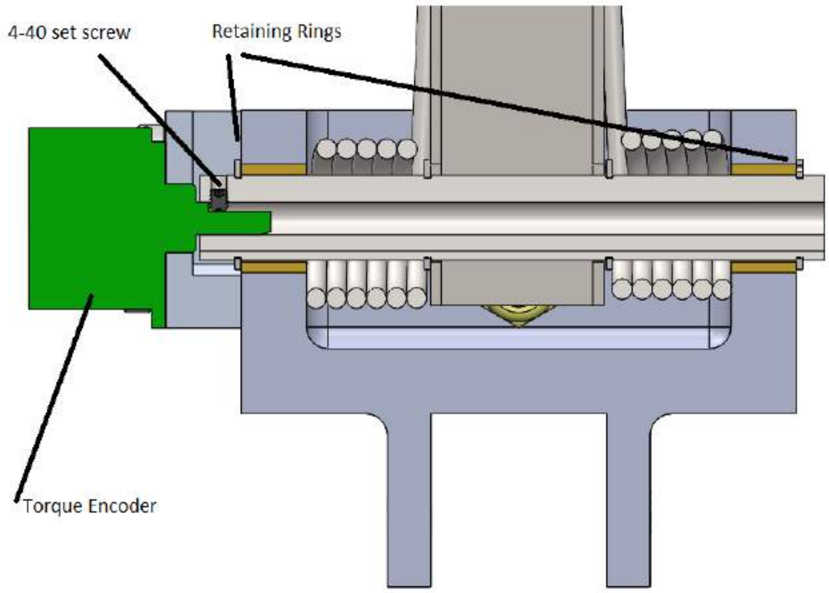


Figure 65: Side view of how the torque encoder connects to the pedal and measures the throttle

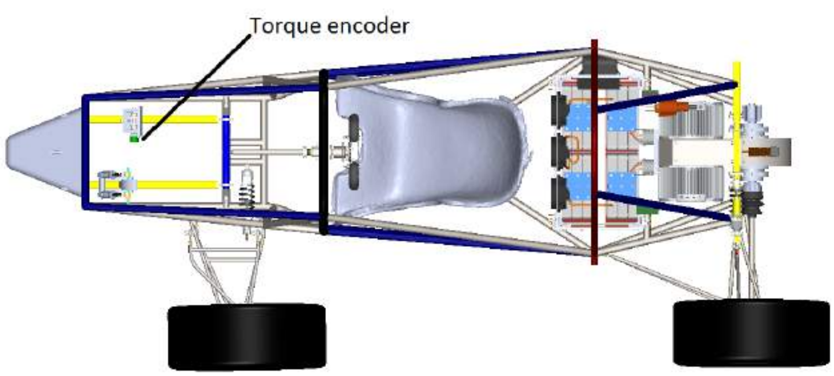


Figure 66: Overall view of the torque encoder's position in the car, top down view

8 Additional LV-parts Interfering with the Tractive System

8.1 LV Part 1: GLV Power

8.1.1 Description

The GLV system will be powered by a 12V lead acid battery. Please see figure 67 for the fusing and electrical connections of the GLV battery.

8.1.2 Wiring, Cables

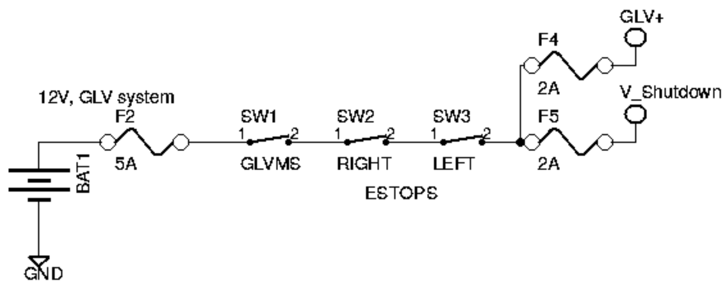


Figure 67: Fusing of the GLV system

The GLV battery will be fused to 5A, and after the two emergency shutdown buttons, the system is fused in parallel with two 2A fuses (the system voltage will be fused to 2A and the shutdown system will be fused to 2A). The GLV system voltage will be split in parallel again and then regulated to 5V for the sake of the CAN ATmega. All of these wires, will be 20 or 22 AWG.
The fuses used for the GLV system is described in the tables below.

Fuse manufacturer and type:	Littlefuse, MINI Series (MIN2BP)
Continuous current rating	5A
Maximum operating voltage	32V
Type of fuse	Fast acting
I2t rating	2.8 A2s
Interrupt Current (max. current at which the fuse can interrupt the circuit)	1000A at 32 VDC

Table 27: GLV system fuses, MIN type

Fuse manufacturer and type:	Littlefuse, MINI Series (MIN2BP)
Continuous current rating	2A
Maximum operating voltage	32 V
Type of fuse	Fast acting
I2t rating	2.8 A2s
Interrupt Current (max. current at which the fuse can interrupt the circuit)	1000A at 32 VDC

Table 28: GLV 12V and Shutdown circuit fuses, MIN type

8.1.3 Position in Car

The GLV battery and all of its fuses will be located in the motor controller housing, as shown by figure 4.

8.2 LV Part 2: Dashboard Node

8.2.1 Description

The Dashboard node will have a variety of tasks. It will act as the Control Panel interface (for displaying information to the driver and receiving data from the driver), Emergency Button sensor, AMS light, IMD light and start button.

The control panel interface is used for debugging and driver driver control of vehicle. The CAN system has nodes all over circuits in the car. If the CAN system is still live (when an E-stop hasn't been pushed and the GLV master switch is on), then this CAN node will alert the driver if there is an error and what it is.

8.2.2 Wiring, cables

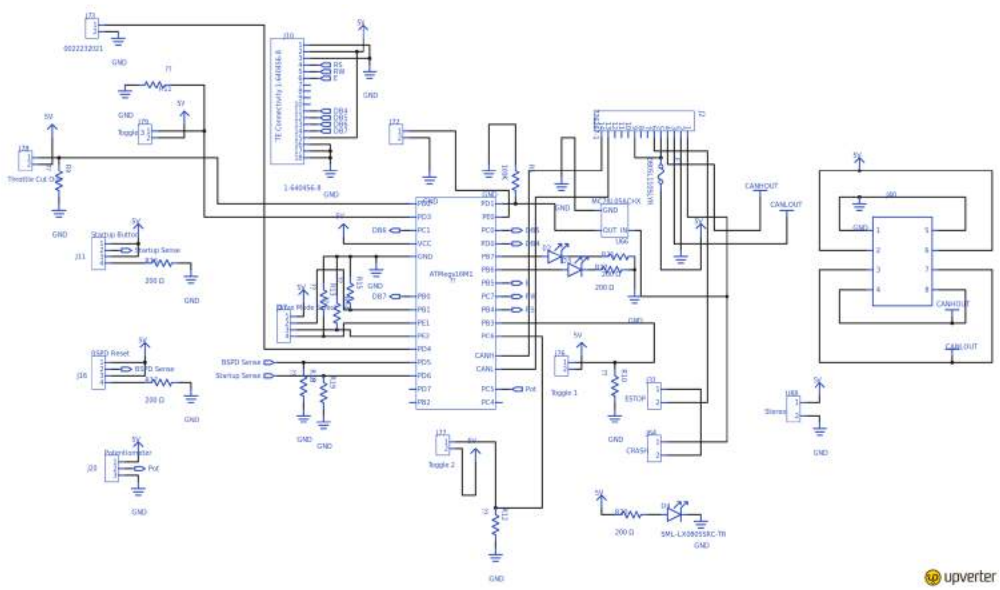


Figure 68: Dashboard node schematic

The dashboard PCB includes a CAN node (ATmega16M1), start button, IMD light, AMS light, BSPD reset button, inertia switch, a linear potentiometer,LCD screen and the cockpit e-stop. The LCD screen is there for the driver to read the cause of vehicle shutdown in the event that a sensor with an input to the CAN system fails. The other controls are for the driver to be able to reset the vehicle and note any emergency situations. This PCB is still in progress, but it will include only low voltage circuitry.
The board will have a 1A resettable fuse on the 12V supply line. It is described in the table below.

Fuse manufacturer and type:	bel Fuses, PTC resettable 0ZCK Series
Continuous current rating	1A
Maximum operating voltage	15V
Type of fuse	Fast trip time, Resettable
I2t rating	6.4 A2s

Table 29: Fuse on 5V line to PCB.

8.2.3 Position in Car

The dashboard node will be located behind the dashboard, and connecting to certain switches and lights on the dashboard. The dashboard CAD render can be shown in Figure 69.

Figure 69: Render of the Dashboard, the location of the dashboard node.

8.3 LV Part 3: Side Panel Node

8.3.1 Description

The side panel node, located next to the IMD and ready to drive sound, monitors the IMD's output and will activate the ready to drive sound when the car is in ready mode. It will also be connected to the rest of the CAN system around the car and listen to CAN messages for anomalies through its watchdog functionality. If the watchdog node receives a CAN error message or doesn't receive a "heartbeat" from other CAN nodes, it will open the watchdog relay in the shutdown circuit. This will be useful for maintaining the health of the motor controllers and debugging software while on the vehicle. TS wiring to the IMD/TSAL/R2D circuitry leaves the accumulator with an 8-pin Ampseal wrapped in conduit, with the conduit strain relieved against the connector (see rules clarification #5198), using 22 Awg wire.

8.3.2 Wiring, Cables

Please see figure 70 for the PCB schematic (which includes TS wiring for the TSMPs, IMD and R2D sound). The CAN node is wired to the third pole of the IMD relay, and the node will always read low until the pole is no longer pulled because the IMD's output is low and the IMD has found a ground fault. There is a pull up resistor and the pole, in its disconnected state the can input will read 5V instead.

As an output, the CAN node is also wired to a relay's coil controlling a switch in the tractive system parallel to the motors. When the CAN system knows it's in ready to drive mode, it'll send the message to send 5V to this coil, therefore closing the switch that will give the ready to drive sound buzzer power to make noise.

Also an output of the CAN node is the watchdog relay that controls a switch in the shutdown circuit. As watchdog of the CAN system, if a CAN node goes silent and suddenly stops messaging the rest of the system, this node will take notice and stop sending 5V to this coil, making it open the shutdown circuit. This will protect the motor controllers and offer redundancy for the rest of the shutdown circuit.

