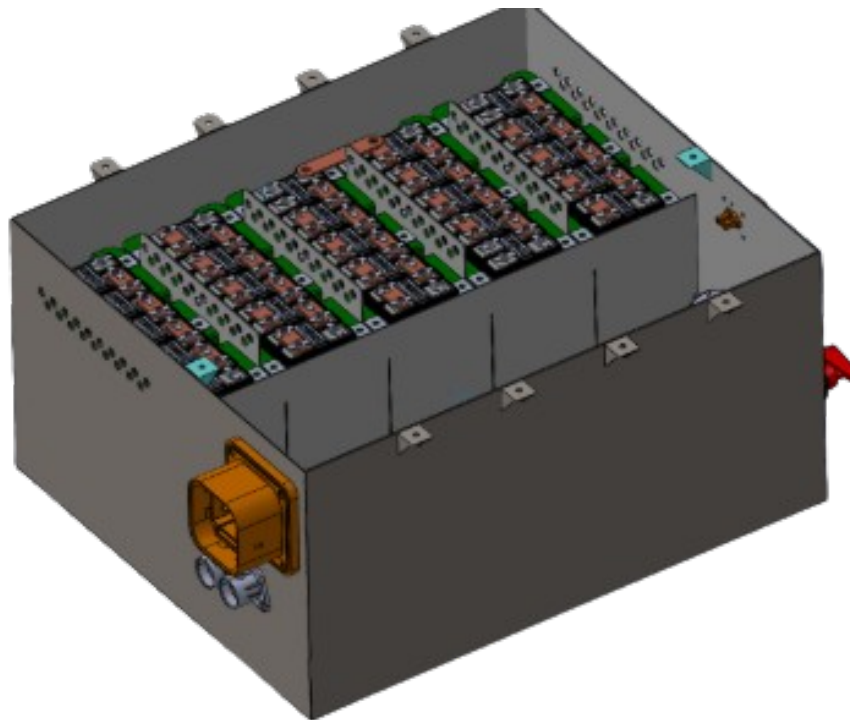




Design Report Battery Pack FSAE-EV 2025

Colorado State University



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1 Introduction

Each year, SAE hosts a competition where college teams design and build a 1/3-scale Formula-style race car, competing in design, manufacturing, performance, and cost. Colorado State University FSAE team, has excelled in combustion vehicles but is now developing its first electric race car to adapt to industry trends.

This project focuses on designing and building the high-voltage battery pack, including cells, fuses, and a battery management system, while complying with FSAE rules and performance goals. Since the team has never built one before, extensive research and design iterations were necessary. Learning from other FSAE EV teams, the design evolved to meet technical and packaging constraints. With the finalized design, the next step is component procurement and fabrication, aiming for spring testing.



Figure 1.1. 2013 RAM Racing Formula SAE Car

2 Electrical Specifications

Each battery module consists of 8 cells in parallel (8p) using **Molicel P28A** lithium-ion cells. The full pack connects **50 modules in series**, yielding a high-voltage accumulator. Table 1 summarizes the key electrical specifications for a single 8p module versus the complete 50-module pack:

Specification	Single Module (8p)	Full Pack (50s8p)
Energy Capacity	~82 Wh	~4,100 Wh
Charge Capacity	22.4 Ah	22.4 Ah
Nominal Voltage	3.6 V	180 V (3.6 V × 50)
Maximum Voltage	4.2 V	210 V (4.2 V × 50)
Minimum Voltage	2.5 V	125 V (2.5 V × 50)
Standard Charge Current	22.4 A (1×C)	22.4 A
Max Charge Current	48 A (2×C)	48 A (limited per module)
Max Discharge Current	210 A	210–220 A
Weight (approx.)	0.38–0.50 kg	19–20 kg

Table 1. Battery Module vs. Full Pack Specifications (Molicel P28A cells)

Each 8p module has a nominal ~3.6 V output and ~22.4 Ah capacity, storing about 82 Wh of energy. The 50-module series pack therefore delivers ~180 V nominal (210 V max, 125 V min) and ~22.4 Ah, for a total energy of approximately 4.1 kWh. The pack's **maximum discharge current** is designed around $\approx 210\text{--}220\text{ A}$, which is about a 9–10C discharge rate relative to the 22.4 Ah capacity. This high current capability is enabled by the P28A cells; each cell can continuously discharge up to ~35 A, and eight in parallel safely support ~210 A



Figure 2.1. Battery Module

In practice, 220 A is used as the system's peak current limit to build in a slight margin. The **charge current** is set to a standard 1C (22.4 A) per module for normal charging, with a maximum charge rate of about 2C (≈ 48 A) if faster charging is needed. Voltage limits per cell are 4.2 V (fully charged) and 2.5 V (minimum safe discharge), corresponding to the pack limits stated above.

3 Wiring and Current Ratings

The battery pack's high-voltage wiring is carefully selected to handle the expected current. The maximum pack current of **220 A** was chosen to align with the rating of the primary high-voltage cable: a **1/0 AWG Champlain EXRAD XLE HVFX shielded cable**. This cable is rated for up to approximately **335 A** continuous (ampacity in free air at 40 °C) well above the 220 A limit, providing a healthy safety margin. It also has a **600/1000 V** insulation rating easily meeting the pack's ~210 V maximum, and a high-temperature tolerance (150 °C continuous). The EXRAD HVFX cable features a **cross-linked polyolefin insulation** that is thin-wall, flame-retardant (FT-1), and highly flexible, with a braided shield for EMI suppression and added safety. In summary, the selected 1/0 AWG cable's specifications are:

- **Conductor Size:** 1/0 AWG ($\approx 50 \text{ mm}^2$ cross-section), tinned copper, with braided shielding.
- **Ampacity:** ~335 A continuous in open air (at 40 °C ambient) more than sufficient for the 220 A maximum system current.
- **Voltage Rating:** 1000 V DC (600 V AC) per ISO 6722 standard, which covers the pack's voltage with a wide margin.
- **Insulation & Jacket:** Cross-linked (XLE) polyolefin insulation rated to 150 °C, and an outer jacket with excellent flexibility and abrasion resistance.

The cable is **shielded** to meet high-voltage EV requirements (reducing electromagnetic interference and allowing the shield to be grounded for safety).

All high-current connections are designed for **220 A** continuous load, so the 1/0 HV cables and connectors are the bottleneck by design. By limiting current to 220 A, we ensure the cable never exceeds its thermal rating in operation, and voltage drops are kept reasonable. The cable's large cross-section minimizes resistive losses over the distances in the pack, preserving efficiency and reducing heating.

