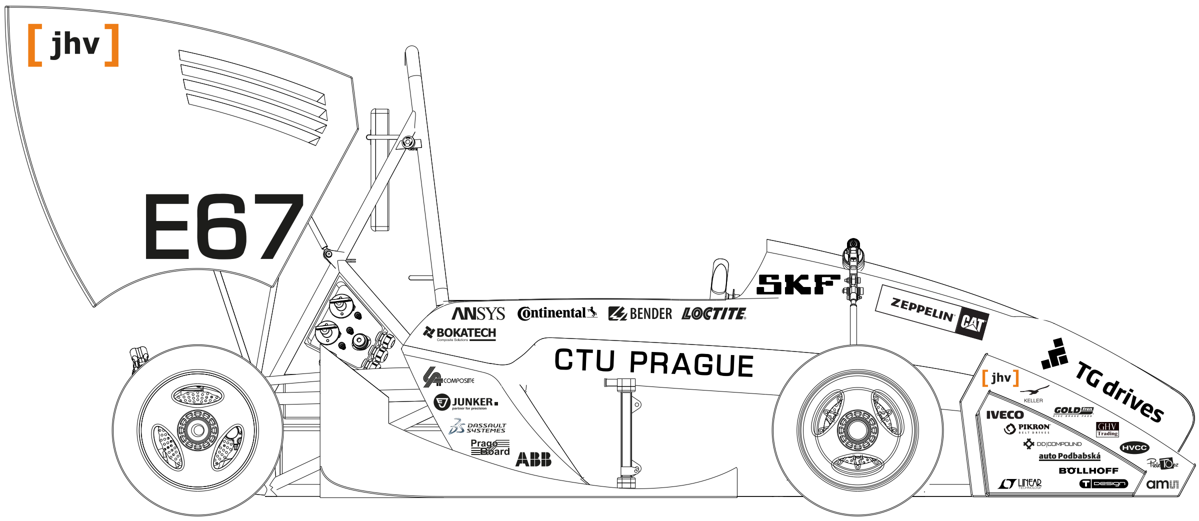
Electrical Safety Form FSAE-E 2018



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List of Acronyms

AIR accumulator isolation relay.

AIRs meaning both accumulator isolation relay-s.

AMS accupack management system.

BOTS break over travel switch.

BSPD break system plausability device.

FAIL Front Axels InterLock.

HV high voltage.

IMD Isoaltion measuring device.

LV low voltage.

MC Motor controller.

SDB shut down button.

TS Traction system - (everything HV that influence motor torque and speed).

TSMS traction system master switch.

VDCU Vehicle Dynamics Control Unit.

1 System Overview

Electrical systems of the car are divided into small blocks. The concept is to have all the systems distributed by 2 CAN buses (1st CAN_Powertrain for systems crucial data to proper function, 2nd CAN_Aux for all the other systems) and, if possible, all the signals transferred just by CAN bus. Baud rate is 500kbps and CAN is terminated in ECUP in front of car and in front motor controller by 120 Ohm resistor. There are in total 5 main control units of course all the units are fully self-made (HW and FW).

- ECUP (Electronic Control Unit Pedal) This device measures brake pedal and acceleration pedal positions, implements safety algorithms regarding to rules about torque encoder check and outputs these values to the CAN bus as drivers foot requests. It also monitors Shutdown Circuit point BOTS.
- VDCU (Vehicle Dynamcs Control Unit) This device reads drivers foot requests, actual every wheel speed provided by ECUM and implements Traction Control Algorithms. The result is sent over private CAN bus to the MCF and MCR.
- MC (Dual Motor Controller) 2 units in total Front (MCF) and Rear (MCR). These units drives 4 motors in total, so every unit drives 2 motors. It provides speed of every wheel by actual RPM, temperatures and so on. Field Oriented Control is implemented with Resolvers as a position feedbacks.
- ECUF (Front + Dashboard) Interaction with driver in cooperation with ECUS (Steering Wheel LCD inside) by informing, warning and error LEDs, switches, rotary switches, push buttons. This is like a drivers CAN bus console.
- ECUB Providing low voltage power distribution to all the control units and periphery (Li-Ion LV battery with BMS inside). This unit implements all the safety and control algorithms regarding to Shutdown Circuit rules. The main function is to latch SDC and evaluation of SDC interruption point.
- ECUA DC-DC converter, BMS, Pre-charge and AIR controlling is implemented. This unit also communicate with Charging Station. There are other control and measuring systems not listed above, but systems listed are most important for safety and control.

There are other control and measuring systems not listed above, but systems listed are most important for safety and control.

Table 1: General parameters

Maximum Tractive-system voltage:	400 VDC
Nominal Tractive-system voltage:	345.6 VDC
Control-system voltage:	24 VDC
Accumulator configuration:	96s9p
Total Accumulator capacity:	7.78 kWh
Nominal HV Accumulator current:	270 A
Maximum HV Accumulator current:	315 A
HV accumulator cell type:	Lithium-Ion
LV Accumulator cell type:	Lithium-In
Motor type:	PMSM with resolvers
Number of motors:	4, one per wheel
Maximum combined motor power in kW	109

2 Electrical Systems

2.1 Shutdown Circuit

2.1.1 Description/concept

Shutdown circuit (SDC) starts in ECUP unit, then goes through all SDC elements in the car and ends in ECUA, which is placed inside the Accumulator Pack. In ECUP SDC starts from LV power +24V and ends in ACP by powering AIR coils switching circuit (See Figure 1: SDC scheme). The SDC consists of 2 master switches, 3 shut-down buttons(SDB), the brake-over-travel-switch(BOTS), the insulation monitoring device (IMD), the inertia switch, the brake system plausibility device(BSPD), interlocks in Motor Controllers and Accumulator Pack and the accumulator management system (AMS). All of these crucial parts do not act through any power stage, but carry directly the AIR current.

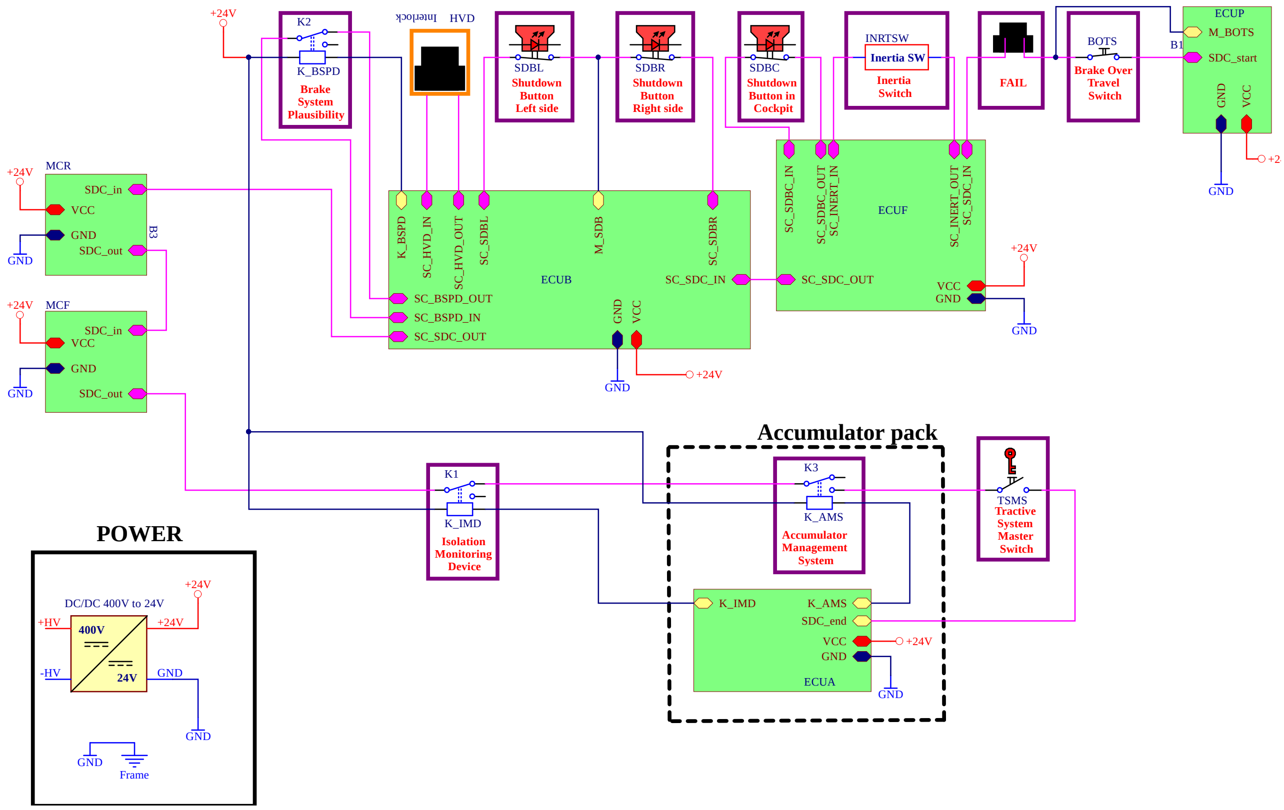


Figure 1: SDC scheme.

Table 2: List of switches in the shutdown circuit

Part	Function
Main Switch (for control and tractive-system; CSMS, TSMS)	Normally open
Brake over travel switch (BOTS)	Normally closed
Shutdown buttons (SDB)	Normally closed
Insulation Monitoring Device (IMD)	Normally open
Battery Management System (BMS)	Normally open
Inertia Switch	Normally closed
Interlocks	Closed when circuits are connected
Brake System Plausibility Device	Normally Open

Monitoring SDC

Every part of SDC is monitored by specific ECU (Electronic Control Unit) in order to identify disconnected element. BOTS is measured by ECUP, SDB-center and Inertia switch are measured by ECUF , interlocks in

Motor Controllers are measured by Motor Controllers, Interlock in Accumulator Pack is measured by ECUA and finally SDB-right, SDB-left and TSMS are measured by ECUB. Every piece of information regarding the state of closure SDC are running between ECUs by CAN.

We designed SDC to be single wire alike and distanced it from the system as much as it was possible. In order to remain SDC as a stand-alone wire we used optocouplers for main points of SDC. Optocouplers are connected in such a way, that they become active only in case of nonzero voltage occurance at a certain point of SDC.

ECUB monitors the last poit of SDC (behind TSMS). If a state of error od SDC is detected ECUB latches the off-state of SDC to stay off. If the ocured error is non-critical, it allows pilot to re-enter the TSON state. If monitored error is criticall (such as IMD etc.), it notes the error to the memory-storrage and does not allow SDC to become active until appropriate steps are taken. The logic flow-chart is shown in **??**: **??**. For more info about this look to next and Reset / Latching for IMD and BMS sections. SDC error states that require special handling

??: **??** ECUB is last part of SDC before TSMS. It implements latching function using external memory so even in case of total shutdown of LV power it is possible to remember error states that occurred before the breakdown. The ECUB implements enough capacitor storrage, that it is able to write the error to the memory even in case of imidiate power-loss cased by the error. It is not possible to reactivate SDC and close AIRs until all the steps required by rules are done.

Master Switch

We use Autolec Mini-Master battery cut-out switches with continuous current rating 100A, shown on Figure 2: TSMS.

Figure 2: TSMS.

Shutdown Switch

We use OMRON A165E shutdown buttons, which have 3A current rating at 30VDC.

On the cockpit it is OMRON A165E-LS, shown on Figure 3: Cockpit SDB.

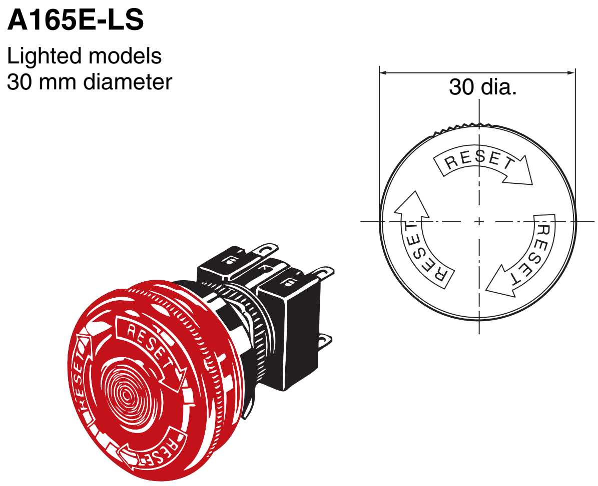


Figure 3: Cockpit SDB.

On the left and on the right sides there are OMRON A165E-LM buttons, shown on Figure 4: SDB left and right.

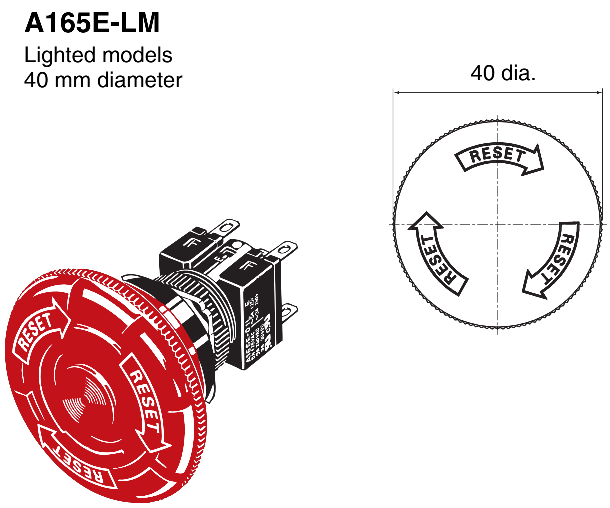


Figure 4: SDB left and right.

Brake Over Travel Switch

It is type A165E-M, current raging 3A, shown on Figure 5: Brake over travel switch

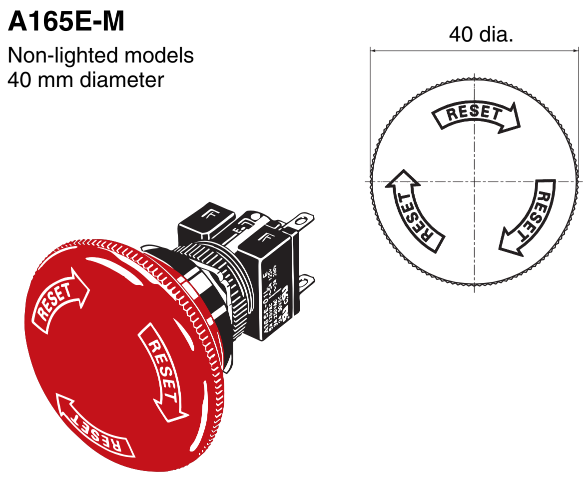


Figure 5: Brake over travel switch.

2.1.2 Wiring / additional circuitry

If connector is used to connect SDC between control units, disconnecting any of them results in opening SDC and therefore opening AIRs as well. In other words the SDC directly carries the current driving the accumulator isolation relays(AIRs). All circuits that are part of the shutdown circuit have been designed in a way, that, when in disconnected state, they remove the current controlling the AIRs.

The cross-section of Shutdown System wire is AWG22. Block wiring scheme shown on Figure 6: Example of used SDC monitoring method with optocouplers.