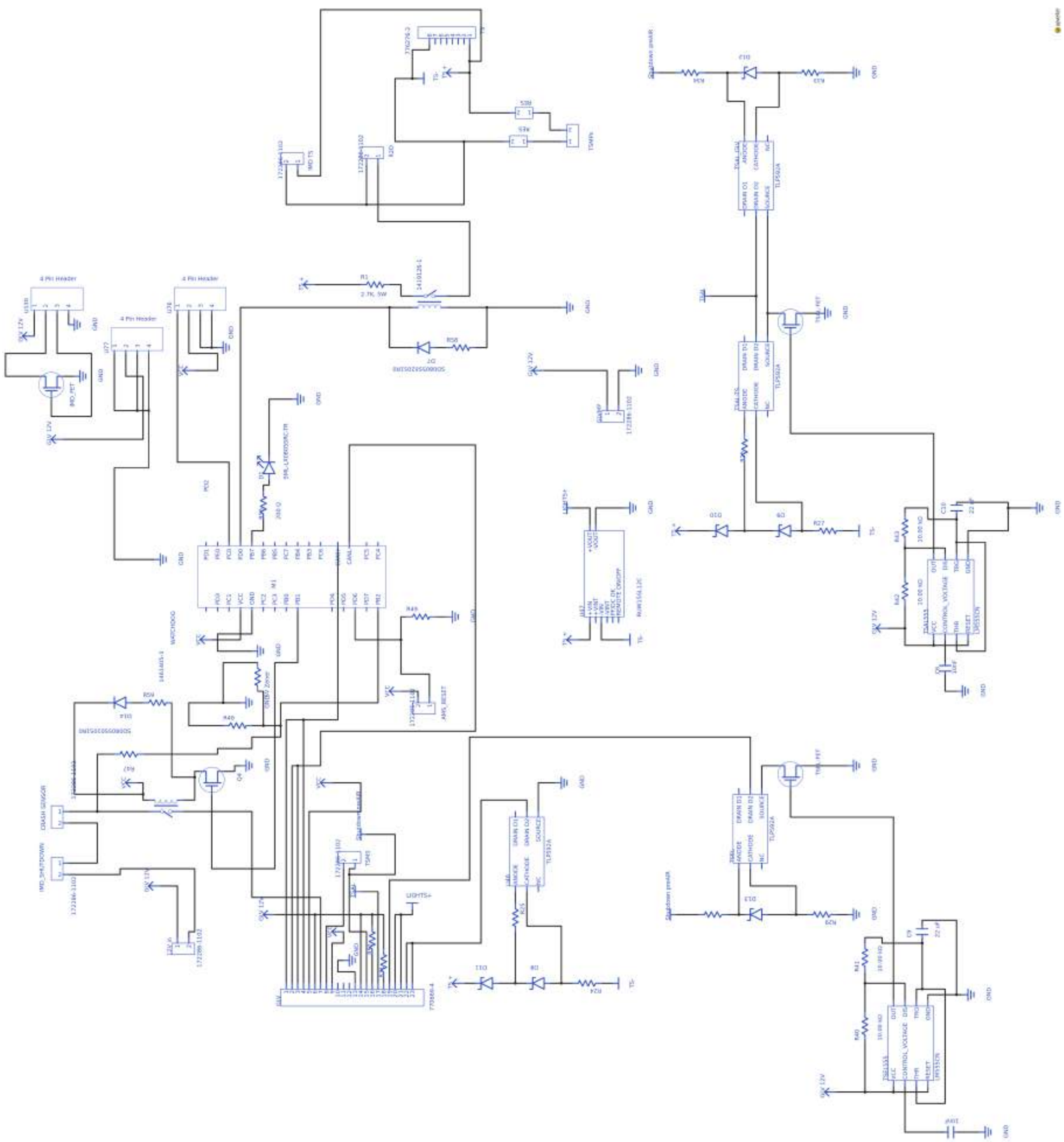


Figure 70: Schematic for the side panel node, including TS wiring for TSMPs, IMD, and R2D sound

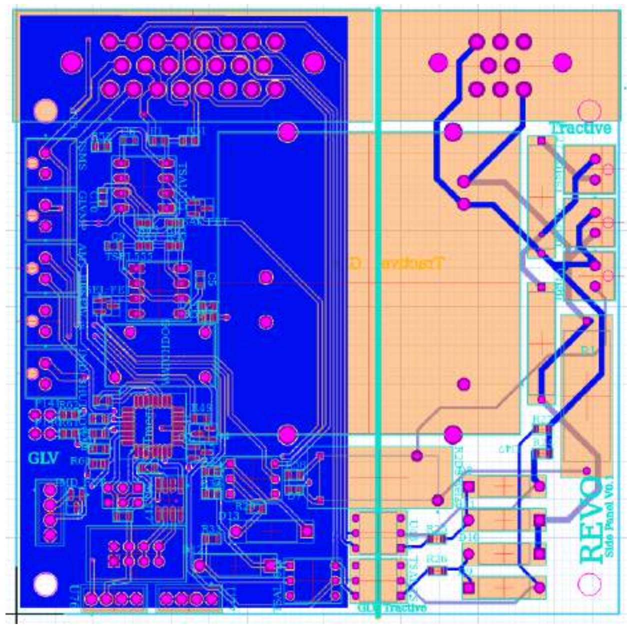


Figure 71: PCB for the side panel node. The separation is located around the cyan line, and the minimum distance is 1/4 in.

The same resettable fuses will be used as in table 29.

8.3.3 Position in Car

The side panel node will be contained in the enclosure shown in Figure 4.

8.4 LV Part 4: Motor Controller Controller (MCC) Node

8.4.1 Description

The node is located right next to both motor controllers. It receives torque requests from the throttle node and sends torque information to the motor controllers. The motor controllers take in analog input which controls the torque output. The analog input to the motor controllers is opto-isolated from the GLV system using opto-couplers. The motor controllers also require a Forward Switch which is also provided by the MCC node using an opto-coupler. The MCC node will handle all torque vectoring by lowering the torque request to one of the motor controllers. The MCC node will never increase the torque requested by the driver.

The motor controller controller (MCC) node is a CAN node that listens to the CAN system for throttle information and if the start button has been pressed and the vehicle is in a ready state, the node will pass on the information to the motor controllers via an isolated analog signal out.

Also on the board are the Brake System Plausibility Device (BSPD) as well as brake light wiring and other components necessary for the BSPD. This includes the hall effect sensors which have their power requirements supplied by the board.

8.4.2 Wiring, Cables

Please see figure 72 for the schematic which includes the TS vs. GLV wiring. The CAN node is wired into the CAN bus in order to get information from different nodes about torque information. The brake pressure switch line is connected to the analog input of the ATmega as well as the input to the BSPD. There is a pull-down resistor in order to ensure that the input is never floating. The BSPD is connected to the shutdown

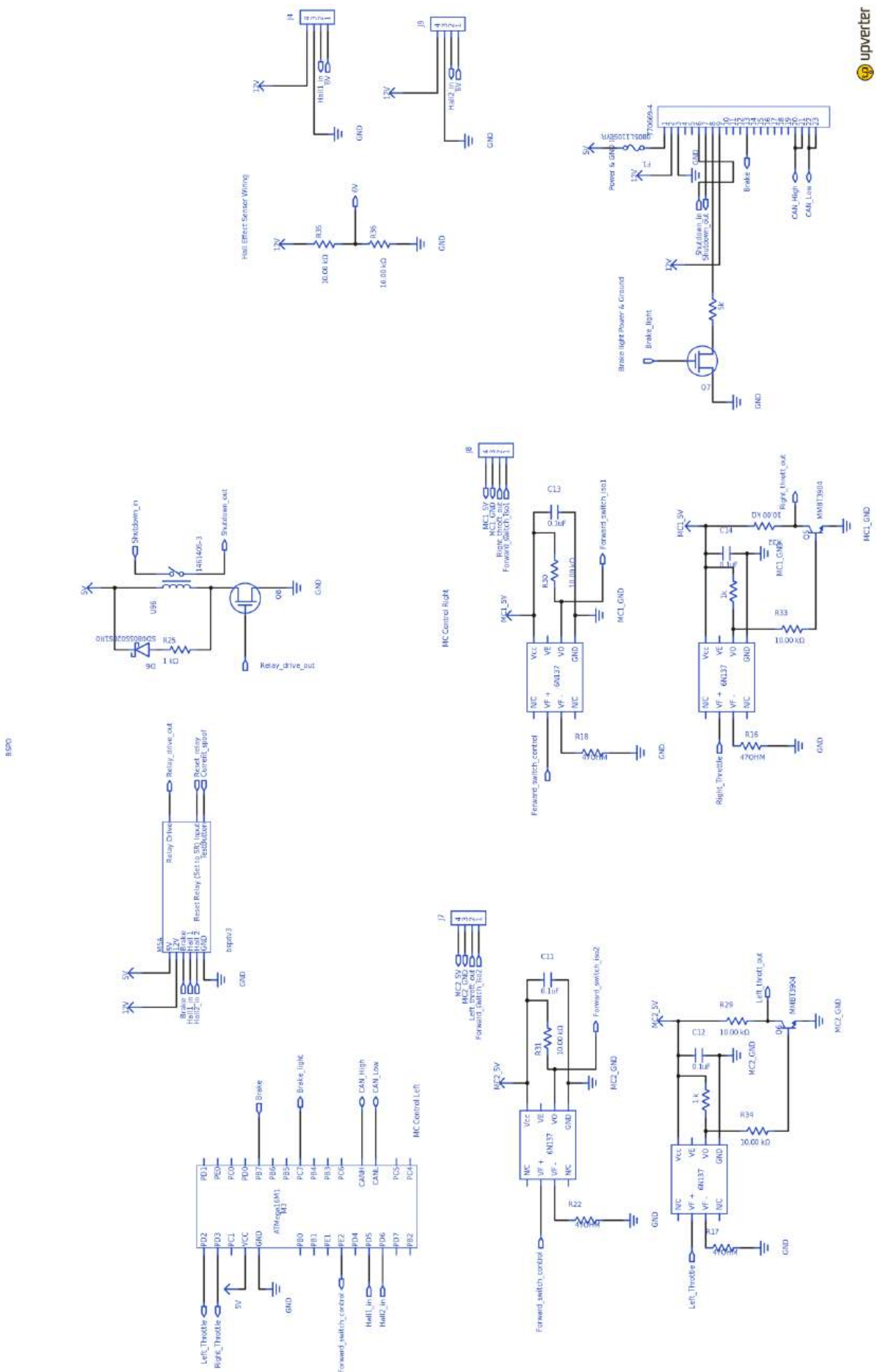


Figure 72: Schematic for the motor controller controller node

circuit via a relay on the board. The hall effect current sensors are given 12V, Ground and a reference 6V. The output of the Hall Effect current sensors goes to an analog input pin of the ATmega as well as to the BSPD. The motor controllers are wired into the system with 4 connections. Motor controller 5V and motor controller ground are used to power the receiving side of the opto-coupler. There is a Forward Switch line, which is necessary for our motor controllers, and is either 5V or 0V. The last wire is the analog control for the motor controllers. All connections are isolated from GLV.

The ATmega microcontroller on the board is able to reset the BSPD as well as allow for testing of the BSPD. In order to reset, the microcontroller gives a high pulse to the "set" pin of an RS-latch which will reset the BSPD if it has tripped. In order to test the BSPD, the microcontroller has an output that goes into the BSPD and simulates high current to the motor controllers.

The brake light is controlled by this node and is activated by the microcontroller via a low-side drive MOSFET.