4 Configuration

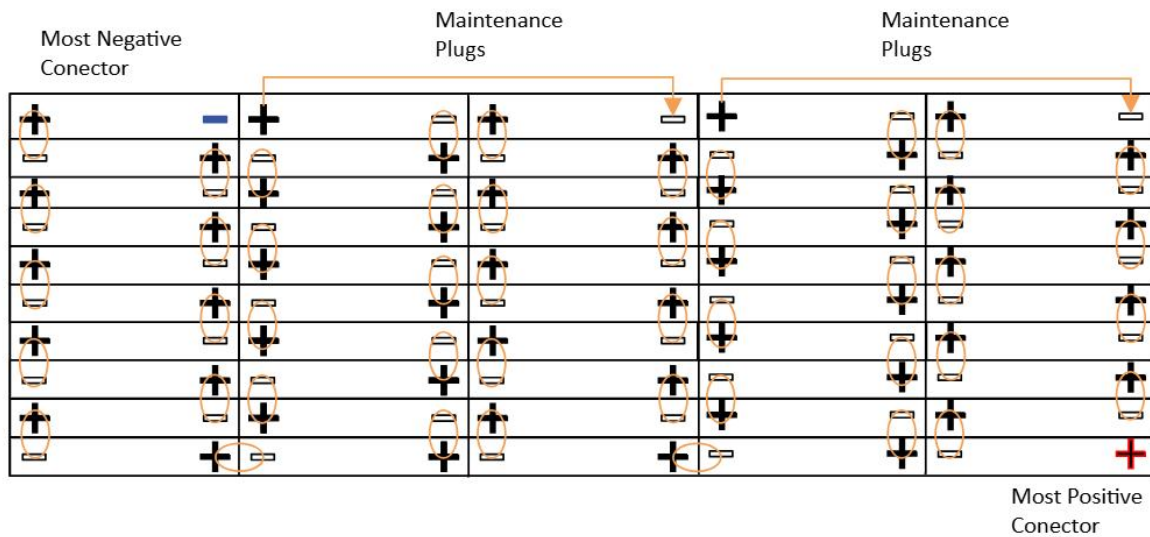


Figure 4.1. Battery Modules Configuration

The battery pack is configured as **50 modules in series (50s)** to achieve the target high voltage (~180 V nominal). To improve safety and serviceability, the series stack is segmented using **maintenance plugs** that divide the pack into three sections, each with a maximum voltage of about ~70–80 V. In this design, the 50-module string is split into three sub-pack sections (for example, 17 modules + 17 modules + 16 modules), each well below 120 V. When the maintenance connectors are opened, no section exceeds ~80 V, allowing safer handling during maintenance or assembly. This segmentation is critical for compliance with rules and safe work practices: it ensures that when the accumulator is disconnected into segments, each segment is at an extra-low voltage (reducing shock hazard and falling below certain regulatory voltage thresholds for service work).

Within each segment, the modules are linked **cell-to-cell by copper busbars**. Each module has M6 terminals designed for busbar connection.



Figure 4.2. Custom Copper Busbars

Copper busbars provide a low-resistance, rigid connection capable of carrying the full pack current with minimal voltage drop and heat. They also add structural rigidity to the module stack. The use of solid busbars (as opposed to flexible cables between every module) simplifies the module interconnects and keeps the assembly compact and neat. At the locations where the pack is divided (the maintenance plug interfaces), the busbar connection is replaced with high-voltage connector interfaces as described in the next section.

5 Construction Details

This section outlines the physical construction of the battery pack, including module materials, bonding techniques, electrical connections, and interface hardware. Each design decision prioritizes safety, serviceability, and reliable high-current performance under motorsport conditions

5.1 Module Materials & Bonding

Each module (the “Lithium Block” module from CIE Solutions) is built with a robust, insulating enclosure made of **glass-filled, fire-retardant ABS plastic**. This material provides strength and flame resistance, protecting the cells and containing any venting in case of cell failure.



Figure 5.1. Battery Case

The cells within a module are joined using **ultrasonic wire bonding**, which fuses the cell terminals with aluminum or copper bonding wires. This method not only creates a low-resistance connection between parallel cells, but also serves as a built-in fuse for each cell: if a cell experiences a short or high fault current, the bond wire will melt and isolate that cell (preventing a cascading failure). Each module has **M6 threaded terminals** (inserted brass terminals) on its positive and negative ends to facilitate connections. These M6 terminals are the attachment points for either busbars (module-to-module connections) or connector adapters at the segment boundaries.

5.2 Inter-module Connections and Maintenance Plugs:

For most series connections, **copper busbars** are bolted between the M6 terminals of adjacent modules, as noted. At the locations where the pack is split into segments, a high-voltage **maintenance connector** is used instead of a direct busbar. These connectors utilize **Amphenol RADSOK® contact technology** for high current capacity. In particular, the design uses **RADSOK-based plug connectors (Amphenol UPC series, 9.1 mm size)**, which are rated for **up to 200 A** continuous when fitted with 50 mm² conductors.

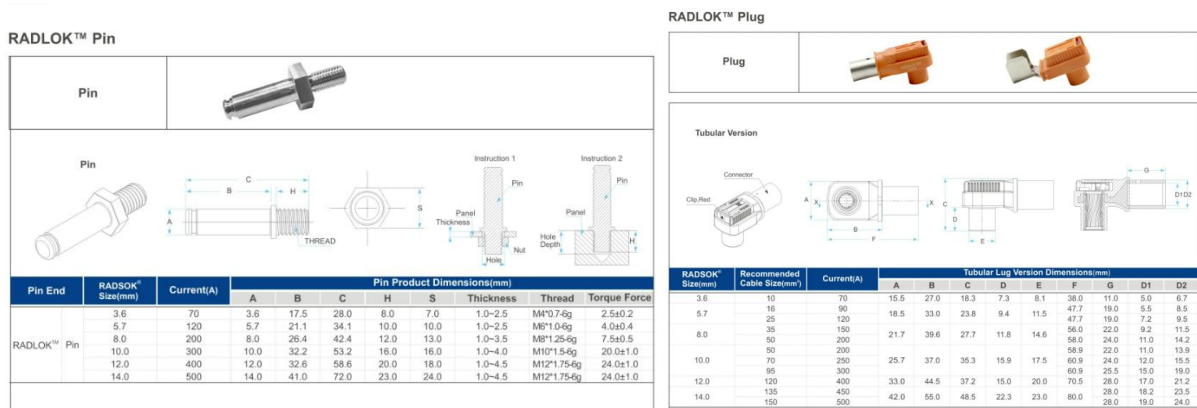


Figure 5.2. RADLOK Pin and Plug Specifications

Each maintenance interface consists of a matching plug and receptacle: one side attached to the end of one sub-pack segment, and the other side to the beginning of the next segment. The connectors are **touch-proof** featuring a twist-grid socket that provides low contact resistance and robust mating for many cycles. They are sized to accommodate the pack’s 1/0 AWG (50 mm²) cables on the connector pigtails.

5.3 Pin Connectors

To adapt the module’s M6 terminal to the larger connector interface, a **special M6-to-RADSOK pin adapter** from Bracket Boyz is used. This adapter screws into the module’s M6 threaded terminal and provides an **8 mm diameter pin** that fits the RADSOK 9.1 mm socket, effectively turning the module’s terminal into a male connector post. It allows direct mating of the high-current connector without modifying the module terminals. The Bracket Boyz adapter is designed specifically for batteries with M6 female threads (common in motorsports batteries) to enable using larger **RadLok/RADSOK style connectors with 1/0 gauge cables**, without adding excessive bulk.



Figure 5.3. The Bracket boyz Pins

By using this adapter, the connection remains compact and secure, and it preserves the original M6 interface for flexibility. The connectors at the maintenance plugs are wired with short lengths of **50 mm² cable** to the adapters, matching the main cable's size to avoid any bottleneck. Each maintenance plug assembly is rated for 200 A continuous (with some overhead for the ~210–220 A peak), and is keyed and shrouded to prevent any misconnection or exposure of live contacts.

