Contents

Electrical Systems

4.1 Introduction

4.1.1 (b) List of all discrete electrical subsystems.

We are implementing the following subsystems:

- LV Battery
- HV Battery System, including
  - Battery Management System
  - Insulation Monitoring Device
- Traction Inverter
- Propulsion Motor
- Sense and Control System

4.1.2 (a) Brief overview with the main points of the HV and LV systems.

Our electrical system provides the electrical power for the propulsion and control systems. We have a low voltage circuit nominally rated at 24V (for control systems) and a high voltage level circuit at 444V (for the traction system). The low voltage circuit activates and controls the high voltage power supply through the Battery Management System and is hence designed for reliability.
The high voltage circuit is designed for safety, being potentially lethal, and power, in order to maximize the use of the motor. An OEM Insulation Monitoring Device checks for the (lack of) resistance between chassis and the HV power line in case of short circuits.
The traction inverter uses the electric power of the high voltage battery to power the motor, converting DC power into AC phases. We use an OEM device that is used in automotive purposes.

The motor is a lightweight motor from Emrax. Even though it belongs to the traction system, we will document it in the electrical section, as the development team of the originally planned inhouse-built inverter took over the duty of the electrical part of the motor system, too.

The Sense and Control System is not part of the EHW definition of the electrical systems. Since we have to provide a documentation nonetheless and the team designing the electrical subsystem also designed the Sense and Control system, we decided to include it as a part of the electrical subsystem documentation. It controls the brakes, the thermal pump, the telemetry line and the telemetry unit, as well as additional physical sensors.

Our general design of this season is inspired by conventional modes of transportation, as we have not had the capacity to start developing a levitation system by this season Thus, we focussed on an electrical system that drives our friction-based motor with excelling acceleration, which is a problem that railway systems frequently face.

In between design and production phase, we received a sponsorship of Leadrive, a local startup for research on automotive power electronics. Furthermore, the institute for electrical systems (ISEA) of our home university offered us assistance in the production of battery cells. Therefore, our workload was eased, which turned out to be favorable because of our lack of team members in the electrical field. This has been a crucial constraint in the design and planning process of the electrical department since the last season. Only shortly before submitting the ITD, we were able to make an estimation of realistic goals for the new team.

This year, we would like to set the path for magnetic levitation in the future, relying on an active system inside the vehicles. This was taken into consideration when designing the power dimensions, keeping plenty of overhead for the future, which aligns with our goal of sustainability. By having reusable modules, the design process of the upcoming years will be simplified.

We collaborate with the following institutions for support in the electrical department (including S&C):

- **Altium:** Sponsored Licenses of PCB design software
- **Festo:** Sponsored mechanical components and sensors for pneumatic systems.
- **Mouser Electronics:** Sponsored certain electronics.
- **Würth Elektronik:** Sponsored certain electronics.
- **Leadrive:** Sponsored traction inverter
- **Vector Informatik:** Sponsored CANoe Suite, including technical training for CAN networks.
- **Bender:** Sponsored Insulation Monitoring Device.
- **ISEA:** Assembling our battery pack.

4.1.3 (c) Wiring diagram of the HV system.

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4.2 LV Battery

4.2.1 Overview

Main requirements and constraints that drive the design

Our Low Voltage system drives all electrical and digital control systems of the Fermion, which is equivalent to all electronic systems but the inverter for propulsion. As stated previously, reliability is crucial in this case. A failure of any component may lead to the shutdown of critical systems, such as the battery management system. Furthermore, an overvoltage may potentially damage these systems, causing safety hazards. We had the option between building a LV battery pack from spare LiPo cells we ordered for the HV battery pack, and using

automotive-grade ventilated lead-acid batteries. After considering the safety problems of LiPo cells and the efforts of either building a second (smaller) LV BMS or taking the risk of having a singular point of failure by controlling both systems with the same BMS, powering the BMS with the cells it controls, we went for the approach with lead-acid batteries, that is widely used in automotive systems. It is regarded as more reliable and robust compared to the Lithium-Ion pendants that we use for the High Voltage System.
Furthermore, the safety risks of lead-acid batteries are much lower than those of LiPo cells, for example in the case of crashes and overcharging/overdischarging.