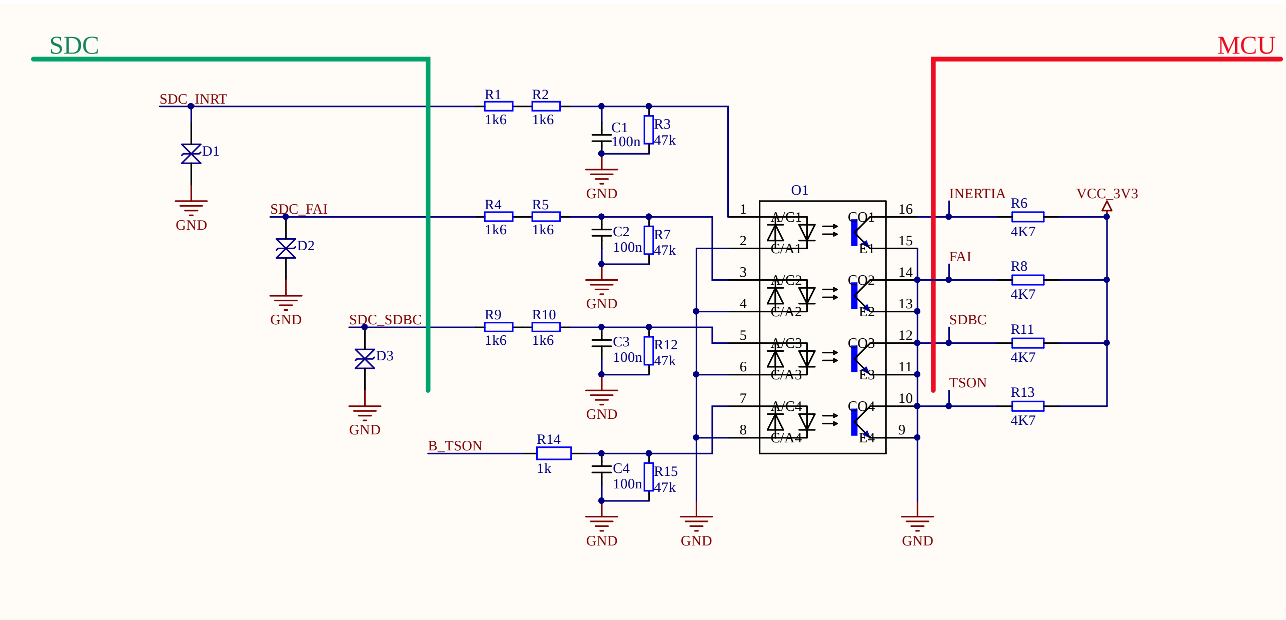


Figure 6: Example of used SDC monitoring method with optocouplers.

As shown, 4k7 resistors are used to limit current through optocoupler. With 24V supply that makes 15,2mA per optocoupler. We used 8 optocouplers =¿ 12*15, 2= 182,4mA.

Table 3: Wiring Shutdown circuit

Total Number of AIRs:	2
Current per AIR:	70mA
Additional parts consumption within the shutdown circuit:	182,4mA
Total current:	322,4mA
Cross sectional area of the wiring used:	0,322mm2 (AWG22)

2.1.3 Position in car

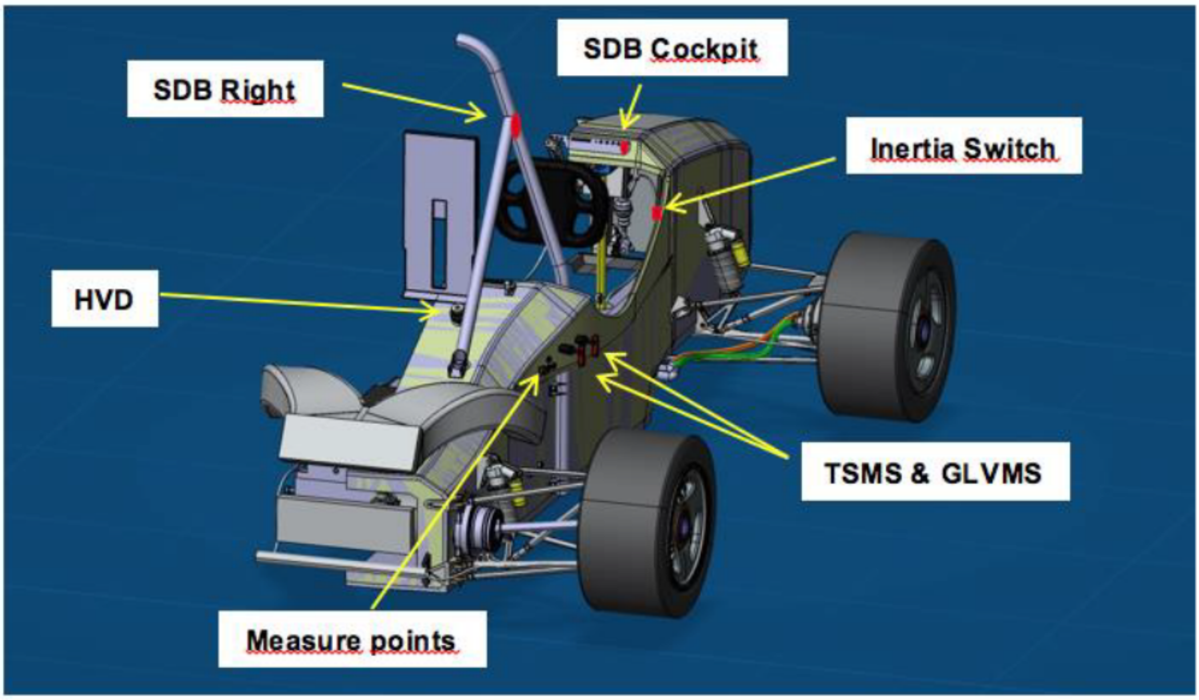


Figure 7: Inertia switch, SDB Left, Right and Cockpit, TSMS, GLVMS, HVD, Measure points.

2.2 IMD

2.2.1 Description (type, operation parameters)

We use A-ISOMETER IR155-3203 Insulation monitoring device (IMD) for unearthed DC drive systems. Our maximum tractive voltage is 403.2 VDC. The rules require minimal insulation value between TS and GLVS 500 Ohm/V. Minimal resistance value for our car is 403.2*500 = 201 600 Ohm. This was set as request for manufacturer, and device was programmed in factory.

Table 4: Parameters of the IMD

Supply voltage range:	10..36VDC
Supply voltage	24VDC
Environmental temperature range:	-40..105C
Selftest interval:	Always at startup, then every 5 minutes
High voltage range:	DC 0..1000V
Set response value:	201.6k (500/Volt)
Max. operation current:	150mA
Approximate time to shut down at 50% of the response value:	20s

2.2.2 Wiring/cables/connectors/

Describe wiring, show schematics, describe connectors and cables used and show useful data regarding the wiring including wire gauge/temp/voltage rating and fuses protecting the wiring.

2.2.3 Position in car

Provide CAD-renderings showing the relevant parts. Mark the parts in the rendering, if necessary

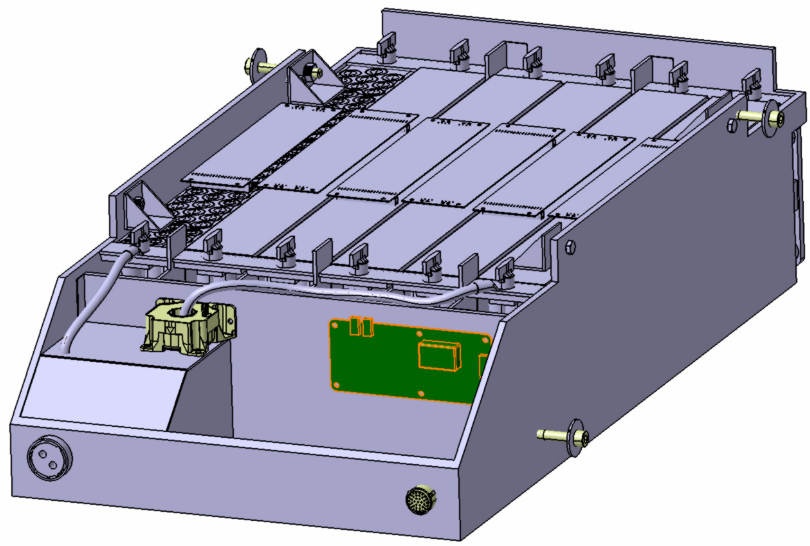


Figure 8: IMD position.

2.3 Inertia Switch

2.3.1 Description (type, operation parameters)

Inertia switch opens shutdown circuit in case of acceleration more than 6g. After acting the driver can reset this switch.

Table 5: Parameters of the Inertia Switch

Inertia Switch type:	Sensata 510FCS01-01
Supply voltage range:	No supply needed
Supply voltage:	No supply needed
Environmental temperature range:	-30..120C
Max. operation current:	10A
Trigger characteristics:	6g for 60ms / 11g for 15ms

2.3.2 Wiring/cables/connectors

Inertia switch is electrically placed between Shutdown button center on dashboard and the Shutdown input to ECUB, where is connected right Shutdown button on main hoop. Inertia switch will be connected by FQCT connectors. Wiring of inertia switch is shown on Figure 1: SDC scheme. Wiring of inertia switch is shown on **??**: **??**.

2.3.3 Position in car

Inertia switch is placed on the right side in the cockpit clearly shown in Figure 7: Inertia switch, SDB Left, Right and Cockpit, TSMS, GLVMS, HVD, Measure points.

2.4 Brake Plausability Device

2.4.1 Description/additional circuitry

BSPD is represented by a PCB with an on-board current transducer. Its function is to monitor power drawn from ACP and brake pedal pressure, and open SDC in case both signals are above allowed threshold for more than 0,5 seconds. Also, the event of disconnection of SDC is latched, thus it gets to reset only in case of the main power reset.

Table 6: BSPD data

Brake sensor used:	Piezoresistive Pressure Transmitter PA-21Y / 100bar / 81691.1
Brake sensor physical response value:	Voltage, 4,5V
Tractive system power sensor type	Current Transducer LEM HTFS 200-P
Tractive system sensor physical response value:	Voltage of 85mV
Tractive System power sensor current treshold (5kW/Nominal TS voltage):	14A
Supply voltages:	5V
Maximum supply currents:	22mA
Operating temperature:	-40..105◦C
Output used to control AIRs:	Open a MOSFET in SDC

2.4.2 Schematic

The BSPD PCB is mounted on a HV wire in such manner, that the HV wire goes through the current transducer. Current transducer provides analog voltage output of a value proportional to actual current (resp. power) drawn from ACP. This voltage is amplified and is converted to twostate logic levels voltage with the use of comparators. The value of High current signal logic level is set to be at 5kW of power drawn from ACP (14A).

Brake state is measured in ECUP, converted with help of a comparator to two-state logic levels voltage and is sent directly to BSPD via wiring.

Both logic signals are connected to NAND inputs. When both inputs are at High level, a capacitor C1 starts to charge through resistance R16. When voltage on C1 is higher than 2,5V, a comparator U1B sends signal to open SDC.

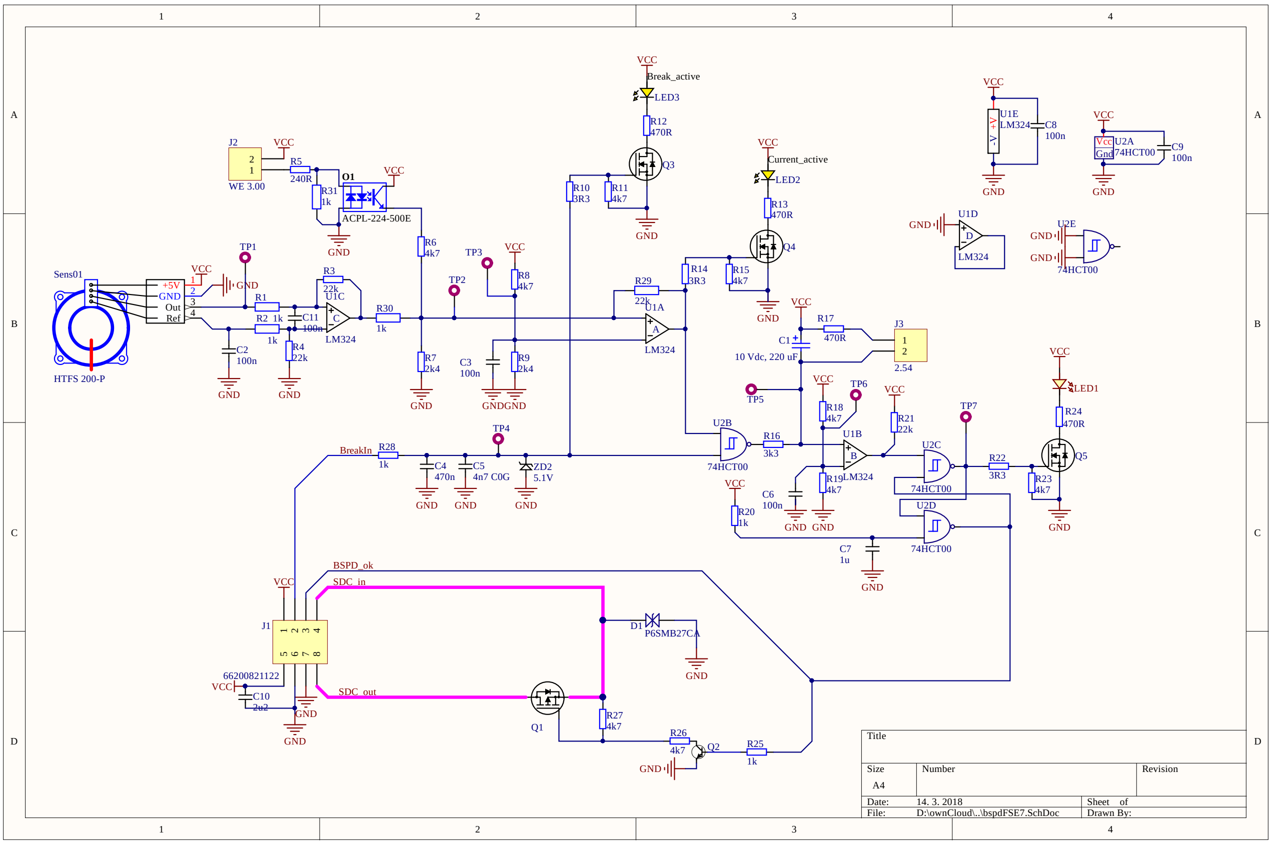


Figure 9: BSPD schematic sheet

2.4.3 Connection with shutdown circuit

The connection to SDC is provided by an NPN transistor Q2 and a P-Channel MOSFET Q1, that are connected to act as a normally-closed switch in SDC loop. Thus in case of a trip event Q1 stops conducting current between Drain and Source. See Figure 9: BSPD schematic sheet.

This state is latched by a latch-circuit, that consists of two NAND gates.

2.4.4 Position in car/mechanical fastening/mechanical connection

Provide CAD-renderings showing all relevant parts and discuss the mechanical connection of the sensors to the pedal assembly. Mark the parts in the rendering, if necessary.

Figure 10: BSPD position

2.5 Reset / Latching for IMD and BMS

2.5.1 Description/circuitry

2.5.2 Wiring/cables/connectors

Measuring, what was original problem, is done by two optocouplers in ECUB. Figure 16 - Example of used SDC monitoring with optocouplers.

2.5.3 Position in car

Latch as well as reset of IMD and BMS error is placed in ECUB box on the back of car. See **??**: **??**.

2.6 Shutdown System Interlocks

2.6.1 Description/circuitry

We have interlocks in ACP HV connector (connector HV_A), Motor controller HV inputs and outputs, HV connector in Service box, HVD and in the LV connectors from ECUMs (ECUM Rear and ECUM Front) to motor (connectors M1, M2, M3 and M4). In the M1-4 connectors we have a loop, that protects motor from disconnecting from a vehicle (disconnection of any of them triggers the Shutdown circuit).

2.6.2 Wiring/cables/connectors

Scheme of entire Shutdown circuit can be found at Figure 6 - Block SDC wiring scheme

2.6.3 Position in car

HVD is clearly shown above in Figure 8 - Inertia switch, SDB Left, Right and Cockpit, TSMS, GLVMS, HVD, Measure points. For Service box position see Figure 17 - Motor controllers

Last interlock is in Accumulator Pack HV Connector shown in ACP HV Connector.

2.7 Tractive System Active Light

2.7.1 Description / circuitry

Our TSAL system is consists of two parts, LEDs and generator of frequency with power-switch. Generator is in ECUB protected by fuse. The waveform is generated with a 555-based circuit. The TSAL uses pairs of anti-parallel LEDs and is connected with two wires. Color of the light is decided by the polarity of the driving voltage. The following table shows the operation mode depending on conditions C1, C2:

EV4.12.1 is achived by U4 in Figure 21 - TSAL HV part schematic comparing the voltage on R59 with 3v3 reference. MHVout is connected to output connector of accumulator. O4 carries the information about HV presence to LV system and enables powerto TSAL by opening Q5.

