



Electrical System Form FSAE-E 2017 Car E238

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List of Abbreviations

- MSD- Manual Service Disconnect
- CONN- Main accumulator connector
- APPS- Accelerator Pedal Position Sensor
- AMS/BMS- Accumulator Management System / Battery Management System
- TS+ / TS- - High and Low pole of the tractive system

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 vehicle's electrical system is designed to support all necessary functions of electric vehicle locomotion, while simultaneously ensuring driver and team member safety. The vehicle's electrical system is comprised of two major galvanically isolated subsystems: a 298.8V maximum high power tractive system and a 14V maximum sensing and control system.

The tractive system consists of a custom-designed and fabricated accumulator container which houses 72 LG Chem proprietary pouch cells, as well as a Rinehart Motion Systems PM100DX motor controller driving an Emrax 228 Medium Voltage outrunner motor. Communication to the motor controllers is achieved via the CAN network built into the low voltage system.

The low voltage system consists primarily of a shutdown circuit and a series of peripheral sensors to gather data about vehicle state and performance, all powered by a 12V nominal sealed lead acid battery that is recharged by a DC/DC converter. The Shutdown circuit monitors the vehicle for dangerous conditions such as impacts or isolation faults of the Tractive System, and de-energizes the vehicle in case of emergency. The low voltage system also contains a CAN communication network between Atmel ATmega16m1 microcontrollers that fulfill several rules-required functions like the Ready-to-Drive sound, as well as collecting data and serving as a debugging tool for both high and low power electrical systems.

See figure 1 for a block diagram of the Tractive System and interfacing GLVS parts.

| | |
|------------------------------------|------------------------------------|
| Maximum Tractive system voltage | 298.8 VDC |
| Nominal Tractive system voltage | 266.4 VDC |
| Control-system voltage | 12 VDC |
| Accumulator configuration | 72s1p |
| Total Accumulator capacity | 27 Ah |
| Motor type | permanent magnet synchronous motor |
| Number of motors | 1 |
| Maximum combined motor power in kW | 100 kW |

Table 1.1: General parameters

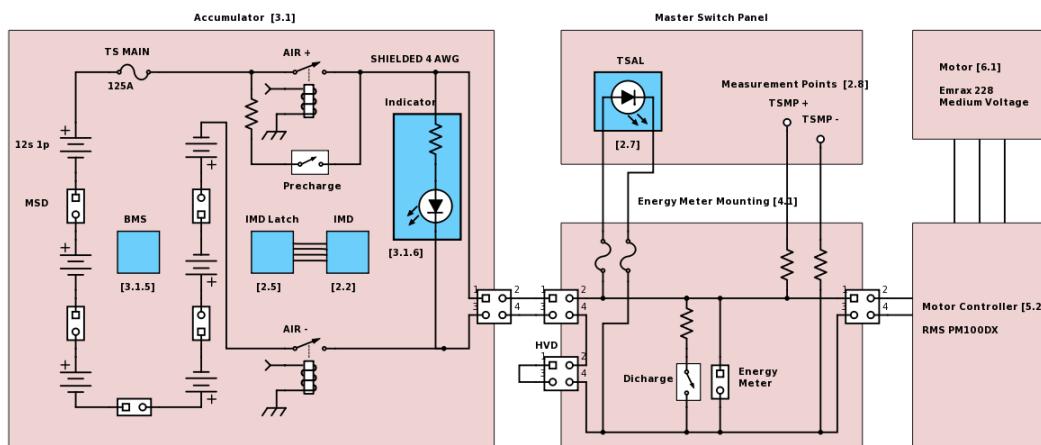


Figure 1: Block diagram of the enclosures of the Tractive System

2 Electrical Systems

2.1 Shutdown Circuit

2.1.1 Description/ concept

The shutdown circuit directly controls the current that closes the AIRs. Since each switch/relay on the shutdown circuit is connected in series, that current must pass through every switch and safety check. If any device on the circuit is triggered by an unsafe condition, the current to the AIRs is cut off and the AIRs open, disconnecting the accumulator from the tractive system. Any capacitive load on the tractive system outside the accumulator is then discharged to ensure that all high voltage is contained inside the accumulator.

- The GLV Master Switch (GLVMS) controls power to the entire low voltage system including the AIRs. As a result, high voltage cannot be present when the low voltage system is not active. The GLVMS has a lockout such that the vehicle can be safely worked on.
- The Left E-Stop is a large red push-rotate button located at approximately the height of the driver's head on the left side of the vehicle.
- The Right E-Stop is identical to the Left E-Stop located on the other side of the vehicle.
- The Brake System Plausibility Device (BSPD) holds a normally open relay closed when it has not detected an implausibility. When it does detect an implausibility, it latches in a low state until the GLV system is power cycled. This shuts down the Tractive System in the event that the brake is pressed while the motors are being significantly driven.
- The Brake Over Travel Switch (BOTS) is a push pull switch located behind the brake pedal. If the pedal over travels, the switch is pushed into an open state and stays that way until it is pulled back into the closed state. This shuts down the Tractive System in the event that brake pressure is lost.
- The Dashboard E-stop functions the same as the other E-stops. It is located such that it can be easily pressed by the driver.
- The Inertia Switch operates as a crash sensor that opens the shutdown circuit in the event that it detects an acceleration indicative of a collision. This ensures that the vehicle is electrically safe in an emergency situation.
- The Battery Management System (BMS) monitors the condition of the accumulator. It holds a normally open relay closed while the lithium cells are operating within safe temperature and electrical conditions.
- The Insulation Monitoring Device (IMD) detects any loss of isolation between the Tractive and GLV systems. Its output is held high while isolation is maintained. This holds a normally open relay closed through a latching circuit that prevents the IMD from re-closing the relay if the output goes low and then returns high. This latches the Tractive System in a shutdown state until the GLV system is power cycled.
- The HVD interlock closes the shutdown circuit whenever the HVD is present. This automatically shuts down the Tractive System whenever the HVD is removed.
- There is an interlock on the Tractive System connector on the accumulator which can be removed without tools. If the connector is removed, the Tractive System automatically shuts down.
- The Tractive System Master Switch (TSMS) is the last switch in the shutdown circuit before the AIRs. It has a lockout such that the vehicle can be safely worked on.
- Both the Pre-charge Relay and positive pole AIR have software controlled MOSFETs in series after them such that the timing of the pre-charge can be controlled by the sensing system.

| Part | Function |
|---|-------------------------------------|
| GLV Main Switch (GLVMS) | Normally open, with lockout |
| Shutdown buttons (SDB) (Left, right, cockpit) | Normally closed |
| Brake System Plausibility Device (BSPD) | Normally Open |
| Brake over travel switch (BOTS) | Push-pull normally closed button |
| Inertia switch | Normally closed |
| Battery Management System (AMS) | Normally open |
| Insulation Monitoring Device (IMD) | Normally open |
| Interlocks | Closed when TS connections are made |
| Tractive System Main Switch (SMS) | Normally open, with lockout |

Table 2.1: List of switches in the shutdown circuit

2.1.2 Wiring / additional circuitry

Figure 2 on the following page shows the wiring of the shutdown circuit except the interlocks, which are detailed in section 2.6. The AIRs can only be closed and the tractive system energized when all of the elements of the shutdown circuit are closed. The shutdown circuit is expected to handle a maximum peak current of under 8A, so the wire gauge being used is 20AWG, protected by an appropriately-rated circuit breaker that is housed in the master switch panel.

| | |
|---|--|
| Total Number of AIRs: | 2 |
| Current per AIR | 3.9A peak while closing, 0.23 A average |
| Additional parts consumption within the shutdown circuit: | 0.067 A (pre-charge and discharge relays) |
| Total current: | 7.867 A peak (everything closing simultaneously) |
| Cross sectional area of the wiring used: | 0.52 mm ² (20 AWG) |

Table 2.2: Wiring- Shutdown Circuit

2.1.3 Position in car

The shutdown circuit passes through five major enclosures on the vehicle. It originates in the master switch panel, then passes through the BSPD in the bulkhead enclosure, then through the cockpit E-stop in the dashboard, and into the IMD and the BMS latches in the accumulator, finally going to the AIRs and out to the discharge circuit in the energy meter enclosure. It also passes through the side E-stop switches along the way.

The shutdown circuit is wired between enclosures through waterproof TE Ampseal automotive connectors, is wrapped in abrasion-resistant mesh, and positively retained to chassis members with zip ties. Low voltage wiring is independently retained from high voltage wiring, and a minimum of 30mm separation is maintained.

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 detects an isolation fault. The output is then sent to the IMD latch board, where it powers a SPST-NO relay which closes a switch in the shutdown circuit. The output of the IMD is also monitored directly by an Atmega on the AIR control board. The status of the shutdown circuit is monitored by the MSP board. If the MSP board detects the relay is open it activates the IMD light. The IMD has a start up time of $\leq 2\text{s}$. Further information on the IMD can be found in the appendix, section 11.2.2.

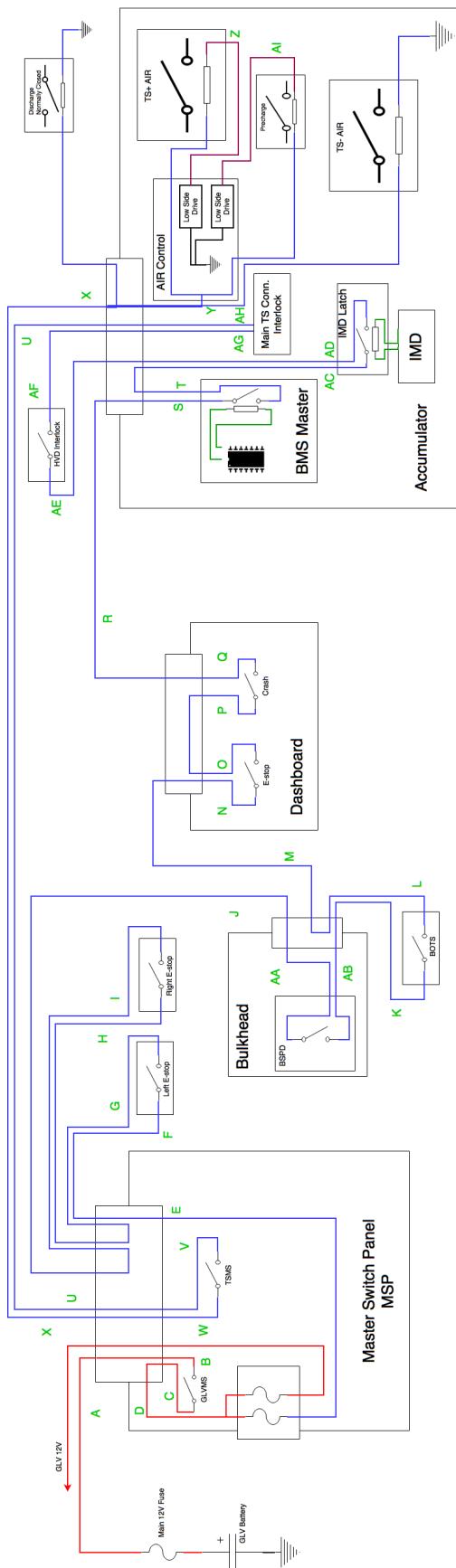


Figure 2: Block Diagram of Shutdown Circuit

| | |
|---|---|
| Supply voltage range: | 10..36VDC |
| Supply voltage: | 12VDC |
| Environmental temperature range: | -40..105°C |
| Selftest interval: | Always at startup, then every 5 minutes |
| High voltage range: | DC 0..1000V |
| Set response value: | 100kΩ |
| Max. operation current: | 150mA |
| Approximate time to shut down at 50% of the response value: | ≤ 40s |

Table 2.3: Parameters of the IMD

2.2.2 Wiring/cables/connectors/

The IMD uses the TYCO-MICRO MATE-N-LOK 1 x 2-1445088-8 connector and its mate. It connects to the IMD latch using 5-pin Molex LLC 1722861105 connectors. The signal is also sent to the accumulator interface board using the same type of connectors. The 18 AWG wire is more than sufficient for 150mA current draw of the IMD. The 18 AWG ribbon cable has a cross sectional area of .83mm², and is rated for at least 90°C, 300 V, and 16 amps. There is a 1 amp fuse protecting the high voltage wiring of the IMD, which is the same as the TSAL fuse in section 2.7.

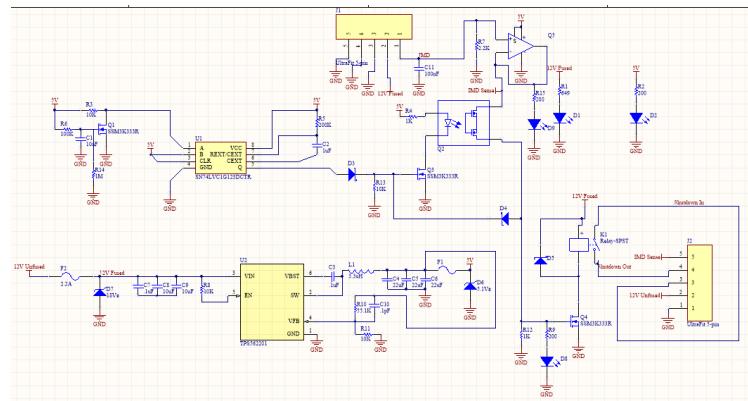


Figure 3: The schematic for the IMD Latch.

The IMD latch shown in figure 3 uses the signal from the IMD to close a relay in the shutdown circuit. In order for the shutdown relay to close a second relay needs to be closed. The second relay is initially powered by a one shot 4 second pulse from the GLV system. After the first four seconds the signal from the IMD is used to keep the secondary relay closed. If the IMD signal goes low the secondary relay will open. This opens the shutdown relay and makes it impossible for the IMD to close the shutdown relay again until the latch has been manually reset. The initial 4 second pulse is necessary to ensure that anomalous start up behavior from the IMD does not cause the secondary relay to open and force a manual reset.

2.2.3 Position in car

The IMD will be located inside the accumulator, as shown in figure 27 on page 28. 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 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 characteristics | Operate above 11g peak, 60ms duration Not operate below 6g peak, 60ms duration |

Table 2.4: Parameters of the Inertia Switch

2.3.2 Wiring/cables/connectors/

The Inertia switch will be wired to 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 on page 4 for the position of the inertia switch relative to the other shutdown system components.

2.3.3 Position in car

The inertia switch will be located on the side of the dashboard enclosure. It is mounted upwards, so the top body panel will have to be temporarily removed to reset it, as seen in figure 4.

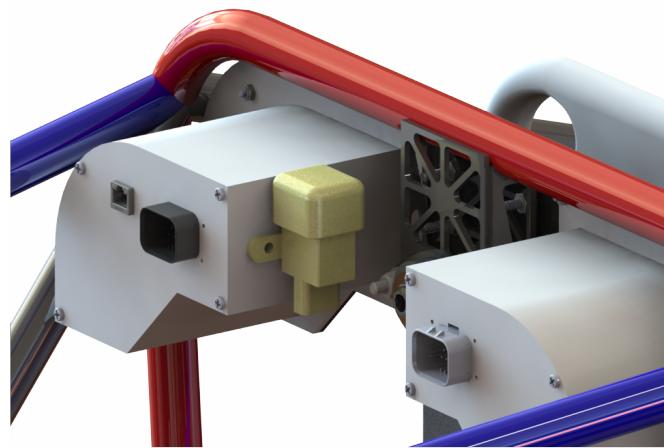


Figure 4: Positioning of the inertia switch alongside the dashboard enclosure

2.4 Brake Plausibility Device (BSPD)

2.4.1 Description/additional circuitry

The Brake System Plausibility Device (BSPD) is a custom circuit designed to open a relay in the shutdown circuit if the brakes are being pressed while there is positive-current being delivered to the motors for more than 0.5 seconds. The custom circuit takes in two digital signals, the brake signal and a boolean yes/no whether or not positive-current is being delivered to the motor. The positive-current will be sensed with our BMS using a hall-effect current sensor and a comparator which will output high when positive-current is being delivered to the motors.

There are two main sections to the circuit: the timing section and the latching section. The timing section consists of a 555-timer in monostable mode which is configured to be powered from the output of an AND-gate which takes in both the brake signal and the positive-current signal. This 555-timer will output a high pulse if the AND gate outputs a high voltage for more than 0.5 seconds.

The latching section of the circuit is a simple SR-latch, which will hold the relay open when tripped by the timing section. It will remain in this state until a reset signal is given, which will be from an ATmega. This reset signal will only be done when the GLV system is first powered on, thus making it non-driver resettable.

The schematic can be seen in figure 5 on the next page.

| | |
|------------------------------|---------------------------------------|
| Brake sensor used: | Pegasus Brake Light switch, part 3601 |
| Torque encoder used: | Magni-Tec MHR5621 |
| Supply voltages: | 5V |
| Maximum supply currents: | 15 mA |
| Operating temperature: | -55 to 150°C |
| Output used to control AIRs: | Opens a relay |

Table 2.5: Torque Encoder Data

2.4.2 Wiring

The output of the BSPD circuit will low-side drive a relay in series with the shutdown circuit. This board has not been fully designed, but it will utilize components common across other circuits.

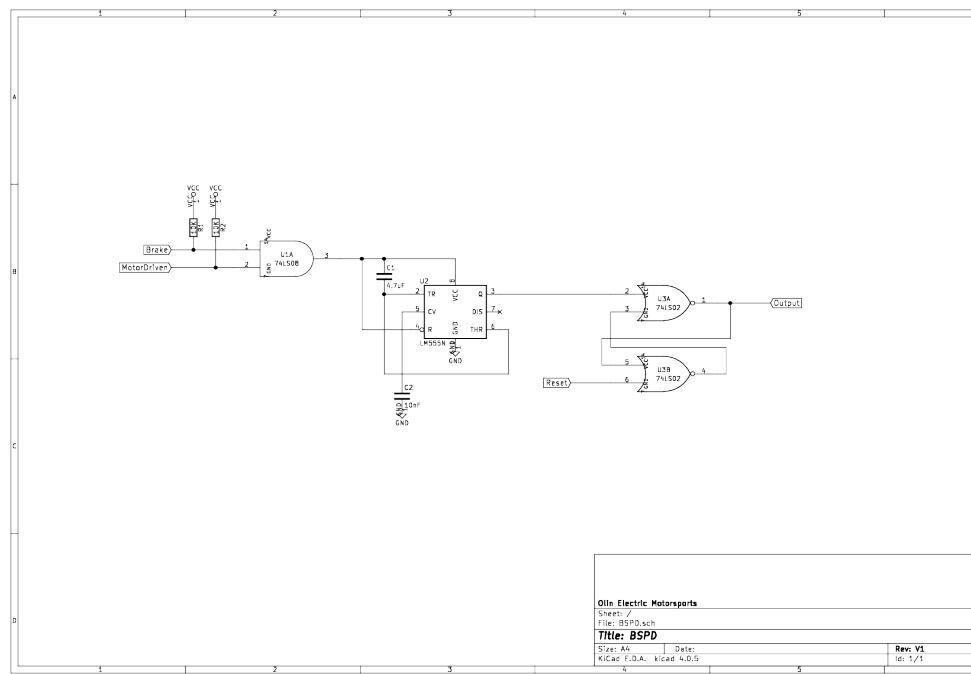


Figure 5: Schematic for BSPD circuit

2.4.3 Position in car/mechanical fastening/mechanical connection

This board is located in the bulkhead enclosure at the front of the car.

2.5 Reset / Latching for IMD and BMS

2.5.1 Description/circuitry

Resetting the IMD latch, which is shown in figure 3 on page 5 , requires restarting the GLV system. Restarting the GLV system will cause the IMD latch to send a pulse. If the output of the IMD is high because there is no ground fault, the pulse from the GLV activation will close the secondary relay, which allows the signal from the IMD to close the shutdown circuit.