Power requirements

We consider the power consumption of all components in the low voltage power line for the power requirements:

- **Solenoid Valves:** According to the data sheet, the valves use 2.25 Watts à 4 valves = 9 Watts. While switching, which takes 3.5 ms, they use 8.5 Watts. Assuming that we switch all four valves 20 times, we have an additional consumption of $0.595J$, which is almost negleglible. We will assume a power consumption of 10 Watts for tolerance.
- **Thermal Pump:** Given the water flow rate, we calculated a theoretical need of 34 Watts for the pump. As we do not have experimental data, we assume that 75 Watts are required at maximum.
- **Raspberry Pi 4:** One Raspberry Pi 4B consumes 10 Watts.
- **Raspberry Pico W:**
- One Raspberry Pico W does not consume more than 1 Watt.
- **Microcontrollers (TIC2000 F280039C):**
  - According to datasheet, one microcontroller uses $3.3V * 0.11A = 0.363W$. The controller circuits will not exceed 5 Watts in total.
- **BMS (Orion BMS 2, 180 Cells):** Our BMS consumes up to 2 Watts, according to the datasheet.
- **Leadrive Inverter:** Using the nominal power ratings of 3 A at 24 V, we have a power consumption of 72 Watts. The producer informed us that the average consumption is significantly lower, which we confirmed after testing the inverter with no load, which uses approximately 25 Watts.
- **IMD**: Our IMD consumes up to 2 Watts, according to the datasheet.
- Network transceiver: We use the Rocket M2, which consumes up to 6 Watt of energy, according to the datasheet.
- Precharge relay and contactors: Our precharge relay uses $0.32W$, our main contactors use $2 * 12V * 1A$ in total. We will calculate with 25W.

Now, summing up all the (excessively computated) power requirements, we have $10W + 50W + 10W + 1W + 5W + 2W + 72W + 2W + 6W + 25W = 183W$, which is roughly 7.7 A at 24V. Using the discharge chart of the data sheet of the LV Battery,

it is evident that even at full power (9A - including some headroom for losses), we can run our low voltage system for 20 minutes. During the competition, we can rule out that we will use that much power over the whole 20 minutes. Assuming that the pump is activated while the HV system is at work, and that this duration takes 2 minutes maximum (the actual run will be much less - max. 20 seconds), and we assume only a usage of 111 W for the rest of the time, we can use the LV battery for well over 20 minutes.
In conclusion, the capacity of 9Ah is a trade-off between the mass and the available runtime of the system.