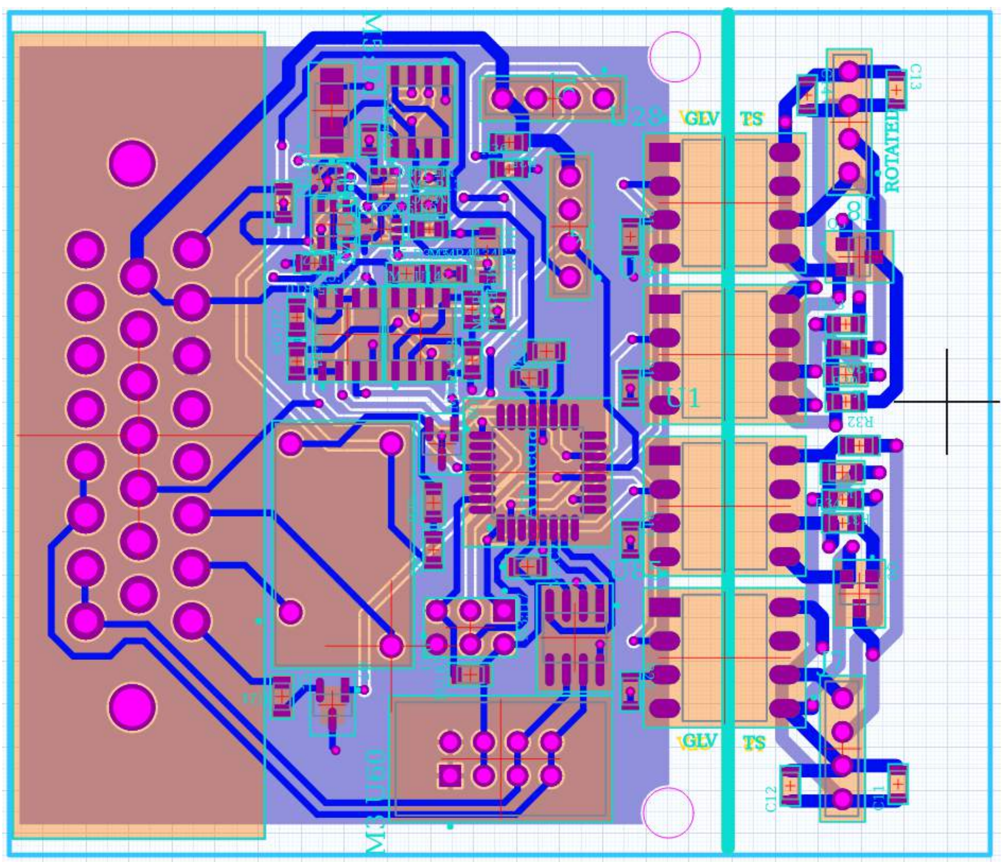


Figure 73: PCB for the motor controller controller node. The separation is located around the cyan line, and the minimum distance is 6.73mm in.

The same resettable fuses will be used as in table 29.

8.4.3 Position in Car

The MCC node will be contained in the motor controller housing, as seen in figure 4.

8.5 LV Part 5: Bulkhead Node

8.5.1 Description

The bulkhead CAN node collects throttle and brake information. It also connects to the front wheel speed sensors (ABS hall effect style) and the steering sensor (potentiometer) mounted to the steering rack. Torque vectoring is no longer in place, and the steering angle/wheel speed sensors are not installed. We expect to use this chassis as a test bed for competition next year. Our torque signal is never increased, meeting EV 2.3.12.

8.5.2 Wiring, Cables

Please see figure 62 for the bulkhead node schematic.

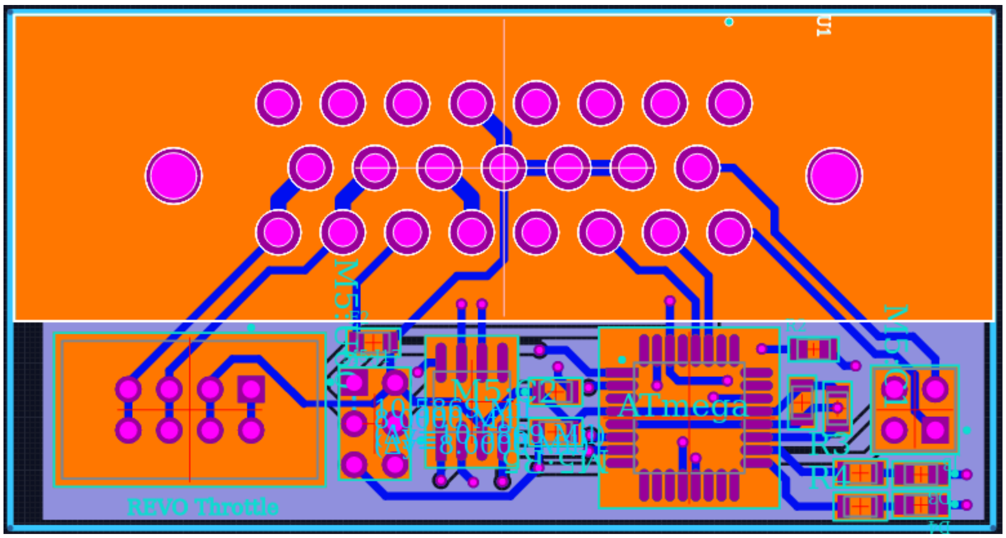


Figure 74: PCB for the bulkhead node. There is only low voltage circuitry on this PCB.

The same resettable fuses will be used as in table 29.

8.5.3 Position in Car

Predictably, the bulkhead node is located at the front of the pedal box. It is a 3D printed housing with integrated 23-pin TE connectivity Ampseal connector.

9 Overall Grounding Concept

9.1 Description of the Grounding Concept

The chassis is used as GLV ground. This ground is established at the panel mount holding some of the shutdown components and the TSMPs, GLV DC-DC converter and GLV battery. All mechanical systems in the vehicle, such as the accumulator, drivers seat, and pedal box, achieve low resistance to ground because they are either welded directly to the chassis, or fastened using uncoated, conductive metal fasteners. Electrical systems that are satellite to the main panel mount that need to establish a connection to ground for sense purposes are grounded to the chassis using ring terminals. Ring terminals can be included in the bolt stack up of mechanical systems to ensure a secure connection to ground that is positively retained with a lock nut. There are no ground wires provided in the wiring harness, so all of the grounding is directly to the chassis.

9.2 Grounding Measurements

The conductive components within 100mm of the tractive system or a GLV component will be measured with a multimeter to have less than 300 mΩresistance to ground. All fastened mechanical systems will be measured for a ground connection individually and exhaustively. Continuity will be checked during manufacture and assembly before the GLV system is in place. There will not be any carbon fiber on the vehicle.

10 Firewall

10.1 Firewall 1

10.1.1 Description/Materials

The firewall is constructed of two layers. The layer facing the tractive system is 24 gauge Aluminum sheet metal, with a chamfered edge. The second layer facing the cockpit is 1/8 in. Flame-Retardant Multipurpose Garolite (G-10/FR4). The assembly is fastened together using sheet metal rivets. The chassis has welded sheet metal tabs that fasten to the firewall with bolts and lock nuts. Because the firewall is fastened to the chassis using conductive fasteners it is connected to GLV ground.
All high voltage and high temperature systems are contained in the rear of the vehicle, so only one firewall will be used. There are GLV systems in the dashboard and pedal box so a small grommeted hole will be made in the firewall for GLV wiring.

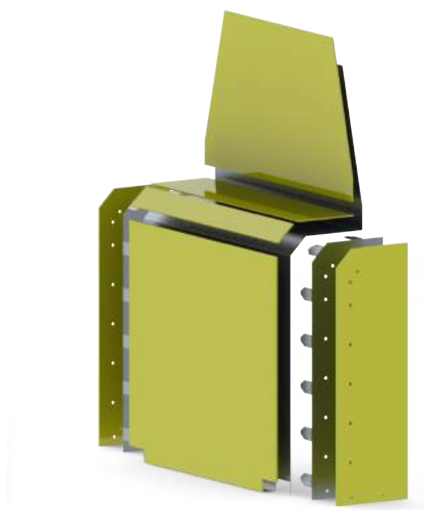


Figure 75: Exploded view of the firewall

10.1.2 Position in Car

The firewall is located between the driver and the accumulator, to protect the driver from the tractive system. Figure 76 shows the position with the driver seat removed for visual aid. The seat will go in the gap between the wheel and the firewall, facing away from the firewall. The top corner of the extruded part of the firewall is chamfered in order to protect the driver and will also be covered with padding.

Figure 76: CAD render of the firewall's position in the car

10.2 Firewall 2

There is only one firewall in the vehicle.

11 Appendix

11.2.1.1 Shutdown Switches

Cockpit E-Stop Button Datasheet here.
Right and Left E-Stop Buttons Datasheet here.
Tractive System and GLV System Master Switches, product link here, no datasheet available.
Main connector to the accumulator, also an interlock, datasheet here.
See section 11 for the AMS and BSPD relays. See section 11 for the IMD relay. See section 11 for the HVD.
See section 11 for the inertia switch.

11.2.2 IMD datasheet

Supply voltage U_S	DC 10…36 V
Nominal supply voltage	DC 12 V / 24 V
Voltage range	10 V…36 V
Max. operational current I_S	150 mA
Max. current I_k	2 A 6 A / 2 ms Rush-In current
Power dissipation P_S	<2 W
Line L+ / L- Voltage U_n	AC 0 V…800 V peak; 0 V…560 V rms (10 Hz…1 kHz) DC 0 V…800 V
Protective separation (reinforced insulation) between	(L+ / L-) – (Kl.31, Kl.15, E, KE, M_{HS}, OK_{HS})
Voltage test	AC 3500 V / 1 min
Load dump protection	< 40 V
Under voltage detection	0 V…500 V; Default: 0 V (inactive)
System leakage capacity C_e	≤ 1 μF
Reduced measuring range and increased measuring time at C_e	> 1μF (E.g. max. range 1 MΩ @ 3 μF, t_{an} = 68 s @ change over R_F 1MΩ > R_{an}/2)
Measuring voltage U_m	+/- 40 V
Measuring current I_m at $R_F = 0$	+/- 33 μA
Impedance Z_i at 50 Hz	≥ 1.2 MΩ
Internal resistance R_i	≥ 1.2 MΩ
Measurement range	0…10 MΩ
Measurement method	Bender AMP Technologie
Relative error at SST (≤ 2 s)	Good > 2 * R_{an}; Bad < 0.5 * R_{an}
Relative error at AMP	0…85 kΩ ▶ +/-20 kΩ 100 kΩ…10 MΩ ▶ +/-15 %
Relative error Output – M (base frequencies)	+/- 5 % at each frequency (10 Hz; 20 Hz; 30 Hz; 40 Hz; 50 Hz)
Relative error under voltage detection	U_n ≥ 100 V ▶ +/-10 %; at U_n ≥ 300 V ▶ +/-5 %
Response value hysteresis (AMP)	25 %
Response value R_{an}	100 kΩ…200 kΩ ▶ higher tolerances at R_{an} < 85 kΩ; (Default: 100 kΩ)
Response time t_{an} (OK_{HS}; SST)	t_{an} ≤ 2 s (typ. < 1 s at U_n > 100 V)
Response time t_{an} (OK_{HS}; AMP)	t_{an} ≤ 10 s
Switch-off time t_{ab} (OK_{HS}; AMP)	t_{ab} ≤ 26 s
Self test time	10 s (only at power on)

Figure 77: Response value information from IMD datasheet

Full IMD Datasheet here.
IMD 4PDT Relay Datasheet Here. Referred from section 11.
Fuse that protects the IMD, 251/253 series (1A)

11.2.3 Inertia switch

Sensata Resettable Crash sensor datasheet here. Referred from section 11.

11.2.4 Brake Plausibility Device

BSPD relay. Reffered from section 11 (shutdown system), and section 11 (AMS).
See section 11 for the brake sensor's datasheet.

11.2.7 Tractive System Active Light

DC-DC converter for the TSAL datasheet.
24-12V Linear Voltage Regulator for TSAL
Product information for the TSAL.
Zener with 56V breakdown, for activating the TSAL.

11.2.8.2 Tractive System Measuring Points

Expected multimeter to measure the TS voltage, datasheet here.
5K, 3W resistors for the TSMP datasheet here.
Red and Black TSMP 4mm banana jack datasheet here.

11.2.9 Precharge System

Download Precharge relay datasheet here

11.2.10 Discharge system

Discharge resistor datasheet here
Discharge relay datasheet here.
Referred from section 2.10

11.2.11 HVD

HVD Anderson connector datasheet here. Referred from section 11.

11.2.12 Ready to Drive Sound

Ready to drive sound buzzer datasheet.
Ready to drive sound relay datasheet

11.3.1.2 Cell Description

Battery health research that confirms our general cell safety.
We are working with Nissan to allow us to use their datasheet for the modules. Please see the following pages for the US Department of Energy's information on Nissan Leaf cells.