The BMS is latched with identical circuitry to the IMD, as shown in figure 3 on page 5, and is also reset by a GLVS power cycle. The BMS latch circuitry, however, will be on the master BMS PCB in the accumulator, and will control a separate on-board relay to open the shutdown circuit. In the case that the BMS detects a fault in cell temperature or voltage that requires a vehicle shutdown, the ATmega16m1 on the board will pull the BMS latch output pin low, latching the BMS latch circuit into a low state and opening the shutdown circuit. The master BMS will also serve as a CAN network monitor, and if another node in the vehicle detects a fault condition that requires vehicle shutdown that is not rules-required to be analog circuitry, that node will send a shutdown message to the master BMS that will open the shutdown circuit.

2.5.2 Wiring/cables/connectors

The IMD latch will be connected to the accumulator interface board board via a 5-pin Molex LLC Ultrafit 1722861105 with 18 AWG wire, and the IMD connector using another 5-pin Molex LLC Ultrafit of the same type. The 18 AWG wire has a cross sectional area of .83mm², and is rated for at least 90°C, 300 V, and 16 amps. This provides a considerable safety margin. The ribbon cable carries signals from the IMD. 18 AWG

wire is used for the shutdown circuit and to supply power and ground to the IMD latch. The 18 AWG wire has a cross sectional area of .83mm², and is rated for 16 amps for chassis wiring and 2.3 amps for power transmission. The 18 wire will be rated for at least 90°C and 300 V, as required by the rules for wiring in the accumulator (see EV3.3.8 and EV4.5.4).

Similarly to the IMD latch, the BMS latch will be housed in the accumulator, and thus all of the shutdown circuit connections to and from it will be made with 18AWG wire rated to over 300V and 90°C in order to handle the maximum of 8A inrush current to the AIRs and maintain compliance with accumulator wiring regulations. PCB traces will also be appropriately sized to handle 8A peak current.

2.5.3 Position in car

The IMD, IMD latch, and the BMS are in the accumulator, as shown in figure 27 on page 28. BMS is positioned there for ease of access to the battery, and the IMD latch is positioned there in order to be close to the IMD, which is located in the accumulator for continual monitoring of pack isolation while the accumulator is removed for charging.

2.6 Shutdown System Interlocks

2.6.1 Description/circuitry

The vehicle's tractive system connectors are all lever action locking connectors from the TE Connectivity HVP 800 series. Their arrangement in the tractive system can be seen in figure 6. These connectors can be removed without tools. In compliance with EV 3.3.6, these connectors all contain an interlock that opens the shutdown circuit when they are not installed.

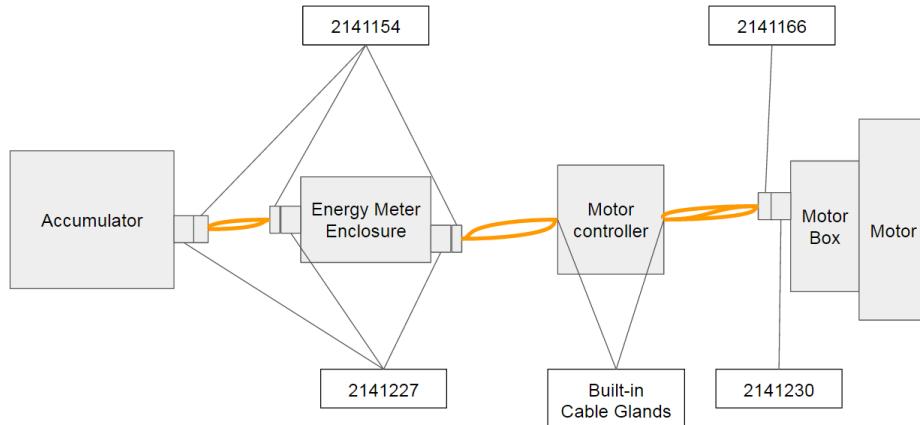


Figure 6: Diagram of HV connectors in the tractive system. They are labelled with TE Connectivity part numbers.

In order to close the shutdown circuit during charging when the accumulator is removed from the vehicle, a connection must be made that overrides the interlocks in the HV connectors that remain with the vehicle. Our solution is a shunt in the LV charging connector that bypasses the circuit that normally connects to the energy meter, HVD, and motor connector interlocks. The main accumulator connector interlock is still required to close the shutdown circuit, so EV 3.3.6 compliance is maintained. A schematic of this interlock circuitry can be seen in figure 7 on the following page.

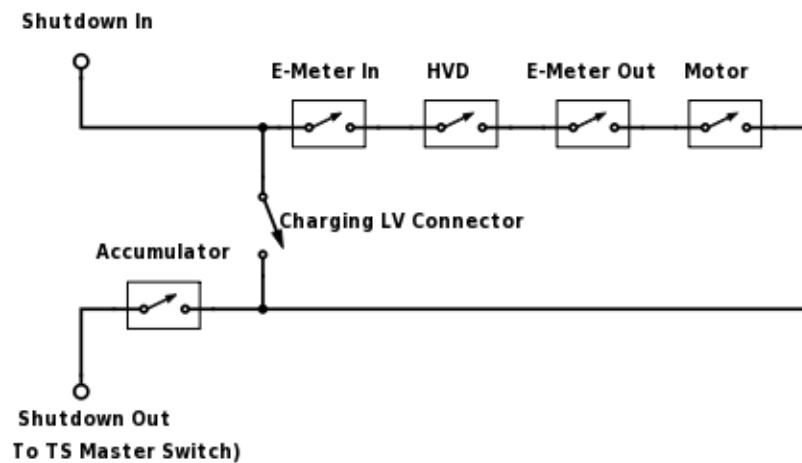


Figure 7: Schematic of the HV interlocks in the vehicle. Note the LV connector that allows the shutdown circuit to close the AIRs when the vehicle is charging.

2.6.2 Wiring/cables/connectors

The shutdown circuit interlock wires will be 20 or 22 AWG and rated to over 300V and 90°C and are protected by the main shutdown circuit breaker as in section 2.1.2 on page 3.

2.6.3 Position in car

Interlocks are built in to each HV connector. The connectors are panel-mounted to the accumulator housing, the energy meter housing, and the motor housing. See the render of the rear of the car in figure 8.

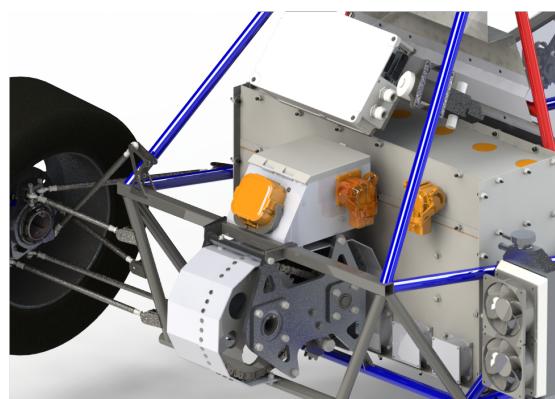


Figure 8: Render of the rear of the vehicle showing location of HV connectors. Connectors are highlighted in orange.

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.

| | |
|---------------------------------|-------------|
| Supply voltage: | 12V |
| Max. operational current: | 1.2A |
| Lamp type: | LEDs |
| Power consumption: | 14.4W (max) |
| Brightness: | Unknown |
| Frequency: | 2 Hz |
| Size (length x height x width): | 41x41x32 mm |

Table 2.6: Parameters of the TSAL

See the appendix here for a link to the TSAL Datasheet.

2.7.2 Wiring/cables/connectors

The circuitry designed has a TS-controlled digital isolator whose power is supplied by the TS through two linear voltage regulators. When the TS is over 60V, a voltage divider with resistors of 30.1K and 1.91K causes the digital isolator to go logic high which allows the down regulated GLV to switch on the MOSFET allowing current to flow through the TSAL low side drive. The frequency of the TSAL will be controlled by built in settings to flash at 2Hz. See figure 9 for a schematic diagram of the TSAL circuit.

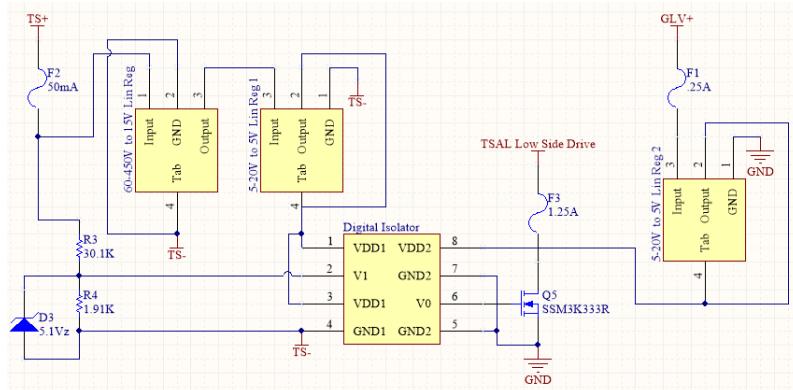


Figure 9: Schematic for the TSAL

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 be fused to 50mA. The GLV voltage will be fused to 25A on the supply line for the digital isolator and 1.25A on the power line for the TSAL with traces of at least 60 mil, able to handle 1.5A of current due to the 1.2A max current draw of the TSAL.

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 4.12.3 and 4.12.4 using a robust 3D printed (Kevlar reinforced Nylon) bracket integrating the light and necessary wiring. This enclosure has not been designed yet. The PCB will be located in the master switch panel enclosure.

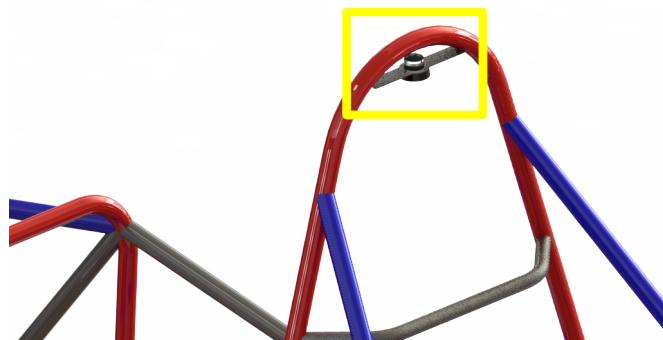


Figure 10: CAD rendering of TSAL position under apex of main roll hoop

2.8 Measurement points

2.8.1 Description

The TSMPs and GLVS ground measurement points are located on the master switch panel on the side of the vehicle, which also houses the TSAL circuitry in section 2.7. They will be a set of three clearly labeled and easily accessible shrouded banana jack connectors with hinged panel-mount covers to prevent any unintentional contact. These are visible in figure 12 on page 14. The measurement points provide a means for safe measurement of the tractive system potential, a secondary manual method for detecting isolation faults, and a reference point for system grounding measurements.

2.8.2 Wiring, connectors, cables

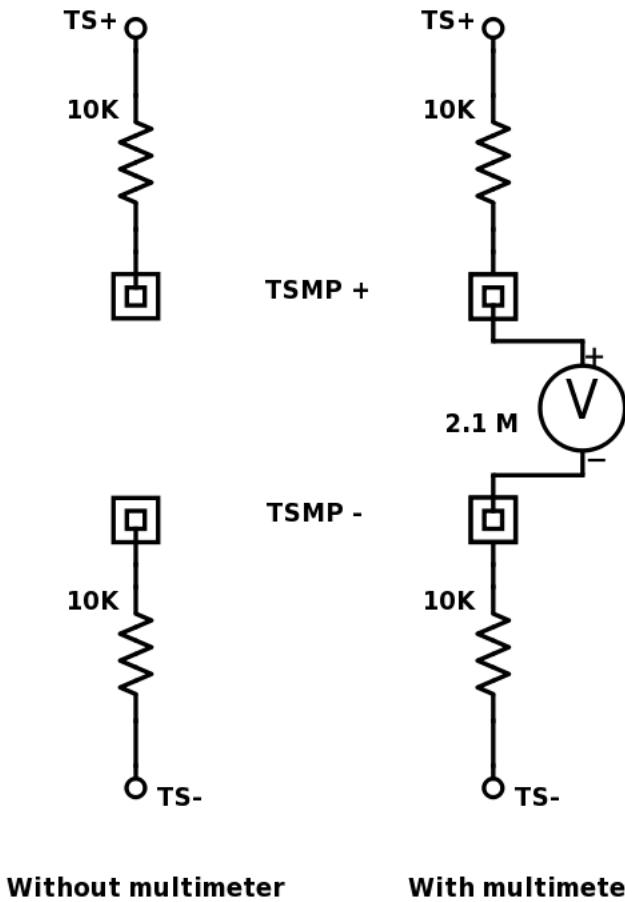


Figure 11: Schematic of TSMP wiring, illustrating the circuit with and without the multimeter, showing the protection resistors and the approximate expected resistance of the multimeter.

There are **four** measurement points: HV+, HV-, **GLVS+**, and GLVS chassis ground. The HV TSMP connections will be protected with **10kΩ** current-limiting resistors. These resistors limit the maximum fault current (a short circuit between the measurement points) in accordance with EV4.4.6.

$$\begin{aligned}
 V &= I * R \\
 300V &= I * 20,000\Omega \\
 I &= 0.015A
 \end{aligned}$$

$$\begin{aligned}
 P &= I * V \\
 P &= 0.015A * 300V \\
 P &= 4.5W
 \end{aligned}$$

According to the above calculations, the resistors will have to be rated to at least 5W and 300V. We will be using Vishay PAC500001002FAC000 10k 5W resistors. The datasheets for the resistors, the connectors, and an example multimeter can be found in section 11.2.8 on page 55.

The TSMPs are protected with current-limiting resistors because protecting the wires with fuses introduces the failure mode in which one of the fuses has blown, and a measurement across the TSMPs shows an open circuit even though the tractive system is still energized.

In case of gross operator error that results in connecting a multimeter from a TS measurement point to the GLVS ground measurement point, the IMD will detect a loss of isolation and open the shutdown circuit.

2.8.3 Position in car

The TSMPs will be located in the master switch panel enclosure shown in figure 12 along with TSAL circuitry. The housing will be made of non-conductive material, and proper spacing between TS measurement point wiring and any part of the GLVS of 30mm through air will be maintained in accordance with EV 4.1.5.

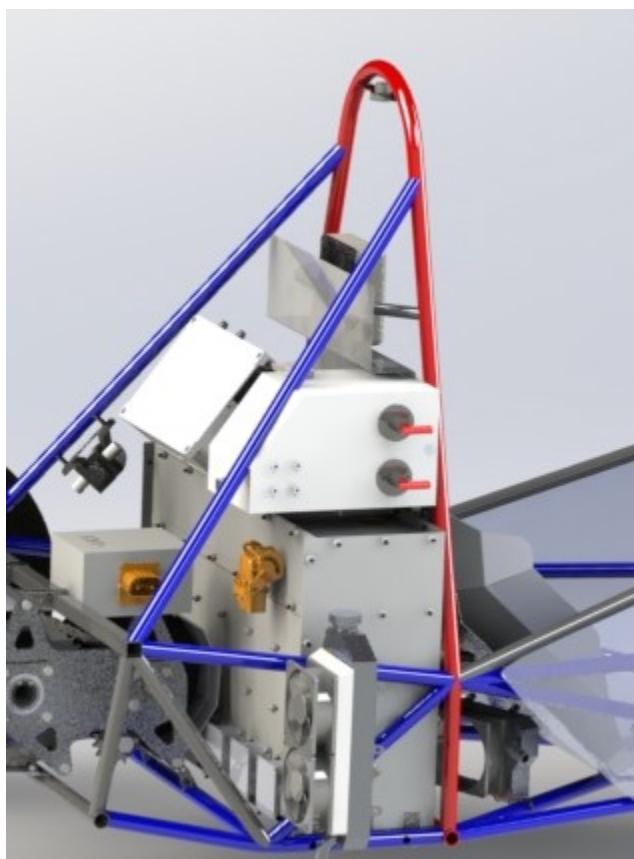


Figure 12: CAD rendering of the master switch panel showing TS and GLVS master switches, and TS and GLVS ground measurement points. This current render has the enclosure protruding from the chassis envelope, but the enclosures team is currently redesigning the face of the master switch panel to be flush with the chassis members.

2.9 Pre-Charge circuitry

2.9.1 Description

In order to prevent inrush current that could damage the motor controller or AIRs, and to comply with EV4.11.1, our pre-charge circuit slowly charges the capacitive load of the motor controller through a power limiting

resistor before closing the TS+ AIR. When the shutdown circuit closes, the TS- AIR is immediately closed, but the software controlled MOSFETs seen in figure 13 will prevent the pre-charge relay and TS+ AIR from closing. After a short delay, the pre-charge relay is allowed to close. This delay is included to allow detection of a welded pre-charge relay. The motor controller tracks its pre-charge state, and signals over the CAN network to allow the TS+ AIR to close when pre-charge is complete.

2.9.2 Wiring, cables, current calculations, connectors

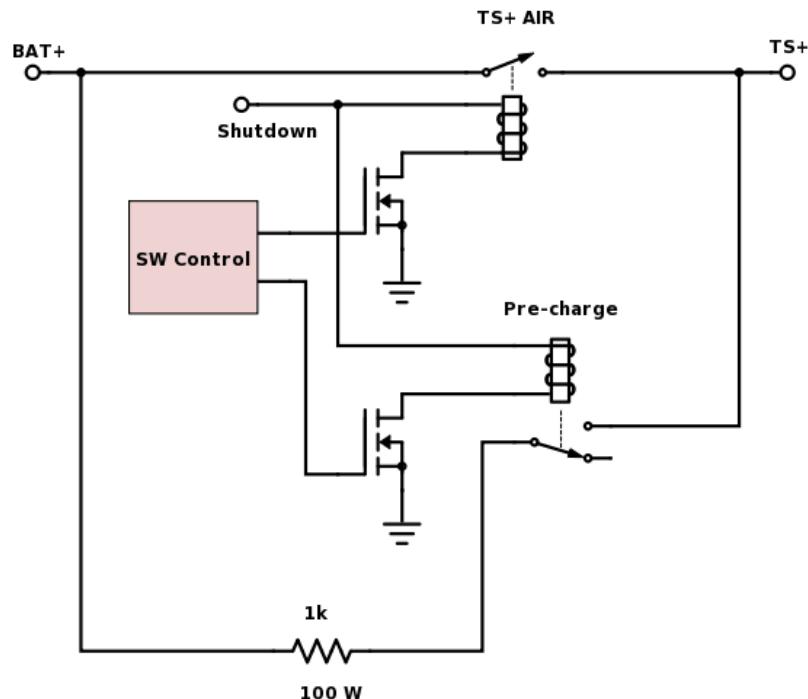


Figure 13: Schematic of the pre-charge circuit. Although the TS+ AIR and pre-charge relay are software controlled, the circuit is designed such that they cannot close if the shutdown circuit is open.