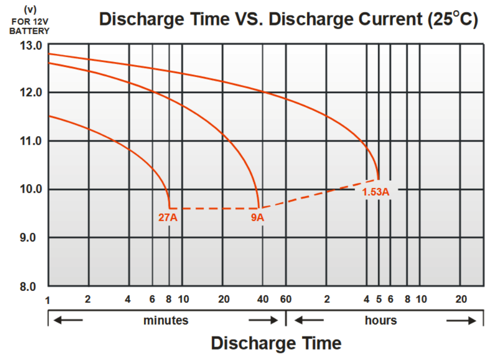

Figure 4.1: Discharge chart of LV battery cell

4.2.2 Electrical and mechanical design process

Schematic

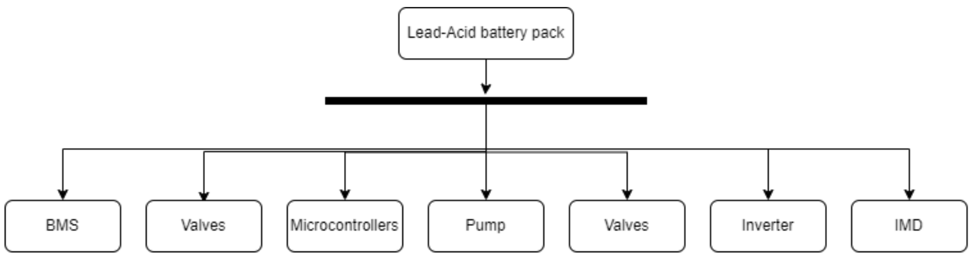

Figure 4.2: Diagram of LV connections

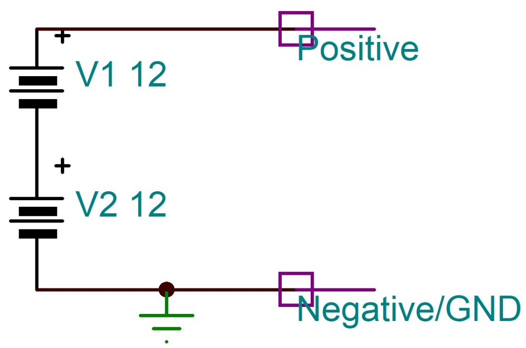

Figure 4.3: Schematic of LV battery cell

(b) Present temperature simulations for vacuum conditions.

We did a rough estimation based on the internal resistance of the battery, which is around 0.014Ω according to the datasheet. We will assume 0.02Ω. Using the equation of heat loss, we get $P = I^2 * R = 8^2 * 0.02 * W = 1.28W$.
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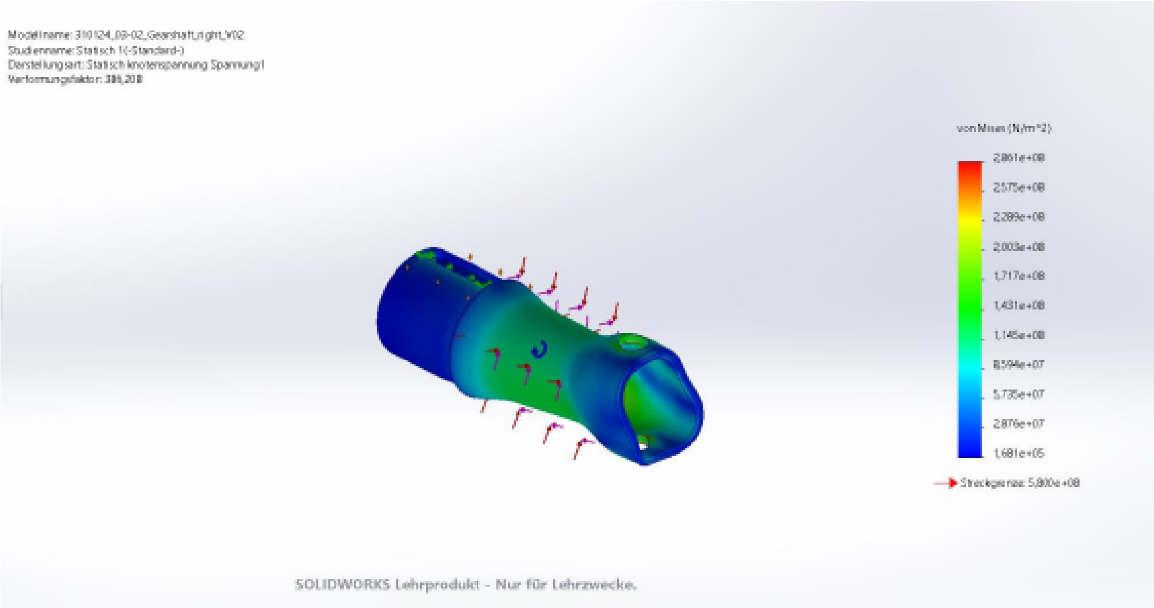


Figure 4.4: Simulation results

For our heat simulations, we used the software of ANSYS. By vacuum conditions, we assumed the lack of gas flow, which eliminates the cooling heat flow from winds. The simulation tool solves the heat transfer equation $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$ by discretizing through Finite-Element-Methods.