The main output of the battery pack is routed through an **Accumulator Isolation Relay (AIR)** system – essentially high-voltage contactors that serve as the pack's main on/off switch (and crash safety disconnect). The pack's positive and negative output cables (50 mm², 1/0 AWG) run from the end of the series chain to the AIRs and then to the external output connector. At the connection points to the AIR contactors and the high-voltage disconnect points, **heavy-duty ring terminals** are used. These lugs are sized for **1/0 AWG cable and 1/4" stud** (approximately M6 bolt), and the ring terminals ensure a low-resistance, robust connection capable of the full current. The terminals are insulated with dual-wall heat shrink tubing and protective boots to prevent accidental contact.



Figure 5.4. Heavy Duty Ring Terminal 1/0

Finally, the battery pack's output is made accessible through an **Amphenol Heavy-Duty High Voltage "UPC" Power Connector**. This is a two-pole high-voltage connector (from the Amphenol UPC series) mounted on the battery enclosure as the main output receptacle. It also uses the same RADSOK 9.1 mm contacts as the internal maintenance plugs, providing **200 A continuous rating (with 50 mm² cables)** and up to 1000 V capability.

5.4 Amphenol High Voltage Connector



Figure 5.5. Amphenol High Voltage Connector

The UPC connector allows the entire accumulator to be quickly disconnected from the car's powertrain by simply unplugging the main connector, for example in an emergency or during pack removal. It is a **plastic shell, bayonet-lock connector** with IP67 sealing and an integrated HVIL loop. The mating half of this connector is attached to the vehicle's high-voltage cable harness leading to the motor controller/inverter. The connector choice was driven by its safety features (touch-proof, locking, interlock), high current capacity, and motorsport-grade durability (rated for at least 100 mating cycles). With this in place, the battery pack can be considered a plug-and-play module: all high-voltage interfaces are via proper connectors or enclosed terminals, minimizing exposure of live conductors and simplifying maintenance.

5.5 Battery Cells

Using high-performance Molicel P28A lithium-ion cells, the battery pack is expected to deliver strong performance in terms of longevity, reliability, and power delivery:

Cycle Life: The Molicel P28A cells are designed for high power output while maintaining a decent cycle life. Under high discharge conditions (e.g. continuous 20 A discharge per cell, which is $\sim 0.9C$ for the 22.4 Ah module or about a 9C rate per cell), the cells can achieve roughly 400 cycles before dropping to 80% of their original capacity

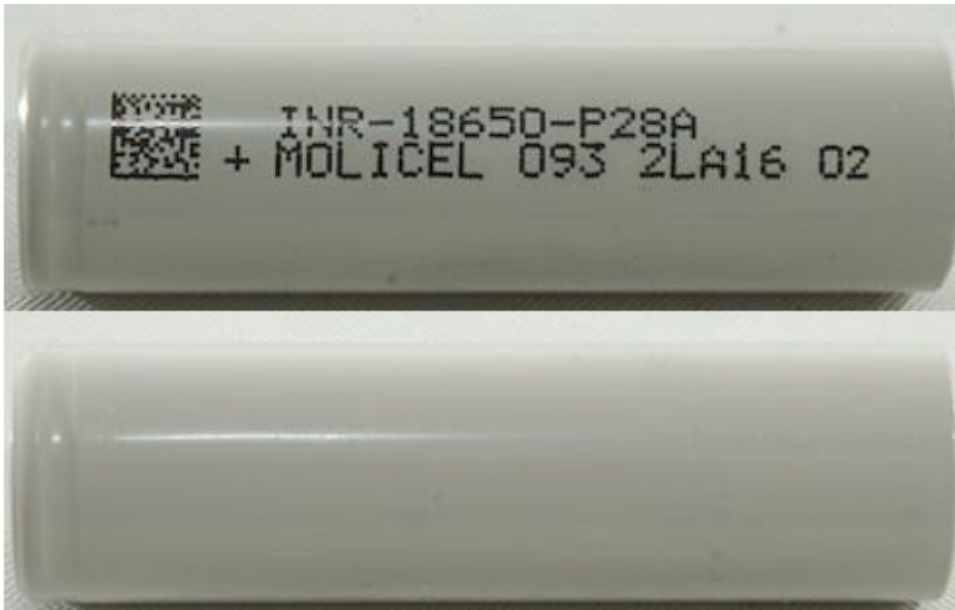


Figure 5.6. Molicell P28 Cell

In an FSAE context, where typical duty might involve short high-current bursts and partial cycling rather than full 100% depth-of-discharge each run, the cycle life can be significantly higher. With more moderate use (lower discharge rates or partial depth cycles), one can expect well over 500 cycles with minimal degradation. The pack is more than capable of lasting multiple racing seasons, as FSAE endurance events and testing will amount to only dozens of full equivalent cycles. Proper thermal management (keeping cells within their 0–60 °C operating window) will further ensure longevity.

5.5.1 Self-Discharge

Lithium-ion cells have very low self-discharge, and the P28A is no exception. The pack can be stored for extended periods with minimal loss of charge. Typical self-discharge for Li-ion is on the order of only 2–3% per month at room temperature (after an initial drop right after charge). The pack includes a battery management system (BMS) that draws a negligible current, so even over many weeks of inactivity the state of charge will remain high.

5.5.2 Internal Resistance and Power Delivery

The P28A cells have a very **low internal resistance** of about 20 mΩ per cell (measured at 1 kHz AC or DC pulse)

$$R_{module} = \frac{20 \text{ m}\Omega}{8} \approx 2.5 \text{ m}\Omega$$

(ignoring minor additional resistance from busbars and connections)

For the full pack (50 in series), the internal resistance is:

$$V_{drop} = I \cdot R \approx 200 \text{ A} \times .125 \Omega = 25 \text{ V}$$

So at nominal 180 V, the pack would still provide ~ 155 V under 200 A load – a sag of about 14%, which is very manageable. The cells' chemistry (likely NMC-based) also gives them a strong high-rate performance. The pack's power output capability can be estimated as:

$$P = V \times I = 180 \text{ V} \times 20 \text{ A} \approx 3.6 \text{ kW}$$

Even accounting for sag, the pack can comfortably supply on the order of 35–40 kW, which meets the power needs of an FSAE race car (which typically might draw peak power in the tens of kW range). The high power delivery is available without excessive temperature rise, as the internal cell resistance (and thus I^2R losses) are low – each cell dissipates only a few watts at 30–35 A load, which the module design can effectively dissipate via its air-cooled configuration.

6 Shutdown Circuit

6.1 Overview

The shutdown circuit is a series interlock loop that ensures the tractive system (high-voltage system) is only active when all safety conditions are satisfied.

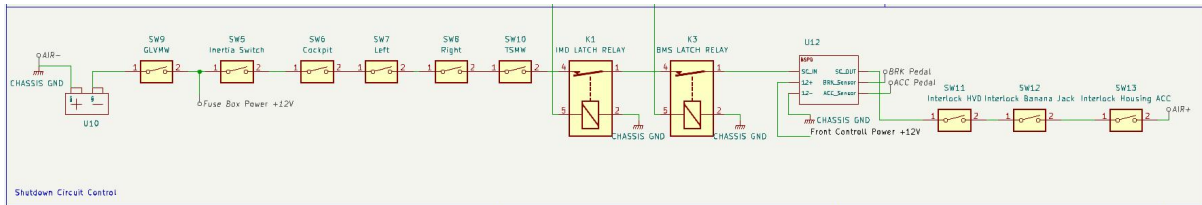


Figure 6.1. Shutdown Circuit Schematic

6.2 Master Switches

It begins with the Grounded Low Voltage Master Switch (GLVMS), which is the main 12 V supply switch for the low-voltage control system. When the GLVMS is turned off, it completely cuts power to the low-voltage system (GLVS), preventing any activation of anything in the car this means that unless the GLVMS is ON, none of the tractive system controls (relays, contactors, etc.) can energize.