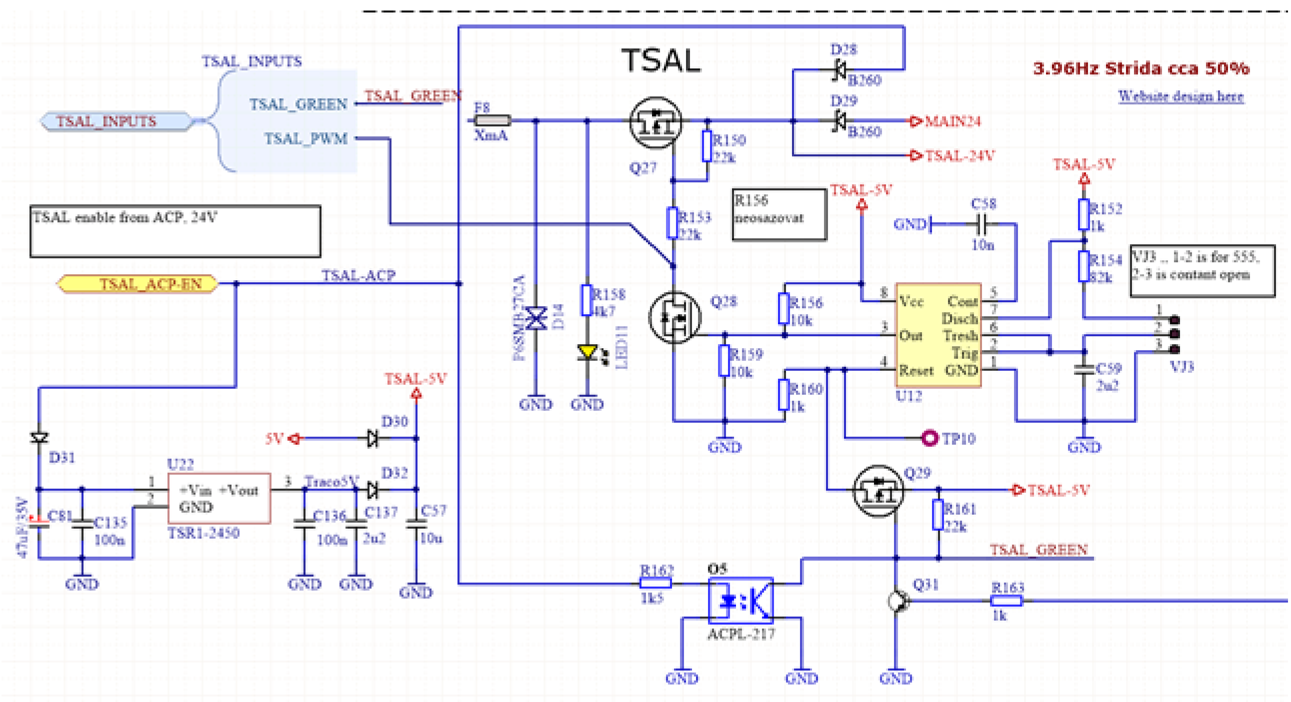


Figure 11: Schematic of generator for TSAL.

Table 7: Parameters of the TSAL

Supply voltage:	+/- 24VDC
Max. operational current:	300mA
Lamp type	Bi-color LED
Power consumption:	7.2 W
Brightness	124 Lumen (red), 29 Lumen (green)
Frequency:	3.96Hz
Size (length x height x width):	128mm x 20mm x 32mm

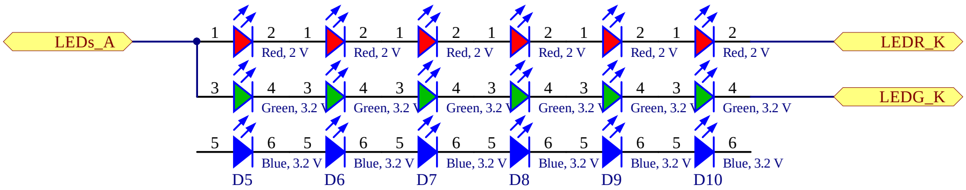


Figure 12: TSAL schematic.

Figure 13: TSAL HV part schematic.

Explanation of TSAL circuit

Left top corner of Figure 13: TSAL HV part schematic (input marked as HV-Viper) is directly connected to the output HV pins of ACP. The circuit is designed with STM chip VIPER16HN. It behaves as normal fly-back, with input voltage range from 50V up to 500V. Output of flyback is used to directly power the TSAL. ACP indication led is powered from primary side of transformer. To ensure corect beahviour we also measure and comapre input voltage (using U12A OAMP as comparator with little hysteresis), to enable output (Q36 & Q33) only if input voltage is ¿=60VDC.

Figure 14: TSAL enable scheme

Function of circuit on Figure 14: TSAL enable scheme is that the TSAL is enabled even when the 60VDC limit is not reached but the AIR is closed nonetherless. In such state, the TSAL is enabled by signal AIR_EN. The circuit is powered by MAIN24 power (which is equal to the 24V enabled by GLVMS) or by the TSAL_ACP-EN power signal from the Viper-TSAL schematic (Figure 15: ACP indication LED wiring) below.

Figure 15: ACP indication LED wiring

2.7.2 Wiring/cables/connectors

LEDs are supplied from ECUB (by Harness_D by connector D1) by 2-wire low voltage cable (Figure 16: Wiring TSAL from ECUB).

Figure 16: Wiring TSAL from ECUB

2.7.3 Position in car

TSAL is placed under the main roll hoop, see Figure 17: TSAL position

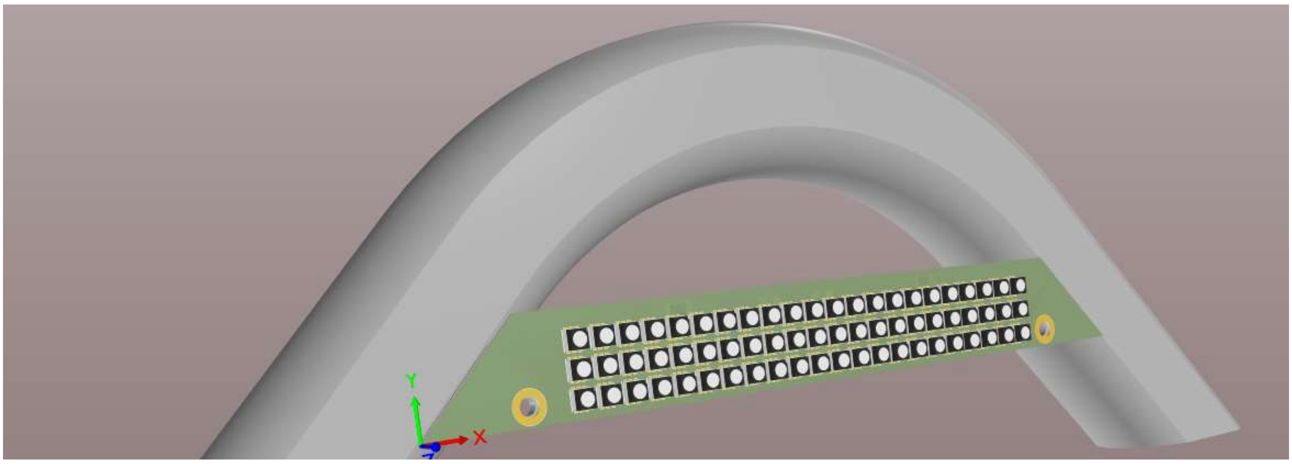


Figure 17: TSAL position.

2.8 Measurement points

2.8.1 Description

High voltage measurement points (HVMP) are placed in the Service box. When not in use, they are covered with protective cups made from silicone rubber. From backside they are protected by sealed Service box all the time.

2.8.2 Wiring, connectors, cables

They are connected to ECUB (by Harness_G with connector G1). In ECUB is TSAL switch circuit and discharge circuit is in ECUM (ECUM is connected to ECUB by Harness_E connectors are E1 from ECUB and E2 into ECUM Rear). HVMP wires will be connected to the board in ECUB box, where is TSAL switch circuit, discharge circuit and 2 resistors 15k 1W (R1, R2) for HVMP. Value of this resistor can be measured from measuring points by multimeter with switched TSMS off.

2.8.3 Position in car

Measure points are placed on panel next to Master switches and HVD, see Figure 7: Inertia switch, SDB Left, Right and Cockpit, TSMS, GLVMS, HVD, Measure points.

2.9 Pre-Charge circuitry

2.9.1 Description

Pre-charge circuit is controlled by ECUA. (Isolation on PCB is refered from 8.3Electronic control unit acp (ECUA)) Our pre-charge is assembled from 3 resistors. 2 of them have the same value 470R, the third is mainly part of safety precaution and has value 2k2. There is always a chance that the resistor fails, in that case the remaining resistors may be used as fully functional pre-charge, only slower.

TS ON button sets whole car in state pre-charging. ECUA starts pre-charge process. It takes safety precautions and then relay and AIR are switched to close pre-charging current. Fully closed SDC and ECUA decision are needed to start pre-charging. If every point is fulfilled and pre-charge is successfully finished, second AIR closes. Pre-charge relay opens and car leaves pre-charge state. (Pre-charge relay is normally open type.)

Pre-charge safety on ECUA

Except from what rules require we implemented several safety precautions. In case, that SDC error doesnt occur and driver pushed TS ON button following safety precautions are taken to prevent switching AIR in case of problem that has not yet been detected.

First one is completely non-programmable protection against switching voltage difference by AIR. It uses voltage measurement and then comparators and logic to disable microcontroller decision in case of SW error. Second one is measuring all states and voltages by microcontroller on ECUA which can determinate error before non-programmable protection would have to act.

Third (time-out) protection is used when everything seems to be OK, but the charging is too slow caused by too high pre-charge resistance (any of pre-charge resistors fails), or some leakage of charge in capacitor or any other possible error occurs. If voltage difference is not equaled in time less them 2seconds, the ECUA stops pre-charge and waits 5 seconds before trying again. (In order to not overpower resistors.) If number of attempts to pre-charge is in this state higher then 8, something is clearly wrong and ECUA opens SDC and indicates error. Sending message about error and sets car into not-ready state.

2.9.2 Wiring, cables, current calculations, connectors

Describe wiring, show schematics, describe connectors and cables used and show useful data regarding the wiring.

- Give a plot Percentage of Maximum Voltage vs. time
- Give a plot Current vs. time
- For each plot, give the basic formula describing the plots

Additionally, fill out the tables:

Table 8: General data of the pre-charge resistor

Resistor Type:	
Resistance:	
Continuous power rating:	
Overload power rating (1 sec):	
Overload power rating (5 sec):	
Overload power rating (15 sec):	
Voltage rating:	
Cross-sectional area of the wire used:	

Table 9: General data of the pre-charge relay

Relay Type:	
Contact arrangment:	
Continuous DC current:	
Voltage rating	
Nominal Coil Voltage:	
FET type:	
Maximum Drain-Source Current:	
Drain-Source Breakdown Voltage:	
On Charasteristics Gate Threshold Voltage:	
Cross-sectional area of the wire used:	

2.9.3 Position in car

Provide CAD-renderings showing all relevant parts. Mark the parts in the rendering, if necessary.

2.10 Discharge circuitry

2.10.1 Description

Discharge circuit is activated whenever SDC is open, this is ensured by ECUB which monitors latching of SDC. The idea of discharging capacity is to have discharge resistors in the device with that capacity so in both Motor Controllers. So ECUB sends message to Motor Controllers and they close circuit with Discharge resistors banks. When AIRs are closed, ECUB informs Motor Controllers and they open discharge circuits.

Figure 18: Discharge circuit.

2.10.2 Wiring, calbes, current calculations, connectors

Following Figure 18: Discharge circuit shows a siplified connection of a discharge resistors. It is connected the same way, only unnecessary detail parts of the circuit were cover as a block. The resistor is placed in MC right next to only capacity that provides a storrage for potencially dangerous charge/energy. If the HV cable is disconnected on either side, the SDC opens due to the interlocks and AIRs open. Because there is no output capacitance in ACP there is no way the power could be on ACP output HV connector.

The capacity of all the capacitors in Motor Controllers is in the sum 2360 uF. For discharging this capacity in less than 5 seconds to voltage under 60V, maximum value is calculated by solving R from the formula

with values: VC = 60 V VS = 403.2 V t = 5 s C = 1180-6 F The resulting R = 1000 Ohm. In total 8 discharge resistors are used in configuration 2s4p so 2s2p in each motor controller. Each resistor is type THS151K5J (1k5, 15W). In total the final value of Discharge Resistor Bank is R = 750 Ohm, which is less than 1316 Ohm. The 60V threshold with this configuration is reached in 2,84s. Calculated plot Voltage vs. time:

Figure 19: Voltage vs. time plot.

I assume the plot Discharge current vs. time as a plot of discharge current through 1 resistor. So the Discharge current of the whole Discharge resistor bank can be obtained by multiplication Y values by 4. So Discharge current (through 1 resistor) vs. time:

Figure 20: Discharge current on resistor vs. time.

The formula describing the plot is: I = VS / RB / 4 VS Capacitor voltage function RB Discharge Resistor Bank resistance = 750 Ohm (resulting resistance of 2s4p 1k5 resistor connection) 4 Number of parallel connection, so through 1 resistor flows of total current Power on 1 resistor is expressed by multiplication VS with resistor current described above.

Figure 21: Power on resistor vs. time.

Peak power is 15 W and the resistor can handle this power over 20 s, see **??**: **??**.

Table 10: General data of the discharge circuit

Resistor Type:	THS151K5J (in configuration 2s4p)
Resistance:	1500Ω
Continuous power rating:	15W
Overload power rating (1 sec):	
Overload power rating (5 sec):	
Overload power rating (15 sec):	
Voltage rating:	265V (2 in series result in 530V)
Maximum expected current:	0.1A per resistor, (2s4p configuration with total 0.4A current)
Average current:	0.04A on resistor(taking account 4 seconds of discharging)
Cross-sectional area of the wire used:	0.129 mm

Table 11: General data of the dis-charge relay

Relay Type:	
Contact arrangment:	
Continuous DC current:	
Voltage rating	
Nominal Coil Voltage:	
FET type:	
Maximum Drain-Source Current:	
Drain-Source Breakdown Voltage:	
On Charasteristics Gate Threshold Voltage:	
Cross-sectional area of the wire used:	

2.10.3 Position in car

Discharge resistors are mounted on aluminum cooler also with IGBT modules in Motor Controller boxes.

2.11 HV Disconect (HVD)

2.11.1 Description

A circular connector ASHD 0 24-44420 S N + ASHD 6 24-44420 P N is used as HVD. By disconnecting HVD positive and negative pole of Tractive System is quickly disconnected. Disconnection is done by turning the plug left, this motion is clearly hinted by a label. By turning left the lever system in connector disconnect pins and release plug. There are sockets used in the receptacle rather than pins, therefore no harm can be done to crew by touching the receptacle.

Interlock is achieved by using ASHD 0 24-44420 S N - 016 as a receptacle and ASHD 6 24-44420 P N - 016 as plug. This connector has several other low current pins size AWG 22. Two of them are used as interlock, there is only shunt loop at the plug.

Datasheet is to be seen in Figure 48: HVD interlock datasheet.

2.11.2 Wiring, cables, current calculations, connectors

HVD is placed between Accumulator Pack and Motor Controllers, Energy Meter is also placed after Motor Controller in the circuit. Positive pole of Tractive system is interrupted. There are four pins connected to each other in the plug and the back of the plug is sealed. OLFLEX HEAT 180 SiF are used as HV wires, four pins are used. One HV pin is rated to 200A.

2.11.3 Position in car

HVD is placed on panel next to Maser switches and Measure points, see Figure 22: HVD position.