2011 Nissan Leaf – VIN 0356

Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results

VEHICLE DETAILS, BATTERY DESCRIPTION AND SPECIFICATIONS

Vehicle Details

Base Vehicle: 2011 Nissan Leaf
VIN: JN1AZ0CP5BT000356
Propulsion System: BEV
Electric Machine: 80 kW (peak), Permanent Magnet AC Synchronous, Air Cooled

Battery Description

Manufacturer: Automotive Energy Supply Corporation
Type: Lithium-ion – Laminate type
Cathode/Anode Material: $LiMn_2O_4$ with $LiNiO_2$/Graphite
Pack Location: Under Center of Vehicle

Battery Specifications

Number of Cells: 192
Cell Config.: 2 Parallel Strings of 96 in Series
Nominal Cell Voltage: 3.8 V
Nominal System Voltage: 364.8 V
Rated Pack Capacity: 66.2 Ah
Rated Pack Energy: 24 kWh
Maximum Cell Charge Voltage[2]: 4.2 V
Minimum Cell Discharge Voltage[2]: 2.5 V
Thermal Mgmt.: Passive, Vacuum-Sealed Unit
Pack Weight: 294 kg

BATTERY LABORATORY TEST RESULTS SUMMARY

Vehicle Mileage and Testing Date

Vehicle Odometer: 6,696 mi
Date of Test: May 5, 2012

Static Capacity Test

Measured Average Capacity: 57.6 Ah
Measured Average Energy Capacity: 21.0 kWh

EVPC Test

Pulse Discharge Power @ 80% DOD[3]: 201.0 kW
Pulse Charge Power @ 20% DOD[3]: 71.2 kW

Constant-Power Discharge Test

Capacity Discharged: 56.8 Ah
Energy Discharged: 20.0 kWh

NOTES:

1. Vehicle details, battery description and specifications were either supplied by the manufacturer or derived from a literature review.
2. Maximum cell charge voltage and minimum cell discharge voltage are based on similar battery chemistries from the same battery manufacturer.
3. Calculated power values based on battery charge and discharge voltage limits (see Note 3) at 80% and 20% DOD for discharge and charge power, respectively.

Test Results Analysis

Test results for the beginning-of-testing (BOT) battery testing are provided herein. Battery test results include those from the Static Capacity Test and the Electric Vehicle Power Characterization (EVPC) Test, based on recommended test procedures from the United States Advanced Battery Consortium (USABC) at the time of testing.

Static Capacity Test Results

Static capacity test results are summarized in the fact sheet on the previous page. The test was performed on May 5, 2012 with a vehicle odometer reading of 6,696 miles. The average measured C/3-rate capacity was 57.6 Ah compared with the manufacturer's rated capacity of 66.2 Ah. The average measured energy capacity was 21.0 kWh.

Figure 1 is a graph of battery voltage versus energy discharged. This graph illustrates the voltage values during the constant-current discharge versus the cumulative energy discharged from the battery at a C/3 discharge rate.

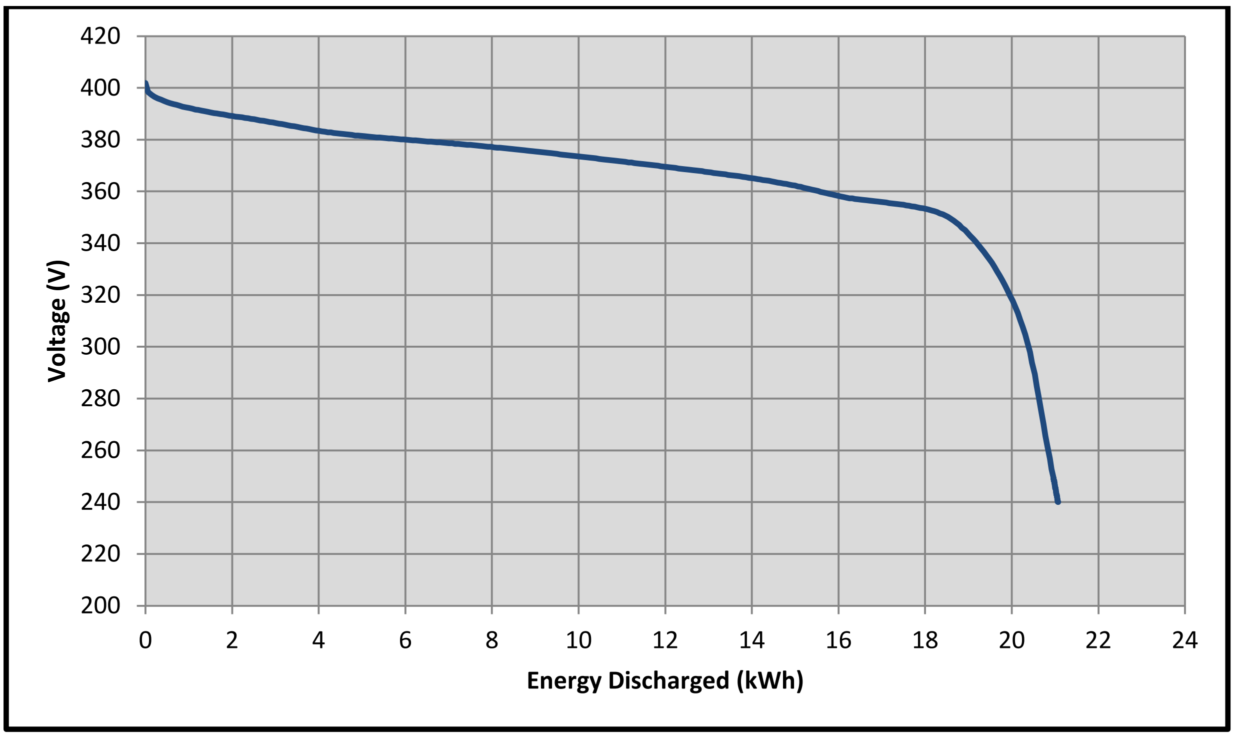


Figure 1: Voltage vs. Energy Discharged

EVPC Test Results

EVPC test results are summarized in the fact sheet on the first page. The peak pulse discharge power is 201.0 kW at 80% depth of discharge (DOD). The peak pulse charge power is 71.2 kW at 20% DOD. The maximum and minimum cell voltages used for this analysis were 4.20 V and 2.50 V, respectively.

Figures 2 and 3 illustrate the battery's charge and discharge pulse resistance graphs which show internal resistance at various DOD. Each curve represents the resistance at the end of the specified pulse interval.

Figures 4 and 5 illustrate the battery's charge and discharge pulse power graphs which show the useable power at various DOD. Each curve represents the pulse power at the end of the specified pulse interval at the cell voltage limits.

These tests were performed for DOE's Advanced Vehicle Testing Activity (AVTA). The AVTA, part of DOE's Vehicle Technology Program, is conducted by the Idaho National Laboratory and Electric Transportation Engineering Corporation dba ECOtality North America.