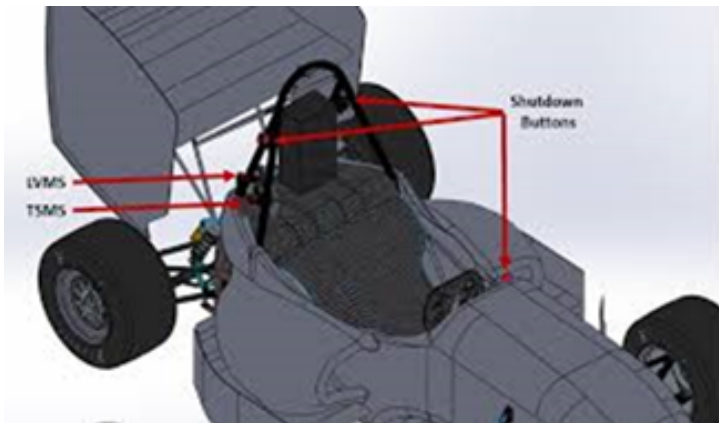


Figure 6.2. Master Switches and Shutdown Button Locations

6.3 E-STOP

In series after the GLVMS, the circuit includes multiple Emergency Stop (E-Stop) buttons as required by FSAE rules. There are three E-Stops: one on each side of the vehicle (externally accessible behind the driver’s compartment, near driver’s head level) and one within the cockpit for the driver. All E-Stop buttons are red, push-pull emergency switches of ≥ 40 mm diameter

externally (≥ 24 mm in cockpit). Pressing any E-Stop immediately opens the shutdown circuit . In practice, this means the E-Stop buttons are wired in series – if any one is pressed, the series loop is broken and the tractive system is rapidly de-energized. This design allows trackside or driver intervention to instantly shut down the high-voltage system in an emergency, as mandated by Formula SAE safety rules

Parameter	Value
Model	LAY7 (PBCY090) LAY37
Standard	IEC 337
Voltage Rating (Ui)	660V
Current Rating (Ith)	10A
Application Category	AC-15
Type	Push Button Switch

Table 2. Emergency Stop Button Specifications



Figure 6.3. Emergency Stop Buttons (E-Stops)

6.4 Inertia Switch

An Inertia Switch (a crash sensor) is also integrated in series with the E-Stops. The inertia switch used is a Sensata-style automotive crash switch that mechanically latches open when subjected to a sudden deceleration (approximately 8–11 g threshold). In the event of a collision or heavy impact, the inertia switch will trigger and open the shutdown circuit. It remains latched

open until manually reset, ensuring that after a crash the tractive system stays disabled until the team verifies the vehicle's safety.



Figure 6.4. Inertia Switch

Parameter	Value
Model	LAY7 (PBCY090) LAY37
Standard	IEC 60947-5
Voltage Rating (Ui)	660V
Thermal Current (Ith)	10A
Protection Level	IP55

Table 3. Inertia Switch Specifications

6.5 IMD and BMS Error State

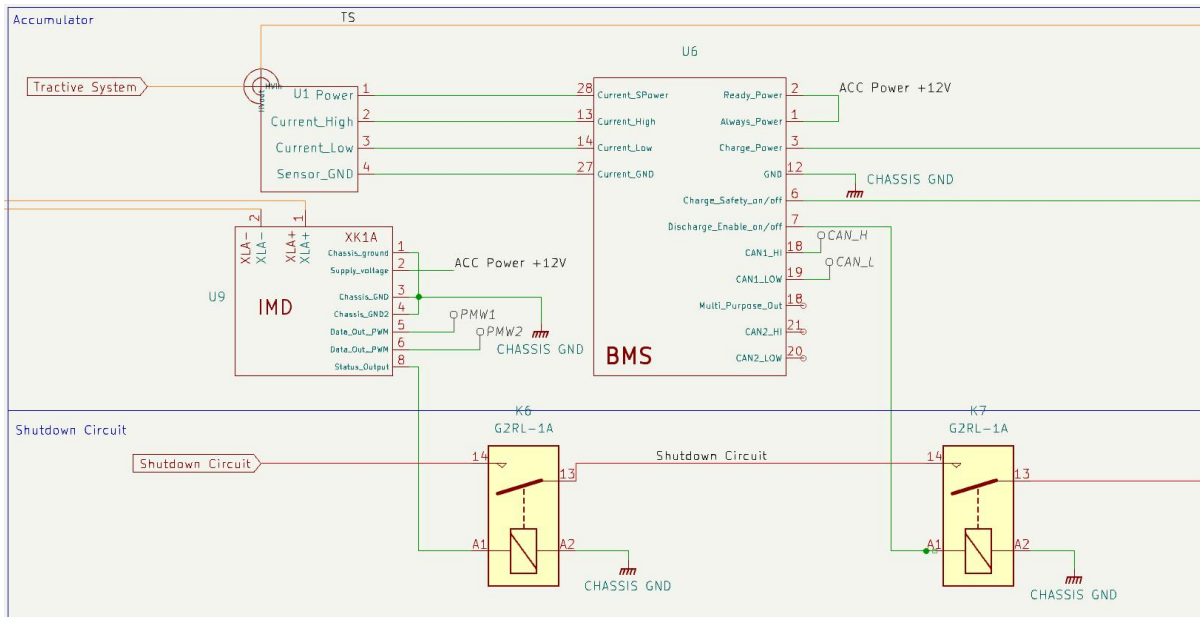


Figure 6.5. IMD and BMS Shutdown Control Logic

In the accumulator shutdown system, both the BMS (Orion BMS 2) and the IMD (Bender ISOMETER IR155-3204) provide fault detection signals that control the shutdown relays. Under normal operating conditions, these signals remain HIGH, keeping the relays energized and allowing the system to function. However, when a fault is detected—such as insulation failure detected by the IMD or a critical battery issue identified by the BMS—the respective unit drives its output LOW. This LOW signal de-energizes the relay, causing it to open and break the shutdown circuit.

6.6 Brake System Plausibility Device (BSPD).

The BSPD is a standalone hardware circuit (non-programmable logic as required by FSAE) that monitors the brake pedal usage and motor power output

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It takes inputs from the brake pedal (hydraulic pressure or brake light switch) and the throttle (accelerator pedal position or motor current). If it detects an implausible condition – specifically, if the brakes are applied *hard* while the motor is delivering significant power (equivalent to >5 kW) for more than 0.5 seconds – it interprets this as a potential accelerator pedal fault (driver “standing on the brakes” while the car still tries to drive). The BSPD will then open the shutdown circuit, cutting power to the motor.