4.2.3 Electrical system characteristics

Battery Type	Lead-Acid(integrated)
Capacity[Ah]	9
Nominal Voltage[V]	12
Cell configuration	2s
Max. discharge [A]	10
Weight per cell [Kg]	2,7
Dimensions per cell (L x W x H)[mm]	151 x 65 x 94

Table 4.1: LV battery cell characteristics

4.2.4 Interface with other system

All the electric subsystems are located within the pod.
It powers the entire sensing, control and telemetry system. The LV battery itself does not communicate. Its sensor data is processed by the thermal control board. When the voltage drops below a certain threshold, the complete system shuts down.

Battery Type	Lead-Acid(integrated)
Capacity[Ah]	9
Nominal Voltage[V]	24
Cell configuration	2s
Max. discharge [A]	10
Weight [Kg]	5.5
Dimensions (L x W x H)[mm]	151 x 65 x 94

Table 4.2: LV battery pack characteristics

4.2.5 Final system description

The two lead-acid batteries, chained in series, provide a nominal voltage of 24V (12V each). When fully charged, the voltage can increase up to 26 V. The lead acid batteries' voltage will drop while discharging. Hence, we monitor the voltage while using the LV battery system. Through monitoring the voltage, we can also determine the state of charge, as lead-acid battery cells have characteristic discharge curves. We will not discharge the batteries to more than 30% of their capacity. Furthermore, we monitor the temperature through a NTC thermistor

Voltage	Capacity
12.89V	100%
12.78V	90%
12.65V	80%
12.51V	70%
12.41V	60%
12.23V	50%
12.11V	40%
11.96V	30%
11.81V	20%
11.70V	10%
11.63V	0%

Table 4.3: Discharge curve of sealed L-A battery

to prevent usage under overtemperature. Refer to the high voltage sectioin for details.
The 24 V power source gets transferred down to 12V (for the Thermal Pump) and 5V for the micro-controllers by buck converters, and drives the valves and several sensors at 24V simultaneously.
After reaching out to the EHW technical committee, we were able to clarify that a BMS, used

by Lithium-Ion batteries, is not required for lead-acid batteries due to the inherently different chemical structure which makes over- and undercharging much less critical.
Both terminals of the battery cells are marked red and black, respectively. To avoid reverse plugging, we use an automotive connector solution from Amphenol (ATP04-2P-MM01BLK + ATP06-2S-MM01BLK). They cannot be plugged in reverse and are rated for 25A, which is well above our limit. The wire gauge of 14-12 AWG fits the requirements of the other components. For charging, we are using a battery charger specified for 12V and 24V lead acid cells from Würth 0510955908. The charging of lead-acid batteries in series is unproblematic, given that we regularly test for drifts and manually balance the cells.

4.2.6 Manufacturing process

Parts List:
As the cells come in hard-shell covers already, the manufacturing process is not very com-

Component	Company/Product Name	Quantity	Mass [kg]	Size [mm]	Producer	Nominal Voltage
LV Battery	KingLong WL1236W	x2	9	$151 \times 65 \times 96$	Bought	12
Casing	Polycarbonate	x1	0.5	155 x 70 x 100	self-built	-
NTC Thermistor	Vishay NTCLE413E2103F102L	x1	0.03	1000 x 3 x 3	Outsourced	500

Table 4.4: Parts List - Power Electronics

plicated. We will 3D-print a case from Polycarbonate material which permits flow of air and prevents short circuits physically.