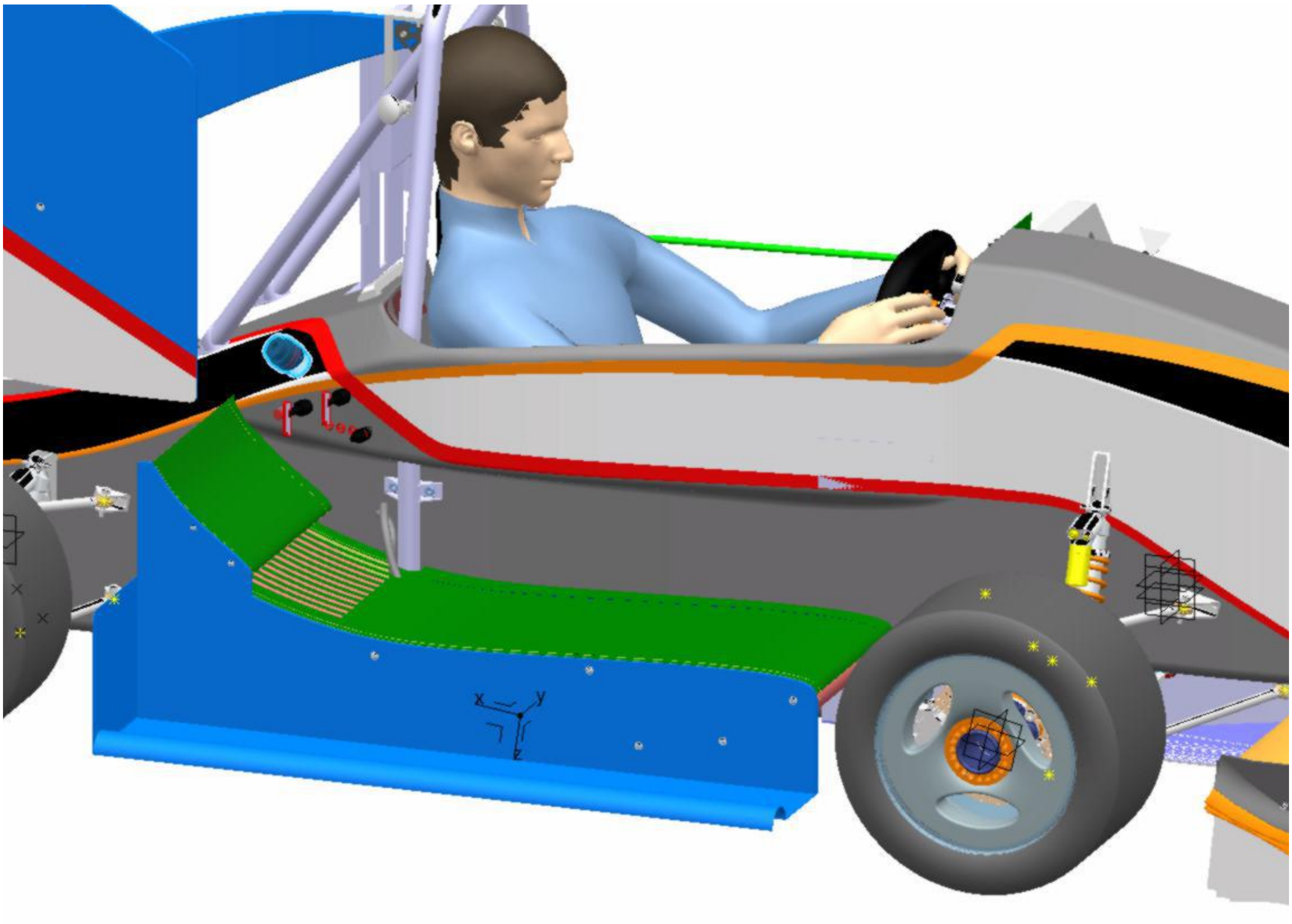


Figure 22: HVD position.

2.12 Ready-To-Drive-Sound (RTDS)

2.12.1 Description

We use piezo siren AE20M. The siren makes sound when ECUB recognize ready-to-drive state of car, it receives message from ECUF about TS ON button and SDC is in non-error state, if message would be lost ECUB doesnt send confirmation status and ECUF does not allow to activate ready to drive status. Sound pressure level of this siren is more than 90 dB(A) at 1 m, Output frequency is from 2,9 kHz. Controlling of RTDS is done by ECUB by transistor. RTDS beeps 2 seconds.

Figure 23: RTDS.

2.12.2 Wiring, cables, current calculations, connectors

There are only two wires from ECUB to RTDS piezo siren, one switched by transistor and and the second is ground (block connections is on Figure 24: RTDS wiring).

Figure 24: RTDS wiring.

2.12.3 Position in car

Ready to drive sound is placed on the top of Accumulator Pack next to the Motor Controller, see Figure 25: RTDS position.

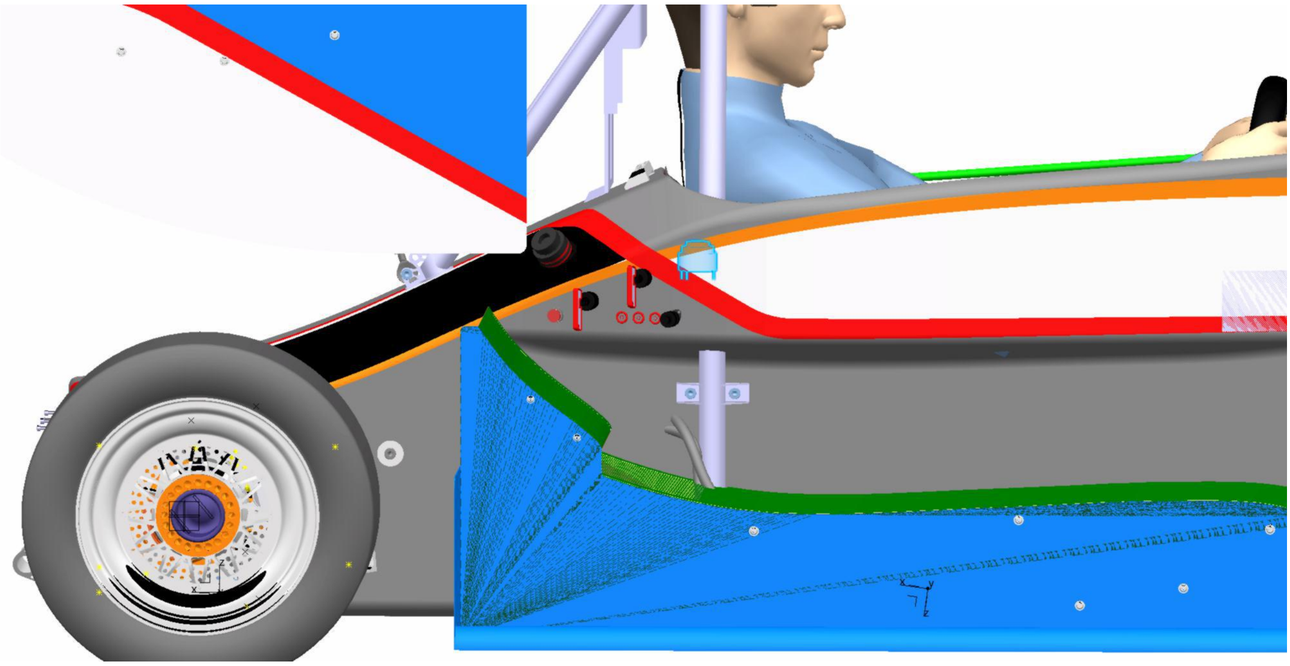


Figure 25: RTDS position.

3 Accumulator

3.1 HV Accumulator pack

3.1.1 Overview / description/parameters

Describe concept of accumulator pack, provide table with main parameters like number of cells, cell stacks separated by maintenance plugs, cell configuration, resulting voltages-¿minimum, maximum, nominal, currents, capacity etc. Fill out the following table:

Table 12: Main accumulator parameters

Maximum Voltage:	400 VDC
Nominal Voltage:	345.6 VDC
Minimum Voltage:	182 VDC
Maximum output current:	315 A (until any cell reaches 80 °C)
Maximum nominal current:	270 A
Maximum charging current:	54 A
Total numbers of cells:	864
Cell configuration:	96s9p
Total Capacity:	27.99 MJ
Number of cell stacks ¡ 120VDC	6

3.1.2 Cell description

Describe the cell type used and the chemistry, provide table with main parameters. Fill out the following table:

Table 13: Main cell specification

Cell Manufacturer and Type	SONY VTC5A
Cell nominal capacity:	2.5 Ah
Maximum Voltage:	4.25 V
Nominal Voltage:	3.6 V
Minimum Voltage:	2 V
Maximum output current:	35 A (until cell reaches 80 °C) (14C)
Maximum nominal output current:	30A(12C)
Maximum charging current:	6A(2.4C)
Maximum Cell Temperature (discharging)	80 °C
Maximum Cell Temperature (charging)	60 °C
Cell chemistry:	Lithium-Ion

3.1.3 Cell configuration

Cell configuration is 96s9p. Cells are divided into 6 stacks, configuration of each stack is 16s9p. Cells are connected by welding. Main cells interconnection is done by nickel sheet. This sheet is welded to each cell. There is additional copper sheet welded over the nickel sheet (for lowering resistance of the main current path).

3.1.4 Cell temperature monitoring

The cells temperature is monitored by NTC temperature sensors. The manufacturer is TDK, type is: B57330V2103F260. Insulation of the sensors is done by 3M PTFE Film Electrical Tape. Breakdown voltage of this tape 9.5 kV, operating temperature is 180 °C. Thickness of this tape is 0.1 mm. Sensors are soldered in PCBs that are covered with insulating tape and then mounted to each stack.

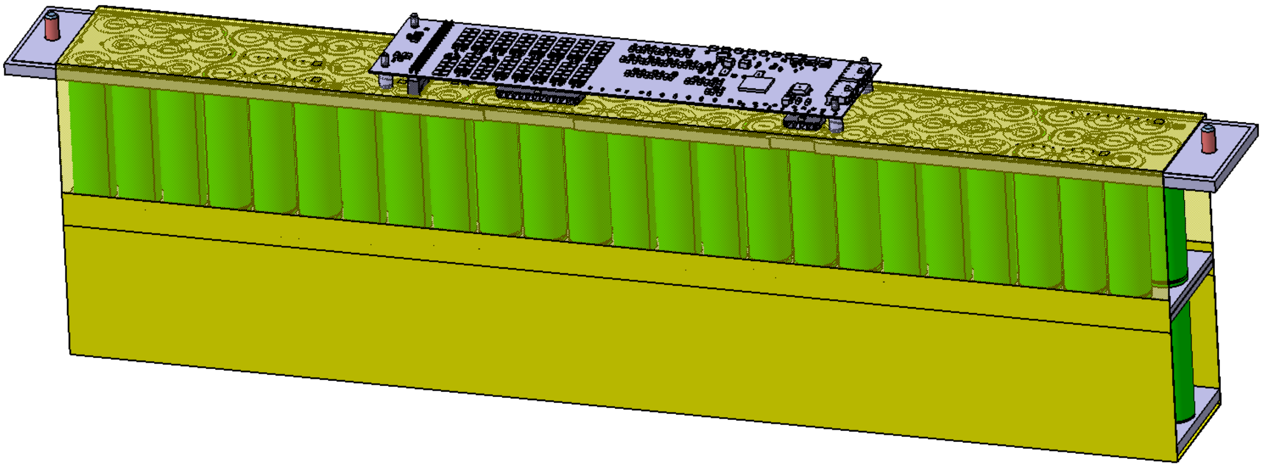


Figure 26: Stack configuration.

Position of temperature sensors on the top of each stack (highlighted objects)

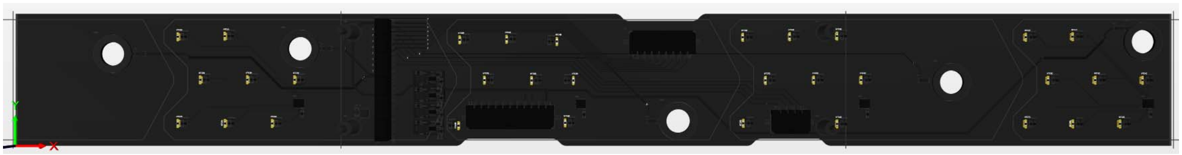


Figure 27: Top position of sensors.

Position of temperature sensors on the bottom of each stack (highlighted objects)

Figure 28: Bottom position of sensors.

Top and bottom view of one stack

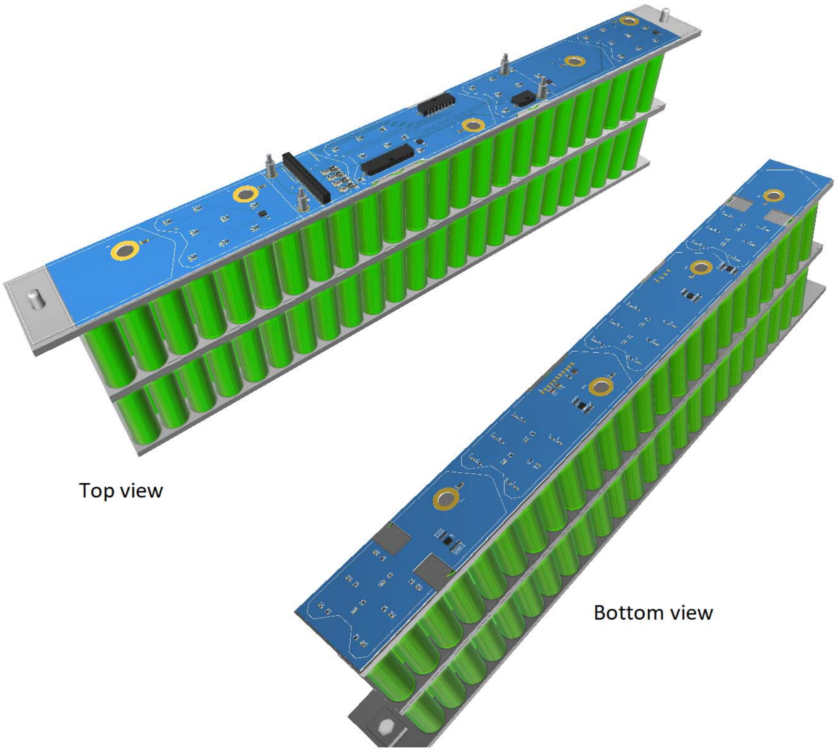


Figure 29: Rear and bottom view.

Table 14: General cell temperature parameters.

Temperature sensor accuracy:	1%
Total number of cells:	864
Total number of sensors:	384
Max. distance from monitored negative cell terminal:	2 mm
AMS opens AIRs during dis-charging if cell temperature is above:	60°C
AMS opens AIRs during charging if cell temperature is above:	60°C

3.1.5 Acumulator Managment System

Describe the AMS used including at least the following:

Table 15: Cell voltage limits.

Minimum cell voltage (shutdown limit):	2.2 V
Maximum cell voltage (shutdown limit):	4.2 V
Measurement precision (mV):	± 0.75

Each sense connection is protected with fuse. There are two types of fuses used:
Littelfuse 0251001.MXL (Those are used, where the cells are contacted via PCB)
Eaton TR/3216LV1-R (Those are used, where measure wires are connected directly to cells)

Cell highest allowed voltage is 4.25 V so AMS reacts when the voltage is above 4.2 V. Cell lowest allowed voltage is 2 V so AMS reacts when the voltage is below 2.2 V. Reaching any of limits causes AIRs disconnection.

Highest allowed temperature (by datasheet) for discharging is 80 °C and for charging 60 °C. Due to FSE rules our battery pack is limited to 60 °C. AMS reacts when the temperature is higher than 60 °C reaching limit causes AIRs disconnection.

Recommended Operating Conditions

TA = 25C and TOP = 57.6 V; Min/Max values stated where TA = 40C to 105C and TOP = 12 V to 79.2 V (unless otherwise noted)

			MIN	NOM	MAX	UNIT
V_{TOP}	Supply voltage	TOP – GND (VSENSE16 = TOP)	12		79.2	V
V_{IO}	Digital interface voltage		2.7		5.5	V
V_{TOP_DELTA}	Max delta, TOP to highest cell [1][2]	VSENSE16 – TOP		0	300	mV
I_{IO}	Output current, any one pin	GPIO0, GPIO1, GPIO2, GPIO3, GPIO4, GPIO5, TX, FAULT_N			5	mA
I_{IO_T}	Output current, sum of	GPIO0 + GPIO1 + GPIO2 + GPIO3 + GPIO4 + GPIO5 + TX + FAULT_N			20	mA

Figure 30: Recomended operating parameters.