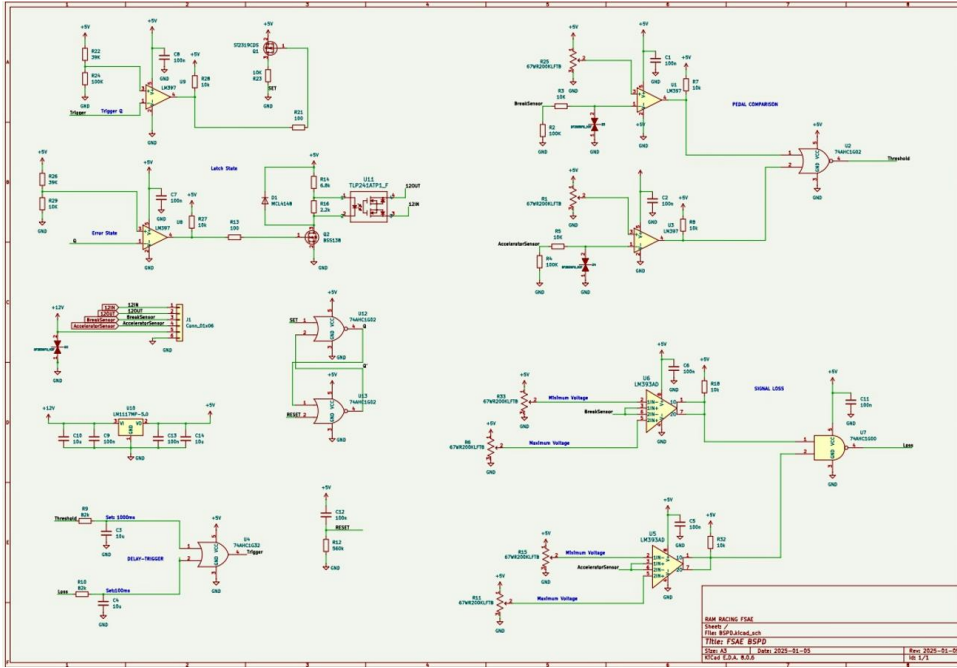


Figure 6.6. BSPD Schematic

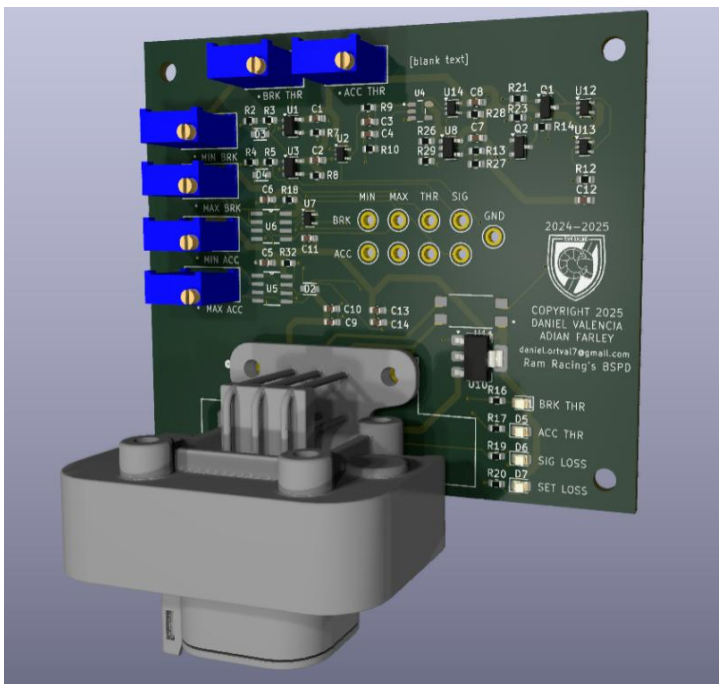


Figure 6.7. BSPD PCB

6.7 Interlock connections

Interlock connections are placed at key high-voltage points to ensure compliance with FSAE rules. Removing the **High Voltage Disconnect (HVD)** or opening the accumulator container **breaks the interlock**, opening the shutdown circuit and isolating the battery. The high-voltage output connector also has an interlock, triggering shutdown if unplugged or exposed. These

low-current interlock wires do not carry power but ensure any disturbance forces an immediate shutdown, preventing accidental exposure to live HV connections.

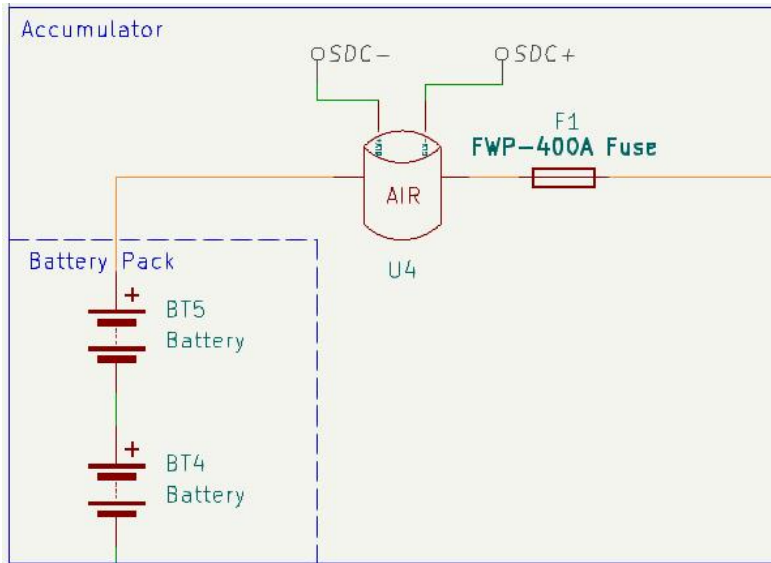


Figure 6.8. Negative AIR

All the aforementioned devices (GLVMS, TSMS/E-Stops, inertia switch, BSPD, BMS fault output, IMD fault output, and interlocks) are wired in series to form the **shutdown circuit loop**. This loop directly controls the coil of the negative Accumulator Isolation Relay (AIR) in our system. Only when the loop is closed – meaning all conditions are nominal (GLVMS on, TSMS on, no E-Stop pressed, inertia switch ok, BSPD ok, no BMS/IMD faults, all interlocks closed) – will the negative contactor coil energize and close the negative AIR. In other words, the negative side of the battery pack is only connected to the tractive system when the car is in a fully safe state to operate.

pletely disconnected from the rest of the car.



Figure 7.2. Relay Contactor TE Connectivity

For safety, the **negative AIR is controlled directly by the shutdown circuit** (as described in EV.4) – it only closes when all safety conditions are met. The **positive AIR is controlled by the motor controller’s precharge logic**: during startup, the positive contactor remains open while the precharge circuit limits inrush current; once the inverter’s capacitors reach $\sim 90\%$ of pack voltage, the motor controller enables the positive AIR to close. This sequencing (negative closes first, precharge, then positive) ensures a controlled charging of the inverter and prevents contactor damage from high inrush currents.