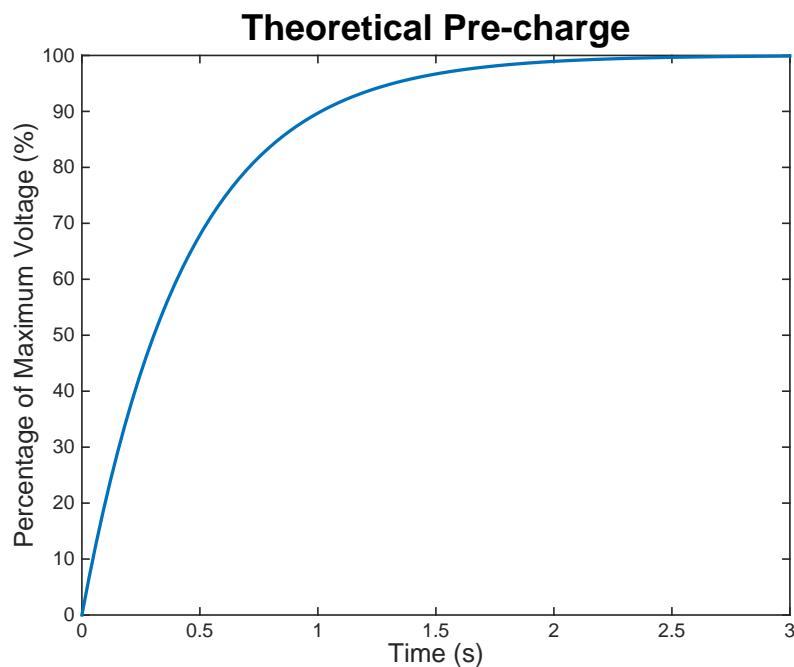


Figure 14: Theoretical pre-charge of the $440\mu\text{F}$ motor controller capacitance using a $1k\Omega$ resistor. This plot was created using the equation, $V(t) = V_{BAT}(1 - e^{-t/RC})$ where V_{BAT} is our maximum pack voltage of just under 300VDC. Our motor controller is expecting an approximately 95% pre-charge within 3 seconds, so this circuit covers the needs of our motor controller and is in compliance with EV4.11.1

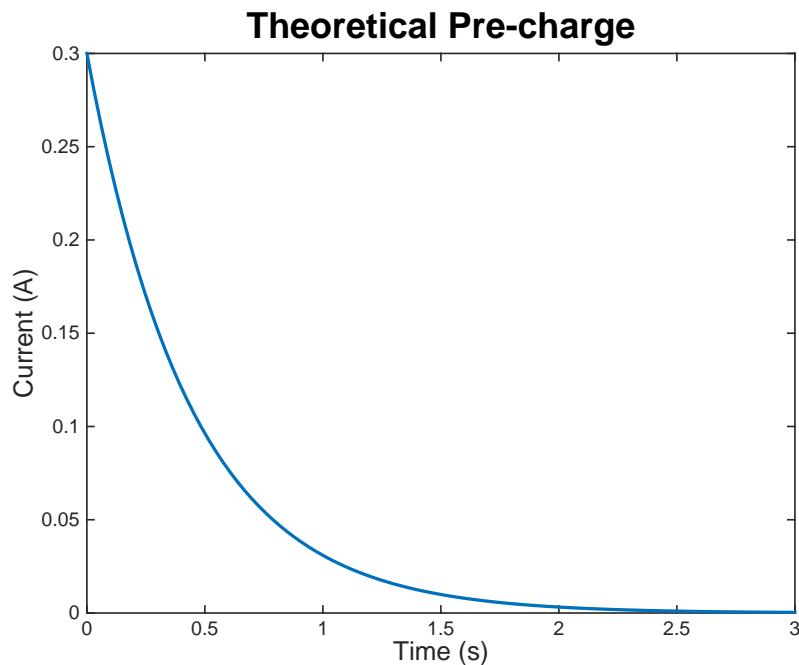


Figure 15: The current of the theoretical pre-charge from figure 14 on the previous page. This plot was created using the equation $I(t) = \frac{V(t)}{R}$ where $V(t)$ is the voltage across the pre-charge resistor found by the equation $V(t) = V_{BAT} * e^{-t/RC}$

| | |
|-----------------------------------|-----------------------------------|
| Resistor type | Riedon PF2470 Power Film Resistor |
| Resistance | $1\ k\Omega$ |
| Continuous power rating | 100 W |
| Overload power rating | 140 W |
| Voltage rating | 700 V |
| Cross-sectional area of wire used | 0.83mm ² (18 AWG) |

Table 2.7: General data of pre-charge resistor

| | |
|-----------------------------------|------------------------------|
| Relay type | Omron G2RL-1-E DC12 |
| Contact arrangement | SPDT |
| Continuous DC current | 16A |
| Voltage rating | 300VDC |
| Cross-sectional area of wire used | 0.83mm ² (18 AWG) |

Table 2.8: General data of the pre-charge relay

2.9.3 Position in car

The pre-charge circuit will be located within the accumulator. ~~The precharge circuitry will be located on the AIR control PCB in the top section of the accumulator, as described in section 3.1.11.~~

2.10 Discharge circuitry

2.10.1 Description

When the car is shut down, and the AIRs have disconnected the accumulator from the rest of the tractive system, there is still energy stored in the capacitive load of tractive system components like the motor controller that could be harmful to the driver, team members, or first responders. The discharge circuit dissipates the energy found on the vehicle side of the tractive system after a shutdown. The circuit is designed to operate even if the vehicle loses all power. When the shutdown circuit is opened, the normally closed discharge relay connects a power resistor across the two poles of the tractive system.

2.10.2 Wiring, cables, current calculations, connectors

Since the power resistor limits the current on the discharge circuit, a fuse is not needed to protect the wiring. It is also dangerous for the discharge circuit to not operate if a fuse were to blow.

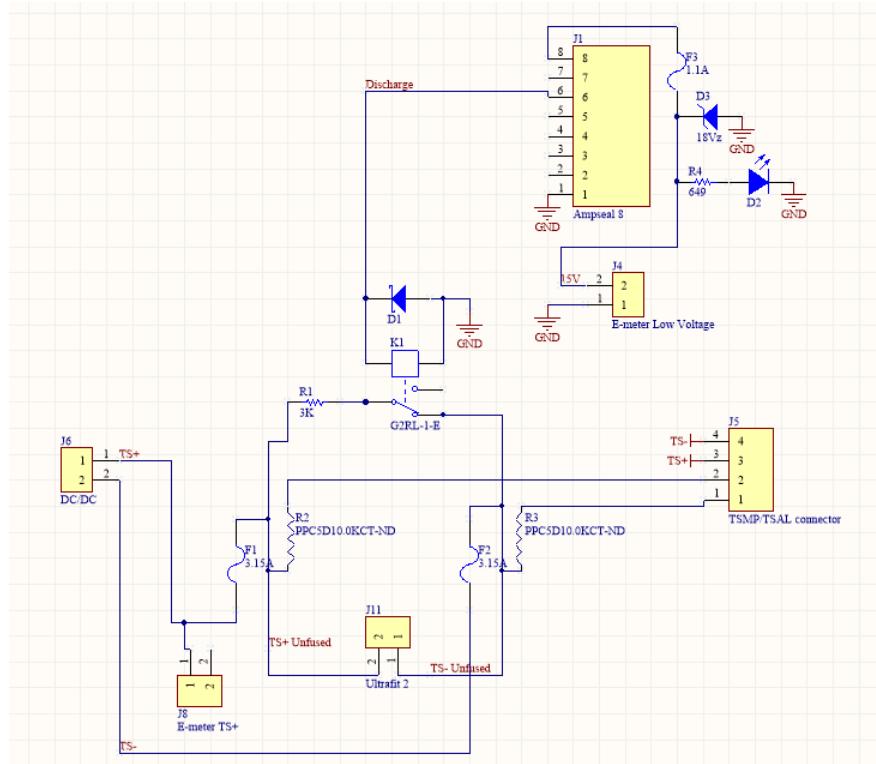


Figure 16: Schematic of the discharge system. The wiring for the TSMPs, TSAL power, and E-meter connections are also visible.

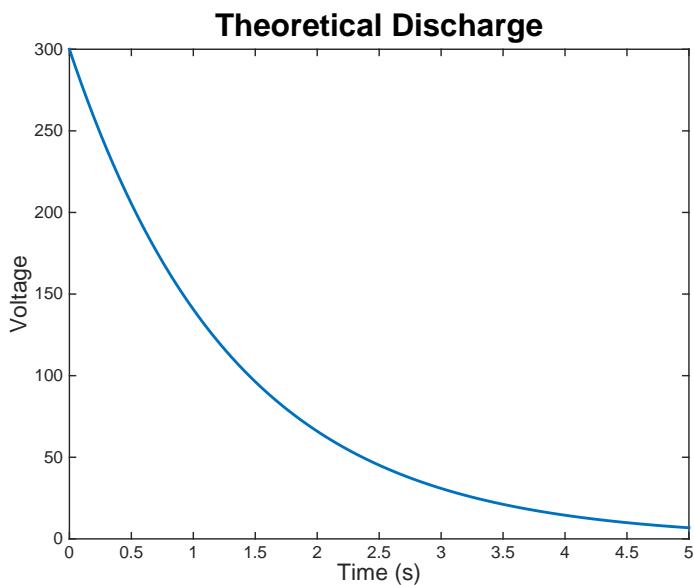


Figure 17: Theoretical discharge of the $440 \mu F$ capacitive load of the motor controller across the $3 k\Omega$ resistor. This was calculated using the equation $V(t) = V_0 * e^{-t/RC}$.

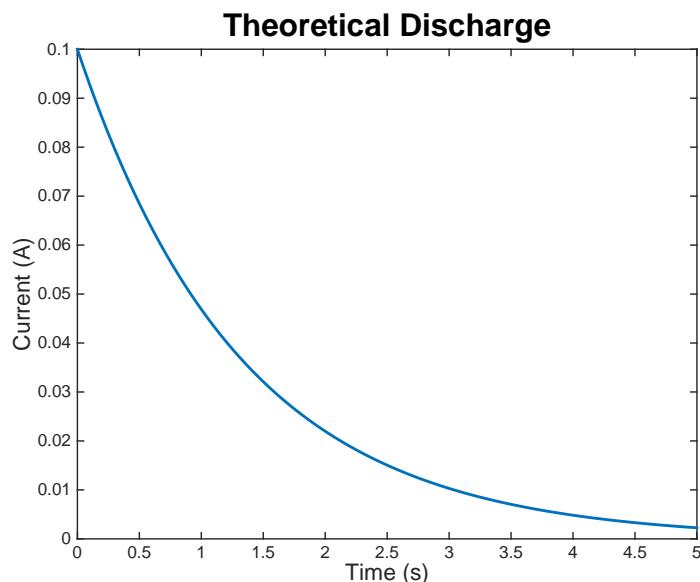


Figure 18: Current of the theoretical discharge from figure 17 on the previous page. This was computed using the voltage exponential and the equation $I = \frac{V}{R}$.

| | |
|---------------------------------------|-------------------------------------|
| Resistor type | Ohmite AP101 TO-247-2 |
| Resistance | 3 kΩ |
| Continuous power rating | 100 W |
| Overload power rating | 1.5 times rated power for 5 seconds |
| Maximum expected current | 0.1 A |
| Average current | 0.0261 A |
| Cross-sectional area of the wire used | 0.83 mm ² (18 AWG) |

Table 2.9: General data of the discharge circuit

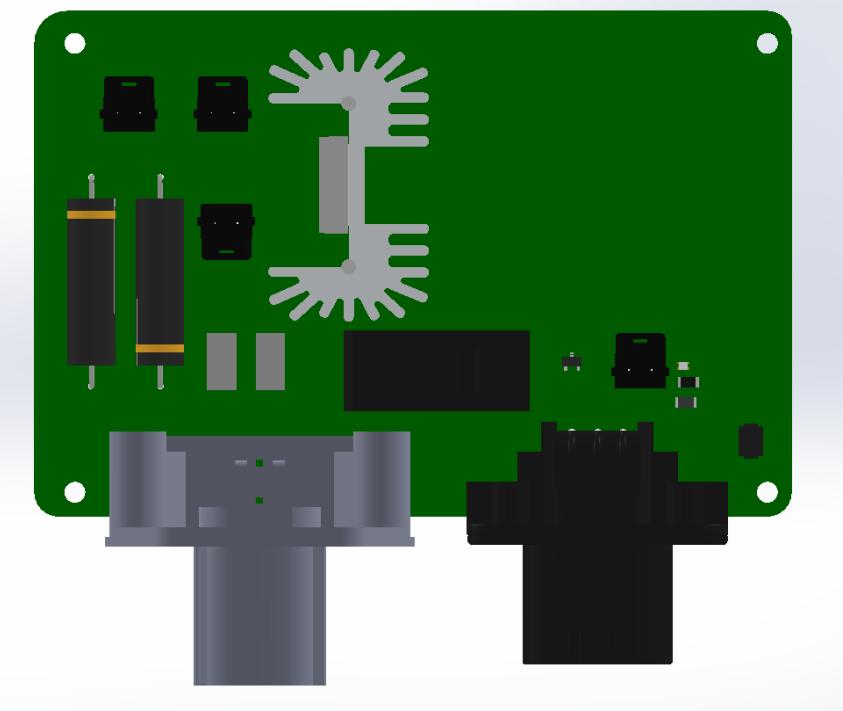


Figure 19: Render of the discharge circuit PCB. The discharge resistor is a TO-247 package mounted to a heatsink.

As shown in figure 19 the discharge resistor is mounted to an Ohmite RA-T2X-25E heatsink. Figure 20 shows the modeled temperature of the discharge resistor under the maximum continuous discharge current for 15 seconds. This temperature curve was computed using the equation,

$$\Delta T = \frac{(P_{in} - P_{out})\Delta t}{m * C_p} \quad (1)$$

Where P_{out} is the power dissipation of the heatsink given by,

$$P_{out} = \frac{1}{R_{therm}}(T - T_{amb}), \quad (2)$$

P_{in} is the power generated by the resistor, Δt is the time step of the simulation, m is the mass of the heatsink in kg, C_p is the specific heat of aluminum, R_{therm} is the thermal resistance of the heatsink under natural convection in $\frac{^{\circ}C}{W}$, T is the temperature of the heatsink, and T_{amb} is the temperature of the ambient air.

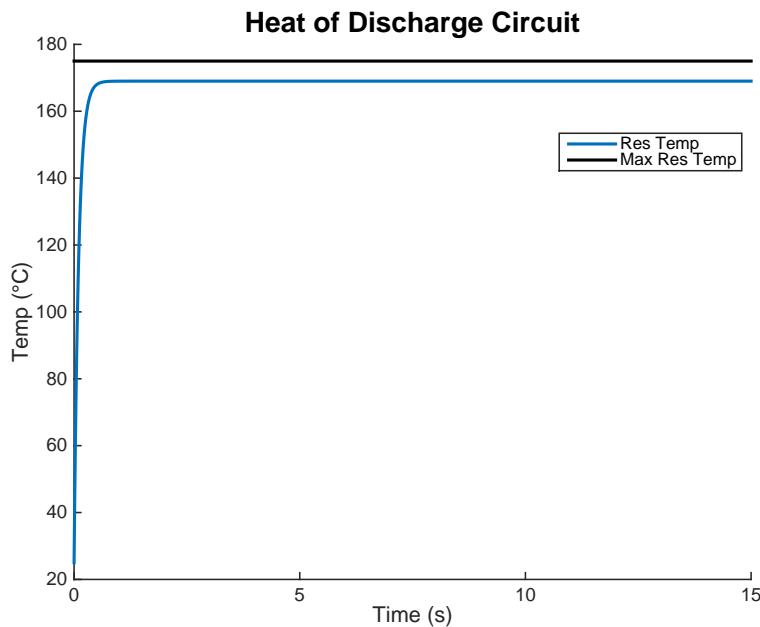


Figure 20: Model of discharge resistor temperature under maximum continuous discharge current for 15 seconds.

2.10.3 Position in car

The discharge circuit is located within the Energy Meter enclosure detailed in section 4, in close proximity to the motor controller which is the main capacitive load in the tractive system.

2.11 HV Disconnect (HVD)

2.11.1 Description

We will be using the shunt version of a TE Connectivity AMP+ Manual Service Disconnect as our HVD. Shown in figure 21 on the following page, it is a sealed, lever operated panel mount device and can be removed without tools. To protect technicians, it has no exposed conductors and provides internal HV interlocking in compliance with EV4.7.5.



Figure 21: The TE Manual Service Disconnect

2.11.2 Wiring, cables, current calculations, connectors

The Manual Service Disconnect is rated for 495V and contains a 630A fuse, which is more than our maximum current of 225A as shown in table 3.1 on page 27. This fuse is superfluous to the TS main fuse, and is simply included as part of the disconnect. It has a dual lever action, which first disconnects the shutdown circuit interlock inside the plug before disconnecting the high power terminals, which causes the AIRs to open and the tractive system to de-energize. The Manual Service Disconnect is a sealed panel mount device, which prevents the ingress of any water or debris.

The datasheet can be found in section 11.2.11.

The HVD is in series with the negative pole of the tractive system, on the vehicle side of the AIRs, as shown in figure 1 on page 1.

2.11.3 Position in car

The HVD is mounted at the rear of the vehicle, on the rear-facing side of the energy meter enclosure, however this enclosure is yet to be designed. It is bright orange, and will be clearly marked and easily accessible from the rear of the vehicle. In accordance with EV 4.7.1, the HVD will be mounted more than 350mm from the ground.

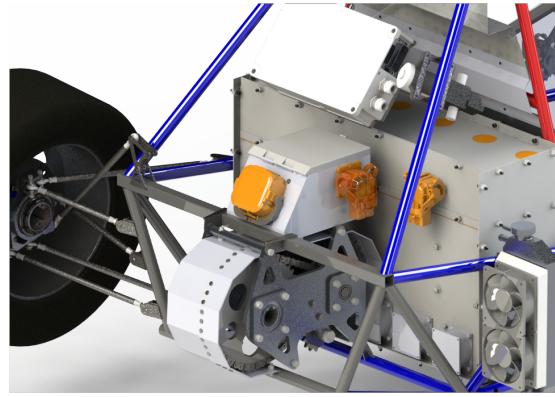


Figure 22: The HVD's location in the car.

As seen in figure 23, the HVD mounting on the energy meter enclosure is currently in violation of EV4.2.1. This is not a final configuration, and the enclosures team is currently redesigning this enclosure and its mounting to move the HVD entirely within the chassis envelope.

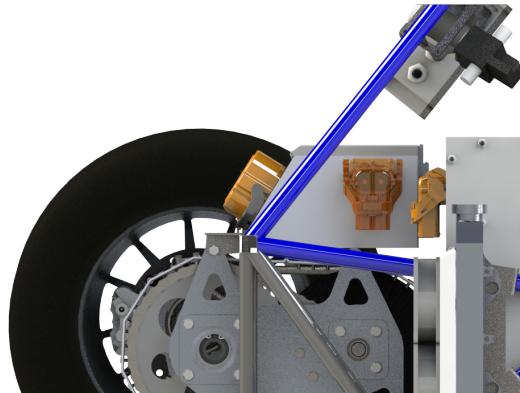


Figure 23: a side view of the HVD mounting, showing protrusion from the chassis envelope. This is a temporary state, and will not be reflected in final design

2.12 Ready-To-Drive-Sound (RTDS)

2.12.1 Description

The Ready to Drive sound is located as a component of the dashboard subsystem, and contains a buzzer (Link: Mallory Sonalert Products Inc. STA20502)11.2.12. The buzzer makes a noise when given a square wave at 1.25kHz, with the loudness proportional to the voltage. When the shutdown sequence is complete, a message will be sent out over the CAN bus. This will then provide the 1.25kHz wave to the gate of an N-FET which will provide a ground path for the buzzer.

2.12.2 Wiring, cables, current calculations, connectors

When the shutdown circuit completes and activates the AIRs, 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 provides voltage to the N-FET for 2 seconds, thus letting the buzzer sound for 2 seconds.