Each AMS board senses whole stack, that means it senses 144 cells, connected in 16s9p configuration. Comms wirings are protected by two 1kV 1nF capacitors CC1206KKX7RCBB102 by Yageo. There is placed one on each side (there is one on every AMS). The AMS is connected to Accumulator ECU that has capability of direct AIRs shutdown. The galvanic isolation between TS and GLV is done by two 1kV 1nF capacitors CC1206KKX7RCBB102 by Yageo. It is located on separated board connected between first AMS and Accumulator ECU.

3.1.6 Accumulator indicator

Describe the indicator, show wiring, provide tables with operation, PCB design, etc

3.1.7 Wiring, cables, current calculations, connectors

Describe the internal wiring, show schematics, provide calculations for currents and voltages and show data regarding the cables and connectors used.

- Discuss maximum expected current, DC and AC how long will this be provided?
- Compare the maximum values to nominal currents

- Give a table for each kind of wire in your tractive-system:
- Describe your maintenance plugs, provide pictures
- Use tables like the one shown below:

Table 16: Wire data of company A, 0.205 mm^2.

Wire type	
Continuous current rating:	
Cross-sectional area	
Maximum operating voltage:	
Temperature rating:	
Wire connects the following components:	

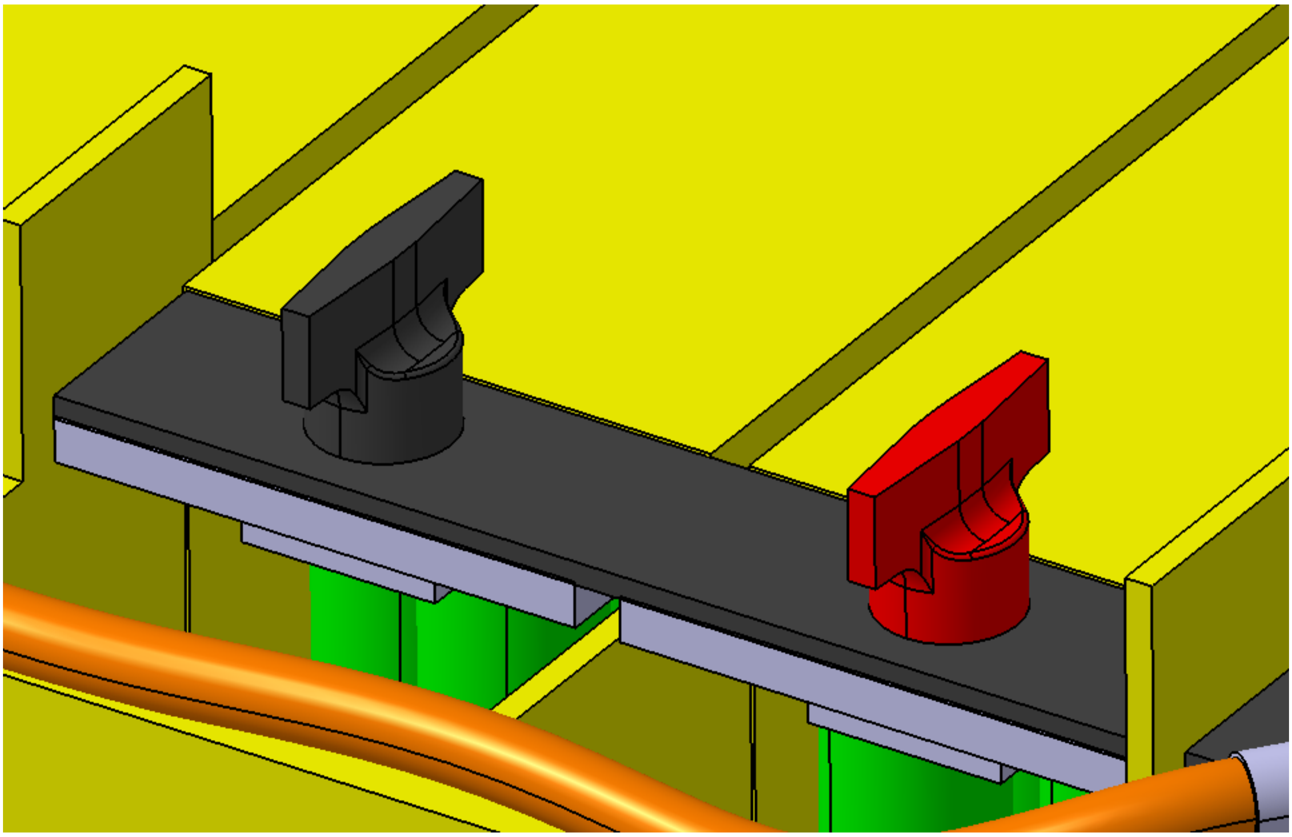


Figure 31: Maintance plugs I.

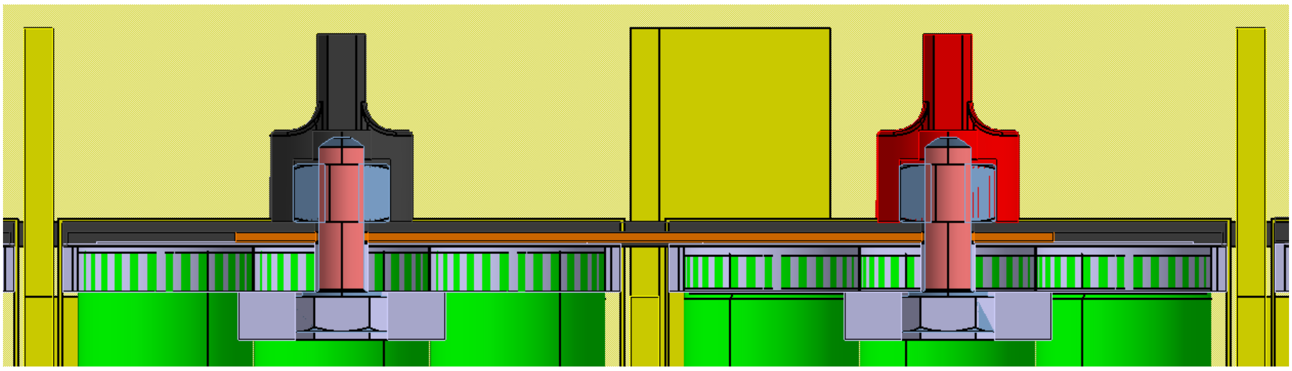


Figure 32: Maintance plugs II.

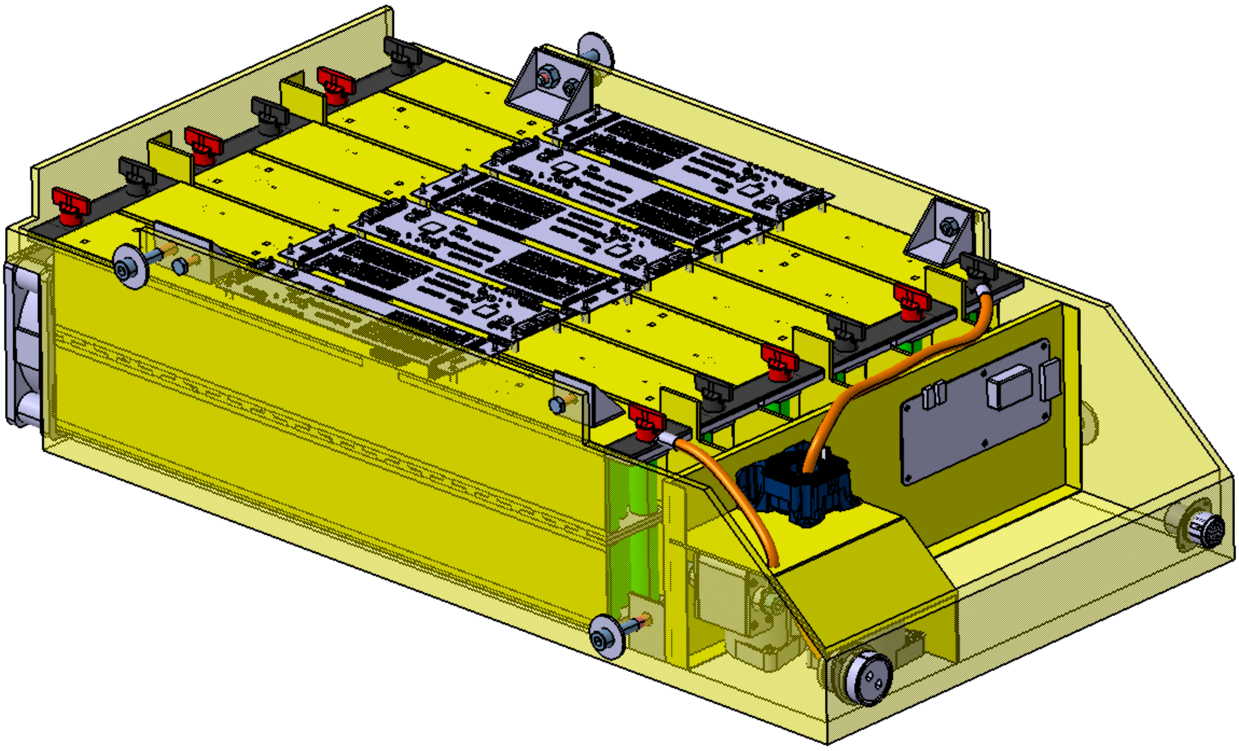


Figure 33: Accumulator pack HV wiring I.

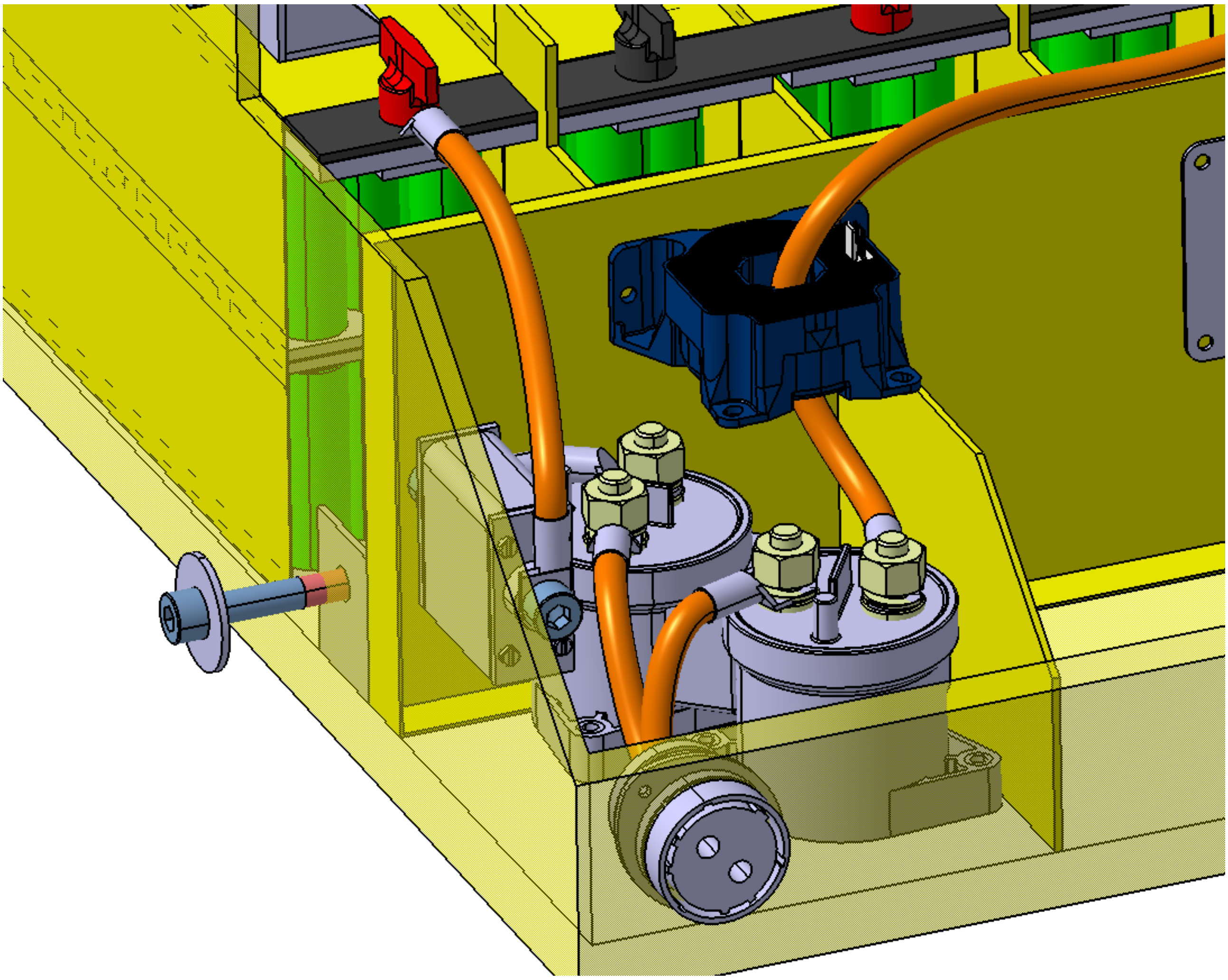


Figure 34: Accumulator pack HV wiring II.

3.1.8 Accumualtor insulation relays

Describe the AIRs used and their main operation parameters, use tables, etc. Additionally, fill out the following table:

Table 17: Basic AIR data.

Relay Type:	
Contact arragment:	
Continous DC current rating:	
Overload DC current rating:	
Maximum operation voltage:	
Nominal coil voltage:	
Normal Load switching:	
Maximum Load switching	

3.1.9 Fusing

Describe the fuses used and their main operation parameters, use tables, etc. Additionally, fill out the following table for each fuse type used:

Table 18: Basic fuse data

Fuse manufacturer and type:	
Continous current rating:	
Maximum operating voltage	
Type of fuse:	
I2t rating:	
Interrupt Current (maximum current at which the fuse can interrupt the current)	

Create a table with components and wires protected by the fuse(s) and the according continuous current rating, below is an example table with some potential entries. Complete this table with information for your design and add/remove additional locations as applicable. Ensure that the rating of all the components is greater than the rating of the fuse such that none of the other components become the fuse.

Table 19: Fuse Protection Table

Location	Wire Size	Wire Ampacity	Fuse type	Fuse rating
Cells to AIRs	2 AWG	XXX	MNO Fuse	XXX
AIR to Motor controller	0 AWG	XXX	2x MNO Fuse	XXX
AIR to TSAL	20 AWG	XXX	EFG Fuse	XXX
Accumulator output connector	2 AWG	XXX		
Cells to AMS				

3.1.10 Charging

Describe how the accumulator will be charged. How will the charger be connected? How will the accumulator be supervised during charging? Show schematics, CAD-Renderings, etc., if needed Additionally, fill out the table:

Table 20: General charger data

Charger Type:	
Maximum charging power:	
Maximum charging voltage:	
Maximum charging current:	
Interface with accumulator	
Input voltage:	
Input current:	

3.1.11 Mechanical Configuration/materials

The whole mechanical structure of the case is made from sandwich structure, kevlar fiber and core, designed to be alternative structure. Basically the case is divided to main box, which is outer walls and floor, five longitudinal walls and one transverse wall divided this space on chambers for six stacks and space in front is used for additional technology (ECU, IMD, AIRs, Fuse, Current sensors, connectors etc.). AIR-Box is constructed of FR4 walls. The last komponent is lid, which i salso the stacks holder, you can see in the picture.

Detailed stack composition is shown below in Figure 35: Mechanical fastening of ACP. Cells are built in a support structure on each side and middle one. There are connecting plates made from welder of Ni201 alloy plate and copper CU99,99% plate and spot-welded to respective cells. The entire stack is covered with an kevlar case. Each pole of a stack is ended by a copper terminal on the top of the stack. There are also vents hole at the cover and rear outer wall at main wall and also on both sides of stack, cells are cooled by air flowing among them. BMS board is placed on the top of each stack.