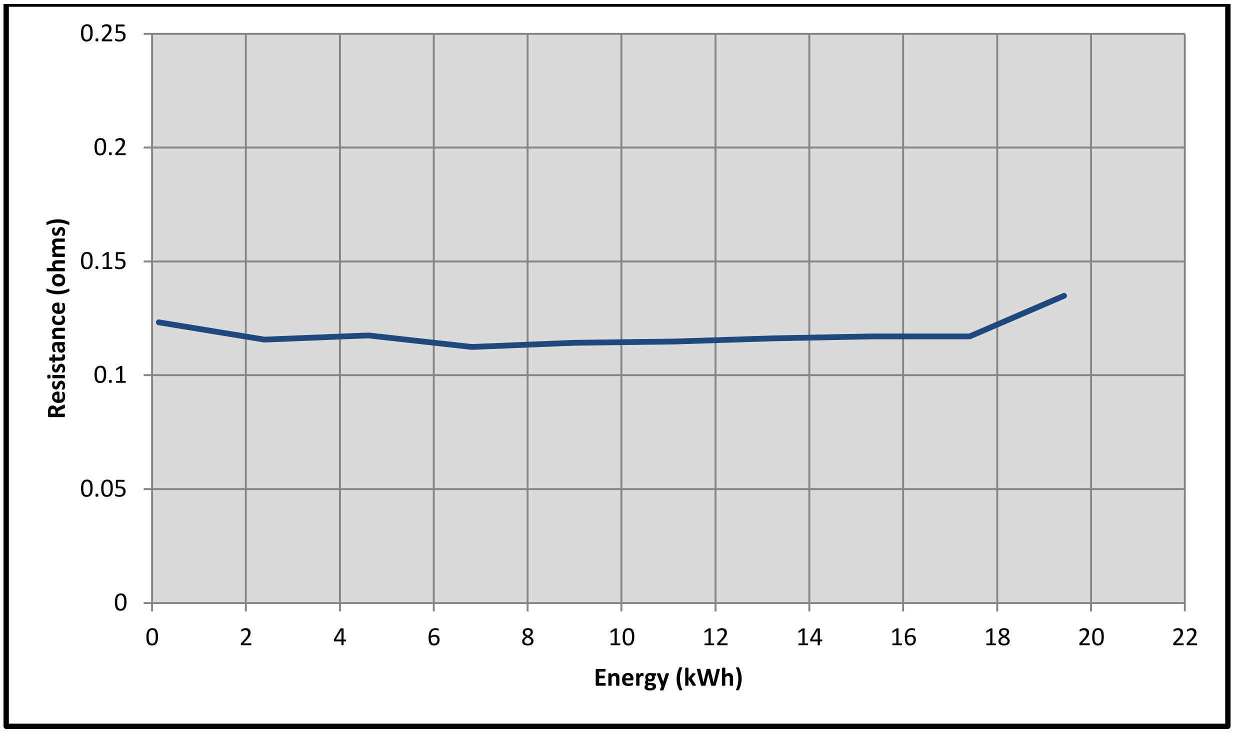


Figure 2: Charge Pulse Resistance vs. Energy Discharged

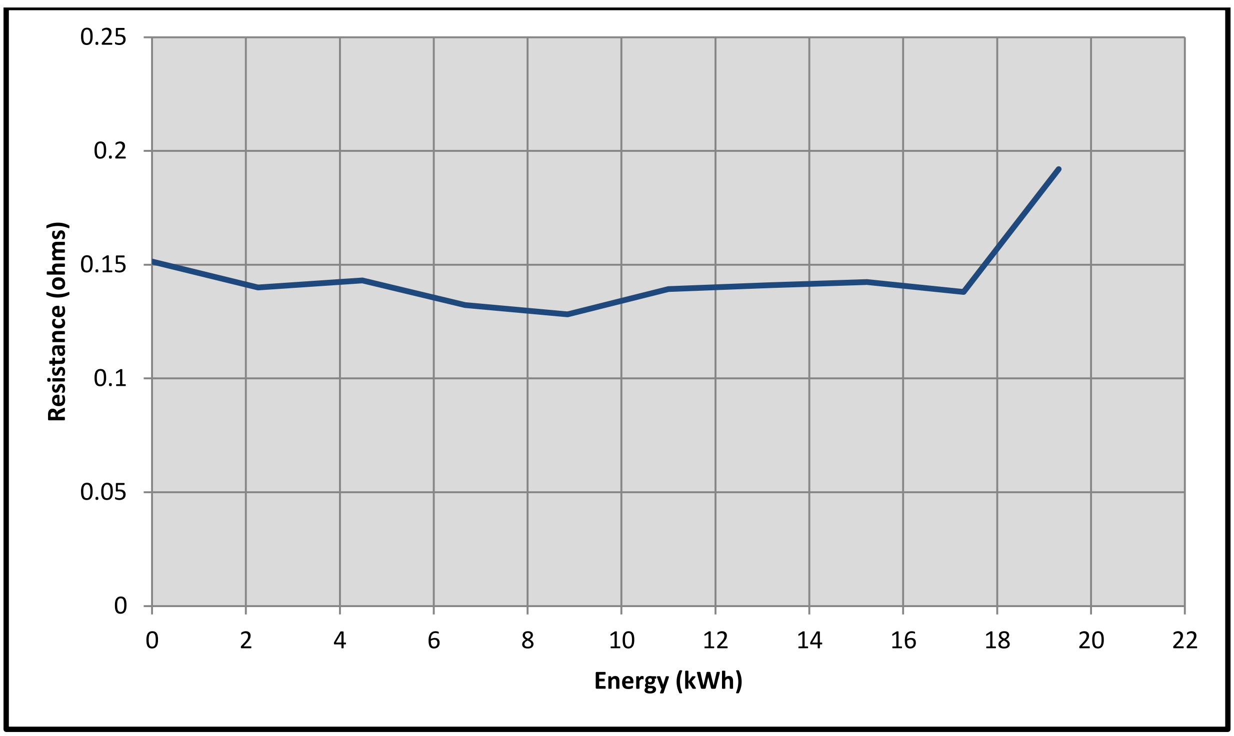


Figure 3: Discharge Pulse Resistance vs. Energy Discharged

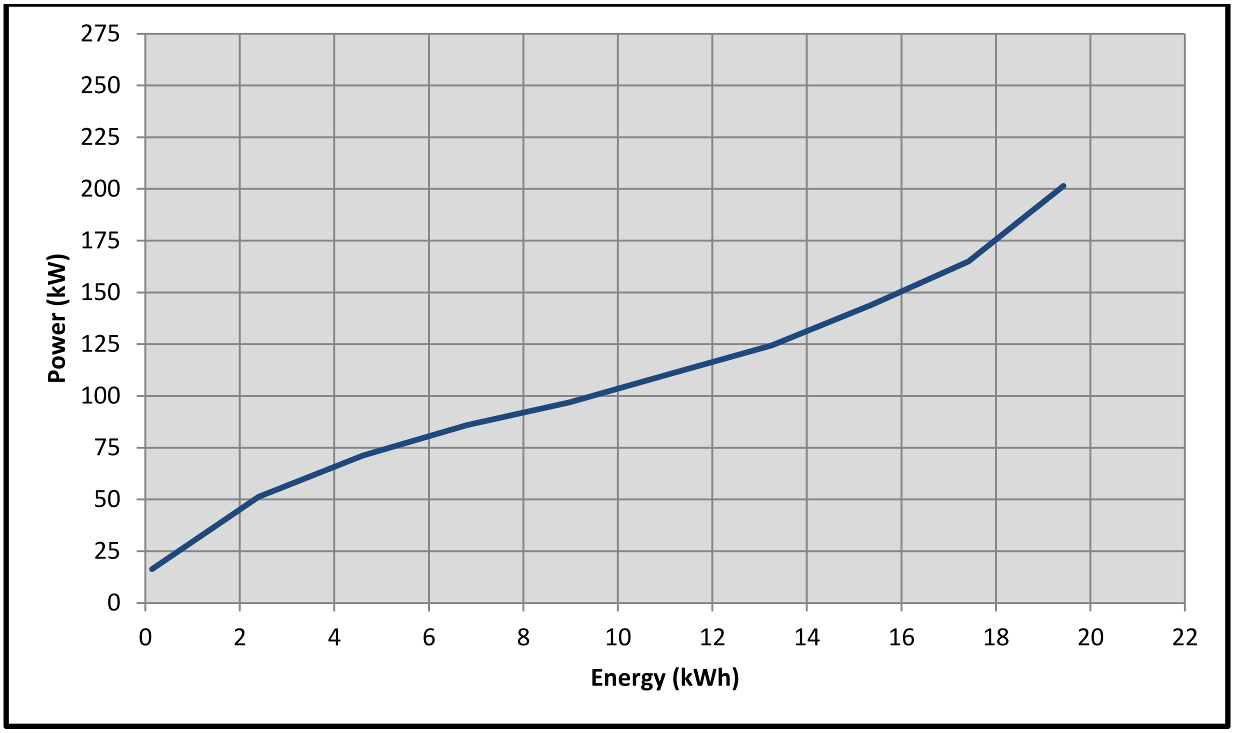


Figure 4: Charge Pulse Power vs. Energy Discharged

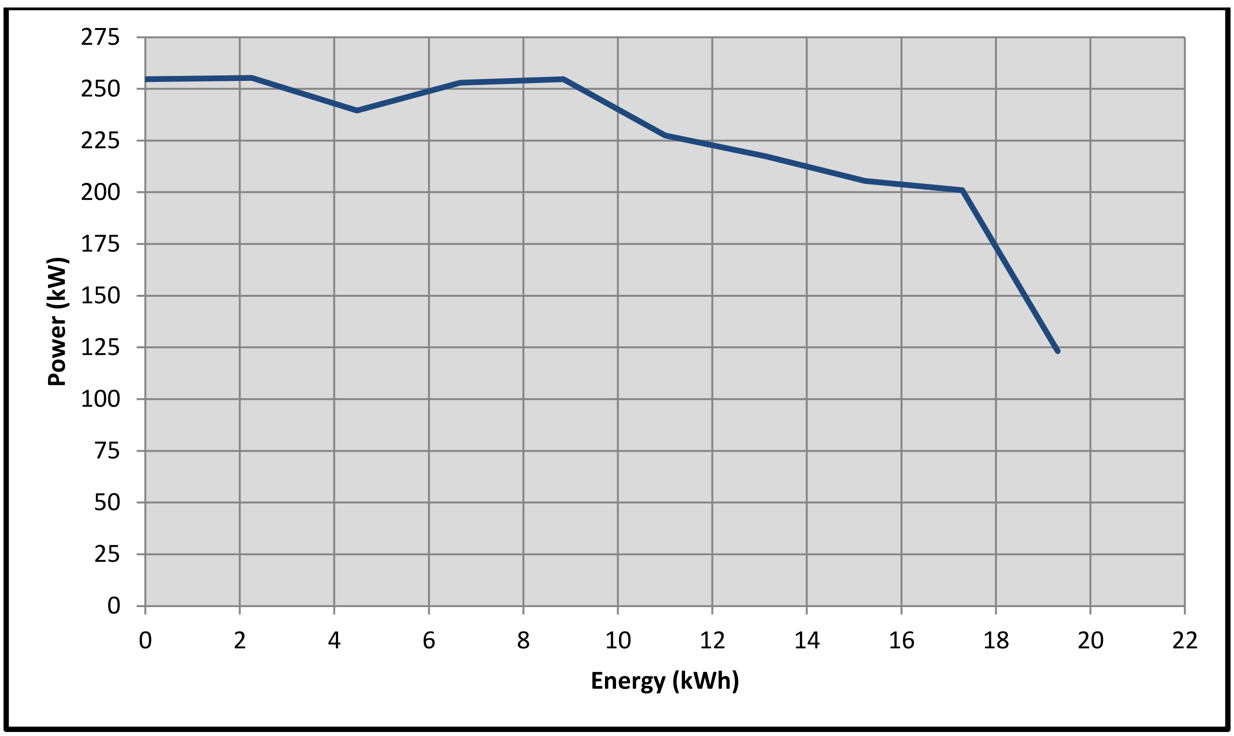


Figure 5: Discharge Pulse Power vs. Energy Discharged

11.3.1.4 Cell Temperature Monitoring

Thermistors measuring cell temperature datasheet.

11.3.1.5 Accumulator Monitoring System

Please see figure 78 for the schematic of the AMS boards. Referred from section 3.1.5. The AMS looks at the voltage of each cell by having differential amplifiers between two cells and get a relative voltage. This relative voltage for each cell is then put through an optocoupler, which then connects a power resistor and transistor to shunt the cell when necessary. There is an isolated CAN node attached to the board so it can communicate to the rest of the shutdown system and activate a relay to open the shutdown circuit when necessary. The BMS connects to the cell-top boards, shown in figure 34.
Please see section 11 for the AMS relay.
The following figures show the compliance of spacing of the BMS board.

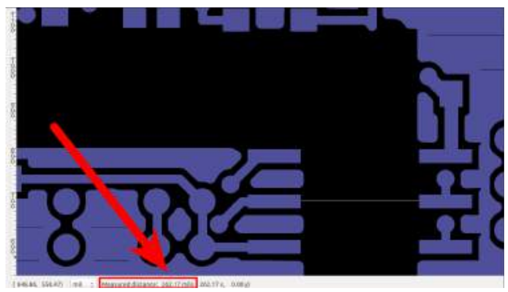


Figure 79: Capture of the separation on each AMS board between TS and GLV power on the top copper (262 mil)

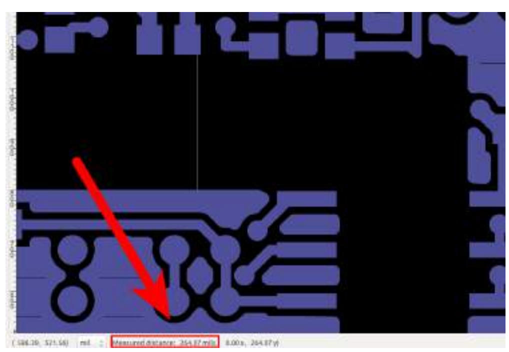


Figure 80: Capture of the separation on each AMS board between TS and GLV power on the top copper (264 mil)