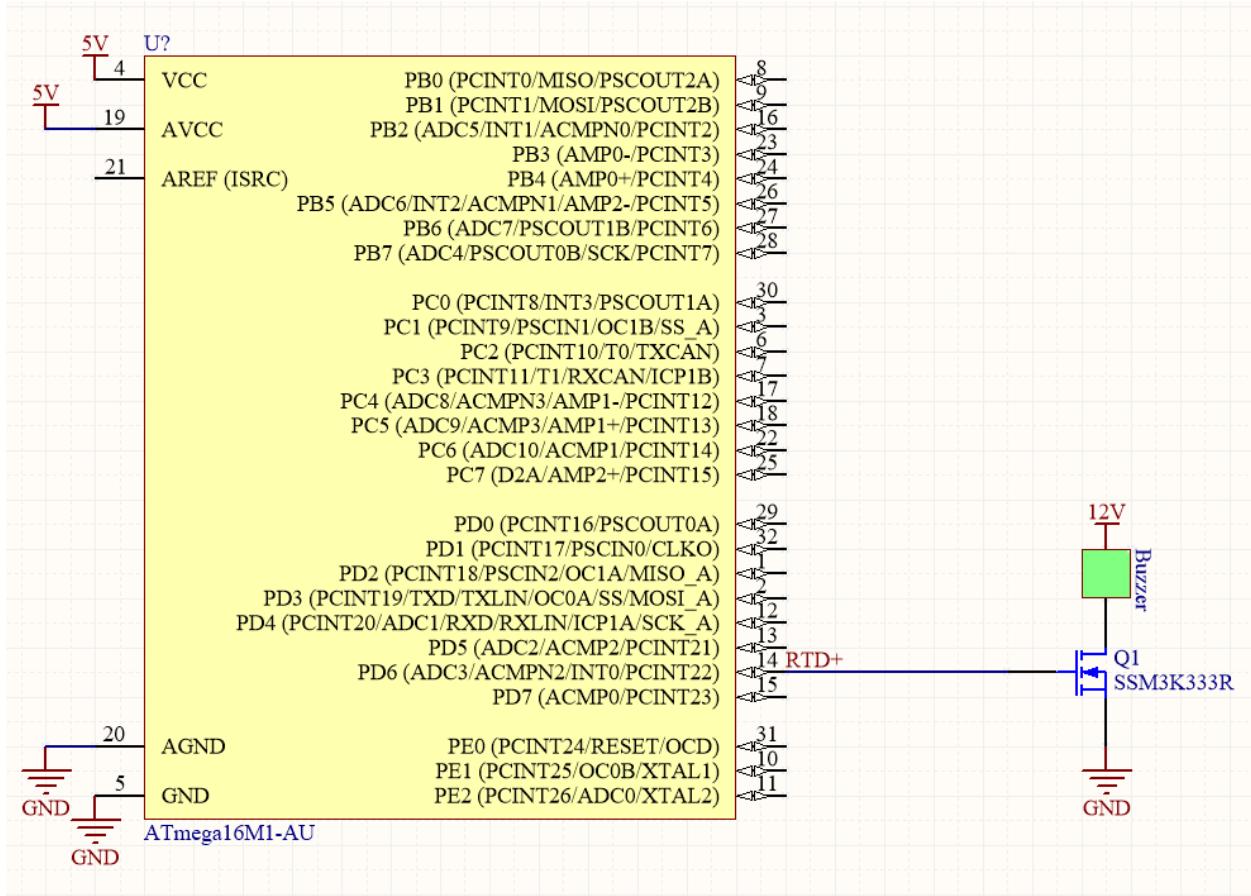


Figure 24: Ready to Drive Sound Schematic as a subsystem of the dashboard's PCB

Sound level L and Distance r

$$L_2 = L_1 - |20 \cdot \log\left(\frac{r_1}{r_2}\right)| \quad L_2 = L_1 - |10 \cdot \log\left(\frac{r_1}{r_2}\right)|^2$$

$$r_2 = r_1 \cdot 10^{\left(\frac{|L_1 - L_2|}{20}\right)} \quad r_1 = \frac{r_2}{10^{\left(\frac{|L_1 - L_2|}{20}\right)}}$$

Figure 25: Inverse Square Law equations needed to calculate the volume at a certain distance

Using the inverse square law as referenced in the appendix for sound pressure levels 11.2.12, 97db at 122cm will translate to 93db at 2m which is a loud enough volume without inducing harm to the listener.

2.12.3 Position in car

The ready to drive sound will be located in the dashboard enclosure. The buzzer will be mounted to the exterior and front side of this enclosure, facing the front of the car as seen in figure 26. It must be contained outside of

the box so that the buzzer is loud enough. The speaker is waterproof, so it doesn't require any extra protection besides using an RTV silicone seal for final instillation.

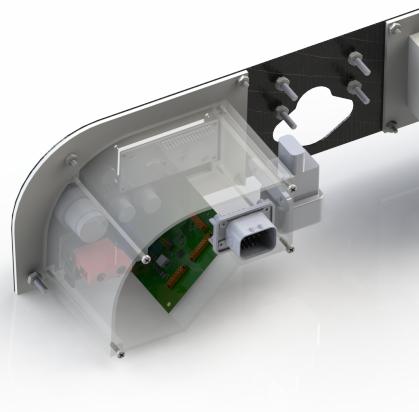


Figure 26: Rendering of Dashboard Right

3 Accumulator

3.1 Accumulator pack 1

3.1.1 Overview/description/parameters

The accumulator pack is based on 72 LG Chem P2.7 LiNiMnCoO₂ pouch cells, in a 72s1p configuration. It is divided into six segments of 12 cells each, which each have their own distributed voltage management and temperature management systems that communicate to a master BMS node that interacts with the car's CAN network and can open the shutdown circuit. Each cell has nominal characteristics seen in table 3.2 on the following page, and together they form an accumulator with a max voltage of 298.8A, and a max output current of 225A, with 27.8 MJ total capacity. Details can be found in table 3.1.

Since we are using proprietary cells, we are not allowed to publish the complete datasheet for the LG Model P2.7 cells. We have been approved to share the ratings found in table 3.2 on the following page.

| | |
|----------------------------------|-----------|
| Maximum Voltage | 298.8 VDC |
| Nominal Voltage | 266.4 VDC |
| Minimum Voltage | 201.6 VDC |
| Maximum output current | 225 A |
| Maximum nominal current | 125 A |
| Maximum charging current | 180 A |
| Total number of cells | 72 |
| Cell configuration | 72s1p |
| Total capacity | 27.785 MJ |
| Number of cell stacks (segments) | 6 |

Table 3.1: Main accumulator parameters



Figure 27: Render of the accumulator with one panel removed to show cell arrangement.

3.1.2 Cell description

The cells we are using are LG Chem Model P2.7, which are lithium nickel manganese cobalt oxide (NMC) pouch cells. The relevant values from the datasheet are shown in table 3.2.

| | |
|--|--------------------|
| Cell Manufacturer and Type | LG Chem Model P2.7 |
| Cell nominal capacity | 25.9 Ah |
| Maximum Voltage | 4.15 V |
| Nominal Voltage | 3.7 V |
| Minimum Voltage | 2.8 V |
| Maximum output current | 225 A |
| Maximum nominal output current | 125 A |
| Maximum charging current | 180 A |
| Maximum Cell Temperature (discharging) | 45°C |
| Maximum Cell Temperature (charging) | 45°C |
| Cell Chemistry | NMC/LMO |

Table 3.2: Main cell specification

3.1.3 Cell configuration

The P2.7 pouch cells are connected in six segments of 12 cells in series, for a total configuration of 72s1p, as shown in figure 28 on the following page.

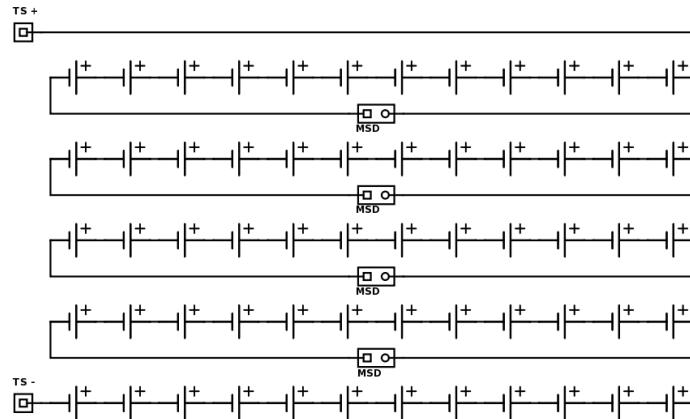


Figure 28: A schematic of the accumulator's cell configuration showing cells in series and manual service disconnects

To connect the cells into segments, they are stacked on one another with 1mm 6061 aluminum heat sinks and neoprene compression foam to distribute load. The cells are alternated in polarity for easy tab connection. Data on the foam can be found in the appendix, in section 11.3.3.

Individual cells are connected by squeezing their tabs together with bolted copper plates. Voltage sensing is done using wires connected to these plates. Each bolted plate assembly is isolated with a 3d-printed cover. This cover protects each terminal from shorts during assembly and maintenance. Each cover is retained with a zip-tie. This is a safer assembly technique than welding the cell tabs together, and allows for replacement of damaged cells if necessary.

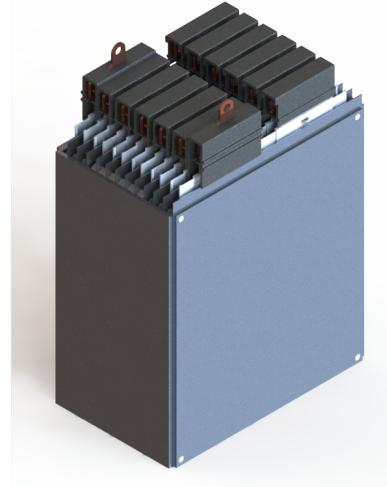


Figure 29: Single segment of 12 cells with 3d-printed covers over clamped cell tabs.

In between the segments, there will be a 4AWG jumper made of the vehicle's HV cable, with a 1-position connector on each end. These will be on the tops of the cell segments, and will be easily removable, so as to act as the manual service disconnects between segments. We are currently in communication with sales representatives from Amphenol about an appropriate connector for our application, and we are considering the Radlok connector system, seen in figure 30 on the next page.



Figure 30: Radlok connector example. The product page can be found [here](#)

3.1.4 Cell temperature monitoring

In compliance with EV3.6.3 and EV3.6.6 the temperature of every cell will be measured within **10mm** of the negative terminal. We will achieve this by **epoxying** an NTC thermistor to the insulated section of the negative terminal of each cell, as close as possible to the body of the cell. The thermistors will be electrically isolated from the terminal by the insulating foil of the cell, and the temperature measurement will most closely approximate the internal temperature of the electrode by being close to the body of the cell.

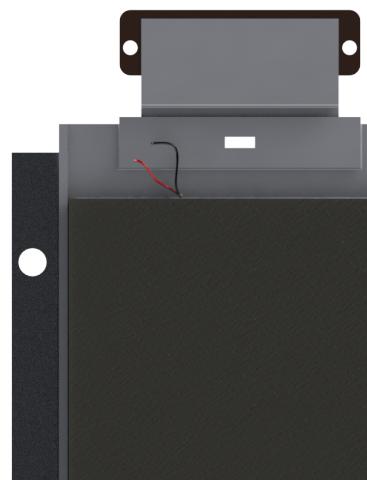


Figure 31: Approximate positioning of the thermistors (seen here with red and black leads) relative to the cells

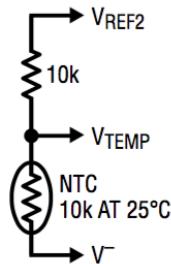


Figure 32: Circuit for sensing NTC thermistors

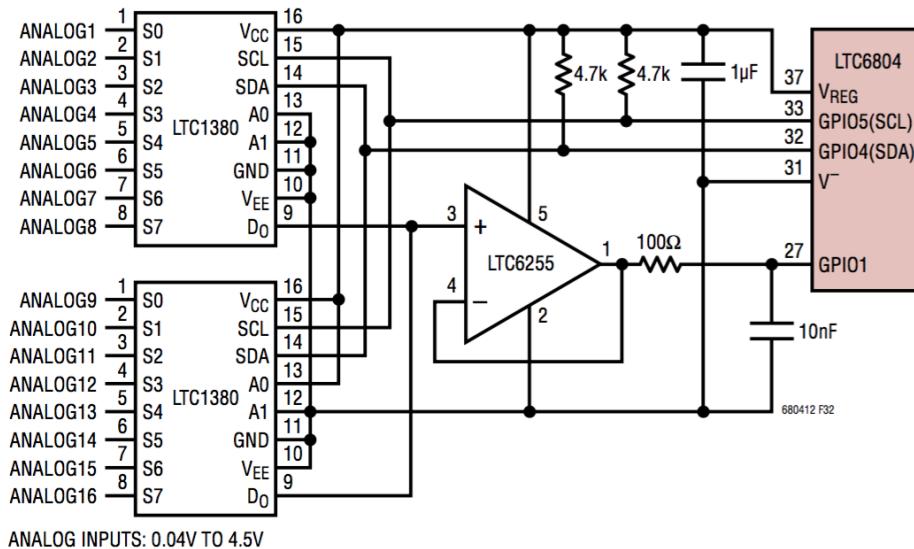


Figure 33: Circuit for multiplexing analog inputs for LTC6804 BMS chip

The NTC thermistors are electrically connected in a voltage divider as shown in figure 32. Each of the temperature measurement voltages are multiplexed into a single GPIO pin on the LTC6804. See section 3.1.5 for a more detailed description of the implementation of the LTC6804 BMS.

The maximum cell operating temperature is 45 °C. Our thermistors are 1% accurate, and the total measurement error of the ADC is <0.1%, then in the worst case we will be reading 44.5 °C when the temperature is actually over the rating. To give the system a small safety margin, the BMS triggers a shutdown if it ever detects a cell temperature of 44 °C or higher.

3.1.5 Battery management system

Each segment of the accumulator will be monitored and controlled for faults by its own distributed battery management system, which in turn communicates with a central master BMS that calculates state of charge, state of health, and monitors power consumption. In the case of a critical fault, the distributed segment BMS will send error messages over CAN to the master BMS, which has a relay that can open the shutdown circuit. In order to ensure that all segments remain in working order, the master BMS will employ a software watchdog timer, which will shut down the car if it fails to receive communication of nominal operation from each segment after a period of time.

The distributed segment BMS is implemented using the Linear Technology LTC6804-1, which communicates over a daisy-chainable galvanically-isolated SPI interface called isoSPI. The LTC6804 is capable of measuring

the voltages of up to 12 lithium-ion batteries, and is also capable of measuring up to 16 analog inputs with its analog multiplexer. We are using the analog inputs to measure cell temperatures as referenced in section 3.1.4. The LTC6804 datasheet can be found in the appendix under section 11.3.4.

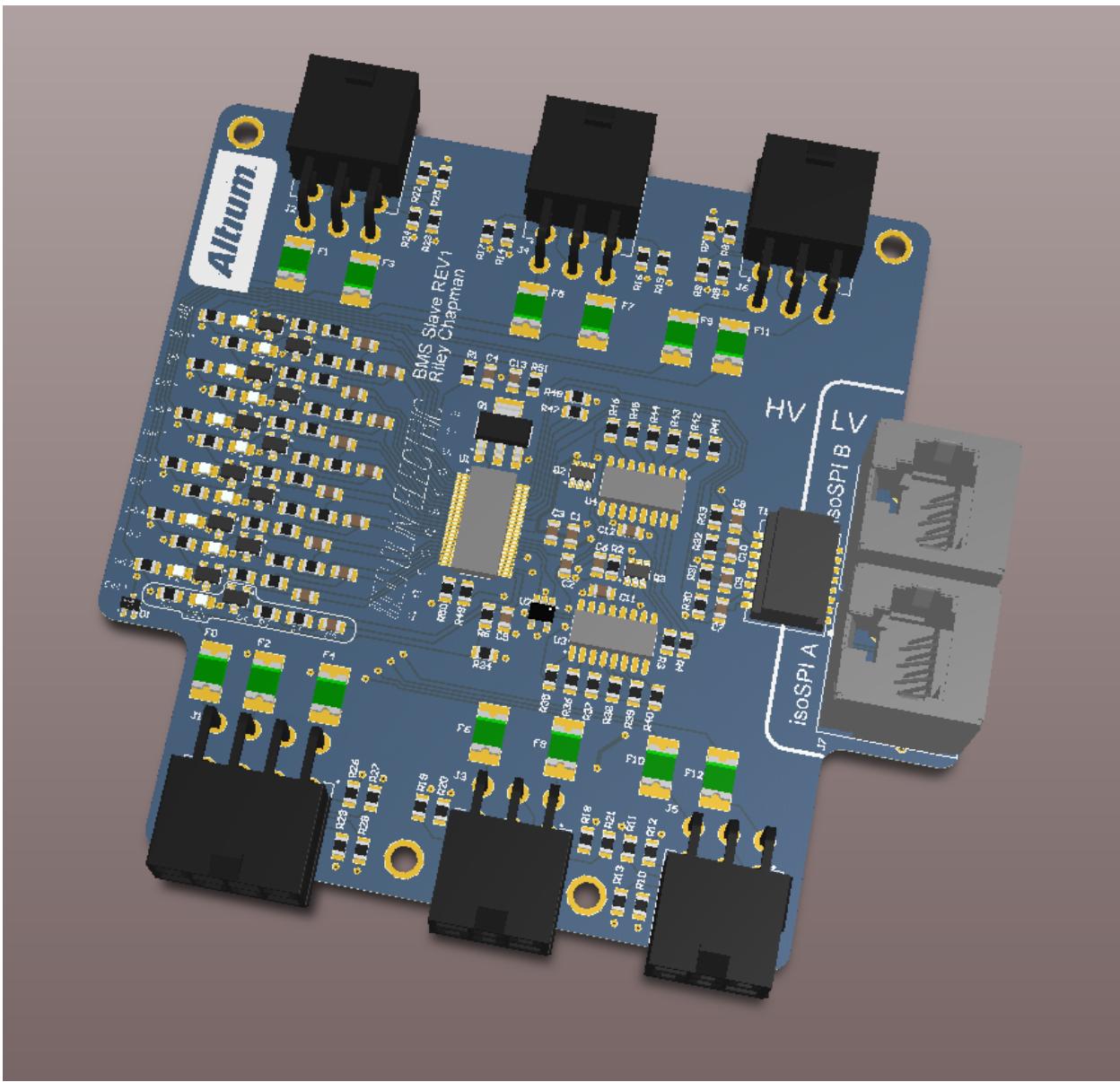


Figure 34: Render of the LTC6804-1 based distributed segment BMS.

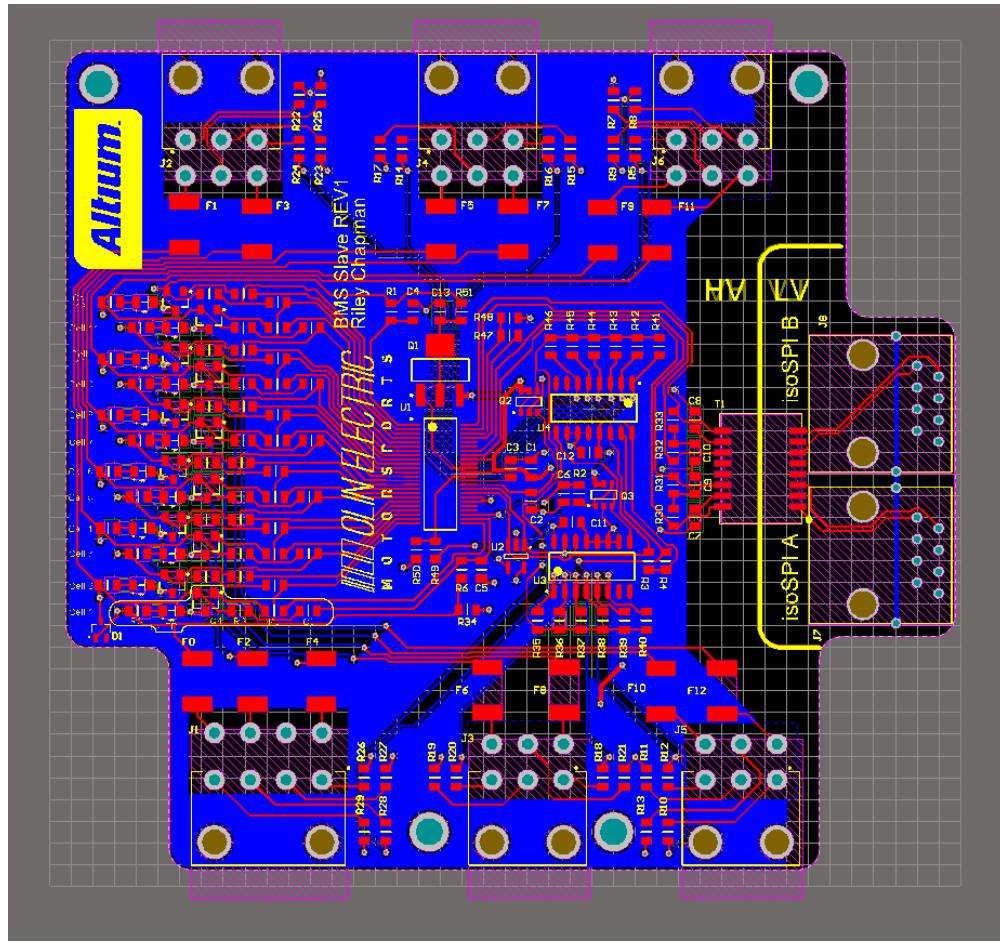


Figure 35: Two dimensional view of distributed segment BMS.