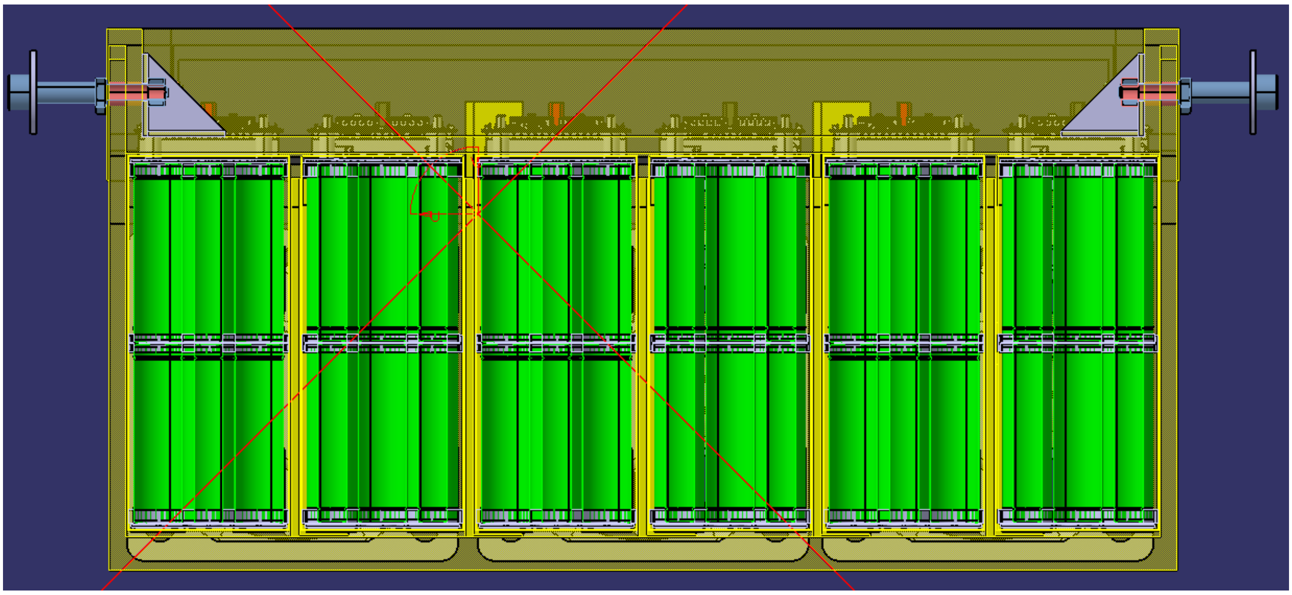


Figure 35: Mechanical fastening of ACP.

3.1.12 Position in car

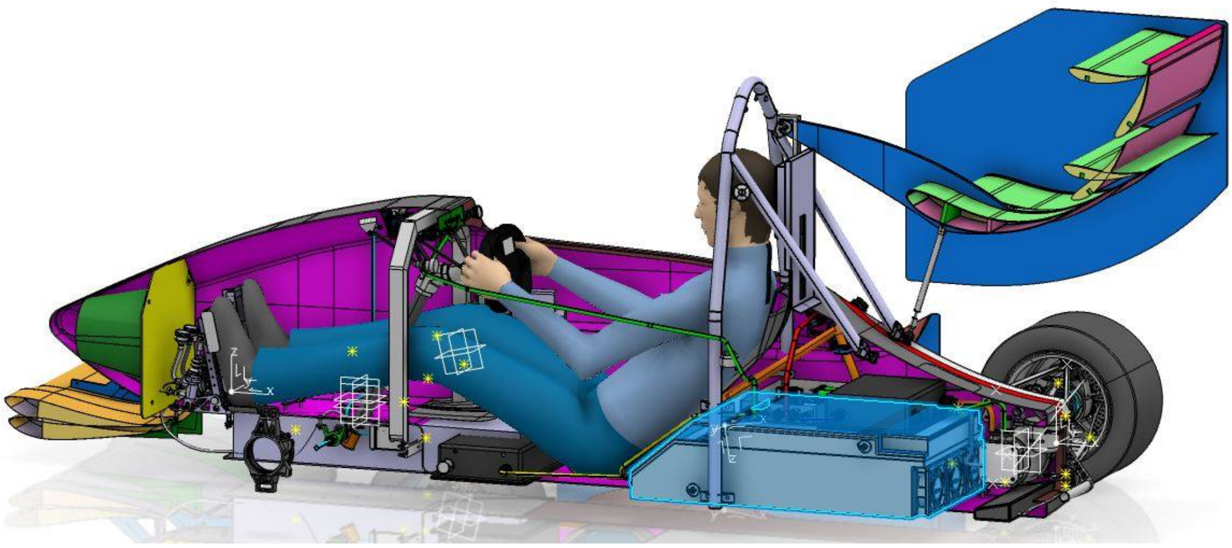


Figure 36: Position of ACP in car.

3.2 GLVS Accmulator

3.2.1 Description

Describe your concept of the GLVS Accumulator.

3.2.2 Wiring, cables, current calculations, connectors

Describe wiring, show schematics, describe connectors and cables and show useful data regarding the wiring. Include information on the working voltage and current rating of the accumulator.

Table 21: GLVS accumualtor general parameters.

Cell/Accumulator:	Li-ion
Accumulator configuration parallel:	1
Accumulator configuration series:	6
Maximum Voltage:	25.5 V
Nominal Voltage:	21.6V
Minimum Voltage:	12V
Max. Continuous Discharge Current:	
Peak Discharge Current:	
Peak Discharge Current Time:	
Max. Continuous Charge Current	
Total capacity[MJ]:	

3.2.3 Position in car

Provide CAD-renderings showing all relevant parts. Mark the parts in the rendering, if necessary.

4 Energy meter mounting

4.1 Description

Describe where the energy meter is mounted and how, etc.

4.2 Wiring, cables, current calculations, connectors

Describe the wiring, show schematics, provide calculations for currents and voltages, and show data regarding the cables and connectors used.

4.3 Position in car

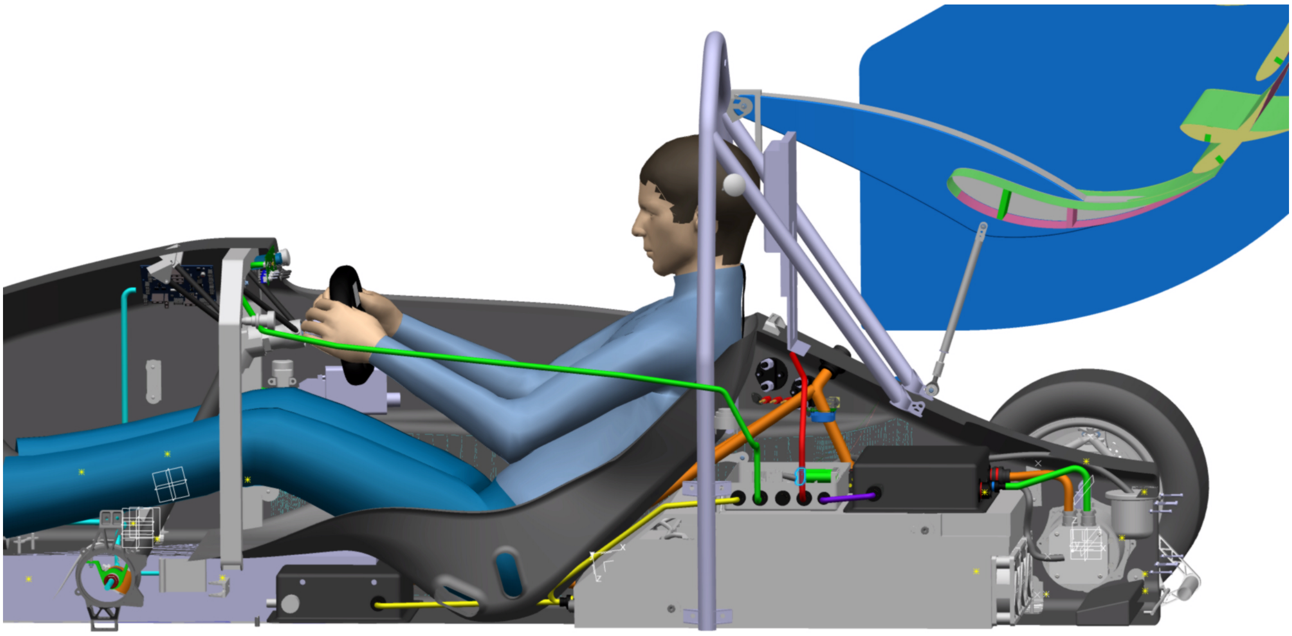


Figure 37: Service box position.

5 Motor Controller

5.1 Motor Controller 1

5.1.1 Description, type, operation parameters

Motor controller is a prototype of MiRy X-Boss Motor Controller. It is fully self-designed for driving 2 PMSM motors simultaneously with Resolver sensors as a position feedback. Field Oriented Control is implemented with galvanic isolated current sensors LEM HTFS 200-P.

Galvanic isolation on PCB is shown in Figure 50: Motor controller TOP and Figure 51: Motor controller BOTTOM. The only place where isolation is smaller then required 4mm is between pins of DC/DC NME1215SC. Real space gap is 1.54mm. The NME1215SC has rated voltage of 1kV. See Figure 49: NME1215SC isolation.

Motor Controller communicate with traction control unit by private CAN bus. If any error occurs in their communication Motor Controller stops driving both motors (error mode). It also implements discharge circuit which is activated by CAN or in case of Auxiliary supply disconnection (resistors are driven by normally-closed relay).

A current limit is set to not overload used motors. For each motor controller different. Rear motor controller has set peak current limit to 202A and temperature limit to 120C. Front Motor Controllers current limit is 70A and temperature limit also 120∘C.

Table 22: General motor controller data

Motor controller type:	MiRy X-Boss
Maximum continous power:	2 x 90kW (in:400V, out:200A)
Maximum peak power:	2 x 146kW for 5s (in:400V, out:300A)
Maximum Input voltage:	410VDC
Output voltage:	282 VAC
Maximum continuous output current:	2 x 200A
Maximum peak current:	2 x 300A for 5s
Control method:	CAN
Cooling method:	Water
Auxiliary supply voltage:	24VDC

5.1.2 Wiring, cables, current calculations, connectors

Motor controllers are connected with HVD box by high voltage cable. High current connector ASHD 0 22-24320 P N by Deutsch is used.

Table 23: Wire data of OLFLEX HEAT 180

Wire type:	OLFLEX HEAT 180 SiF
Current rating:	165A
Fuse current rating:	160A
Maximum operating voltage:	500V
Temperature rating:	180 C

5.1.3 Position in car

The position of both motor controllers is shown in Figure 38: MC position.

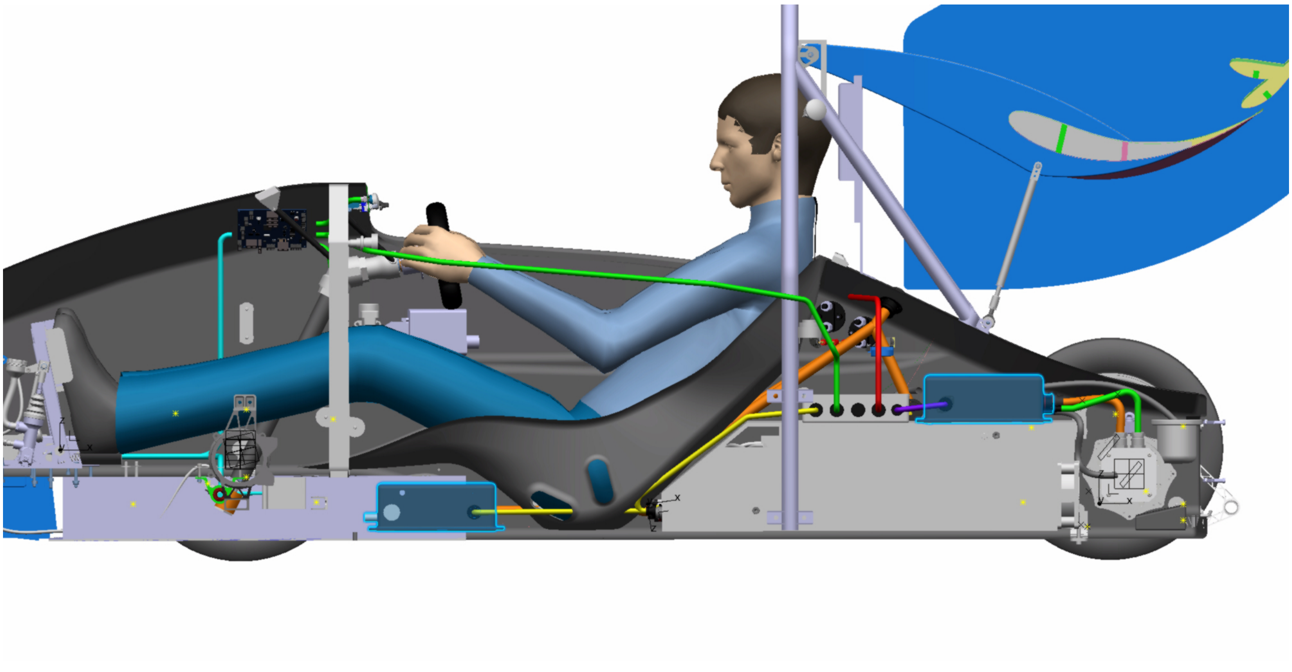


Figure 38: MC position.

5.2 Motor Controller 2

Motor controller 2 is identical as Motor controller 1.

6 Motors

6.1 Motor 1

6.1.1 Description, type, operation parameters

We are using prototype motors from company TG Drives. They developed prototype motors with special parameters and water cooling. We are using two motors on rear axle (motor 1) and two motors on front axle.

Table 24: General motor 1 data

Motor Manufacturer and Type:	TG Drives N5-1600-100-380a-h-special-v2
Motor principle	PMSM
Maximum continuous power:	11.5 kW
Peak power:	35 kW
Input voltage:	260 VAC
Nominal current:	38.2 A
Peak current:	171 A
Maximum torque:	48 Nm
Nominal torque:	11 Nm
Cooling method:	Water

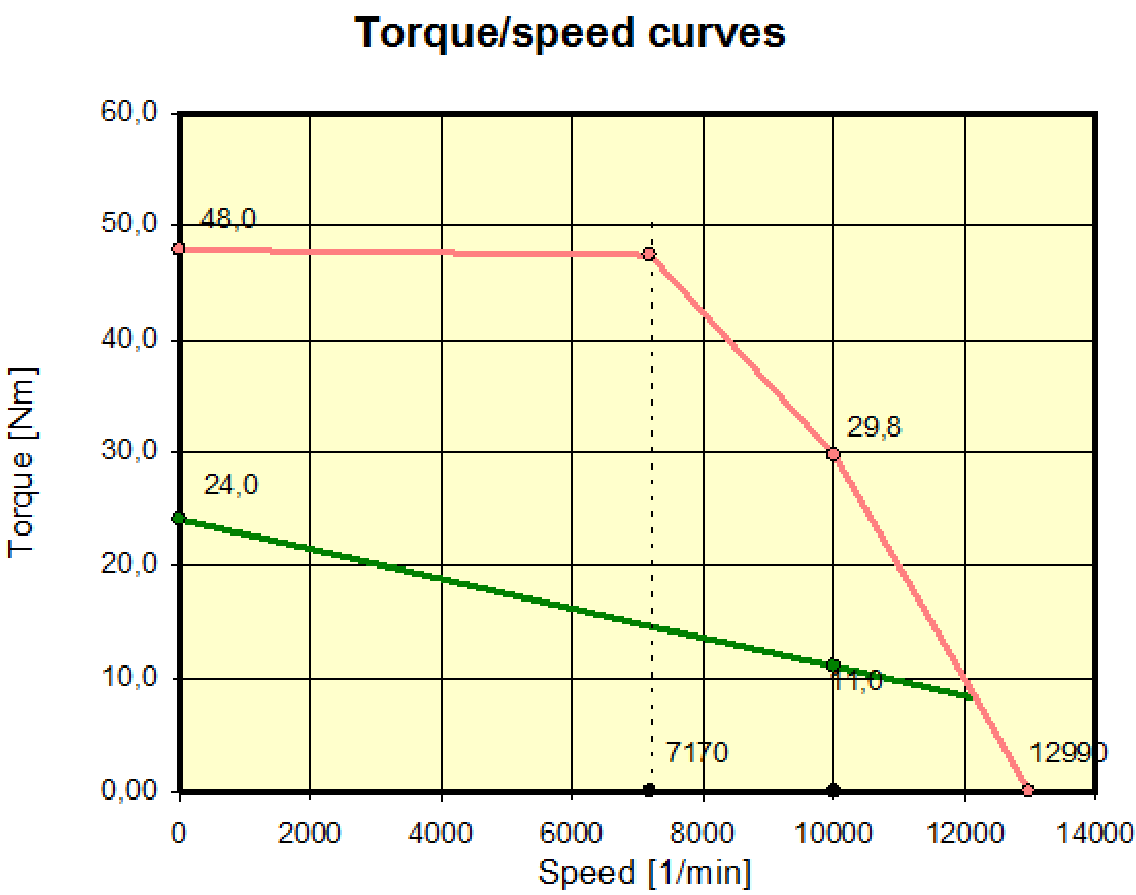


Figure 39: Rear motor characteristics.