Specification	Details
Manufacturer	TE Connectivity (Kilovac)
Model	EV200AAANA
Contact Voltage Rating	Up to 900V DC
Continuous Current	500A
Coil Voltage	12-24V DC
Contact Resistance	$\leq 0.2 \text{ m}\Omega$
Mounting Type	Panel Mount
Weight	$\sim 0.5 \text{ kg (1.1 lbs)}$

Table 4. AIR Specifications

7.3 Battery Management System (BMS)



Figure 7.3. Orion BMS 2

The accumulator is managed by the Orion BMS 2, a widely used lithium-ion battery management system. The BMS monitors every cell in the battery pack via voltage sense taps and monitors temperatures throughout the pack via thermistors. It also uses a hall-effect current sensor to measure pack current in real time. By reading these sensors, the Orion BMS can detect critical conditions such as over-voltage, under-voltage, over-current, and over-temperature at the cell level, as well as overall pack health. If any cell goes outside safe limits (for example, a cell's voltage drops too low or a temperature exceeds the threshold), the BMS will automatically take action to protect the pack.

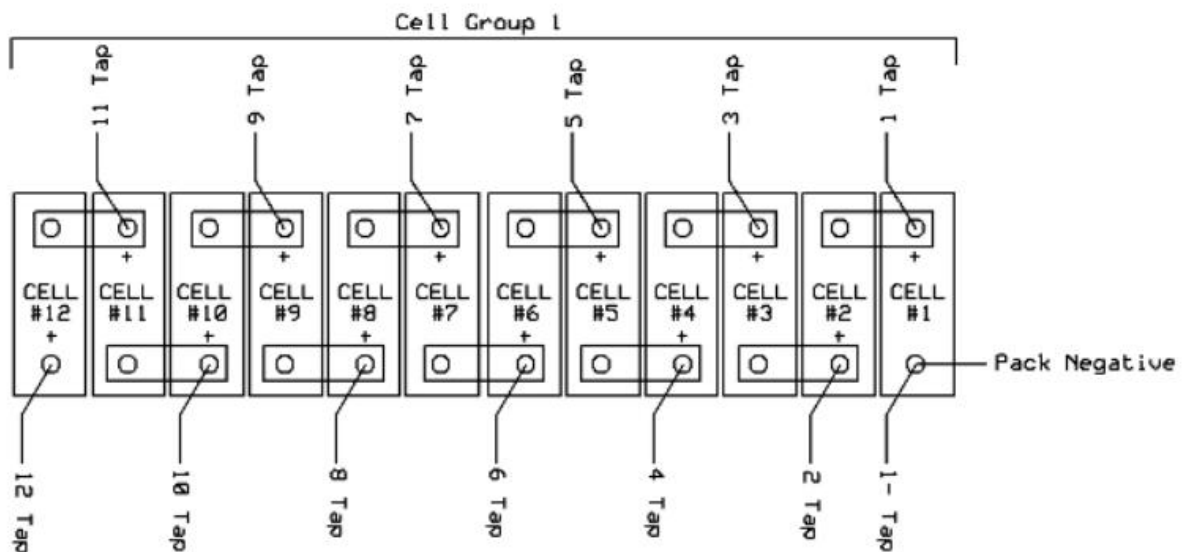


Figure 7.4. Voltage Taps



Figure 7.5. Voltage Tap Assembly



Figure 7.6. Current Sensor and Thermistor

The Orion BMS communicates with other systems over CAN bus, transmitting battery status, State-of-Charge, and fault codes to the vehicle's data logger and dashboard. This allows the team to see values of voltage or temperature.. The BMS also manages cell balancing by bleeding off charge on higher-voltage cells to keep the pack balanced during charging.

7.4 Insulation Monitoring Device (IMD)

To continuously monitor the isolation between the high-voltage system and the chassis, we use an IMD device (Someter IR155-3203/3204, which is equivalent to the Bender ISOMETER® IR155 series as required by FSAE rules). The IMD injects a small signal into the tractive system circuit and measures the resistance to chassis ground. If the insulation resistance falls below the required threshold of 500 Ω/Volt (which, for our pack ~220 V, equates to ~110 kΩ), it indicates a potentially dangerous insulation fault (for example, a wire shorted to the chassis or moisture creating a leakage path). Upon detecting such a fault, the IMD immediately opens its internal relay contact, which is integrated into the shutdown circuit. Per FSAE rules.

Specification	Value
Make / Model	Bender ISOMETER IR155-3204
Supply voltage	12VDC
Environmental temperature range	-40..105°C
Self-test interval	Always at startup, then every 5 minutes
High voltage range	DC 0..1000V
Set response value	126kΩ (500Ω/Volt)

Table 5. IMD Specifications

Integrating the IMD into our safety circuit adds an extra layer of protection against electric shock and fires, as any loss of isolation triggers an immediate system shutdown.

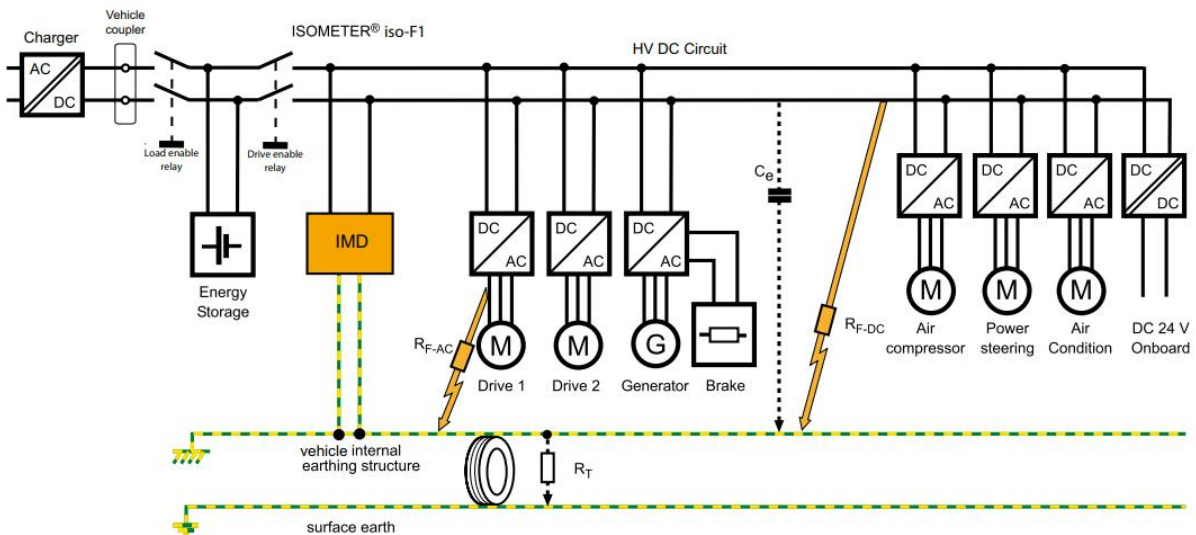


Figure 7.7. IMD Diagram Application

7.5 Tractive System Measuring Points (TSMP)

To facilitate safe measurement of the accumulator voltage during testing and technical inspection, we have incorporated **Tractive System Measuring Points** as per FSAE guidelines. We provide two 4 mm shrouded banana jack connectors (color-coded red) labeled “HV+” and “HV-”, mounted near the master switches on the exterior of the accumulator container. These TSMPs are wired **after the AIRs** on the inverter supply lines.