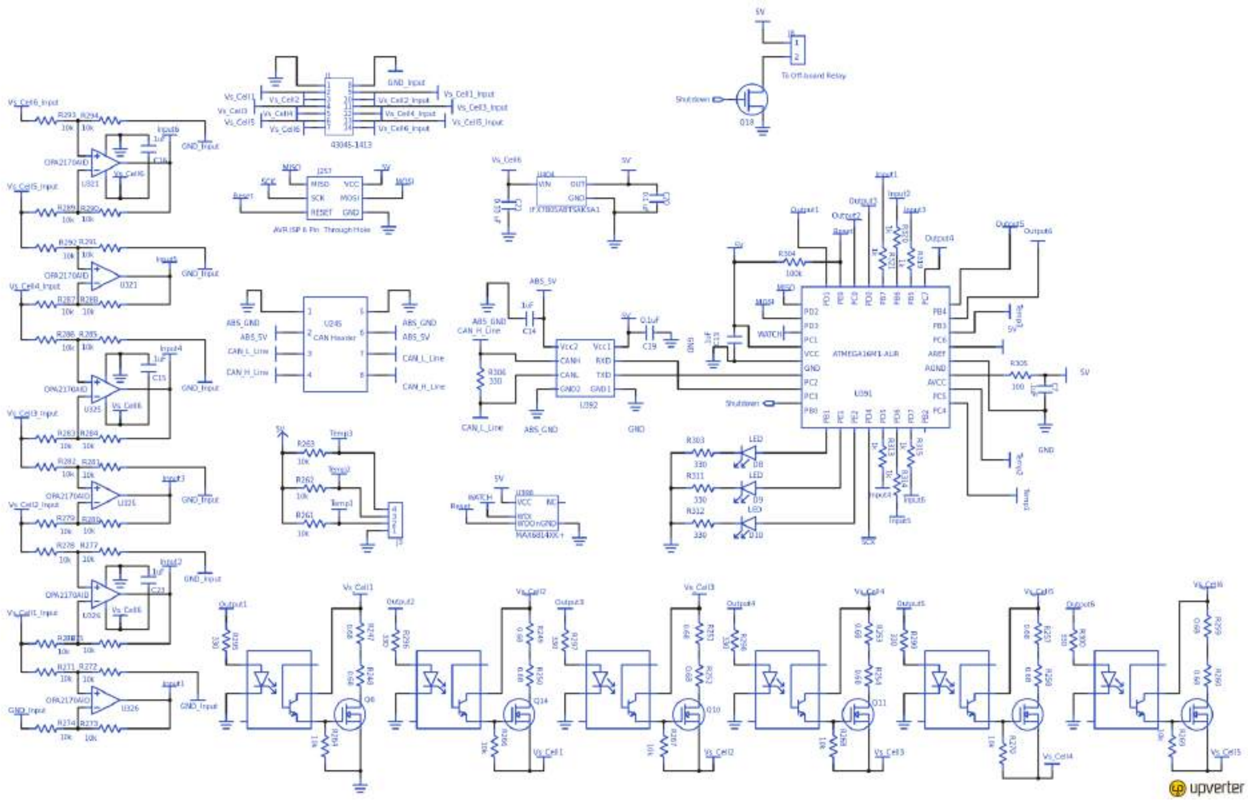


Figure 78: Schematic of one of the accumulator monitoring boards

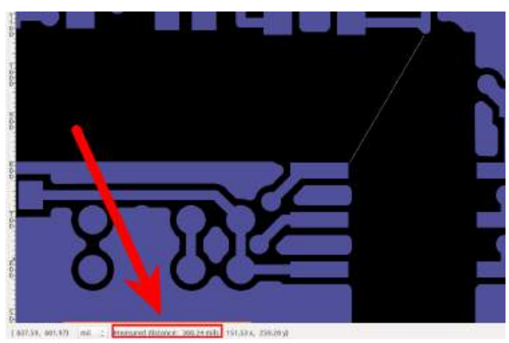


Figure 81: Capture of the separation on each AMS board between TS and GLV power on the top copper (300 mil)

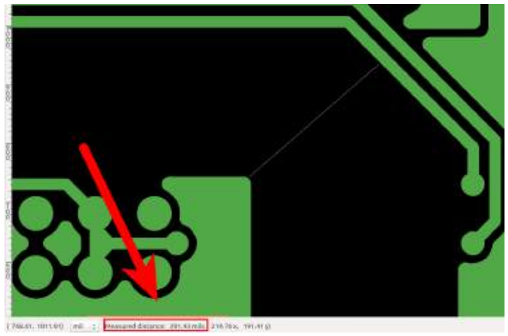


Figure 82: Capture of the separation on each AMS board between TS and GLV power on the bottom copper(291 mil)

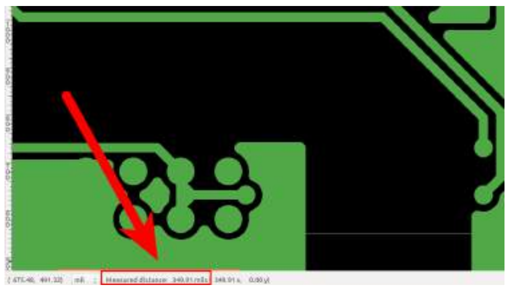


Figure 83: Capture of the separation on each AMS board between TS and GLV power on the bottom copper (349 mil)

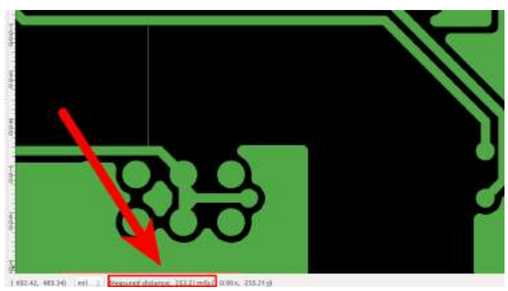


Figure 84: Capture of the separation on each AMS board between TS and GLV power on the bottom copper (253 mil)

11.3.1.8 Accumulator Insulation Relays

Accumulator Insulation Relay datasheets here.

11.3.1.9 Fusing

Referred from section 3.1.9.

Catalog Symbol: LPJ-_SP
Dual-Element, Time-Delay – 10 seconds (minimum) at 500% rated current
Current-Limiting
Ampere Rating: 70 to 600A
Voltage Rating: 600Vac (or less)*
Interrupting Rating: 300,000A RMS Sym.
Agency Information:
UL Listed – Special Purpose†, Guide JFHR, File E56412
CSA Certified, Class J per CSA C22.2 No. 248.8, Class 1422-02, File 53787

*0-600A rated 300Vdc and 20 KAIC.
†Meets all performance requirements of UL Standard 248-8 for Class J fuses.

Figure 85: Ratings for the Bussman LPJ series 175A main TS fuse

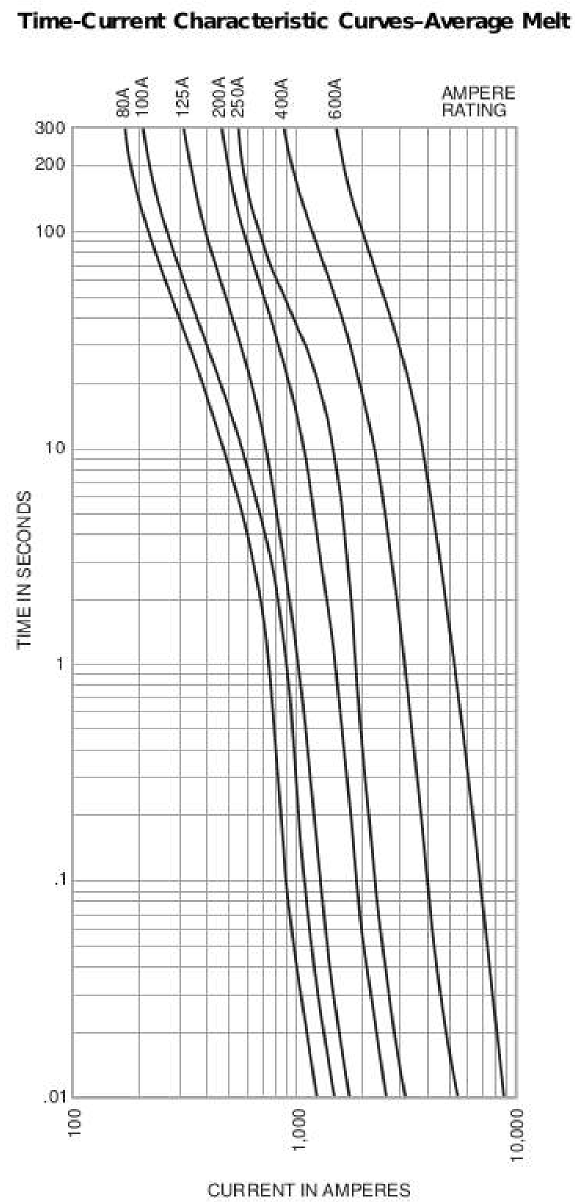


Figure 86: Time-current curve for Bussman LPJ series 175 A main TS fuse

All information found from the datasheet of: Full Bussman Fuse LPJ 175A datasheet here.

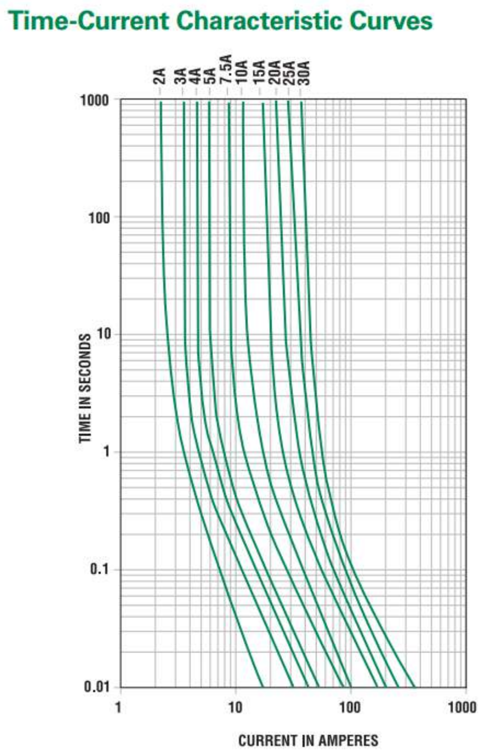
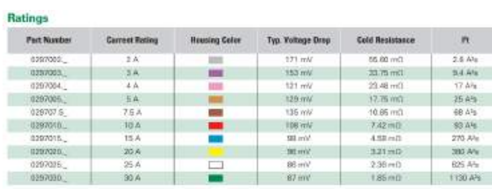


Figure 87: Time-current curve for the MINI series (2A and 5A) fuses

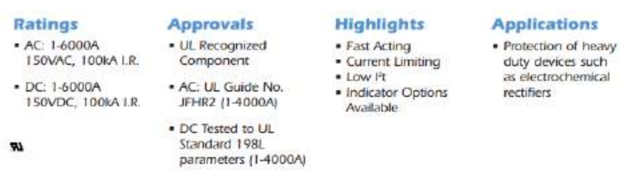


Ratings

Part Number	Current Rating	Housing Color	Typ. Voltage Drop	Cold Resistance	I²t
0297002._	2 A		171 mV	55.60 mΩ	2.6 A²s
0297003._	3 A		153 mV	33.75 mΩ	9.4 A²s
0297004._	4 A		121 mV	23.48 mΩ	17 A²s
0297005._	5 A		129 mV	17.75 mΩ	25 A²s
029707.5._	7.5 A		135 mV	10.85 mΩ	68 A²s
0297010._	10 A		108 mV	7.42 mΩ	93 A²s
0297015._	15 A		98 mV	4.58 mΩ	270 A²s
0297020._	20 A		98 mV	3.21 mΩ	380 A²s
0297025._	25 A		86 mV	2.36 mΩ	625 A²s
0297030._	30 A		87 mV	1.85 mΩ	1130 A²s

Figure 88: Ratings for the MINI series (2A and 5A) fuses

All information found from the datasheet of: Full MINI series 2A and 5A fuse datasheet here.



Ratings
- AC: 1-6000A 150VAC, 100kA I.R.
- DC: 1-6000A 150VDC, 100kA I.R.

Approvals
- UL Recognized Component
- AC: UL Guide No. JFHR2 (1-4000A)
- DC Tested to UL Standard 198L parameters (1-4000A)

Highlights
- Fast Acting
- Current Limiting
- Low I²t
- Indicator Options Available

Applications
- Protection of heavy duty devices such as electrochemical rectifiers

Figure 89: Ratings taken from the A15QS, 7A Keyswitch fuse

All information found from the datasheet of: Keyswitch Fuse datasheet, Semiconductor AC A15QS.