6.1.2 Wiring, cables, current calculations, connectors

We use Raychem TR 16-10-0 and TR 16-6-0. There are leadthrough used for cables in motors and connectors Souriau 8STA 0 18 18 are used in Motor controllers.

6.1.3 Position in car

Rear motors are situated in the rear-most part of the frame.

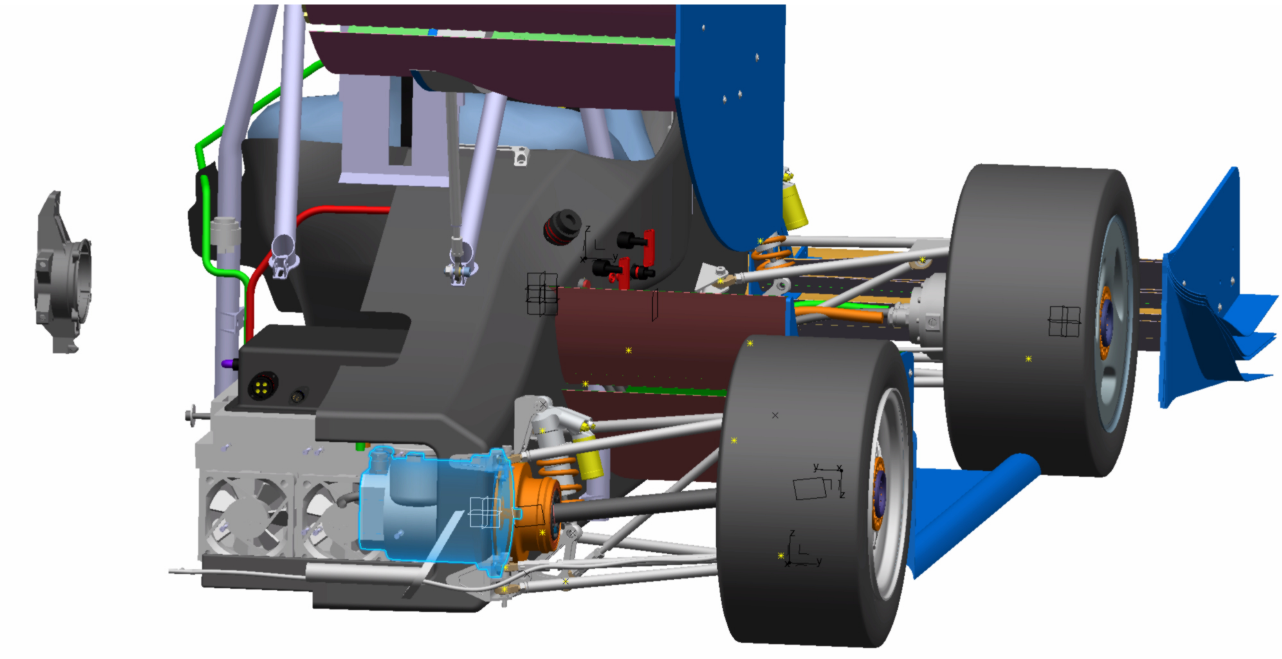


Figure 40: Rear motor position.

6.2 Motor 2

Table 25: General motor 2 data

Motor Manufacturer and Type:	TG Drives M4-0470-90-380a-h-special-water-cooling-lfe-60mm
Motor principle	PMSM
Maximum continuous power:	4.2 kW
Peak power:	8.2 kW
Input voltage:	260VAC
Nominal current:	12.2 A
Peak current:	67 A
Maximum torque:	16.2 Nm
Nominal torque:	4.4 Nm
Cooling method:	Water

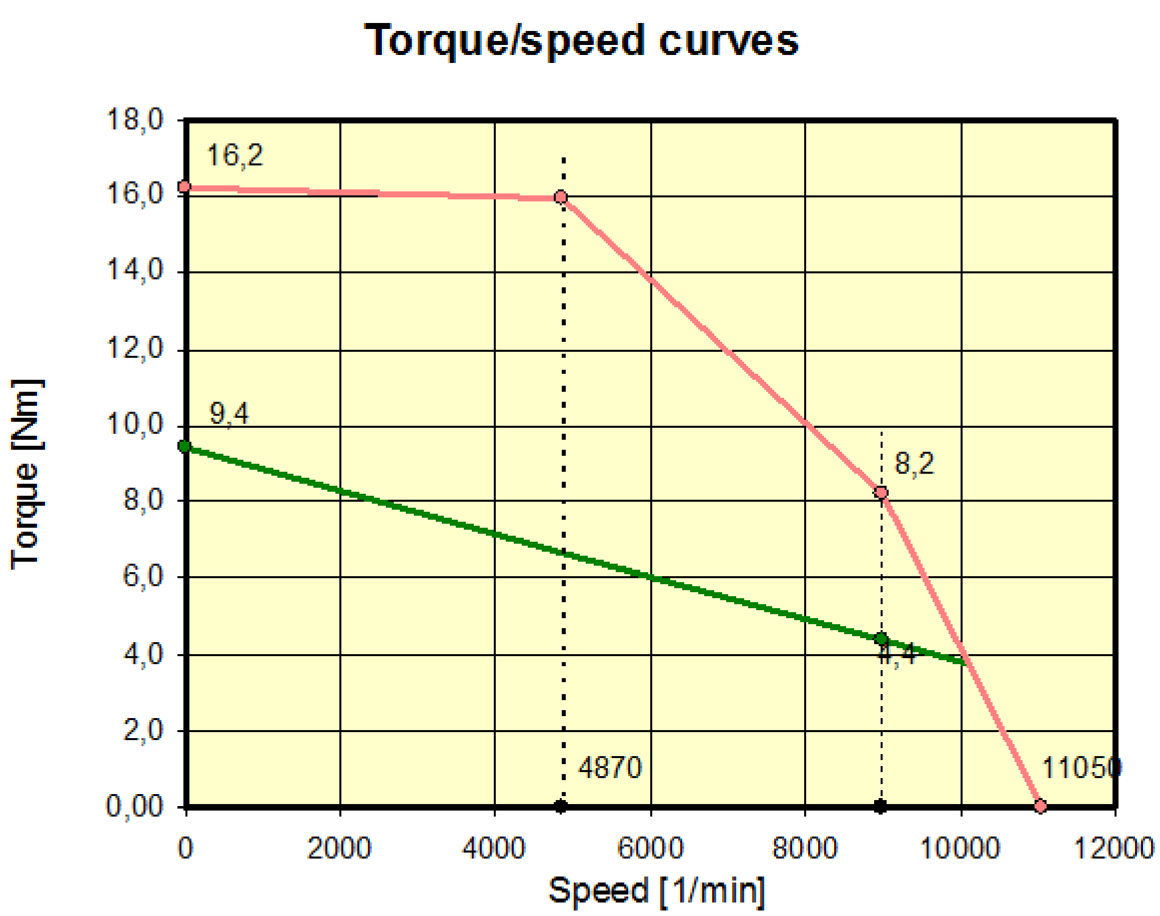


Figure 41: Front motor characteristics.

6.2.1 Wiring, cables, current calculations, connectors

We use Raychem TR 16-10-0 and TR 16-6-0. There are leadthrough used for cables in motors and connectors Souriau 8STA 0 18 18 are used in Motor controllers.

6.2.2 Position in car

Front motors are situated directly in the front uprights.

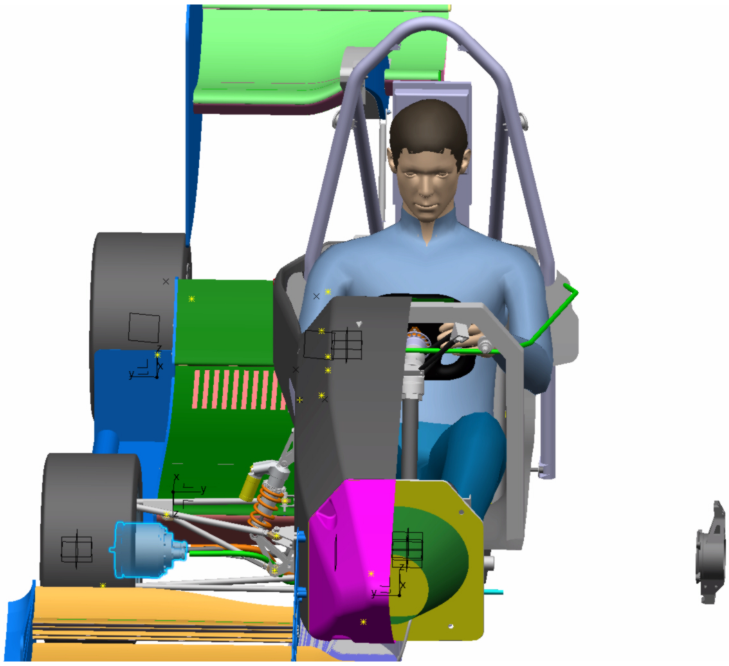


Figure 42: Front motor position.

7 Torque Encoder

7.1 Description/additional circuitry

Car is using two torque encoders for accelerator pedal. Encoders are linear potentiometers. Sensors are powered and measured by ECU-P (electrical control unit - pedals). They output analog voltage signal equal to accelerator pedal position. Both output signals goes through and low pass filters. Then they are fed to ADC (analog to digital converter) and analyzed by MCU (microcontroller unit) for validity and plausability. Information about position and errors is send though CAN.

Table 26: Torque encoder data

Torque encoder manufacturer:	TE connectivity
Torque encoder type:	MLP-50
Torque encoder principle:	linear potentiometer
Total number of Torque Encoder Sensors:	2
Supply voltage:	+5V
Maximum supply current:	1mA
Operating temperature:	-30degC to -150degC
Used output:	DC voltage 0V to 5V

7.2 Torque Encoder Plausability Check

Torque encoder implausability, short circuit and open circuit checks are done by MCU. Sensors are powered from +5V. Used travel of sensors does not contain end positions. Converted analog signal ranges are normalized according to calibration. If any following sensor error is detected, motor controllers are shut down and message is send through CAN to other units.

Electrical check

Using only part of whole range of sensor excluding end positions allows detection of signal short to Ground or voltages higher or equal to sensor's power voltage.

Analog input circuitry of ECUP is shown in Figure 43: ECU-P analog input circuit. In normal conditions, signal from sensor (RAW) goes through R2, then is clamped by D1 and continues through R1 and C1 to filters and other circuits of ECUP (AIN). TEST signal is held *low* but due to high resistance of R3 has minimal impact on input signal.

When ADC measures 0V or value close to 0V, TEST signal logic level is switched *high* to charge C1 through R3. After short while, logic level of TEST signal is read back. If *high* logic level is read, sensor input is evaluated as *open circuit*, otherwise it is *short circuit* to GND. If measured value is close to power voltage of sensor or above measurable range, it is evaluated as *short circuit* to power voltage or higher.

Implausability

Position values difference is calculated and compared with maximal allowed error threshold (10%).

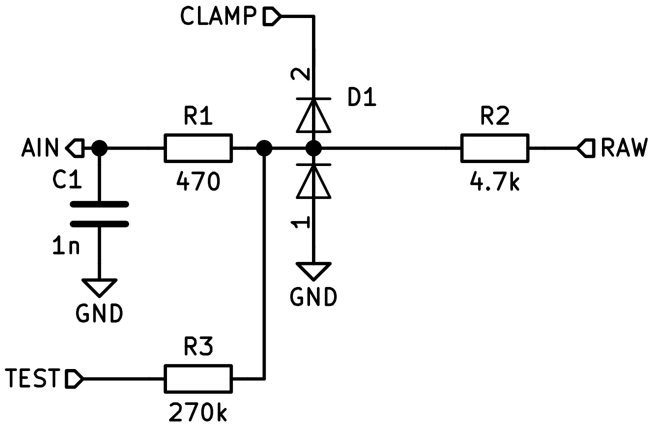


Figure 43: ECU-P analog input circuit

7.3 Wiring

Figure 44: ECU-P sensor wiring is diagram of sensor wiring.

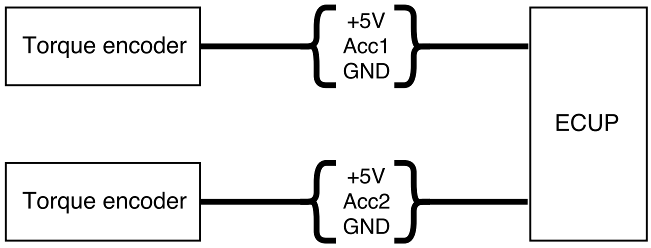


Figure 44: ECU-P sensor wiring

7.4 Position in car/mechanical fastening/mechanical connection

In Figure 45: Torque encoder position is shown position of two torque encoder sensors (piston shape objects).

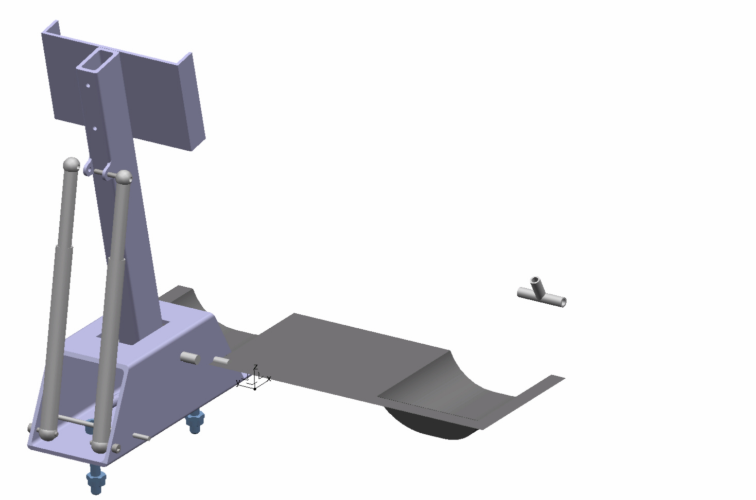


Figure 45: Torque encoder position

8 Brake Encoder

8.1 Description/additional circuitry

Car is using two pressure sensors as encoders for brake pedal. Each one is for separate brake system. Sensors are powered and measured by ECU-P, same unit as . Pressure sensors output analog voltage signal equal to brake system pressure.

Table 27: Brake encoder data

Torque encoder manufacturer:	Keller
Torque encoder type:	PA-21 Y
Torque encoder principle:	pressure sensor
Total number of Torque Encoder Sensors:	2
Supply voltage:	+24V
Maximum supply current:	4mA
Operating temperature:	-40degC to 100degC
Used output:	DC voltage 0,5V to 4,5 V

8.2 Brake Encoder Plausability Check

Implausability is not checked, because eForce does not use brake pedal information to control motor controllers.

9 Additional LV-parts interfering with tractive system

9.1 VDCU(Vehicle Dynamics Control Unit)

VDCU is a vehicle dynamics control unit. It manipulates torque request from driver pedal to calculate final torque for all 4 motors. The calculated torque never exceed driver request as driver request is processed as torque limitation Traction control can only decrease the total amount of requested torque.