4.2.7 Testing

We will test whether the lead acid cells and the thermistors are accurate to their datasheet. This especially includes

- the capacity of the packs at 9A discharge (according to real scenario)
- the heat development while discharging

4.3 High Voltage Power Supply

4.3.1 Overview

Main requirements and design constraints

Our high-voltage battery is required to

- power the EMRAX 188 MV motor, requiring a maximum of 120 A at 504 V for full power, through the traction inverter
- endure multiple runs

- fit into the chassis appropriately
- do not exceed a weight limit of 30kg, also considering the efforts to remove it. Therefore, high energy (and power) density were important, removing the option of lead-acid batteries that are used in the railway sector. The high current ratings made specialized Lithium-Polymer cells one of the few, and the cheapest option available, which was to consider given the limited funds we had.
- be reliable and tested: The team designing the batteries originally come from a diverse background, having experience with manufacturing lithium battery packs. However, experimental innovative designs like supercapacitors or sodium ion cells were not feasible in the time.
- be easily removable for maintenance
- be controlled by a battery management system, due to obvious safety reasons
- life cycle of at least 3 years for financial and environmental sustainability.
- have power headroom for future designs, being able to be reused. We therefore also ordered a surplus of 30 cells.
- cost less than 5000€, as a fund of a local bank is sponsoring us with 5000€ for the battery system (including BMS).
- charge at a rate of approximately 1C for time constraints.
- not heat up excessively, as we only opted for passive cooling.

The main design requirement was to satisfy the motor's needs, which are as follows:

	EMRAX 188 High Voltage			EMRAX 188 Medium Voltage			EMRAX 188 Low Voltage		
AC = Air cooled LC = Liquid cooled CC = Combined cooled (Air + liquid)	AC	LC	CC	AC	LC	CC	AC	LC	CC
Ingress protection	IP21	IP66	IP21	IP21	IP66	IP21	IP21	IP66	IP21
Cooling specifications	ambient air 20ºC 20 m/s	min. 6 l/min, max. 50°C	AC+LC*	ambient air 20ºC 20 m/s	min. 6 l/min, max. 50°C	AC+LC*	ambient air 20ºC 20 m/s	min. 6 l/min, max. 50°C	AC+LC*
Maximum motor temperature [°C]	120								
Motor connection type	UVW or 2x UVW			UVW or 2x UVW			UVW or 2x UVW		
Voltage required for peak power [V_{DC}]**	660 Vdc			390 Vdc			160 Vdc		
Motor peak efficiency [%]	96%								
Peak power S2 2min [kW]	60 kW at 6500 RPM								
Continuous power S1 (kW)	27	34	37	27	34	37	27	34	37
Peak torque [Nm]	100								
Continuous torque [Nm]	40	52	56	40	52	56	40	52	56
Limiting speed [RPM]	8000								
K_V constant at no load [rpm/V_{DC}]	17,73			29,58			72,82		
K_V constant at nominal load [rpm/V_{DC}]	13,61			22,83			56,21		
K_V constant at peak load [rpm/V_{DC}]	9,81			16,61			40,87		
K_T constant [Nm/A_{RMS}]	0,54			0,32			0,13		
Peak motor current [A_{RMS}]	190			310			900		
Continuous motor current [A_{RMS}]	100			160			400		
Internal phase resistance at 25 °C [mΩ]***	14,37			5,04			1,02		
L_D induction of 1 phase [μH]	188,5			40,2			12,5		
Induced voltage [V_{RMS}/RPM]	0,04201			0,02521			0,01024		
Magnetic flux – axial [V_S]	0,03275			0,01965			0,00798		
Temperature sensor on the stator windings	KTY 81/210								
Number of pole pairs	10								
Winding configuration	star								
Rotor Inertia [kg*m²]	0,00989								
Bearing configuration	6205 | 3204								
Weight [kg]	7,1	7,9	7,6	7,1	7,9	7,6	7,1	7,9	7,6

*Combined cooled motor (CC) requires cooling specifications from air and liquid cooled motors, to reach its specifications. It cannot only be cooled as an air-cooled motor.
Every EMRAX motor requires sufficient air circulation. The motors should not be completely enclosed in any condition. Please check EMRAX motor manual to learn more.
Performance in your application will depend on your installation details and boundary conditions. Please contact us to learn more.
**All motors are tested for 833V maximum voltage.
***Measured Phase to Phase divided by 2.