Communication wiring between the distributed segment BMS boards and the master BMS is achieved in a daisy chain via isoSPI, which terminates on the master BMS with an isoSPI interpreting ICs. The communication wiring will be properly retained to maintain spacing of 30mm from any TS voltage.

The master BMS will be a node on the vehicle's CAN system, implemented using an ATmega16m1, a robust CAN-enabled automotive microcontroller. Its primary duties are measuring current leaving the pack via current-sensing coils, estimating state of charge and state of health, and opening the shutdown circuit if the distributed BMS boards sense a fault or fail to report nominal operational parameters.

The maximum Total Measurement Error (TME) of the LTC6804 is 1.2 mV, so in order to account for this error, the max voltage the BMS will react to is 4.1488V, and the minimum voltage is 2.8012V.

The BMS reacts to an upper voltage of 4.100V when charging by shunting excess power from that cell across a discharge resistor. This gives us a 48.8 mV leeway before we approach the max voltage of the cell, corrected for the maximum TME of 1.2 mV. If any cells ever reach 4.1488 V, the BMS will shut down the car by opening the shutdown circuit. This could occur during charging or regeneration in a rare case.

The BMS reacts to critical low voltage of 2.8012V by shutting down the vehicle. This case is harder to remedy, because we can't recharge individual cells on the fly, so to avoid damaging the electrodes inside the cells, the BMS opens the shutdown circuit and de-energizes the vehicle.

3.1.6 Accumulator indicator

The Accumulator Indicator Light (AIL) will be powered directly by the TS voltage using two Zener diodes which will allow enough current to flow through the AIL to turn it on when the supply exceeds 60V. This PCB has not

been designed yet but the general schematic can be seen below in figure 36.

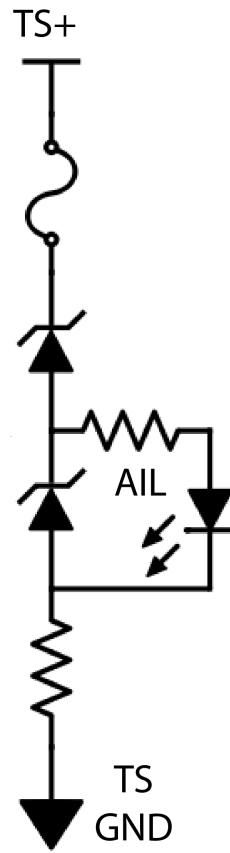


Figure 36: Schematic for the AIL

The AIL will be located on the AIR control board PCB, fused to 1A, and have traces of 20 mil, which are rated for 1.4A. All connections made by wires will be 20 AWG rated for 600V, 125°C and 7A.

3.1.7 Wiring, cables, current calculations, connectors

This wire is used for high power connections in the accumulator. High power connectors are documented in section 2.6.

| | |
|---------------------------|----------------|
| Wire type | 4 AWG Cable |
| Current rating | 190 A |
| Maximum operating voltage | 1 kV |
| Temperature rating | -55°C to 150°C |

Table 3.3: Wire data of the company: Champlain Cable, EXRAD SAE 150 XLE Shielded Cable

3.1.8 Accumulator Insulation Relays (AIRs)

We will use KILOVAC EV200 contactors as our insulation relays. In compliance with EV3.3.5 they are mounted in a compartment separated from the rest of the accumulator by insulating G10/FR4 fiberglass.

| | |
|------------------------------|---------------------------|
| Relay Type: | Normally Open |
| Contact arrangement | SPST-NO-DM |
| Continuous DC current rating | 500A |
| Overload DC current rating | 2000A at 320VDC |
| Maximum operation voltage | 900VDC |
| Nominal coil voltage | 12VDC |
| Normal Load switching | Make and break up to 650A |
| Maximum Load switching | 3 times at 2,000A |

Table 3.4: Basic AIR Data

3.1.9 Fusing

| | |
|--|-----------------------|
| Fuse manufacturer and type: | Bussmann, LPJ type |
| Continuous current rating | 150 A |
| Maximum operating voltage | 600 V |
| Type of fuse | Time delay |
| I ₂ t rating | Not Listed |
| Interrupt Current (max. current at which the fuse can interrupt the circuit) | 300 kA |

Table 3.5: Tractive system main fuse, LPJ type. Datasheet here.

3.1.10 Charging

| | |
|----------------------------|--|
| Charger Type: | ELCON PFC 2000+ TCCH-288-6 |
| Maximum charging power | 24.9 A |
| Maximum charging voltage | 4.15 V (Per Cell) 298.8 V (Overall) |
| Maximum charging current | 5 A |
| Interface with accumulator | TE Connectivity HVP 800 lever action locking connector |
| Input voltage | 125VAC or 230VAC |
| Input current | 15A @ 125VAC or 8A @ 230VAC |

Table 3.6: General Charger data



Figure 37: Elcon PFC 2000+ Battery Charger

The charging system consists of two main components: A charger that connects to the main pack connector and supplies the current needed to charge the accumulator, and a charging circuit that provides power to the AMS, opens the AIRS if the shutdown button is pressed, and displays critical information while charging. This CE-Listed charger supplies constant current at 6A until cell voltages reach 4.15V. Then, constant voltage is supplied at 4.15V per cell, summing to 298.8 volts, until the cells are fully charged. The charging power lines are protected via the charger's short-circuit protection, which automatically stops charging if a short-circuit condition occurs.

The charger interfaces with the accumulator through a lever action locking connector from TE Connectivity's HVP 800 series (P/Ns 2141227(accumulator side) and 2141154(charger side)). These connectors are connected to the charger by 10AWG wires through a charging interlock system that piggy-backs off of the discharge circuit, seen below in figure 38

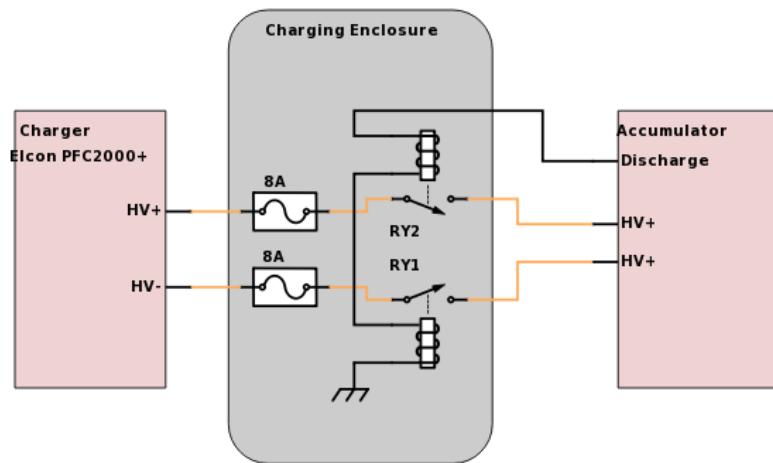


Figure 38: The charging interlock system, showing fuses and relays for charging the accumulator

The charging interlock system consists of two Littelfuse KLKD 10x38 600VDC 8A fuses connected to two Omron G9EJ-1-E 400VDC relays that are powered by the discharge circuit (the end of the accumulator shutdown circuit) mounted inside a protective enclosure on the charging cart. They only allow the charging connector to be energized if the shutdown circuit on the charging cart is closed meaning all of the HV and LV connectors

are properly connected. See appendix section 11.3.10 for datasheets.

The accumulator will only be charged on the charging cart. The cart 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 charging circuit that allows the accumulator to be charged through the main pack connector. The charging circuit mimics the shutdown circuit in the vehicle. The charging circuit will contain a clearly labeled emergency stop push button with a minimum diameter of 25mm which opens the AIRS and the charging relays and stops charging. It will also communicate with the AMS over CAN and display critical information during charging.

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. The AMS will communicate with the Charger over CAN and turn off the charger in the event of a fault to maintain compliance with EV8.3.5.

3.1.11 Mechanical Configuration/materials

The main structure of the accumulator container is made from .050" 430 stainless steel sheet. The front, left, right, and bottom walls are made from one folded sheet. The rear wall is made from another folded sheet. Inside are six segments of 12 cells. The segments are separated by internal vertical walls. The internal vertical walls are made from 20ga (.0359") 430 stainless steel sheet. The internal vertical walls are attached to the bottom wall with spot welds. The internal vertical walls are attached to the external vertical walls with spot welds. All walls are internally lined with a sheet of garolite to provide insulation.

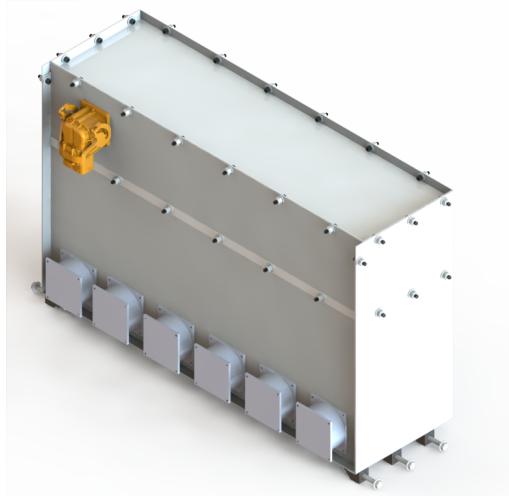


Figure 39: Isometric render of the fully assembled accumulator.

The cells we are using must be compressed on their large face to within the manufacturer recommended range (4-18psi). We are considering two methods of cell compression. In the first, the cells are compressed between two aluminum face sheets by threaded rods. 4 threaded rods are used to compress each segment. In the second method, the threaded rods are replaced by aluminum end caps that set the distance between the aluminum face sheets. In both methods, cell compression pressure will be set by imposing a strain on the stack. The materials will be characterized and the necessary strain will be applied such that the cells remain in the specified pressure range. Each compressed segment is individually installed into the accumulator, then the rear wall is attached.

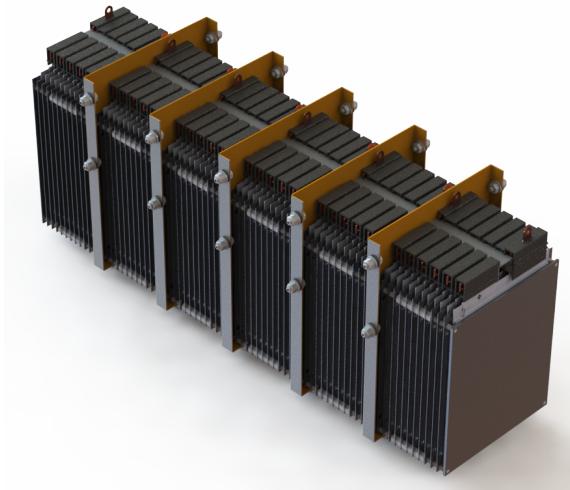


Figure 40: Configuration of cell modules, with dividing walls.

Individual cells are connected by squeezing their tabs together with bolted copper plates. Voltage sensing is done using wires connected to these plates. Each bolted plate assembly is isolated with a 3d-printed cover. This cover protects each terminal from shorts during assembly and maintenance. Each cover is retained with a zip-tie. Thermistors are epoxied to the negative terminal of all cells for temperature monitoring. The Accumulator Interrupt Relays, Main Pack Fuse, Battery Management System, Service Disconnects, and other related electronics are located in the top section of the accumulator. This section is separated from the lower section by a .050" 430 stainless sheet that is insulated on both sides by 1/32" garolite. The divider is fastened with 18 1/4"-20 grade 5 fasteners. The top section is closed with a lid similar to the divider. It is attached to the side walls with an identical fastener pattern. All structural fasteners are secured with nylok nuts. The nylok nuts are all located outside the accumulator container. All insulating garolite is epoxied to the surface it insulates.

3.1.12 Position in car

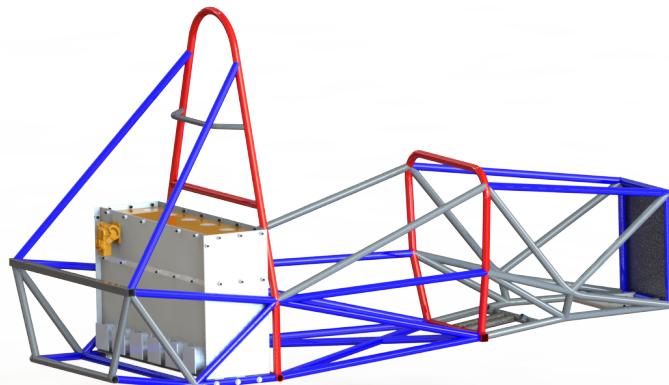


Figure 41: Position of the accumulator in the frame.

3.2 Accumulator pack 2

We only have one accumulator, described in 3.1.

4 Energy meter mounting

4.1 Description

The vehicle's energy meter is mounted in a dedicated tractive system enclosure at the rear of the car that we call the energy meter enclosure. As is visible in figure 1 on page 1, the energy meter enclosure is a pass-through enclosure that connects in series with both poles of the tractive system between the accumulator and the motor controller. Inside are the energy meter, the high-voltage low-current fuses that protect the TSAL (section 2.7), the current-limiting resistors that protect the TSMPs (section 2.8), and the discharge circuit (section 2.10).

4.2 Wiring, cables, current calculations, connectors

The energy meter current calculations require it to be connected in series with the low pole of the tractive system. It is bolted onto custom-made copper bus bars with ~~serrated, distorted-thread locking~~ fasteners to ensure electrical connection, ~~which can be seen in~~ figure 42 on the next page.

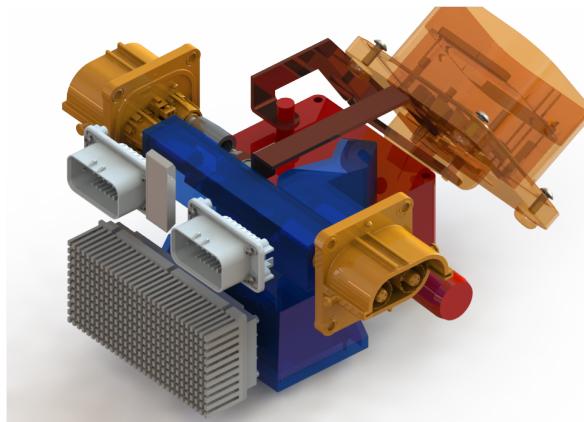


Figure 42: Rendering of the internal geometry of the energy meter enclosure. The energy meter itself is visible in red. The blue solids are insulating covers to separate the individual HV bus bars from one another and to protect the LV energy meter circuitry at the base of the enclosure. See figure 45 on page 42 for a render of the enclosure in the vehicle

Figure 43 shows the internals of the energy meter enclosure from another angle, also including the housing. Internal covers are removed to show bus bar geometry. Bus bars will be wrapped in Kapton polyimide tape with a protective heat-shrink sleeve.

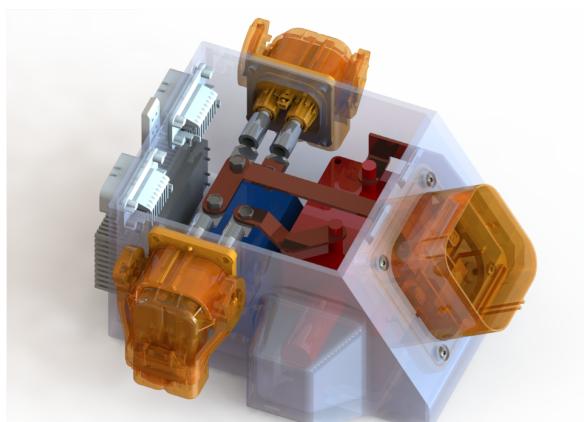


Figure 43: Rendering of the energy meter enclosure showing the housing. Internal bus bar covers have been hidden to show bus bar structure.

Voltage measurement connections to TS+ for the energy meter, and connections for the TSAL fuses and TSMP current-limiting resistors are made via ring terminals to the corresponding bus bars. The wires for the TSMPs, the TSAL, and the energy meter will all be 20AWG rated to 300V and 90°C. The energy meter itself also requires GLVS power, which means that proper HV wire spacing of 30mm will be upheld.

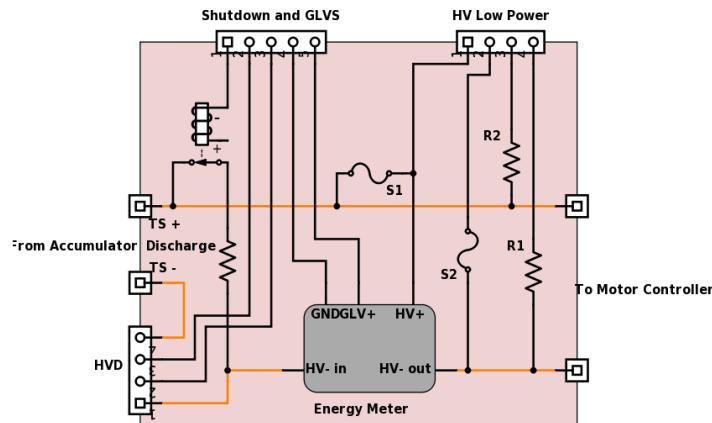


Figure 44: Schematic of the internals of the energy meter. Fuses S1 and S2 are Littelfuse 80812000000s, and resistors R1 and R2 are the TSMP resistors from section 2.8.

Figure 44 shows the internals of the energy meter box [in electrical schematic form](#). The GLVS connector contains the shutdown circuit power for the discharge circuit, the interlock from the HVD, and GLVS power for the energy meter. The high voltage low power connector contains TSMP and TSAL high voltage connections to the master switch panel. High power connections are shown in orange.

The energy meter TS+ connection and the TSAL TS+ measurement wire share the same fused connection, and the TSAL TS- measurement wire has its own fuse. The fuse specifications can be found in table 4.1. The datasheet for the fuse can be found in table 4.1.

| | |
|----------------------------|---------------------------|
| Fuse manufacturer and type | Littelfuse 80812000000 |
| Continuous current rating | 2.00 A |
| Maximum operating voltage | 450VDC |
| Type of fuse | Fast-acting |
| I ₂ T | 0.0610 A ² sec |
| Interrupt current rating | 10,000 A |

Table 4.1: TS+ fuse for energy meter and TSAL TS+ measurement wire

4.3 Position in car

The energy meter housing is mounted to the chassis at the rear of the vehicle, in close proximity to the motor, motor controller, and accumulator, and with the HVD easily visible and accessible from the rear. See figure 45 on the following page.

5 Motor controller

5.1 Motor controller 1

5.1.1 Description, type, operation parameters

The motor controller regulates the power delivered to the motor. This motor controller is preferable for its small package and isolated control interface. We will communicate with it using our CAN bus.