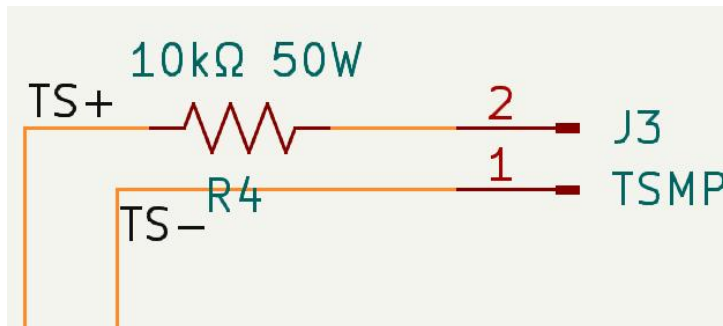


Figure 7.8. Measuring Points Schematic

This placement means that high voltage will only appear at the TSMPs when both isolation relays are closed and the tractive system is active. If the AIRs are open (tractive system off), the TSMPs are not connected to the pack, which adds safety (preventing any voltage at the test points while the car is supposed to be off). Each TSMP is wired through a high-value current-limiting resistor to the high-voltage line, as required by rules. Based on our pack’s max voltage (~ 220 V, which is in the 200–400 V range), we chose a 10 k Ω resistor in series with each test point. This limits the current through the TSMP to a safe level (for example, at 220 V, the maximum current if someone accidentally shorted the TSMPs would be ~ 22 mA). The resistors are sized 10 k Ω per rule and have a sufficient power rating to handle the small continuous leakage current. With this design, an inspector or team member can measure the pack voltage by probing the TSMP banana jacks with a multimeter (which itself presents a high input impedance). The 10 k Ω resistors ensure that even if the meter leads were accidentally touched or shorted, the current is limited to a non-hazardous level. The TSMPs are enclosed by a flip-cover housing to prevent accidental contact and are only accessible with the cover open (no tools required, per rules).

High Voltage Disconnect (HVD) : For the manual service disconnect and over-current protection, we use a TE Connectivity AMP+ Manual Service Disconnect unit, which integrates a high-current fuse. This device serves as our High Voltage Disconnect (HVD) – a directly accessible element that can be pulled out to isolate the accumulator during maintenance or emergency. It is mounted on the accumulator container, above 350 mm from the ground and visible from behind the vehicle (to meet the access requirements).

7.6 Tractive System Main Fuse

Inside the HVD, we have installed a 200 A fuse sized to protect the accumulator and high-voltage system. The choice of 200 A was based on our battery's expected maximum output and the ratings of downstream components. Our accumulator can theoretically deliver peaks around ~ 220 A under extreme conditions, but we limit sustained current draw via the motor controller to stay below 200 A. The fuse is there to blow in case of a severe short circuit or if current spikes above safe levels effectively it's the last line of defense against overcurrent. Notably, our high-voltage connectors (Radlok or AMP+ terminals) and wiring are rated for about 200 A continuous, so the 200 A fuse also ensures we never exceed the safe carrying capacity of those connectors during a fault. In the event of a major fault (e.g. a short downstream of the AIRs or an internal battery fault), the fuse will open and break the circuit, preventing catastrophic overheating or fire.



Figure 7.9. Radlok HVD with fuse

7.7 Precharge Circuit

To prevent damage from inrush currents when connecting the battery to the motor controller, we use a precharge circuit that gradually charges the inverter's DC link capacitors before the main contactor closes. The precharge circuit consists of a 5 A fuse (500 V), a $600\ \Omega$ 50 W resistor, and a 12 V, 30 A automotive relay that bypasses the resistor after precharging. The motor controller governs the precharge sequence: when the driver initiates "TS Active" (tractive system on), the negative AIR closes (if the shutdown loop is intact) and the precharge relay engages, connecting the $600\ \Omega$ resistor between the accumulator and the inverter input. This allows the inverter's

input capacitors to charge up slowly. We calculated the precharge parameters to ensure the capacitors reach about 90% of the pack voltage before the second AIR (positive contactor) closes. Table 1 summarizes the precharge circuit calculations and performance:

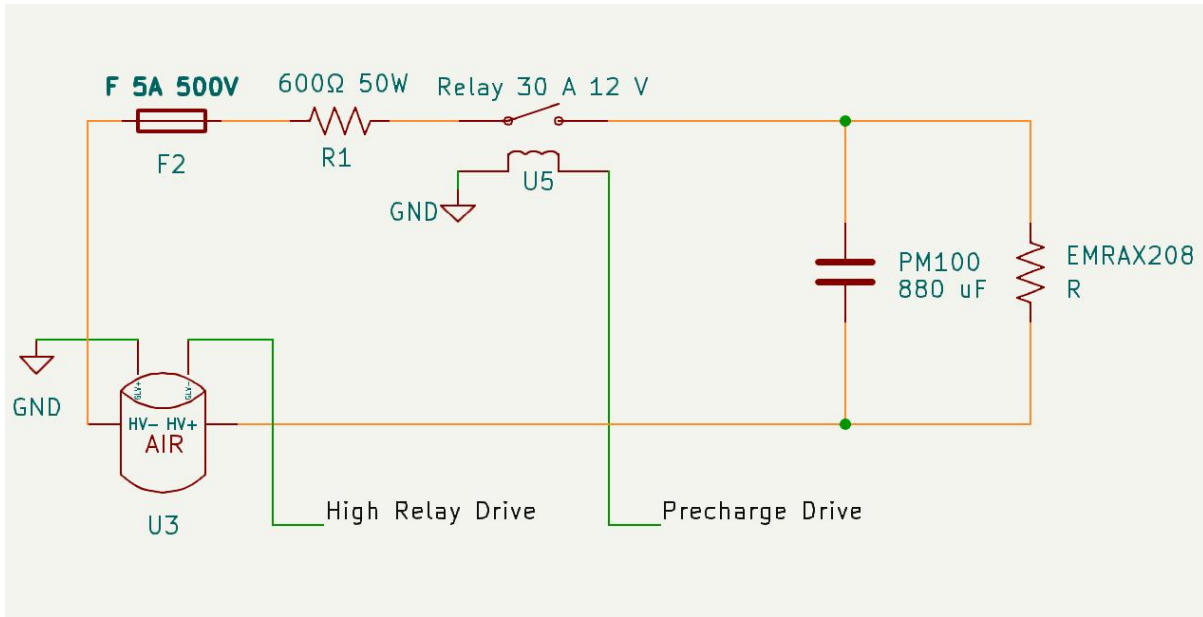


Figure 7.10. Precharge Diagram

Parameter	Value
Accumulator Voltage (Vbus)	220 V DC
Precharge Resistor R	600 Ω (rated 50 W)
Inverter DC Capacitance C	860 μF (total DC link capacitance)
RC Time Constant ($\tau = R \cdot C$)	0.516 s
Approx. 90% Charge Time (3τ)	~1.55 s (about $3 \times \tau$ for ~95% charge; ~1.2 s for 90%)
Initial Precharge Current	~0.367 A (at 220 V, limited by 600 Ω resistor)
Initial Resistor Power ($P = V^2/R$)	~80.7 W (just at startup, then decays rapidly)
Energy Stored in Capacitor ($\frac{1}{2} \cdot C \cdot V^2$)	~20.8 J (at 220 V full charge)
Energy Dissipated in Resistor (during charge)	~10.4 J (approx., during precharge)

Table 6. Precharge circuit Specifications

this serves as protection in case the precharge relay fails (for example, if the main contactor never closes, and the car tries to draw power through the resistor). In such a scenario, if more than ~5 A tries to flow through the precharge path, the fuse will blow, preventing the resistor

from overheating or being used beyond its intended short-duration purpose. Once the capacitor is charged (after $\sim 1\text{--}2$ s), the motor controller triggers the precharge relay to open (or alternatively triggers the positive AIR to close, which bypasses the resistor). At that moment, the inverter is nearly at full voltage, so closing the contactor results in minimal current and no arcing.