Values given are for a standard 3 phase UVW version, please consult EMRAX on 2x UVW values. $R_{1UVW}=2*R_{2UVW}$

EMRAX d.o.o., Molkova pot 5, 1241 Kamnik, Slovenia, EU I support@emrax.com I +386 82053853 I www.emrax.com

Figure 4.5: Motor Specifications

The maximum voltage ratings have been increased several times in the past two years by the manufacturer, allowing for higher voltages. However, we stick to the initial data that we were given in the previous design. We will not reach the level that the motor is tested at (>800V DC maximum voltage).

4.3.2 Electrical and mechanical design process

Our design followed these steps.

For easier simulations, we used a matlab script with different parameters, which is publicly accessible via Github [1]:

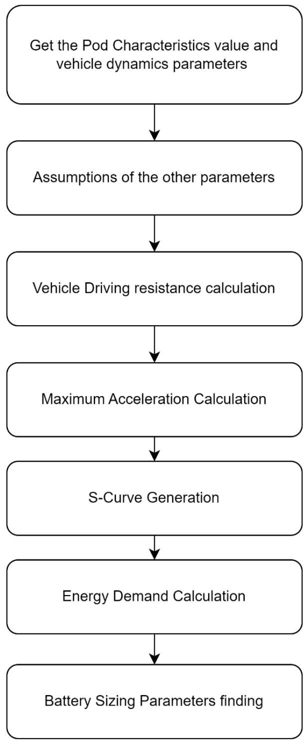


Figure 4.6: Heuristic for Finding Battery Parameter

Pod Characteristics

Some constant mechanical coefficients for the pod's movement that we assumed in our calculations:

$$
\begin{aligned}
m_{\text{fzg}} &= 250\,\text{kg} && \text{(Vehicle Mass)} \\
m_{\text{zul}} &= 50\,\text{kg} && \text{(Payload)} \\
c_L &= 0.8 && \text{(Drag Coefficient)} \\
\rho_L &= 1.2\,\text{kg/m}^3 && \text{(Air Density)} \\
f_r &= 0.02 && \text{(Kinetic Friction Coefficient)} \\
g &= 9.81\,\text{m/s}^2 && \text{(Gravitational Acceleration)} \\
A &= 1.5 \times 0.3\,\text{m}^2 && \text{(Frontal Area)} \\
e_{i1} &= 1.2 && \text{(Mass Factor for Rotating Part)} \\
\text{Gradient} &= 5\% && \text{(Inclination Gradient Percentage)} \\
\alpha &= \arctan\left(\frac{\text{Gradient}}{100}\right) && \text{(Inclination Gradient Angle)}
\end{aligned}
$$

Mass Calculation

Effective mass that will be accelerated:

$$m_{\text{acc}} = e_{i1} \times m_{\text{fzg}} + m_{\text{zul}} = 1.2 \times 300\,\text{kg} = 360\,\text{kg}$$

Vehicle Dynamics Parameters

Parameters related to the pod's movement:

$$
\begin{aligned}
v_{\text{init}} &= 0\,\text{m/s} && \text{(Starting Velocity)} \\
v_{\text{max}} &= \frac{60}{3.6}\,\text{m/s} \approx 16.67\,\text{m/s} && \text{(Maximum Velocity)} \\
s_f &= 150\,\text{m} && \text{(Pod Distance)} \\
R_d &= 0.1\,\text{m} && \text{(Radius of Driving Wheel)}
\end{aligned}
$$

[1] Link to our battery model estimation

Motor Parameters

Motor's specifications:

$$\begin{aligned} P_{\text{peak}} &= 37 \times 1000\,\text{W} && \text{(Power at 7000 rpm)} \\ \text{eff} &= 0.96 && \text{(Efficiency)} \\ P_{\text{motor}} &= 0.96 \times 37000\,\text{W} = 35520\,\text{W} \end{aligned}$$