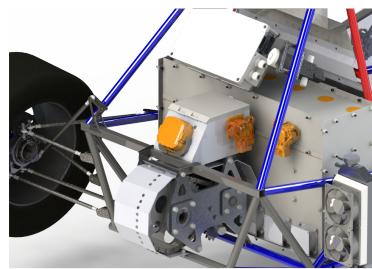


Figure 45: Render of the rear of the vehicle showing the mounting for the energy meter enclosure at the rear of the vehicle

| | |
|-----------------------------------|------------------|
| Motor Controller type | Rinehart PM100DX |
| Maximum continuous power | 86 kVA |
| Maximum peak power | 100 kVA for 10s |
| Maximum input voltage | 400 VDC |
| Output voltage | Not listed |
| Maximum continuous output current | 300 A |
| Maximum peak current | 350 A for 10s |
| Control method | CAN |
| Cooling method | Water |
| Auxiliary supply voltage | 12 VDC |

Table 5.1: General Motor Controller data

5.1.2 Wiring, cables, current calculations, connectors

The PM100DX has five high voltage connections (DC+, DC-, Phase A, Phase B, Phase C) as seen in figure 1 on page 1. Each connection is done with a cable gland that provides strain relief, environmental sealing, and shield termination for the dual insulated shielded 4 AWG cable. The manufacturer recommends this particular cable from Champlain Cable.

| | |
|---------------------------|----------------|
| Wire type | 4 AWG Cable |
| Current rating | 190 A |
| Maximum operating voltage | 1 kV |
| Temperature rating | -55°C to 150°C |

Table 5.2: Wire data of the company: Champlain Cable, EXRAD SAE 150 XLE Shielded Cable

5.1.3 Position in car

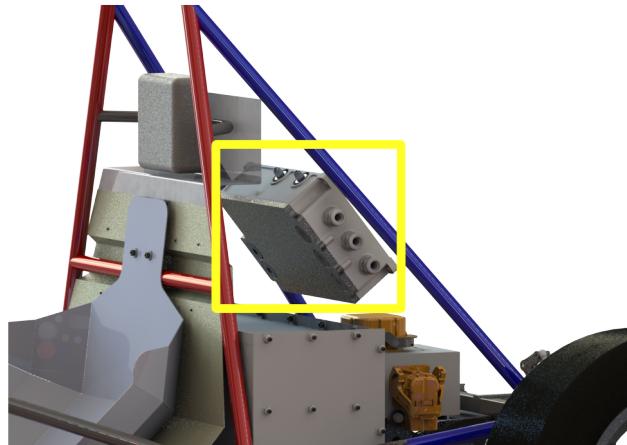


Figure 46: CAD rendering of Motor Controller position

5.2 Motor controller 2

We only have one motor controller, described in 5.1.

6 Motors

6.1 Motor 1

6.1.1 Description, type, operating parameters

Originally designed for aviation use, this out-runner motor delivers remarkable performance for its weight.

| | |
|------------------------------|------------------------------------|
| Motor Manufacturer and Type: | Make: Enstroj Model: EMRAX 228 |
| Motor principle | Permanent magnet synchronous motor |
| Maximum continuous power | 28 - 42 kW |
| Peak Power | 100 kW |
| Input voltage | 50 – 450 V |
| Nominal current | 160 A |
| Peak current | 340 A |
| Maximum torque | 240 Nm |
| Nominal torque | 125 Nm |
| Cooling method | Water |

Table 6.1: General motor data

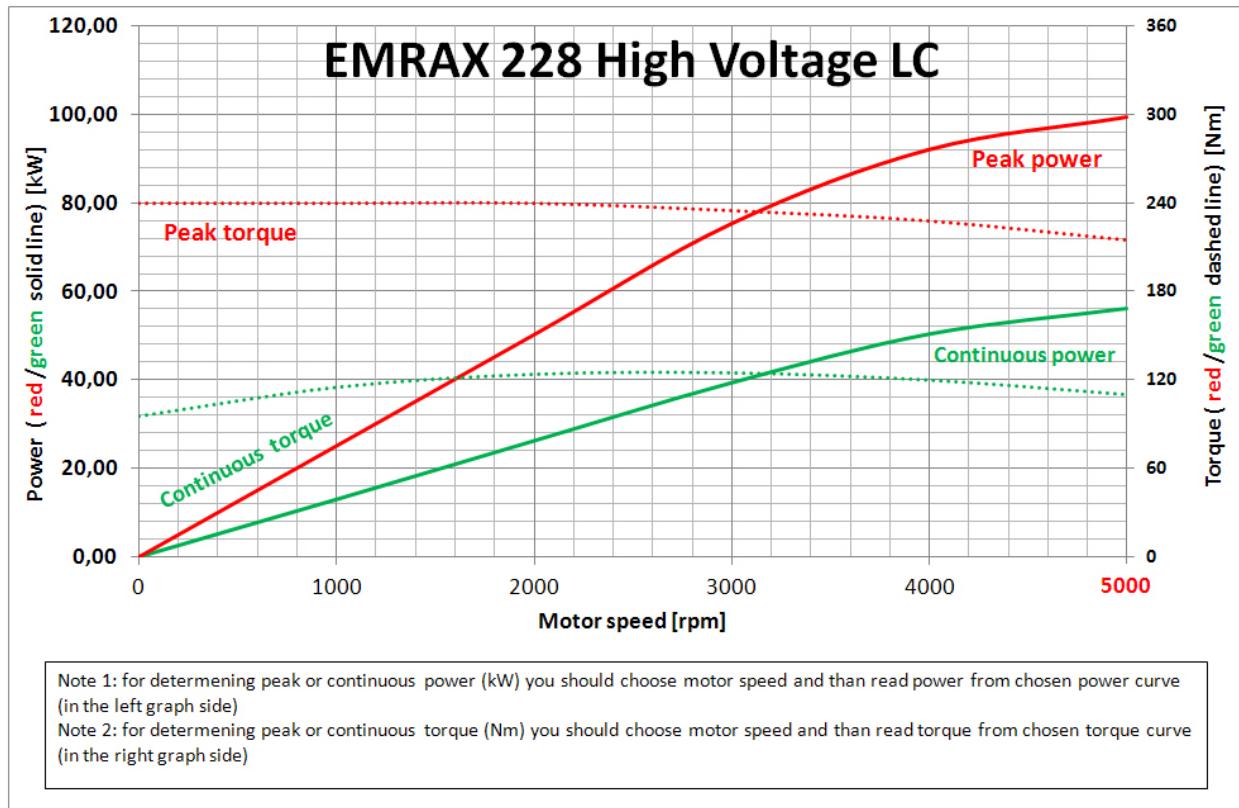


Figure 47: Motor Power and Torque: although we are using the medium voltage version of the motor, the only difference in terms of this plot is the ratio of current and voltage.

6.1.2 Wiring, cables, current calculations, connectors

| | |
|---------------------------|----------------|
| Wire type | 2 AWG Cable |
| Current rating | 255 A |
| Maximum operating voltage | 1 kV |
| Temperature rating | -55°C to 150°C |

Table 6.2: Wire data of the company: Champlain Cable, EXRAD SAE 150 XLE Shielded Cable. Datasheet here

Since the motor leads terminate close to the motor with ring terminals close to the motor as seen in figure 49, the motor will have a 3D printed enclosure around the leads, with a high power connector found here. A CAD render of the motor lead enclosure can be found in figure 48 on the following page. HV and LV segments are separated by a 3D printed wall with an extension designed to protect the LV rotary encoder wires from the motor from HV connections. HV connections will be shielded and double-insulated, so the plastic serves to keep the wires from interfering, not to provide insulation.

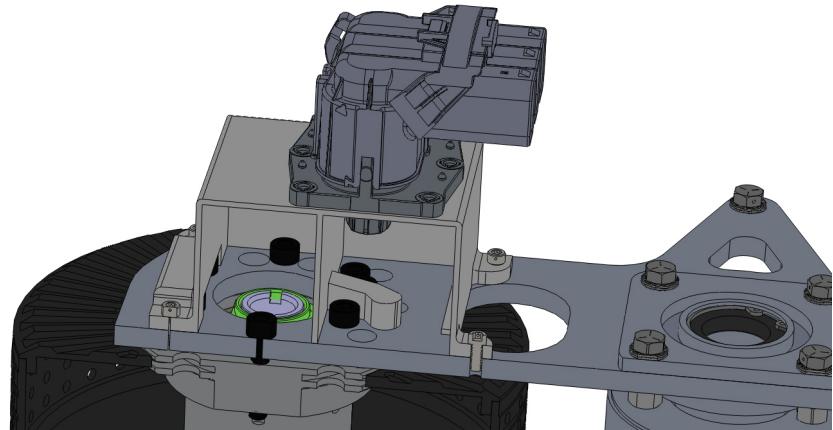


Figure 48: CAD render of 3D printed motor enclosure. HV and LV segments of the enclosure are separated by a PLA wall.



Figure 49: Picture of motor, note ring terminal crimps on leads.

6.1.3 Position in car

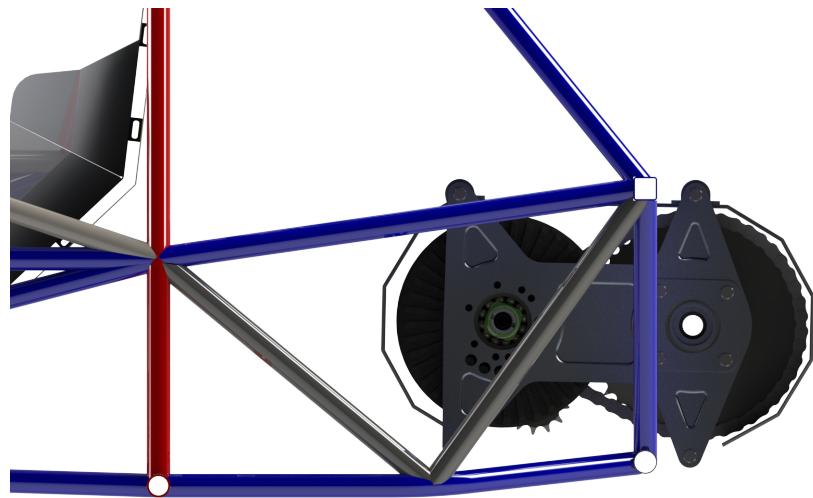


Figure 50: CAD rendering of the motor and transmission in the frame of the vehicle

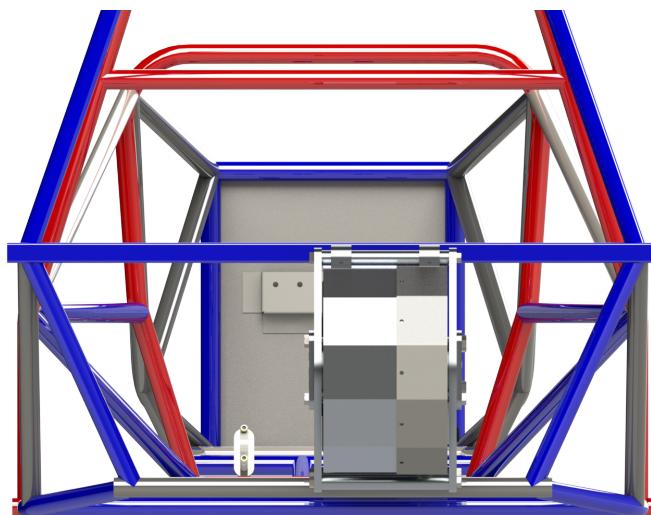


Figure 51: CAD rendering of the motor and transmission in the frame of the vehicle

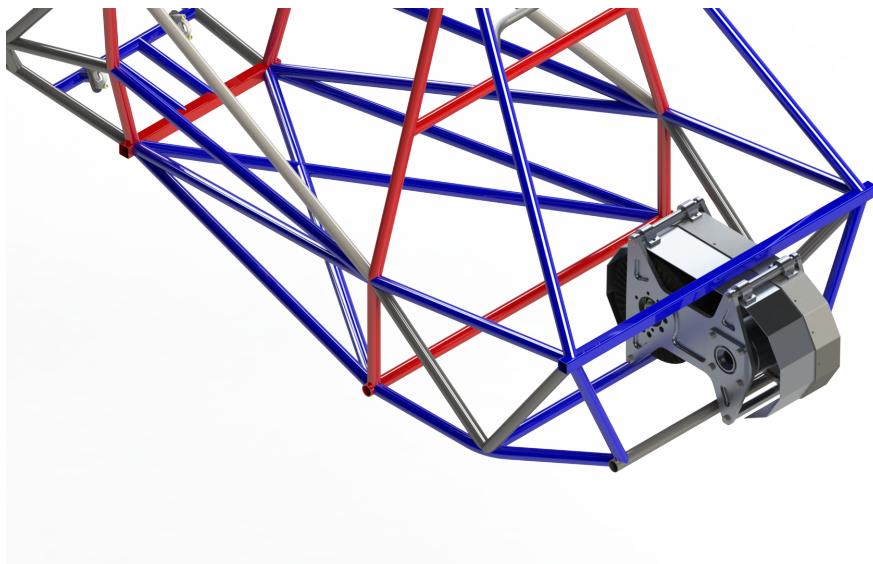


Figure 52: CAD rendering of the motor and transmission in the frame of the vehicle

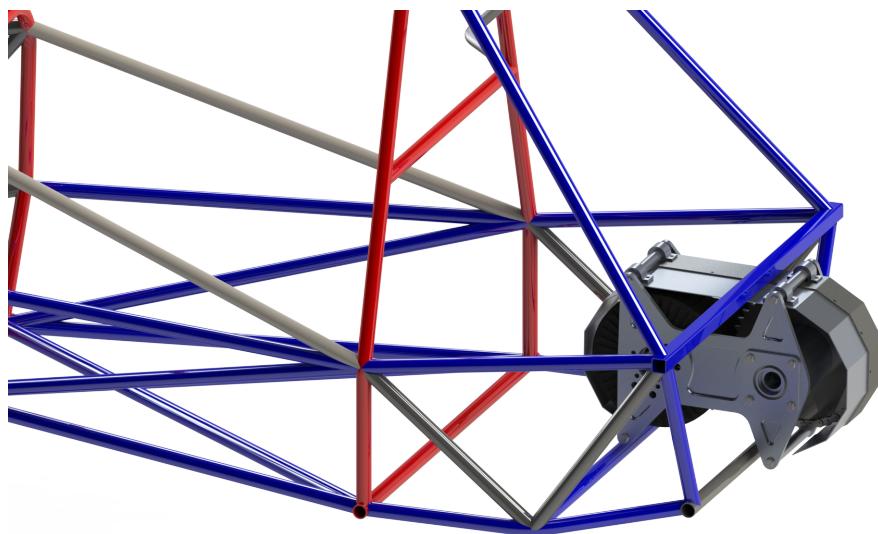


Figure 53: CAD rendering of the motor and transmission in the frame of the vehicle

6.2 Motor 2

We only have one motor, described in 6.1.

7 Torque encoder

7.1 Description/additional circuitry

Two hall-effect-based rotary encoders are mechanically housed in one unit, the Magni-Tec MHR5261, which is mounted to the rotating shaft of the throttle pedal assembly. The use of a single housing eliminates concerns

regarding mechanical backlash and misalignment. See section 11.7 for datasheet. Each output from the encoders will be measured by a CAN-connected ATmega16M1, which will compare the two outputs and send a message via CAN bus to the motor controllers with the requested torque.

| | |
|---------------------------------------|----------------------------------|
| Torque encoder manufacturer and type: | Magni-Tec MHR5621 |
| Torque encoder principle | Hall-effect-based voltage source |
| Supply voltage | 5V |
| Maximum supply current | 15 mA |
| Operating temperature | -55 to 150°C |
| Used output | 0-5V |

Table 7.1: Torque Encoder data

7.2 Torque Encoder Plausibility Check

Two rotary encoders are mounted on the torque pedal. A CAN node probes the voltage dividers which are amplified in different transfer functions using a Texas Instruments Operational Amplifier, part number LMV341QDCKRQ1. One op-amp amplifies the voltage of one encoder by a factor of two and the other amplifies the voltage from the other encoder by a factor of one half. The ATmega will compare the two independent voltages and if an implausibility occurs, a difference in voltage from the Torque Encoder besides what is expected from the transfer function, and persists for more than 100msec, the power to the motor(s) must be immediately shut down completely. If a short circuit or wiring failure with either potentiometer occurs, the input will be outside the normal operating range, and the power to the motor controllers will be shut down. The normal operating range for the throttle inputs will be from 0.5V to 4.5V on the analog line with a gain of 2, and from 2 to 3 volts on the analog line with a gain of 1/2. Upon detecting an implausibility, the ATmega16m1 ADC will trigger an interrupt that the input voltage is outside the defined range, and a software timer will begin. If the software timer reaches 100 msec before the input voltage triggers a "return to normal range" interrupt, then the APPS will trigger a motor shutdown over CAN. 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 accelerator pedal position sensor measures more than 25 percent pedal travel, the power to the motors will be completely stopped until the accelerator pedal indicates less than 5 percent pedal travel. In addition to the torque encoder plausibility check in the ATmega software, we also implement a CAN message timeout in the motor controller for stale throttle signals. If the motor does not receive a CAN message from the throttle CAN node for 300 ms (a parameter in the motor controller configuration) it will stop power to the motors. See appendix section 11.7 for PM100DX motor controller datasheet excerpt.

7.3 Wiring

Two potentiometers are wired with their each input wired through an operational amplifier with a specific amplification, one with an amplification of two and one with an amplification of one half, and their output to the CAN analog input pins. 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 a CAN input pin. The CAN node is wired to send and receive messages to the other nodes.

7.4 Position in car/mechanical fastening/mechanical connection

The torque encoder is bolted to the accelerator pedal assembly with 4x 1/4"-20 bolts. The bolts are safetywired 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

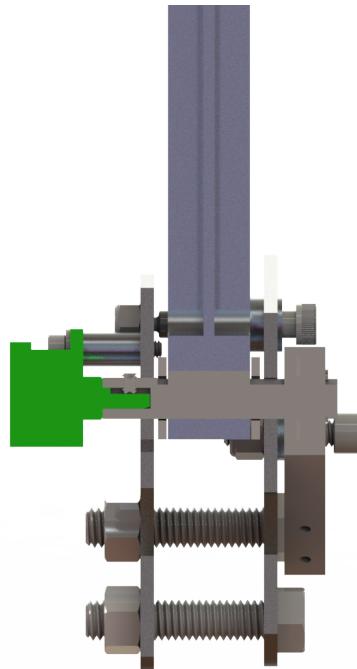


Figure 54: Mechanical fastening and connection to the throttle pedal. Note that the torque encoders are two encoders housed in one package

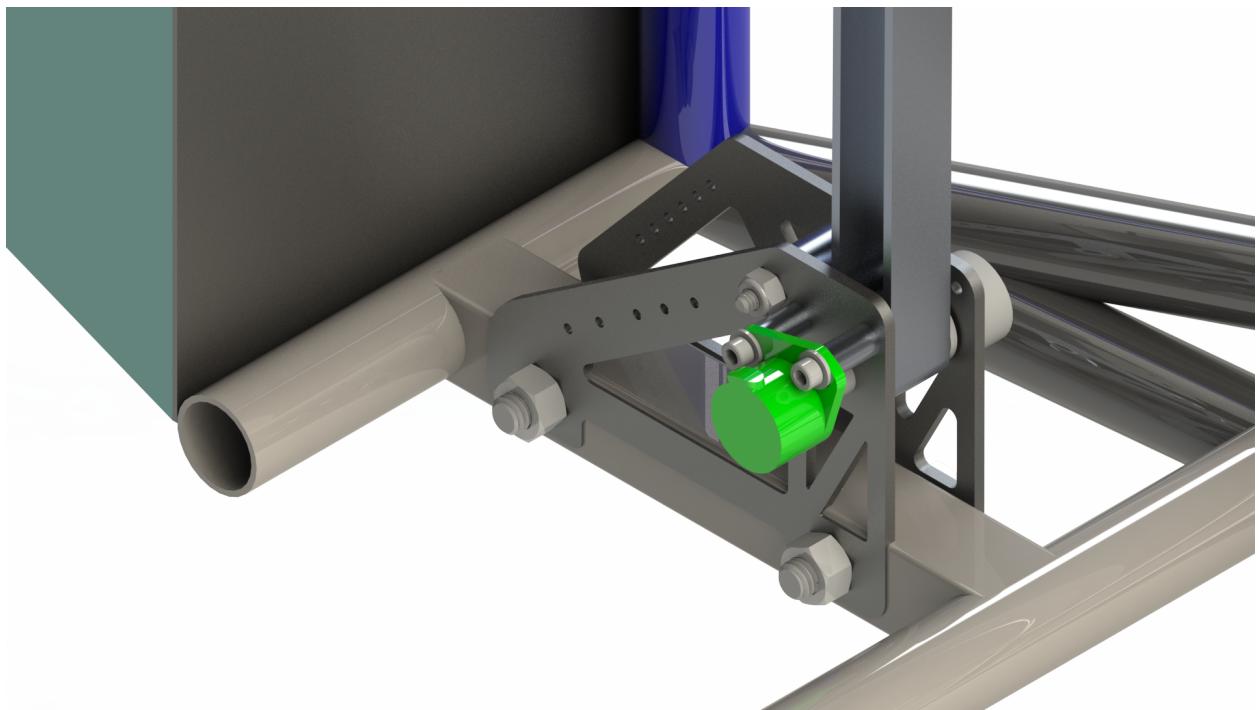


Figure 55: Location of the encoder on the throttle pedal

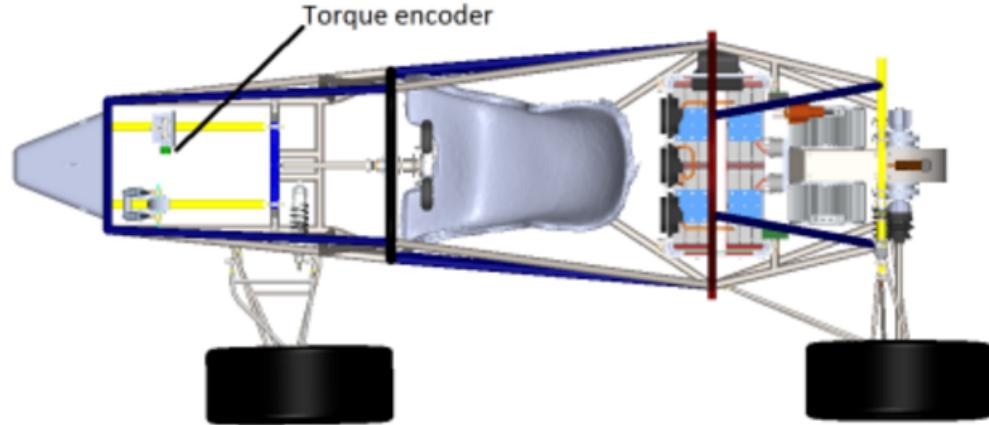


Figure 56: Location of torque encoder in car

8 Additional LV-parts interfering with the tractive system

8.1 LV part 1

There are preliminary design ideas for adding a DC/DC converter into the energy meter enclosure for recharging the GLVS battery, but that design has not yet been considered, and will only appear in a later revision of the ESF if it is included in the vehicle. As of yet all LV parts interfering with the tractive system have been adequately described in other sections.