Discharge Resistor: When the tractive system is shut down (whether by normal turn-off or an emergency event), the inverter’s DC link capacitors can hold a significant charge. We added a discharge resistor to bleed off this charge quickly, as is required to meet the rule that high-voltage (>60 V) must dissipate within 15 seconds of shutdown. Our discharge resistor is a 2 k Ω , 50 W chassis-mounted resistor connected across the inverter’s DC

We calculated the values to ensure rapid discharge: the inverter capacitance is approximately 880 μF , initially charged to 220 V, and we want it to drop to 12 V or less within about 5 seconds.

$$V = V_0 * e^{-t/RC}$$

A 2 k Ω resistor gives a time constant

$$\tau = R \times C = 2000 \Omega \times 880 \times 10^{-6} F = 1.76s$$

Parameter	Value
DC Link Capacitance	$\sim 880 \mu\text{F}$ (inverter input capacitance)
Initial Voltage (V_0)	220 V DC (typical pack voltage)
Final Voltage Target	12 V (after discharge period)
Discharge Time Target	~ 5.12 s
Chosen Discharge Resistor R_{dis}	2000 Ω (2 k Ω , 50 W rated)
Initial Discharge Current (V_0/R)	~ 0.11 A (110 mA)
Initial Power in Resistor (V_0^2/R)	~ 24.2 W
Energy in Capacitor ($\frac{1}{2} \cdot C \cdot V_0^2$)	~ 21.2 J
Average Power (over 5 s)	~ 4.15 W (21.2 J / 5.12 s)
Resistor Power Rating	50 (chosen for ample margin)

Table 7. Discharge Resistor Specifications

7.8 Tractive System Active Light (TSAL)

The TSAL is a safety indicator required by FSAE that informs bystanders and crew whether high voltage is present in the vehicle. Our TSAL is implemented with a custom PCB that uses a hardware comparator circuit and transistor logic (no programmable components) to drive a

dual-color indicator light. In compliance with the rules, when the tractive system is active and voltage above 60 V is present outside the accumulator, the TSAL must blink red at 2–5 Hz. When the tractive system is off (voltage <60 V), it must show a solid green light.

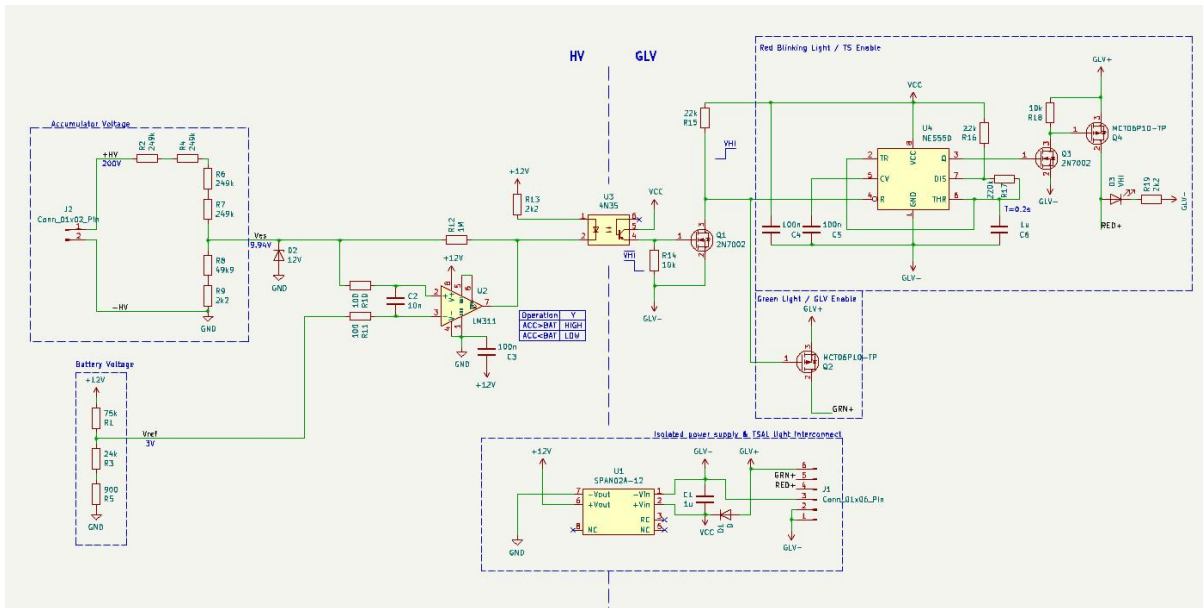


Figure 7.11. TSAL Schematic

Our design achieves this as follows: The TSAL PCB monitors two signals – the accumulator isolation relay status and the DC bus voltage. One part of the circuit is a voltage sensing divider that steps down the DC link voltage to a low-voltage analog signal. This signal is fed into a comparator that is referenced to an equivalent of ~60 V (scaled down). Essentially, the comparator outputs a HIGH logic signal whenever the HV bus exceeds ~60 V. The second part of the circuit monitors the state of the contactors (via a signal from the BMS or inverter indicating “AIRs closed” or from the shutdown loop). Using these, the TSAL logic decides which LED to light.

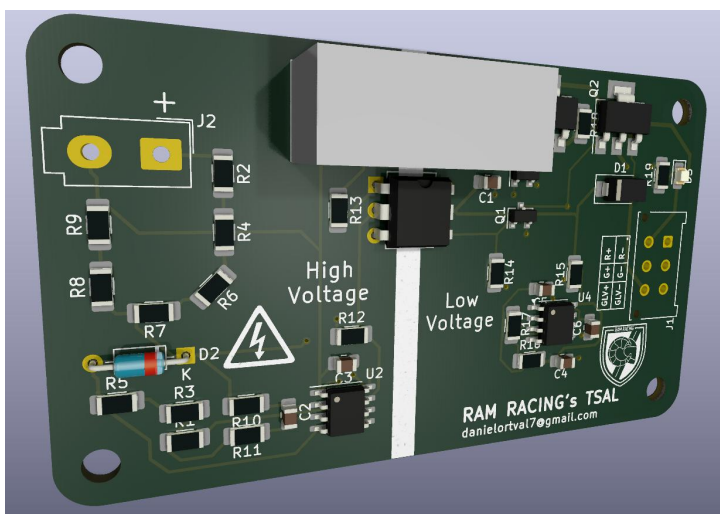


Figure 7.12. TSAL PCB

8 Project Members

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In addition to the individuals mentioned above, the success of this project is a result of strong collaboration, mutual mentorship, and collective contributions from all members of Ram Racing.

Supporters

We thank **PlatteRiver** for being our first sponsor and believing in students as the future of a greener, innovative industry. Special thanks to the team at the **Energy Institute** for their tremendous support. Without them, this project would have been nearly impossible. We deeply appreciate having a new home for the Ram Racing family where students can build their future and shape the industry's tomorrow.

9 Contact Us

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Thank you for reading!