9.1.1 Description

Board uses only LV and 2x CAN bus.
HW :
-Texas Instruments C2000 Delfino F28377 MCU
-5V can transceiver TJA1049

SW:
Board is programmed using simulink embedded coder. Advantage is that we can use our developed code for IPG Carmaker simulation (MIL) directly into our formula. VDCU uses pedal position, inertial measurement, steering wheel sensor, wheel speed sensor and motor encoders to manipulate the torque. Measurements are fed into our yaw rate control system. Output is a torque vector fed to torque vectoring algorithm that calculates the torque distribution for all wheels The resultant torque for individual wheels is lowered by traction control algorithm if needed and fed to motors.

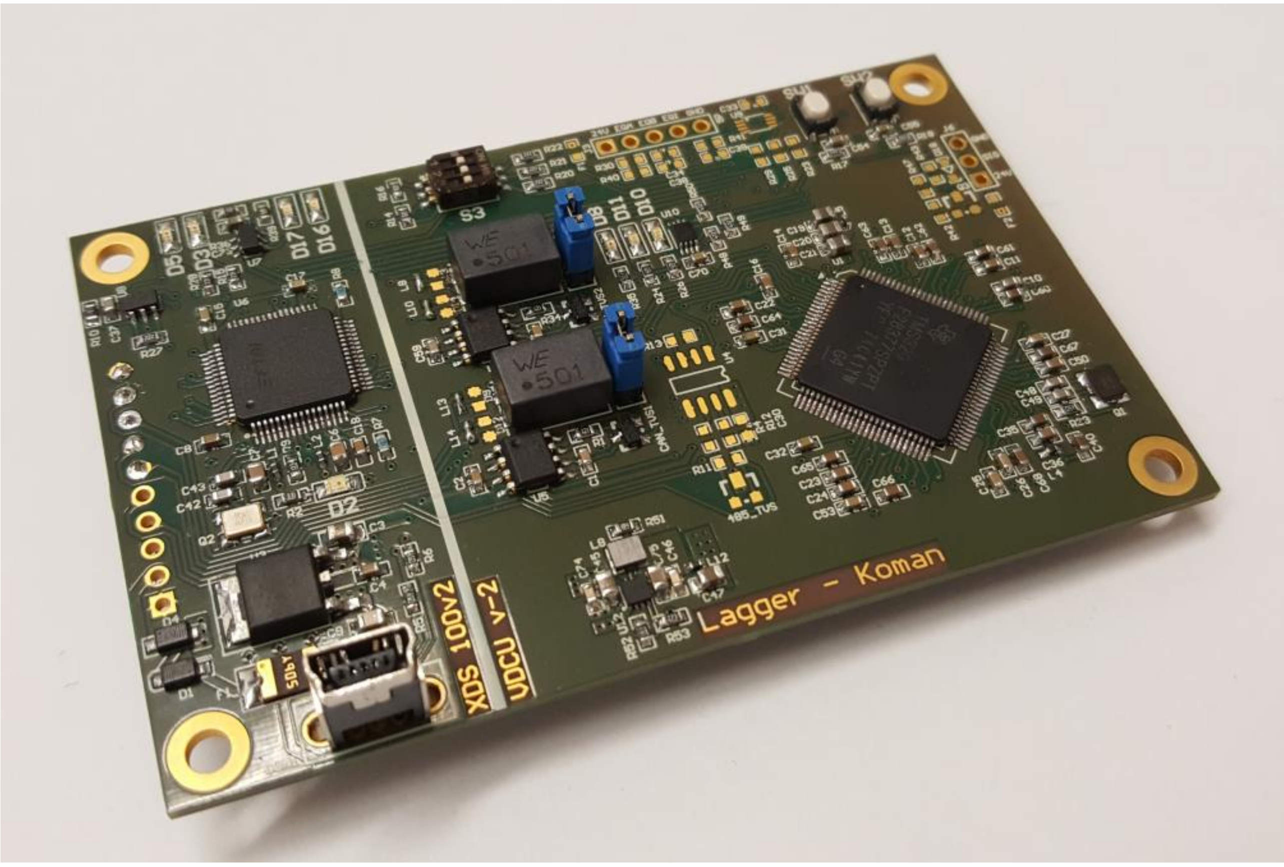


Figure 46: PCB of VDCU.

9.1.2 Wiring, cables

Module is connected using headers to ECUB.

9.1.3 Position in car

Inside ECUB box.

9.2 LV part 2

Describe those parts here which interfere or influence the tractive system, for example a controlling unit that measures wheel speeds and steering angle and calculates a target torque for each motor or a DC/DC-Converter providing power for the LV-system from the HV-system, etc.

9.2.1 Description

Describe the parts used and their circuitry, and provide main operation parameters, use tables or figures, etc.

9.2.2 Wiring, cables

Describe the wiring, show schematics, etc.

9.2.3 Position in car

Provide CAD-renderings showing the relevant parts. Mark the parts in the rendering, if necessary.

10 Overall Grounding Concept

10.1 Description of the Grounding Concept

We are using net of thin wires from grounding point laminated into composite.

10.2 Grounding Measurements

For measuring we are using 4 point method with current power supply to ensure 5 Ohms. In carbon fiber we have copper wires.

11 Firewall

11.1 Description/materials

We are using standard concept of firewall as described in the rules (T4.5.4). So the firewall is made from 2 layers. The first one is 0,5 mm thick aluminum sheet and the second one is 0,8 mm thick glass fiber/polyester plastic sheet with UL 94-V0 certificate (type: UPM 203 / UPM 71/S included in appendix). These are glued together and bended to the shape of final firewall. Aluminum sheet is oriented to the dangerous side and glass fiber to the driver side.

11.1.1 Position in car

Firewalls are located behind the seat and above the front motor controller (under drivers knees). These firewalls are connected with "firewall tunnel" where are located the high voltage cables.

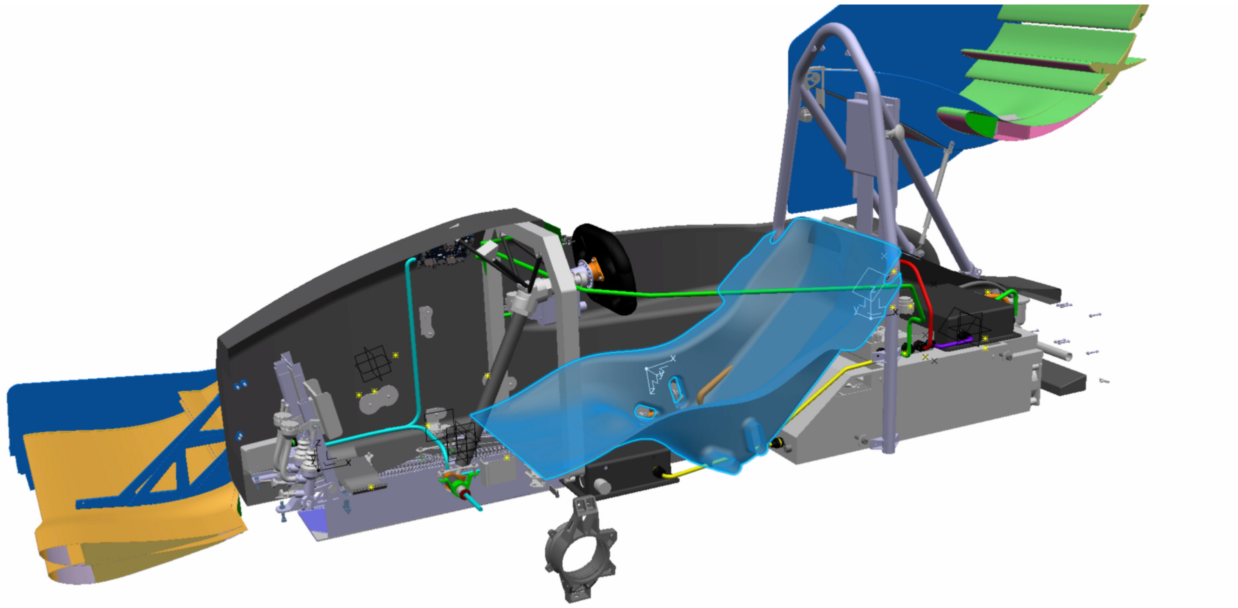


Figure 47: Firewall position.

A Appendix

A.1 HV Disconnect (HVD)


AS Heavy Duty (ASHD) Series Connectors

Autosport design for high current motorsport applications

- Early break / Late mate on data contacts to support safety
- Cable accommodation from 16mm² - 70mm²
- Positive locking coupling mechanism

High performance materials

- Environmentally sealed
- Thermal cycle tested
- Heavy duty rated
- Crimp type solid and gold plated copper contacts

All dimensions are in mm unless otherwise stated.

Appendix 48: HVD interlock datasheet.

Full datasheet http://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=1-1773721-8_as_interconnection&DocType=DS&DocLang=EN

A.2 Motor controller

Datasheet of NME1215SC, refered from section 5: Motor Controller.

Murata Power Solutions

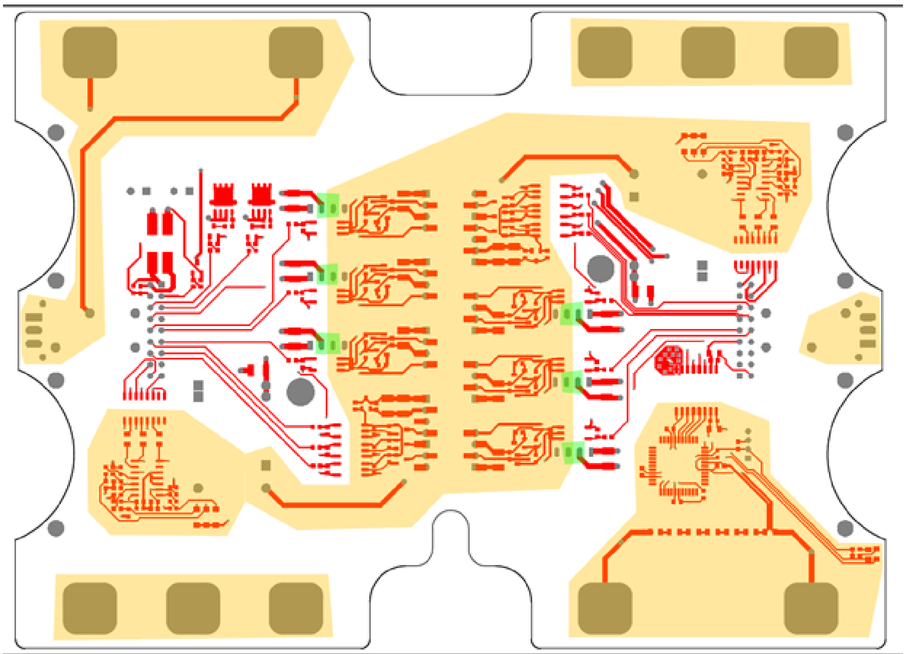
NME 5V & 12V Series

Isolated 1W Single Output DC/DC Converters

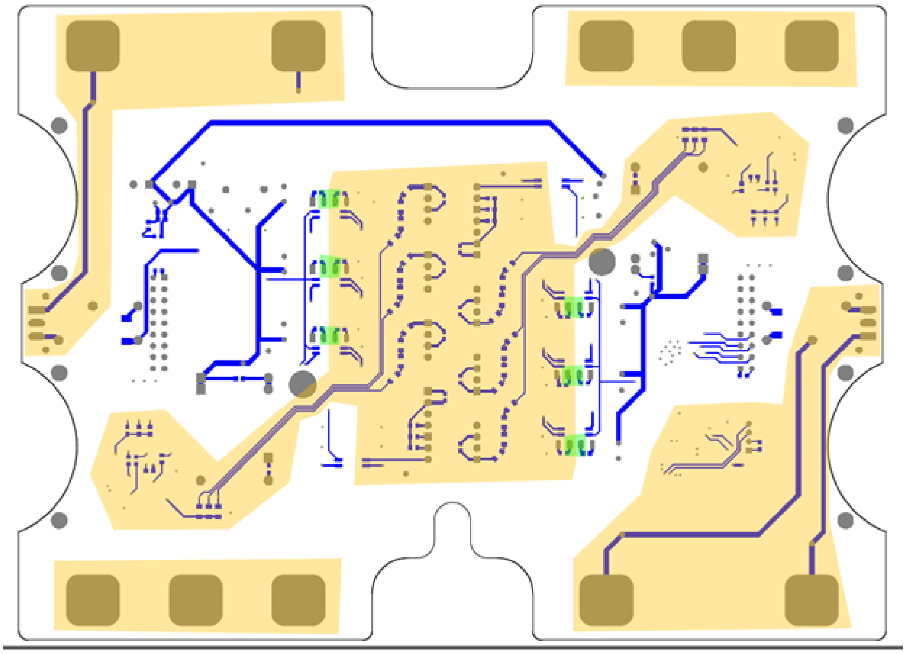
ISOLATION CHARACTERISTICS					
Parameter	Conditions	Min.	Typ.	Max.	Units
Isolation test voltage	Flash tested for 1 second	1000			VDC
Resistance	Viso= 1000VDC		10		GΩ

Appendix 49: NME1215SC isolation.

Full datasheet to be found at http://power.murata.com/data/power/ncl/kdc_nme.pdf



Appendix 50: Motor controller TOP.



Appendix 51: Motor controller BOTTOM.

A.3 Motor

RATED DATA			
Motor type			
M4	0470	90	380
Preliminary data			
Rated Speed	n_n	9000	min^{-1}
DC Bus Voltage	U_{dc}	380	V
Nominal AC Voltage	U_n	260	V
Rated Motor Voltage	U_m	228	V
Rated Torque	M_n	4,4	Nm
Rated AC Current	I_n	12,2	A
Stall Torque	M_o	9,4	Nm
Stall AC Current	I_o	24,2	A
Peak Torque	M_{max}	16,2	Nm
Peak Current	I_{max}	67	A
Max. Speed	n_{max}	9000	min^{-1}
EMF Constant	K_E	23,5	V/1000
Torque Constant	K_T	0,39	Nm/A
Terminal Resistance	R_{2ph}	0,24	Ω
Terminal Inductance	L_{2ph}	1,30	mH
Number of poles	2p	10	
No Load Speed	n_o	11050	min^{-1}
Torque at I_{max}/U_n	M_z	16,0	Nm
Speed at I_{max}/U_n	n_z	4870	min^{-1}
Max. Torque at n_n	M_x	8,2	Nm
El. Time Constant	T_{el}	5,4	ms
Mech. Time Constant	T_{mech}	0,80	ms
Thermal Time Constant	T_{th}	35	min
Rotor Inertia	J	2,9	$kgcm^2$

Appendix 52: Datasheet motor front.

RATED DATA			
Motor type			
N5	1600	100	380
Water cooling			
Rated Speed	n_n	10000	min^{-1}
DC Bus Voltage	U_{dc}	380	V
Nominal AC Voltage	U_n	260	V
Rated Motor Voltage	U_m	197	V
Rated Torque	M_n	11,0	Nm
Rated AC Current	I_n	38,2	A
Stall Torque	M_o	24,0	Nm
Stall AC Current	I_o	73	A
Peak Torque	M_{max}	48	Nm
Peak Current	I_{max}	171	A
Max. Speed	n_{max}	9000	min^{-1}
EMF Constant	K_E	20,0	V/1000
Torque Constant	K_T	0,33	Nm/A
Terminal Resistance	R_{2ph}	0,04	Ω
Terminal Inductance	L_{2ph}	0,33	mH
Number of poles	2p	10	
No Load Speed	n_o	12990	min^{-1}
Torque at I_{max}/U_n	M_z	47	Nm
Speed at I_{max}/U_n	n_z	7170	min^{-1}
Max. Torque at n_n	M_x	30	Nm
El. Time Constant	T_{el}	8,3	ms
Mech. Time Constant	T_{mech}	0,73	ms
Thermal Time Constant	T_{th}	55	min
Rotor Inertia	J	11,5	$kgcm^2$

Appendix 53: Motor controller BOTTOM.

A.4 Overall Grounding Concept

A.5 Firewall