8.1.1 Description

All LV parts interfering with the tractive system have been adequately described.

Wiring, cables

All LV parts interfering with the tractive system have been adequately described.

8.1.2 Position in car

All LV parts interfering with the tractive system have been adequately described.

8.2 LV part 2

All LV parts interfering with the tractive system have been adequately described.

9 Overall Grounding Concept

9.1 Description of the Grounding Concept

The vehicle's steel chassis is used as GLVS ground. This ground will be established inside the master switch panel enclosure by attachment to a positively-retained ring terminal on a chassis member that has been locally stripped of paint. All components of the GLVS will be grounded to this point on the chassis through the wiring harness for simplicity of installation and mechanical robustness. All conductive mechanical enclosures are mounted to the chassis with conductive metal fasteners. Electrical connection of the suspension members and knuckles to the main vehicle frame will be achieved by short jumpers with ring terminals on either end in the suspension member bolt stackup on either side of the spherical bearing.

9.2 Grounding Measurements

All conductive components within 100 mm of any Tractive System or GLVS component will be measured by Kelvin ohmmeter to have a resistance of less than 300 mΩ to chassis ground, measured at the chassis ground measurement point on the master switch panel. All fastened mechanical components and enclosures will be individually measured to ensure proper ground connection. Chassis ground continuity will be tested during and after assembly to ensure complete coverage. Any carbon fiber components will be exhaustively measured to ensure resistance compliance.

10 Firewall(s)

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, and the layer facing the cockpit is 24 gauge Flame-Retardant Multipurpose Garolite. The assembly is attached with marine epoxy between the two layers and nylon fasteners. 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. The firewall is attached to the seat through epoxied 3D printed spacers and foam sprayed between the seat and firewall, seen in figure 57 on the next page. 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 grommet hole will be made in the firewall for GLV wiring.

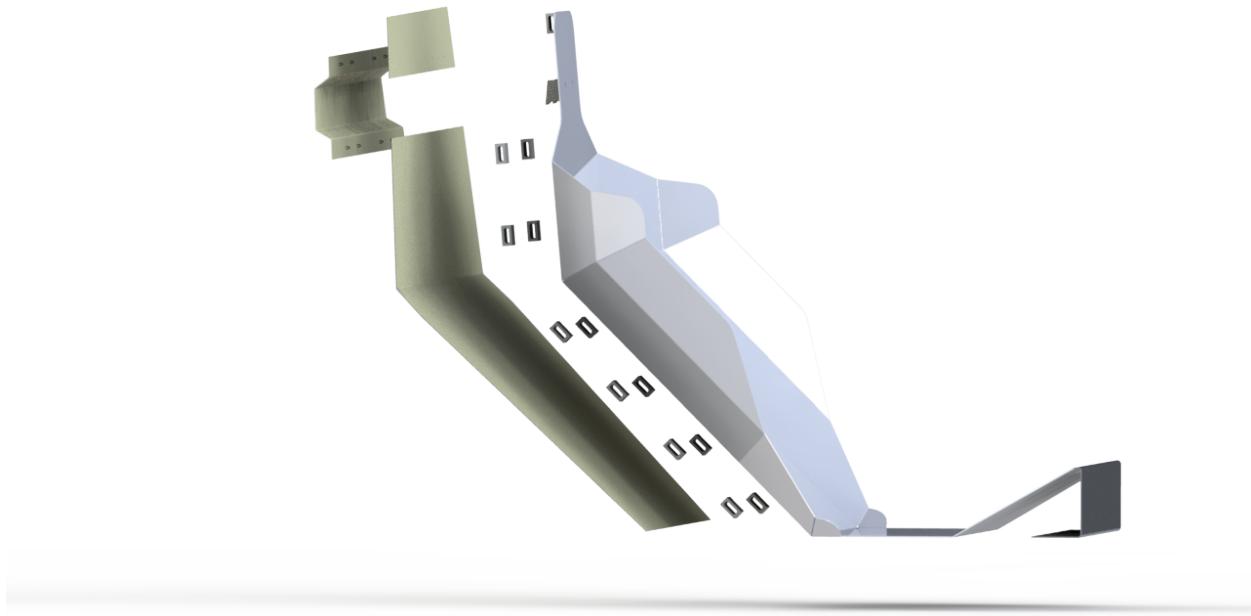


Figure 57: An exploded view of the firewall and seat.

10.1.2 Position in car

The firewall is located between the driver and accumulator, to protect the driver from the tractive system. figure 58 on the following page shows the cockpit view without the seat for visual aid. The seat is between the wheel and the firewall, with the firewall cushioning the seat. The firewall is attached to the frame so that its top corners are flush, eliminating a concern of sharp edges.

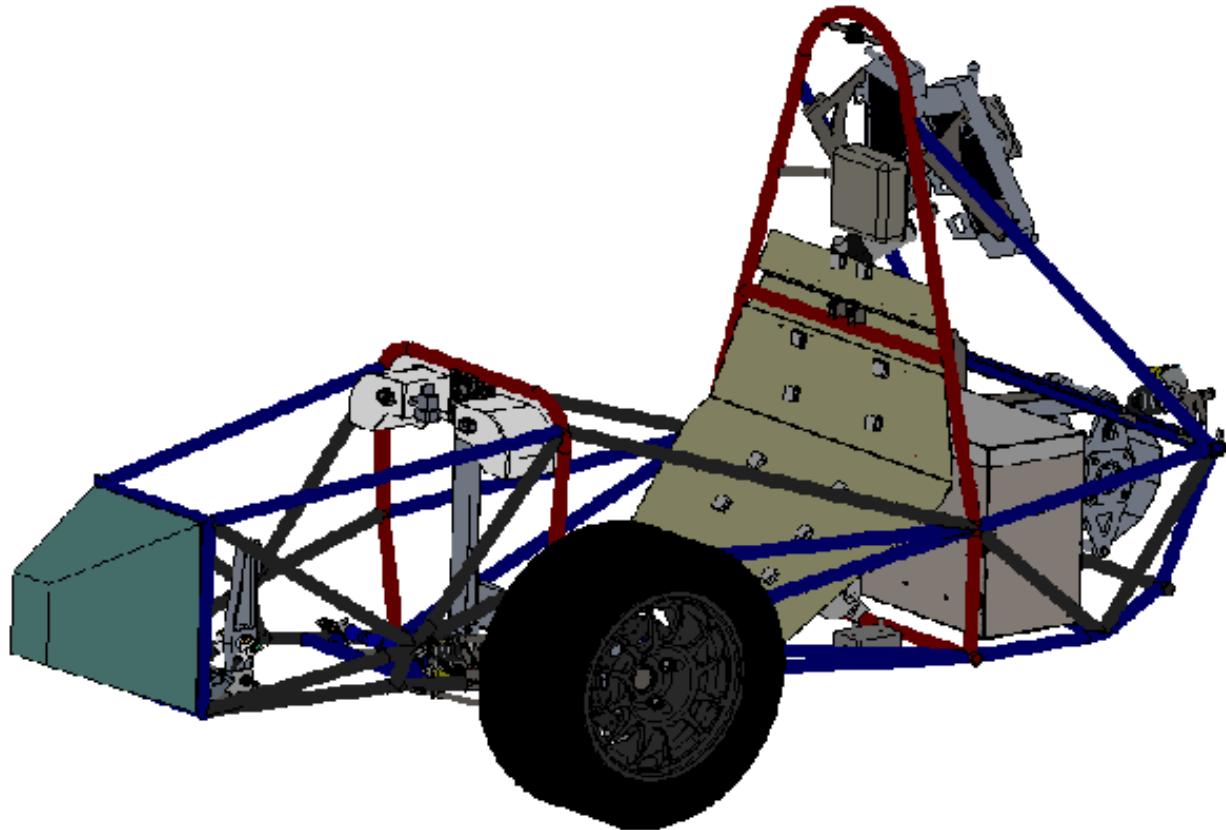


Figure 58: A view of the firewall in the car without the seat.

10.2 Firewall 2

We only have one firewall, described in 10.1.

11 Appendix

11.2 Electrical Systems

11.2.2 IMD Datasheet

Referred from section 2.2.

| Insulation coordination acc. to IEC 60664-1 | | Time response |
|---|---|--|
| Protective separation (reinforced insulation) | | Response time t_{an} (OK_{HS} ; SST) $t_{an} \leq 2$ s (typ. < 1 s at $U_n > 100$ V) |
| between (L+/L-) – (Kl. 31, Kl. 15, E, KE, M_{HS} , M_{LS} , OK_{HS}) | | Response time t_{an} (OK_{HS} ; DCP) |
| Voltage test | AC 3500 V/1 min | (when changing over from $R_F = 10$ MΩ to $R_{an}/2$; at $C_e = 1$ μF; $U_n = DC 1000$ V) |
| Supply/IT system being monitored | | |
| Supply voltage U_S | DC 10 ... 36 V | $t_{an} \leq 20$ s (at $F_{ave} = 10^*$) |
| Max. operating current I_S | 150 mA | $t_{an} \leq 17.5$ s (at $F_{ave} = 9$) |
| Max. current I_k | 2 A | $t_{an} \leq 17.5$ s (at $F_{ave} = 8$) |
| HV voltage range (L+/L-) U_n | AC 0 ... 1000 V (peak value) 0 ... 660 V r.m.s. (10 Hz ... 1 kHz) DC 0 ... 1000 V | $t_{an} \leq 15$ s (at $F_{ave} = 7$) |
| Power consumption | < 2 W | $t_{an} \leq 12.5$ s (at $F_{ave} = 6$) |
| Response values | | $t_{an} \leq 12.5$ s (at $F_{ave} = 5$) |
| Response value hysteresis (DCP) | 25 % | $t_{an} \leq 10$ s (at $F_{ave} = 4$) |
| Response value R_{an} | 100 kΩ ... 1 MΩ | $t_{an} \leq 7.5$ s (at $F_{ave} = 3$) |
| Undervoltage detection | 0 ... 500 V | $t_{an} \leq 7.5$ s (at $F_{ave} = 2$) |
| Measuring range | | $t_{an} \leq 5$ s (at $F_{ave} = 1$) |
| Measuring range | 0 ... 10 MΩ | during the self test $t_{an} + 10$ s |
| Undervoltage detection | 0 ... 500 V default setting: 0 V (inactive) | |
| Relative uncertainty | | |
| SST (≤ 2 s) | good > 2* R_{an} ; bad < 0.5* R_{an} | Switch-off time t_{ab} (OK_{HS} ; DCP) |
| Relative uncertainty DCP | 0 ... 85 kΩ ▶ ±20 kΩ | (when changing over from $R_F = 10$ MΩ to $R_{an}/2$; at $C_e = 1$ μF; $U_n = DC 1000$ V) |
| (default setting 100 kΩ) | 100 kΩ ... 10 MΩ ▶ ±15 % | $t_{ab} \leq 40$ s (at $F_{ave} = 10$) |
| Relative uncertainty output M (fundamental frequency) | ±5 % at each frequency (10 Hz; 20 Hz; 30 Hz; 40 Hz; 50 Hz) | $t_{ab} \leq 40$ s (at $F_{ave} = 9$) |
| Relative uncertainty undervoltage detection | $U_n \geq 100$ V ▶ ±10 %; at $U_n \geq 300$ V ▶ ±5 % | $t_{ab} \leq 33$ s (at $F_{ave} = 8$) |
| | | $t_{ab} \leq 33$ s (at $F_{ave} = 7$) |
| | | $t_{ab} \leq 26$ s (at $F_{ave} = 6$) |
| | | $t_{ab} \leq 26$ s (at $F_{ave} = 5$) |
| | | $t_{ab} \leq 26$ s (at $F_{ave} = 4$) |
| | | $t_{ab} \leq 26$ s (at $F_{ave} = 3$) |
| | | $t_{ab} \leq 20$ s (at $F_{ave} = 2$) |
| | | $t_{ab} \leq 20$ s (at $F_{ave} = 1$) |
| | | duration of the self test 10 s |
| | | (every five minutes; should be added to t_{an}/t_{ab}) |

Figure 59: The datasheet for the IMD.

Full IMD datasheet here.

11.2.6 Shutdown System Interlocks

Referred from section 2.6.

APPLICATIONS

- Battery
- Inverter
- E-motor

MECHANICAL

- Terminal: 8mm pin and socket
- Wire range: 16-50mm² discrete shielded wire
- Latching Style: No tool required
- HVIL: Integrated, internal

ELECTRICAL

- Voltage rating: 1000V
- Current rating: Up to 250A
- Temperature range: -40°C to 140°C
- Shielding: 360° from wire to device
- IP rating: Mated: IP67, IP6k9k
Unmated: IP2xb

STANDARDS AND SPECIFICATIONS

- AK 4.3.3
- LV215-1
- RoHS

Figure 60: Ratings and interlock description for TE HVP 800 connectors

TE HVP 800 complete Datasheet

11.2.7 Tractive System Active Light

Referred from section 2.7.
TSAL Datasheet here.

11.2.8 Measurement points (TSMPs)

Referred from section 2.8.

| STANDARD ELECTRICAL SPECIFICATIONS | | | | |
|------------------------------------|---|-----------------------------------|---|-----------------------|
| MODEL | POWER RATING $P_{25^{\circ}\text{C}}$ W | LIMITING VOLTAGE U_{\max} | RESISTANCE RANGE ⁽²⁾ Ω | TOLERANCE $\pm \%$ |
| PAC01 | 1 | $\sqrt{P} \times R$ | 0.10 to 2.2K | 1 |
| PAC02 ⁽¹⁾ | 2 | $\sqrt{P} \times R$ | 0.10 to 3.6K | 1 |
| PAC03 | 3 | $\sqrt{P} \times R$ | 0.10 to 4.7K | 1 |
| PAC04 | 4 | $\sqrt{P} \times R$ | 0.10 to 8.2K | 1 |
| PAC05 | 5 | $\sqrt{P} \times R$ | 0.10 to 12K | 1 |
| PAC06 | 6 | $\sqrt{P} \times R$ | 0.10 to 12K | 1 |

Notes

- PAC02 WSZ: $P_{25^{\circ}\text{C}} = 1.8 \text{ W}$
- Resistance value to be selected for $\pm 1 \%$ tolerance from E24 and E96
- For Pulse Diagrams see AC.. Series (www.vishay.com/doc?228730)

Figure 61: Ratings for Vishay PAC series resistors. The TSMP resistors are PAC05 (PAC500001002FAC000), shown in the fifth row

Example multimeter for TS measurement. Link to datasheet. Complete datasheet for TSMP current limiting resistors. Datasheet for TSMP banana jack connectors here.

11.2.10 Discharge circuitry

Characteristics

| | |
|---------------------------|--|
| Tolerance (Code): | $\pm 1\%$ (F), $\pm 5\%$ (J), $\pm 10\%$ (K) |
| Operating temperature: | -65°C to +175°C |
| Temperature coefficient: | $\pm 50\text{ppm}/^{\circ}\text{C}$ to $\pm 300\text{ppm}/^{\circ}\text{C}$ (re to ohmic values), referenced to 25°C, ΔR taken at +105°C |
| Operating voltage: | 700V max |
| Dielectric strength: | 1800Vac 60 seconds, $\Delta R \pm 0.15\%$ |
| Insulation resistance: | 10G min |
| Maximum torque: | 0.9 Nm |
| Free air: | 25°C, rated at 3.5W |
| Load Life | $\Delta R \pm 1.0\%$, Rated power, 2,000 hours |
| Solderability | 90% min. coverage, 245±5°C for 3 seconds |
| Momentary Overload | $\Delta R \pm 0.5\%$, 1.5 times rated power and V (dc) $\leq 1.5\text{V}$ Max. for 5 seconds |
| Moisture resistance | $\Delta R \pm 0.5\%$, -10°C - +65°C, RH>90%, cycle 240 hours |
| Thermal Shock | $\Delta R \pm 0.5\%$, -65°C - 150°C, 100 cycles |
| Terminal Strength | $\Delta R \pm 0.2\%$, (Pull Test) 2.4N |
| Vibration, High Frequency | $\Delta R \pm 0.4\%$, 20g peak |

Figure 62: Ratings for Ohmite AP101 series resistors. The discharge resistor is AP101 3K J

| SERIES SPECIFICATIONS | | | | | | |
|-------------------------|---|--------------------|----------------------------|----------------------------|------------|-------------------------|
| Heatsink Part Number | Height (in. $\pm .010$ / $mm \pm .25$) | For Package Type | Ohmite Resistor Series | Surface Area (mm 2) | Weight (g) | Thermal Res.* (°C/W) |
| RA-T2X-25E | 1.0/25.4 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 8,901 | 25 | 4.8 |
| RA-T2X-38E | 1.5/38.1 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 12,983 | 38 | 3.9 |
| RA-T2X-51E | 2.0/50.8 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 17,065 | 51 | 3.5 |
| RA-T2X-64E | 2.5/63.5 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 21,148 | 63 | 3.1 |
| FA-T220-25E | 1.0 / 25.4 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 9,285 | 18 | 4.7 |
| FA-T220-38E | 1.5 / 38.1 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 13,756 | 27 | 3.8 |
| FA-T220-51E | 2.0 / 50.8 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 18,222 | 37 | 3.4 |
| FA-T220-64E | 2.5 / 63.5 | TO-220, -218, -247 | TBH25,TCH35, TEH70, TEH100 | 22,814 | 46 | 3 |

*Natural convection

Figure 63: Ratings for Ohmite F and R series heatsinks. The discharge resistor heatsink is RA-T2X-25E, shown in the first row.

[Complete datasheet for discharge resistor](#) [Complete datasheet for discharge resistor heatsink](#)

11.2.11 HV Disconnect (HVD)

Referred from section 2.11.

[TE AMP+ Manual Service Disconnect Overview here](#). [TE Manual Service Disconnect Test Parameters datasheet here](#).