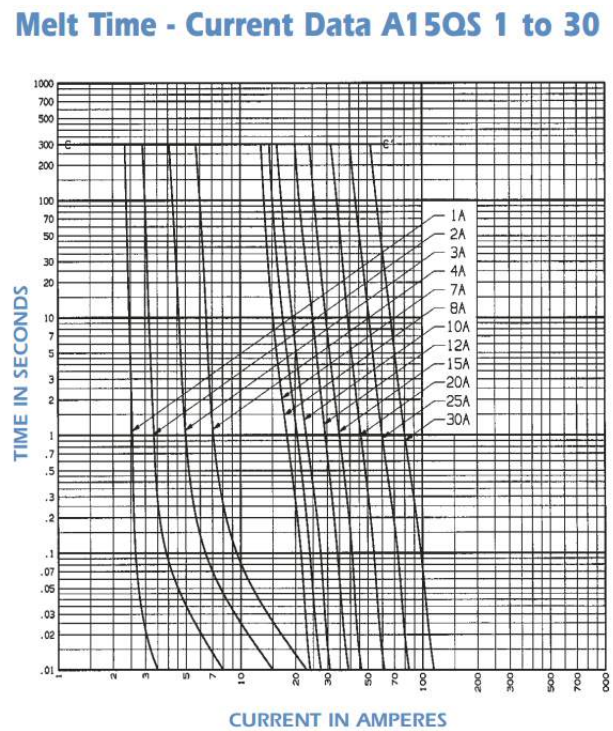


Figure 90: Time-Current curve for A15QS, 7A Keyswitch fuse

Electrical Specifications by Item

Ampere Rating (A)	Amp Code	Ordering Number (Std.)	Ordering Number (Mil.)	Max Voltage Rating (V)	Interrupting Rating	Nominal Cold Resistance (Ohms)	Nominal Melting I²t (A² sec)	Nom Voltage Drop (V)	Agency Approvals: UL	CSA	PSE	TUV	QPL (253 Series Only)	CCC
.062	.062	251.062	253.062	125	300 A @ 125VDC 50A@125VAC For CCC 7A: 70A@125VAC For CCC 10A: 100A@ 125VAC	7.000	0.000113	1.4	x	x			x	
.125	.125	251.125	253.125	125		1.700	0.00174	0.285	x	x			x	
.200	.200	251.200	253.200	125		0.895	0.0048	0.345	x	x				
.250	.250	251.250	253.250	125		0.665	0.0116	0.24	x	x			x	
.375	.375	251.375	253.375	125		0.395	0.0296	0.215	x	x			x	
.500	.500	251.500	253.500	125		0.302	0.0598	0.2165	x	x		x	x	x
.630	.630	251.630		125		0.205	0.08	0.188	x	x				
.750	.750	251.750	253.750	125		0.175	0.153	0.176	x	x		x	x	
1.00	001.	251001.	253001.	125		0.128	0.256	0.194	x	x	x	x	x	x
1.25	1.25	2511.25		125		0.100	0.390	0.2	x	x	x			
1.50	01.5	25101.5	25301.5	125		0.0823	0.587	0.21	x	x	x	x	x	
2.00	002.	251002.	253002.	125		0.0473	0.405	0.141	x	x	x	x	x	x
2.50	02.5	25102.5		125		0.0360	0.721	0.132	x	x	x	x		x
3.00	003.	251003.	253003.	125		0.0295	1.19	0.131	x	x	x	x	x	x
3.50	03.5	25103.5		125		0.0240	1.58	0.1205	x	x	x	x		
4.00	004.	251004.	253004.	125		0.0204	2.45	0.114	x	x	x	x	x	x

Figure 91: 251/253 series, 1A TS low current fuse and 3A HV+ sense line Energy meter

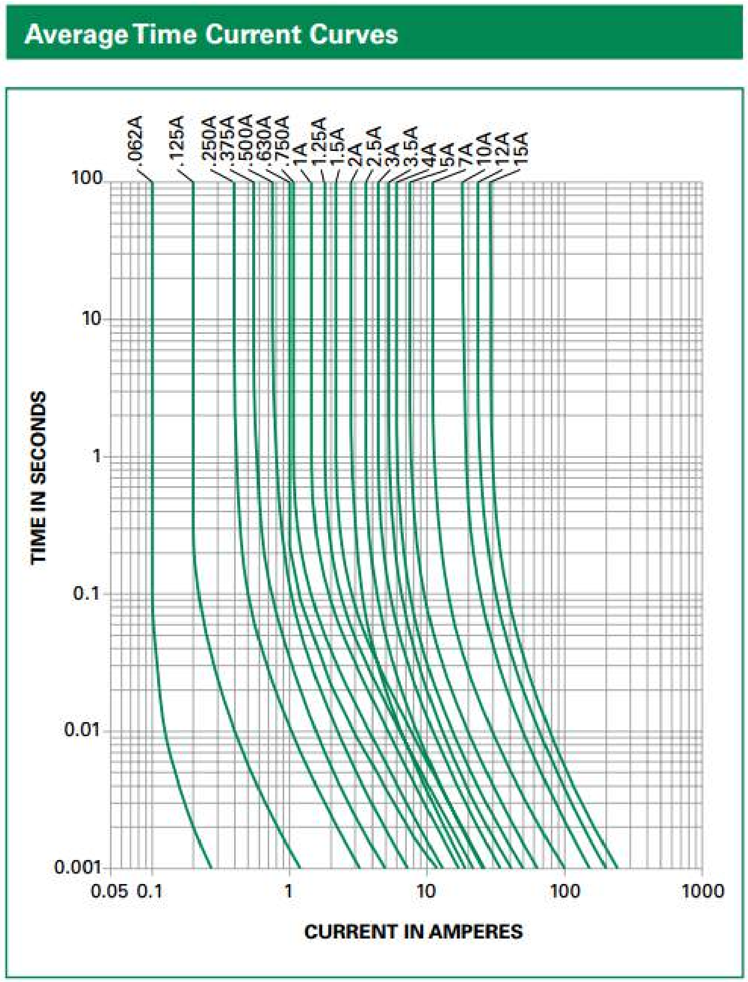


Figure 92: Time-Current curve for 251/253 series 1A TS low current fuse and 3A HV+ sense line Energy meter

All information found from the datasheet of: TS to IMD, TSMP and Lights DC-DC converter, 1A 251/253 Series

Electrical Specifications

CURRENT IN AMPERES

Catalog Number	Ampere Rating (A)	Nominal Cold Resistance (ohm)	Nominal Volt-drop @100% In (Volt) max.	Voltage and Interrupting Ratings	Melting I²T <10 m Sec (A² Sec)	Melting I²T @10 In (A² Sec)	Nominal Power Dissipation @100% In (W)	Agency Approvals		
C1Q 250	250mA	0.85	0.250	See Table of Safety Approvals on Page 1 for Voltage and associated Interrupting Ratings	0.0018	0.0001	0.06	Y		Y
C1Q 375	375mA	0.48	0.222		0.0044	0.0004	0.08	Y		Y
C1Q 500	500mA	0.32	0.195		0.008	0.001	0.10	Y		Y
C1Q 750	750mA	0.175	0.163		0.019	0.002	0.12	Y		Y
C1Q 1	1A	0.124	0.156		0.035	0.004	0.16	Y		Y
C1Q 1.25	1.25A	0.092	0.149		0.057	0.006	0.19	Y		Y
C1Q 1.5	1.5A	0.075	0.142		0.084	0.010	0.21	Y		Y
C1Q 2	2A	0.054	0.140		0.15	0.019	0.28	Y		Y
C1Q 2.5	2.5A	0.042	0.138		0.25	0.032	0.35	Y		Y
C1Q 3	3A	0.035	0.136		0.37	0.050	0.41	Y		Y
C1Q 3.5	3.5A	0.030	0.140		0.53	0.072	0.49	Y		Y
C1Q 4	4A	0.028	0.144		0.67	0.094	0.58	Y		Y
C1Q 5	5A	0.022	0.154		1.10	0.16	0.77	Y		Y
C1Q 7	7A	0.015	0.160		3.10	0.37	1.12		Y	

Consult manufacturer for other ratings

Specifications subject to change without notice

Figure 93: Ratings for C1Q 3A Cell series to AMS fuse

Safety Agency Approvals

SAFETY AGENCY	SAFETY AGENCY CERTIFICATE	VOLTAGE RATING (V)	AMPERE RANGE / VOLT @ I.R. ABILITY*
	LR39772	250mA - 5A / 125V AC 63V DC 7A / 63V AC & DC	250mA - 5A / 125V AC @ 100A 63V DC @ 50A
	E20624		
	E20624		7A / 63V AC & DC @ 50A

* I.R. = INTERRUPTING RATING = SHORT CIRCUIT RATING (AMPS)

Figure 94: Approved Ratings of C1Q series 3A Cell to AMS fuse

Average Time Current Curve

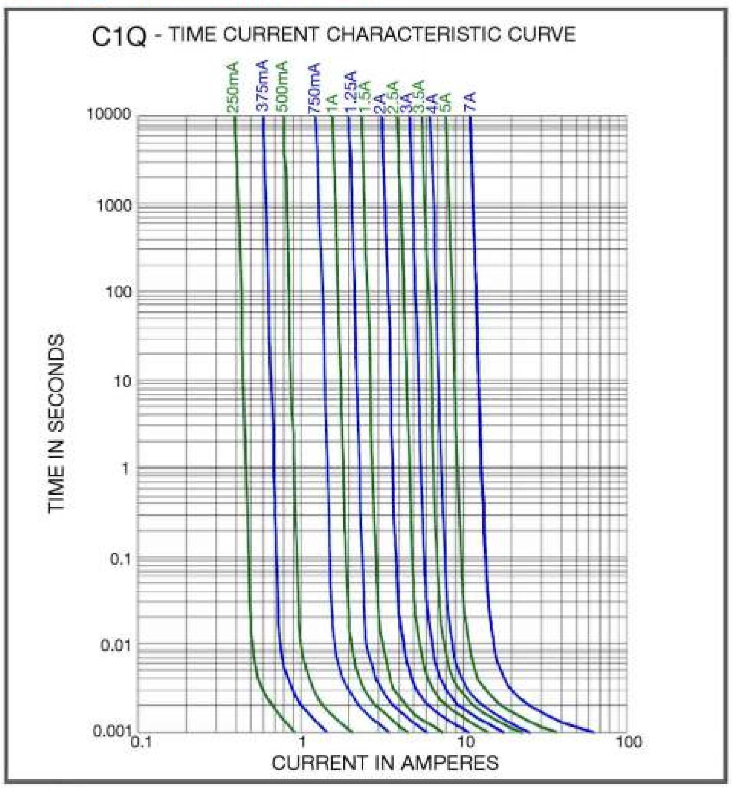


Figure 95: Time-current curve for C1Q series, 3A Cell to AMS fuse

All information found from the datasheet of: Cell to AMS fuse, C1Q type.

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper	Breaking force Soft Annealed Cu 37000 PSI
0000	0.46	11.684	0.049	0.16072	380	302	125 Hz	6120 lbs
000	0.4096	10.40384	0.0618	0.202704	328	239	160 Hz	4860 lbs
00	0.3648	9.26592	0.0779	0.255512	283	190	200 Hz	3860 lbs
0	0.3249	8.25246	0.0983	0.322424	245	150	250 Hz	3060 lbs
1	0.2893	7.34822	0.1239	0.406392	211	119	325 Hz	2430 lbs
2	0.2576	6.54304	0.1563	0.512664	181	94	410 Hz	1930 lbs
3	0.2294	5.82676	0.197	0.64616	158	75	500 Hz	1530 lbs
4	0.2043	5.18922	0.2485	0.81508	135	60	650 Hz	1210 lbs
5	0.1819	4.62026	0.3133	1.027624	118	47	810 Hz	960 lbs
6	0.162	4.1148	0.3951	1.295928	101	37	1100 Hz	760 lbs
7	0.1443	3.66522	0.4982	1.634096	89	30	1300 Hz	605 lbs
8	0.1285	3.2639	0.6282	2.060496	73	24	1650 Hz	480 lbs
9	0.1144	2.90576	0.7921	2.598088	64	19	2050 Hz	380 lbs
10	0.1019	2.58826	0.9989	3.276392	55	15	2600 Hz	314 lbs
11	0.0907	2.30378	1.26	4.1328	47	12	3200 Hz	249 lbs
12	0.0808	2.05232	1.588	5.20864	41	9.3	4150 Hz	197 lbs
13	0.072	1.8288	2.003	6.56984	35	7.4	5300 Hz	150 lbs
14	0.0641	1.62814	2.525	8.282	32	5.9	6700 Hz	119 lbs
15	0.0571	1.45034	3.184	10.44352	28	4.7	8250 Hz	94 lbs
16	0.0508	1.29032	4.016	13.17248	22	3.7	11 k Hz	75 lbs
17	0.0453	1.15062	5.064	16.60992	19	2.9	13 k Hz	59 lbs
18	0.0403	1.02362	6.385	20.9428	16	2.3	17 kHz	47 lbs
19	0.0359	0.91186	8.051	26.40728	14	1.8	21 kHz	37 lbs
20	0.032	0.8128	10.15	33.292	11	1.5	27 kHz	29 lbs
21	0.0285	0.7239	12.8	41.984	9	1.2	33 kHz	23 lbs
22	0.0254	0.64516	16.14	52.9392	7	0.92	42 kHz	18 lbs
23	0.0226	0.57404	20.36	66.7808	4.7	0.729	53 kHz	14.5 lbs
24	0.0201	0.51054	25.67	84.1976	3.5	0.577	68 kHz	11.5 lbs