APPLICATIONS

- HV battery pack-to-pack

MECHANICAL

- Latching style: Finger actuated - 2 stage lever assist
- Mating cycles: Tested to 50
- Stud: M6
- IP rating: Mated: IPx7, IP6k9k
Unmated: IP2xb
- HVIL: 2x integrated, internal

ELECTRICAL

- Fuse rating: Up to 630A
- Voltage rating: 450 VDC
- Operating Temperature: -40°C to 65°C
- Storage Temperature: -40°C to 85°C
- Current rating: Based on fuse selection

STANDARDS AND SPECIFICATIONS

- USCAR-2
- USCAR-37
- IEC 60529
- RoHS

Figure 64: Rating information for the TE AMP+ Manual Service Disconnect

11.2.12 Ready to Drive Sound

Referred from section 2.12.
Ready to drive buzzer datasheet.

| | |
|--|--------------------|
| Voltage Rating | 12 to 24 Vdc |
| Frequency | 1250 Hz \pm 20% |
| Loudness (dB(A) @ 4 ft) | 97 \pm 8 |
| Current Draw (Amps Max) | 0.6 |
| Sound Pulse Rate (pps) | 1 to 2 |
| Operating Temperature | -40°C to +85°C |
| Termination | 8-32 UNC Studs |
| Housing | ABS, Black UL94V-0 |
| Spike Protected | +100 / -400 Volts |
| Conforms to SAEJ994 (OCT 02) Standards | |
| Cross Reference | |
| ECCO | 520 |
| PRECO | 240 |

Figure 65: Specification for Mallory Sonalert STA20502 Buzzer

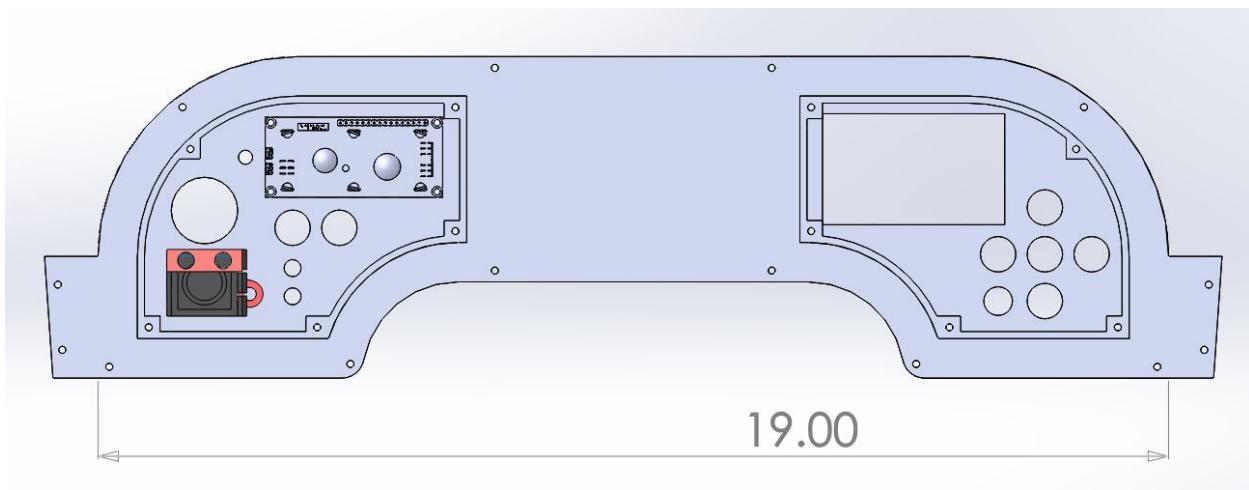


Figure 66: Rendering of the dashboard module as seen from the back

For calculation of sound attenuation over distance, see SengpielAudio Distance Law Equation

11.3 Accumulator

11.3.3 Cell Configuration

Referred from section 3.1.3.

Sheets and Sheeting—Textured Finish



• Temp. Range: -40° to +200°F • Firmness (25% Deflection): 2-5 psi (extra soft), 5-9 psi (soft), or 9-13 psi (firm)
 • Density: Extra soft and soft are 4-8 lbs./cu. ft. and firm is 7-11 lbs./cu. ft.
 Foam meets ASTM D1056, UL 94HF1, MIL-C-3133C, and MIL-STD-670B. Material has a fine cell textured finish and does not have a skin. Sheets have a width tolerance of $\pm 1\frac{1}{4}$ " and a length tolerance of $\pm 2\frac{1}{2}$ ". Sheeting has a width tolerance of $\pm 1\frac{1}{4}$ ".

| Thick. Thick. Tol. | 42" WD. x 72" LG. SHEETS | | | 42" WIDE SHEETING | | |
|--------------------------|--------------------------|--------------|--------------------------|-----------------------|--------------------------|-----------------|
| | Extra Soft Each | Soft Each | Firm Each | Extra Soft Per Ft. | Soft Per Ft. | Firm Per Ft. |
| 1/16" ±0.015" | 8647K106 | \$19.38 | 8647K109 | \$21.36 | 8647K102 | \$16.06 |
| 1/8" ±0.020" | 8647K51 | 28.63 | 8647K71 | 29.62 | 8647K81 | 38.96 |
| 3/16" ±0.026" | 8647K52 | 35.21 | 8647K72 | 37.09 | 8647K82 | 48.35 |
| 1/4" ±0.025" | 8647K53 | 41.79 | 8647K73 | 44.38 | 8647K83 | 56.92 |
| 5/8" ±0.035" | 8647K55 | 66.90 | 8647K75 | 71.03 | 8647K85 | 90.66 |
| 1/2" ±0.040" | 8647K56 | 85.29 | 8647K76 | 92.08 | 8647K86 | 114.04 |
| 3/4" ±0.065" | 8647K58 | 99.61 | 8647K78 | 104.80 | 8647K88 | 127.63 |
| 1" ±0.082" | 8647K59 | 133.01 | 8647K79 | 140.16 | 8647K89 | 177.48 |
| 1 1/4" ±0.095" | 8647K61 | 148.75 | 8647K64 | 157.23 | 8647K67 | 200.68 |
| 1 1/2" ±0.150" | 8647K101 | 167.47 | 8647K107 | 178.93 | 8647K11 | 265.30 |
| 2" ±0.175" | 8647K621 | 216.11 | 8647K651 | 235.86 | 8647K681 | 286.82 |
| | | | | | 8647K102 | 38.96 |
| | | | | | 8647K21 | 5.49 |
| | | | | | 8647K31 | 5.57 |
| | | | | | 8647K32 | 7.44 |
| | | | | | 8647K33 | 7.62 |
| | | | | | 8647K35 | 8.32 |
| | | | | | 8647K36 | 8.80 |
| | | | | | 8647K37 | 14.69 |
| | | | | | 8647K38 | 13.26 |
| | | | | | 8647K39 | 17.99 |
| | | | | | 8647K41 | 19.90 |
| | | | | | 8647K42 | 22.45 |
| | | | | | 8647K43 | 25.76 |
| | | | | | 8647K44 | 28.65 |
| | | | | | 8647K45 | 33.90 |
| | | | | | 8647K46 | 38.47 |
| | | | | | 8647K47 | 43.22 |
| | | | | | 8647K48 | 52.02 |
| | | | | | 8647K49 | 56.24 |

Figure 67: Specifications for the neoprene compression foam that goes in the cell stack.

Complete neoprene information sheet.

11.3.4 Cell Temperature Monitoring

Referred from section 3.1.4.

Link to LTC6804 datasheet used for temperature and voltage measurement

11.3.10 Charging

Referred from section 3.1.10.

Charger datasheet [Note: Per Elcom, a PFC2000+ is a PFC2500 reprogrammed for more power on 115V]
Datasheet.

Charger Information Page Information Page.

Specification

| Spec Model | Output Voltage -Nominal | Output Voltage -Maximum | Output Current -Maximum 230vac | Output Current -Maximum 115vac |
|--------------|-------------------------|-------------------------|--------------------------------|--------------------------------|
| TCCH-36-40 | 36V | 51V | 40A | 38A |
| TCCH-48-35 | 48V | 66V | 35A | 29A |
| TCCH-60-28 | 60V | 82V | 28A | 23A |
| TCCH-72-23 | 72V | 96V | 23A | 19A |
| TCCH-84-20 | 84V | 112V | 20A | 17A |
| TCCH-96-17 | 96V | 130V | 17A | 14A |
| TCCH-120-14 | 120V | 168V | 14A | 12A |
| TCCH-144-12 | 144V | 192V | 12A | 10A |
| TCCH-168-9 | 168V | 233V | 9A | 8A |
| TCCH-216-7.5 | 216V | 289V | 7.5A | 6.5A |
| TCCH-288-6 | 288V | 389V | 6A | 5A |

Figure 68: Charger Output Specifications

AC Input

| | |
|----------------------------|---|
| AC Input Voltage - range | 90 - 260VAC |
| AC Input Voltage - nominal | 120 VAC / 230 VAC |
| AC Input Frequency | 45 - 65 Hz |
| AC Input Current - maximum | 15A |
| Current – nominal | 12 A rms @ 120 VAC / 12 A rms @ 230 VAC |
| AC Power Factor - nominal | > 0.98 |

Mechanical

| | |
|-------------------------|----------------------------------|
| Dimensions | 352mm×195mm×139mm |
| Weight | < 7 kg Standard output cord |
| Environmental Enclosure | IP46 |
| Operating Temperature | -30°C to +50°C (-86°F to 122°F) |
| Storage Temperature | -40°C to +85°C (-104°F to 185°F) |

LED Indicator

| | |
|---------------------------------------|-----------------------|
| Red-Green flash (one second interval) | Battery Disconnected |
| Red flash (three seconds interval) | Repair Battery |
| Red flash (one second interval) | <80% Charge Indicator |
| Yellow flash (one second interval) | >80% Charge Indicator |
| Green flash (one second interval) | 100% Charge Indicator |

Protection Features

- 1.Thermal Self-Protection: When the internal temperature of the charger exceeds 80°C, the charging current will reduce automatically. If exceeds 85°C, the charger will shutdown protectively, there is no current output in this case. When the internal temperature drops to 80°C, it will resume charging automatically.
2. Short-circuit Protection: When the charger encounters unexpected short circuit across the output, charging will automatically stop. By cutting AC power for 10 seconds, the charger can be re-set and will start normally(with the output circuit corrected)
3. High and Low Voltage Protection: When the input AC Voltage is higher or lower than the rated input voltage range, the charger will shutdown protectively, but resume working after the voltage is normal again.

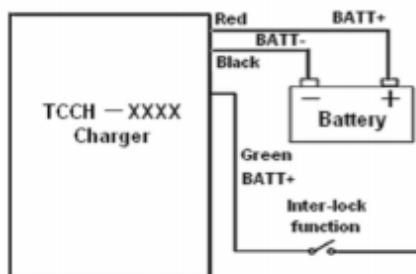
Inter-lock Function

Figure 69: Charger Input and Protection Features

KLKD fuse datasheet

KLKD SERIES 10x38 FUSES

600 Vac/dc • 1/10-30 A • Fast Acting



Specifications

| | |
|-------------------------------|---|
| Voltage Rating: | 600 Vac/Vdc |
| Amperage Rating: | 1/10, 1/8, 2/10, 1/4, 3/10, 1/2, 3/4, 1, 1 1/2, 2, 2 1/2, 3, 3 1/2, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 30 |
| Interrupting Ratings: | AC: 100 kA 200 kA Littelfuse self-certified DC: 1/10-30: 10 kA (UL 2579) 1/10-30: 50 kA (UL 248-14) |
| Material: | Body: Melamine / Caps: Copper Alloy |
| Operating Temperature: | See Rerating Curve |
| Approvals: | UL 2579 Listed (File: E339112) IEC 60269-6 (2-25 A) VDE Certified (No. 40033094) UL 248-14 Listed (File: E10480) CSA Certified Ferrule only (File: LR29862) RoHS Compliant Mexico |
| Environmental: | |
| Country of Origin: | |

Description

The KLKD fuse series is fast-acting with a high DC voltage rating. This family of Midget style fuses (10 x 38 mm) is used in solar combiner boxes and in circuits with DC fault currents up to 50,000 amperes. KLKD fuses are available in standard and board-mount configurations.

In addition, the KLKD series has been designed to meet both the UL and IEC photovoltaic fuse standards.

Littelfuse offers a wide range of ampere ratings to match specific requirements in a variety of applications.

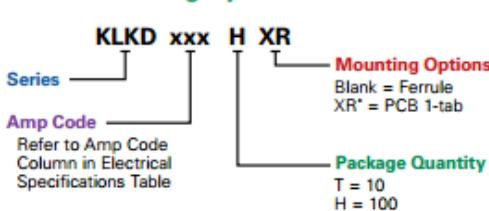
Features/Benefits

- Designed to UL and IEC photovoltaic specifications
- 1/10 - 30 A ratings available
- 50,000 A Interrupting Rating
- Available in ferrule or PCB mount options
- 1-5 A meets UL1741 GFDI requirements

Applications

- Combiner boxes and Inverters
- Power supplies
- Desktop meters

Part Numbering System



| SERIES | AMP | PACKAGE QUANTITY | MOUNTING METHOD | CATALOG NUMBER | ORDERING NUMBER |
|--------|-----|------------------|-----------------|----------------|-----------------|
| KLKD | 1/8 | 10 | FERRULE | KLKD 1/8 | KLKD.125T |
| KLKD | 5 | 100 | FERRULE | KLKD 5 | KLKD005.H |
| KLKD | 15 | 100 | PCB 1-TAB | KLKD 15-R | KLKD015.HXR |

Figure 70: Charging protection fuse datasheet overview

Omron G9EJ-1-E Relay Datasheet

Compact DC Power Relays Capable of Switching 400 V 15 A DC loads

- Actualize a high capacity interruption through the function of extinction of magnetic arc by adopting high-efficiency magnetic circuit.
- Actualize improvement of inrush-withstand performance and a long-life by adopting Omron's own contact driving system.
- Actualize the power saving.
- Small and lightweight type.

Size: H31 mm x W27 mm x L44 mm, Weight: approx. 45 g



RoHS Compliant



Refer to the Precautions on page 5.

Model Number Structure

G9EJ-**□**-**□**-**□**-**□**-**□**
1 2 3 4 5

- | | |
|---|---|
| 1. Number of Poles 1: 1 pole | 4. Classification E: High capacity |
| 2. Contact Form Blank: SPST-NO | 5. Approved standards UVD: UL, CSA, VDE approved standard type |
| 3. Terminal Form Blank: Tab terminals (#250 terminals) P: PCB terminals | |

Ordering Information

| Models | Terminals | | Contact form | Rated coil voltage | Model | Minimum packing unit (quantity) | |
|-------------------------------------|--------------------|--------------------|--------------|--------------------|----------------|---------------------------------|--|
| | Coil terminals | Contact terminals | | | | | |
| Switching/current conduction models | Tab terminals #250 | Tab terminals #250 | SPST-NO | 12 VDC | G9EJ-1-E-UVD | 10 | |
| | PCB terminals | PCB terminals | | 24 VDC | | | |
| | | | | 12 VDC | G9EJ-1-P-E-UVD | | |
| | | | | 24 VDC | | | |

Ratings

● Coil

| Rated voltage | Rated current | Coil resistance | Must-operate voltage | Must-release voltage | Maximum voltage (See note 3) | Power consumption |
|---------------|---------------|-----------------|---------------------------|--------------------------|---|-------------------|
| 12 VDC | 100 mA | 120 Ω | 60% max. of rated voltage | 5% min. of rated voltage | 130% of rated voltage (at 23°C within 10 minutes) | Approx. 1.2 W |
| 24 VDC | 50 mA | 480 Ω | | | | |

Note: 1. The figures for the rated current and coil resistance are for a coil temperature of 23°C and have a tolerance of ±10%.

Note: 2. The figures for the operating characteristics are for a coil temperature of 23°C.

Note: 3. The figure for the maximum voltage is the maximum voltage that can be applied to the relay coil.

● Contacts

| Item | Resistive load |
|---------------------------|-----------------|
| Rated load | 15 A at 400 VDC |
| Rated carry current | 15 A |
| Maximum switching voltage | 400 V |
| Maximum switching current | 15 A |

Figure 71: Charging interlock relay datasheet overview

11.4 Energy Meter Mounting

Referred from section 4.

| Electrical Characteristics | | | | | | | | |
|----------------------------|----------|------------------------|-----|----------------------------|--------------------------------|---|-----------------------|------------------------|
| Ampere Rating (A) | Amp Code | Max Voltage Rating (V) | | Interrupting Rating | Nominal Cold Resistance (Ohms) | Nominal Melting I _{2t} (10In - A ² sec) | Max Voltage Drop (Mv) | Agency Approval cUL us |
| | | AC | DC | | | | | |
| 2.00 | 1200 | 250 | 450 | 200A@250VAC 10KA@450VDC | 0.069 | 0.0610 | 342 | x |
| 2.50 | 1250 | 250 | 450 | | 0.054 | 0.0898 | 300 | x |
| 3.00 | 1300 | 250 | 350 | 200A@250VAC 10KA@350VDC | 0.042 | 0.2007 | 276 | x |
| 3.15 | 1315 | 250 | 350 | | 0.038 | 0.2191 | 270 | x |
| 4.00 | 1400 | 250 | 250 | 200A@250VAC 10KA@250VDC | 0.027 | 0.5445 | 240 | x |
| 5.00 | 1500 | 250 | 250 | | 0.022 | 1.1584 | 215 | x |

Notes:

1. Cold resistance measured at less than 10% of rated current at 23°C.
2. An operating current of 80% or less of rated current is recommended, with further derating required at elevated ambient temperature.
3. Have special electrical characteristic needs? Contact Littelfuse to learn more about application specific options.

Figure 72: Electrical characteristics snapshot for Littelfuse 808 series fast-acting fuses. The high-voltage low-power fuse we use is the 80812000000.

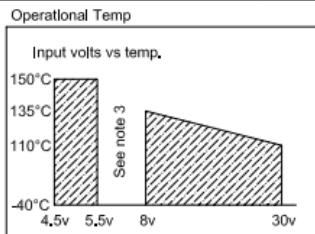
Littelfuse 808 Series datasheet.

11.7 Torque Encoder

Referred from section 7

MHR5600 - 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 | <100 | | mS |
| Input voltage rise time | 0.25 mlnimum | | 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 |
| Monotonic range | 1 - 99% | | |
| Load resistance | >10K | | |
| Output noise | <5 | | |
| Performance Specification | | | |
| Measurement angle | 20 to 360 ±2 in 1° Increments | | |
| Resolution | 0.025 | | |
| Non-Linearity (see note 4) | <±0.25% | | |
| Phasing (see note 5) | <0.5% | | |
| Temperature coefficient | <±0.003% | <±0.011% | FS/°C |
| Update rate | >500 | | |
| Max operating speed | 600 | | |
| General Specification | | | |
| Weight | 23.0 | | |
| Protection/Sealing | Sensing circuit: IP68 & IP69K, Ball-race bearings: IP65 | | |
| Life (Bearings) | > 500 million operations | | |
| Dither life | Contactless - no degradation due to shaft dither | | |
| Operational temperature | -40 to +150 | See de-rating graph | °C |
| Storage temperature | -55 to +150 | | |
| Materials | Case - AlumInium 6026 Module - Thermoplastic Shaft - Stainless steel 316 | | |



- Notes:
1. Incorrect wiring may cause internal damage.
 2. When shaft marking is facing cable exit, instrument is mid-travel (2.5v output).
 3. Do not operate between 5.5V and 8V.
 4. Non-linearity is calculated from Least Squares Best Fit method.
 5. Phasing for the MHR5610 DV-XXX option is at mid-travel only.

Figure 73: Electrical specifications for Magni-Tec MHR5600-series rotary encoders

Magni-Tec MHR5600 Series datasheet.

- **CAN Timeout:**

This parameter is used in CAN mode only. This parameter is set as a multiple of 3 msec. For example, the default value is set to 333 which is equivalent to the actual **timeout** value of 1 second (333 x 3msec). This parameter delays setting the CAN **Timeout** fault for the amount of time it represents.

Figure 74: CAN Timeout parameter for RMS PM100DX motor controller

Rinehart Motion Systems CAN protocol datasheet.