Figure 96: Power Stream Wire Gauge Chart Reference. Reffered from section 3.1.9

11.3.1.10 Charging

QuiQ 1000 Charger Specifications

DC Output	24 VDC	36 VDC	48 VDC	72 VDC	96 VDC
Maximum DC output power	695 W	875 W	1000 W	1000 W	945 W
Maximum DC output current	25 A	21 A	18 A	12 A	8.5 A
Maximum DC output voltage	34 V	51 V	68 V	100 V	135 V
Deep discharge recovery (minimum voltage)	6 V	9 V	12 V	18 V	24 V
Maximum interlock current	1 A	1 A	1 A	0.5 A	0.5 A
Battery type	Lead acid (Wet / AGM / GEL), lithium ion				
Reverse polarity	Electronic protection with auto-reset				
Short circuit	Electronic current limit				

AC Input	
AC input voltage range	85-265 VAC
Nominal AC input voltage	120 VAC / 230 VAC
Supported AC sources	Single phase
AC input frequency	45-65 Hz
Maximum / nominal AC input current	12 A / 9.5 A @120 VAC; 5 A rms @230 VAC
Nominal AC power factor	>0.99 @ 120 VAC; >0.98 @ 230 VAC

Delta Q Technologies 96VDC charger datasheet.
Algorithm: Constant current at 8.5A to 4.056Vpc, then constant voltage at 4.056Vpc until current tapers to 2A

Description:

Basic protection Class G size-rejecting, current limiting fuses. 1/2 to 6A Fast-acting, 7 to 60A time-delay. Time-delay – 12 seconds (minimum) at 200% of rated current.

Specifications:

Ratings

- Volts
  - 600Vac/170Vdc (½-20A)
  - 480Vac/300Vdc (25-60A)
- Amps 1/2-60A
- IR
  - 100kA Vac RMS Sym.
  - 10kA Vdc

Agency information

- UL® Listed, Std. 248-5, Class G, Guide JDDZ, File E4273
- CSA® Certified, C22.2 No. 248.5, Class 1422-01, File 53787
- CE
- RoHS compliant

Figure 98: Approved Ratings of Bussman SC Class G

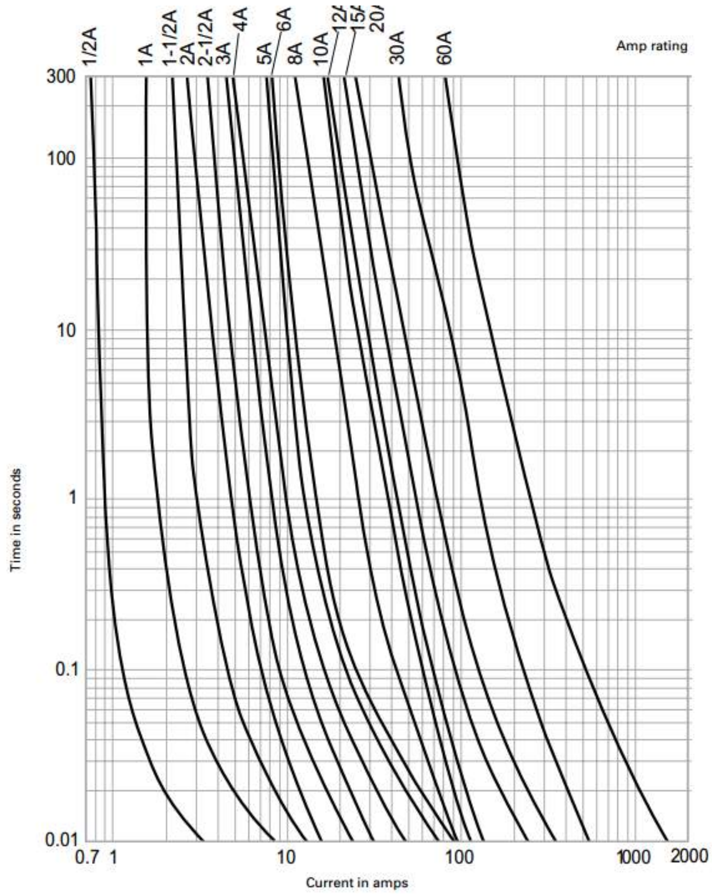


Figure 99: Time-current curve for Bussman SC Class G

All information found from the datasheet of: Cell to AMS fuse, C1Q type.
Charger fuse

11.4.2 Energy Meter Mounting Wiring

Please see section 11 for information on the 3A fuse, as it is the same series and datasheet as the 1A TS low current fuse.

11.5.1 Motor Controller

Motor controller Sevcon Gen 4 Size 4 with battery voltage 96-120V datasheet here.
Sevcon Gen4 Product Manual
Description of Delphi connectors. Delphi Shieldpack HV2000 is the product used for our main connectors (Described on page 32)

11.7 Torque Encoder

Brake light switch datasheet here, part number 3601. Reffered from section 11.

MHR5200 - Electrical & mechanical specification

Input Specification

Supply voltage (Vs)	5.0±10% regulated	8 to 30 unregulated	V DC
Over voltage protection	Up to 50		V DC
Supply current	<15		mA
Reverse polarity protection	Up to -10		VDC
Power on settlement time	<300		mS
Input voltage rise time	0,25 minimum		V/mS

Output Specification

Output type	Analogue		
Output direction	Clockwise or Anticlockwise (specified at time of order)		
Voltage output (Vout)	0-Vs (+5v)	0 - 5,0	V DC
Line regulation	Ratiometric with Vs	<0.01% FS/V	
Monotonic range	1 - 100% measurement range		Vout
Load resistance	>10k		Ohms
Output noise	<5		mV rms

Performance Specification

Measurement angle	20 to 360 ±2 in 1° increments		°
Resolution	0,025		% of measurement angle
Non-Linearity (see note 4)	<±0,25%		FS
Temperature coefficient	<±0,003%	<±0,01%	FS/°C
Update rate	>500 Nsm		Hz
Max operating speed	600		rpm

Figure 100: Important parameters of the MHR5621 Active Sensors Torque Encoder

MHR5621 Active Sensors Torque Encoder datasheet.

11.8.1 LV Part 1: GLV battery

12V to 5V module datasheet here.

Specifications

Interrupting Rating:	1000A @ 32 VDC
Voltage Rating:	32 VDC
Operating Temperature Range:	-40°C to +125°C
Terminals:	Ag plated zinc alloy
Housing Materials:	PA66
Complies with:	Meets SAE J2077 ISO 8820-3 UL 248 Special Purpose Fuses

Figure 101: Ratings for MINI series, 2A Shutdown circuit, GLV 2A 12V fuses and 5A GLV battery fuses

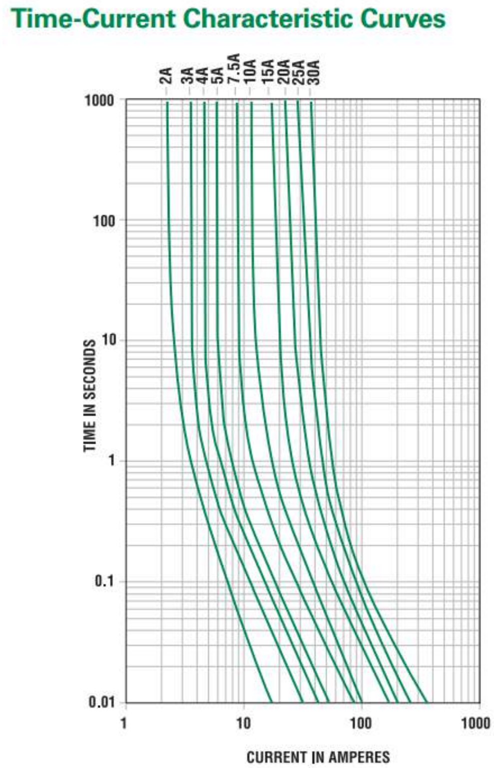


Figure 102: Time-current curve for MINI series, 2A Shutdown circuit, GLV 2A 12V fuses and 5A GLV battery fuses

All information found from the datasheet of: GLV 12V power, Shutdown, and GLV battery circuit fuses, MINI series 2A or 5A

11.8.2 LV Part 2: Dashboard node

.
CAN node microcontroller (ATmega16M1) datasheet here.

0ZCK Series

HF PB 0ZCK Series -0805 Chip — RoHS 6 Compliant & Halogen-Free

Application
All high-density boards

Product Features
0805 Chip Size , Fast Trip Time, Low DCR Resistance

Operating (Hold Current) Range
100mA - 1A

Maximum Voltage
6 - 15V (per table)

Temperature Range
-40ºC to 85ºC

Agency Approval
TUV (Std. EN60738-1-1, Cert. R50102117)
UL Component (Std. UL1434, File E305051)
UL Conditions of Acceptability:
1. These devices have been investigated for use in safety circuits and are suitable as a limiting device.
2. These devices have been calibrated to limit the current to 8 amps within 5 seconds, per ANSI/NFPA 70, "National Electrical Code".

LEAD FREE = PB
HALOGEN FREE = HF

Figure 103: Ratings for the bel Fuse 0zck series 1A 5V per-GLV-board fuse

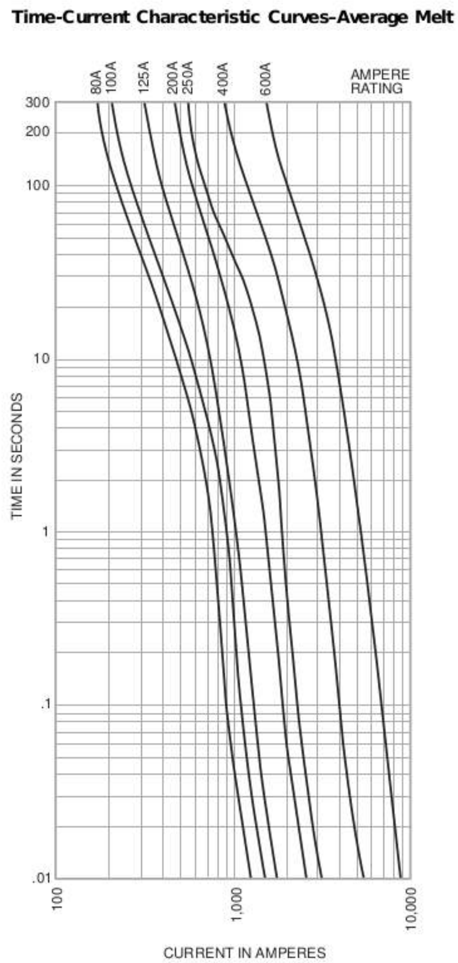


Figure 104: Time-current curve for bel Fuse 0zck series 1A 5V per-GLV-board fuse

All information found from the datasheet of: Full bel Fuse 0ZCK 1A datasheet here.