Resistance Calculation for Continuous Power

We add all resistive forces against the pod's motion, taking into account that we drive in a non-vacuum environment:

$$\begin{aligned} F_{\text{roll}} &= 0.02 \times 300 \times 9.81 \times \cos\left(\arctan\left(\frac{5}{100}\right)\right) \\ F_{\text{luft}} &= 0.5 \times 0.8 \times 1.2 \times (1.5 \times 0.3) \times (16.67^2) \\ F_{\text{st}} &= 300 \times 9.81 \times \sin\left(\arctan\left(\frac{5}{100}\right)\right) \end{aligned}$$

Maximum Acceleration Calculation

Pod's maximum acceleration:

$$a_{\max} = \frac{\left(\frac{35520}{16.67}\right) - F_{\text{roll}} - F_{\text{luft}} - F_{\text{st}}}{360}$$

S-Curve Generation

Timing for acceleration and deceleration phases:

$$T = \left(\frac{a_{\max}}{j_{\max}}\right) + \left(\frac{16.67}{a_{\max}}\right) + \left(\frac{150}{16.67}\right)$$

Energy Demand

Energy demand for the journey: energy_bed_wh = Energy demand in Wh

Battery Parameters

$$
\begin{aligned}
V_{\text{bed}} &= 490\,\text{V};\\
I_{\text{bed}} &= 100\,\text{A};\\
U_{\text{zell}} &= 4.2\,\text{V};\\
C_{\text{zell\_ah}} &= 6.1\,\text{Ah};\\
C_{\text{rate}} &= 35;\\
\text{SoC\_max} &= 80\%;\\
\text{SoC\_min} &= 40\%;
\end{aligned}
$$

Required battery configuration:;

$$
\begin{aligned}
n_{\text{ser}} &= \left\lceil \frac{V_{\text{bed}}}{U_{\text{zell}}} \right\rceil;\\
C_{\text{tot}} &= \frac{\text{energy\_bed\_wh}}{n_{\text{ser}} \times U_{\text{zell}} \times \text{eff\_mech}};\\
n_{\text{par}} &= \left\lceil \frac{C_{\text{tot}}}{C_{\text{zell\_ah}} \times \left(\frac{\text{SoC\_max}-\text{SoC\_min}}{100}\right)} \right\rceil;
\end{aligned}
$$

The S-curves are simple, as follows:

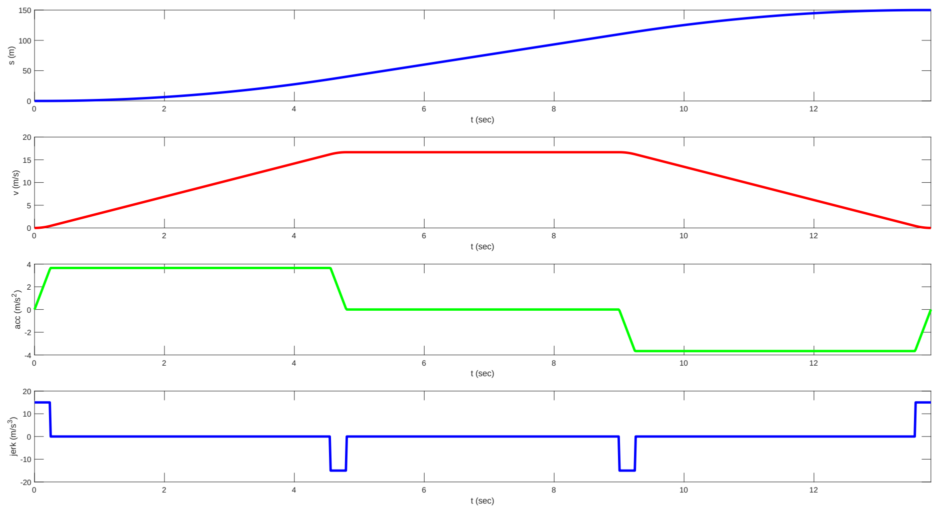


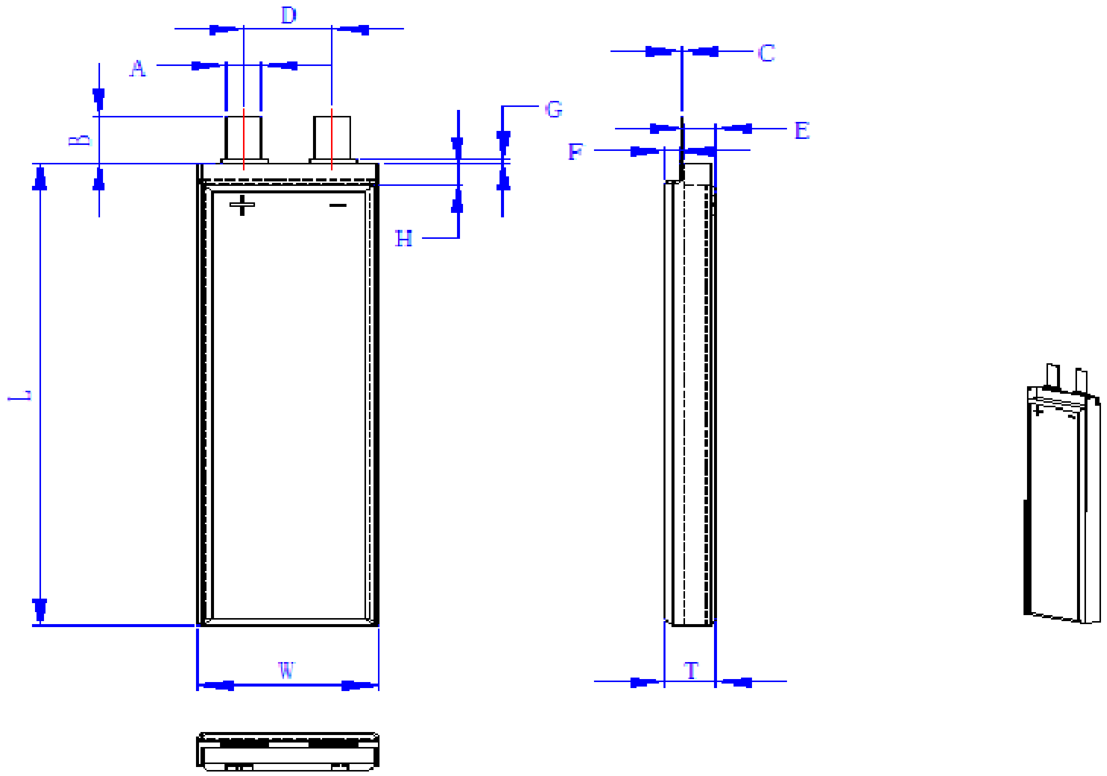
Figure 4.7: Run model

The results showed that we needed 117 x 1 cells in series, which can be explained because we assumed to be able to use the maximum voltage, not the nominal voltage of the battery cells. We are able to run 27.47 runs, even with keeping our state of charge between 40 and 80 percent, saving battery health [2].

Schematics and drawings.

The battery cell is in a standard pouch format. It has bigger tabs, presumably because of the high currents.

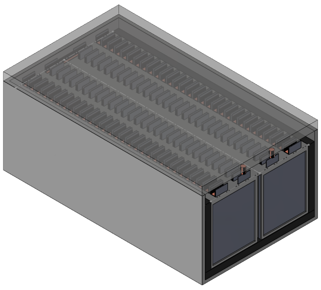
[2]We follow general advice that the optimal SOC lay between 0.2 to 0.8, and exceeding this range is not per se damaging to the battery, but shortening its life span, which we try to avoid



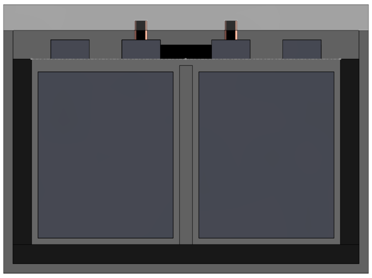
尺寸	厚度 Thickness(T)	≤5.0mm
	宽度 Width(W)	≤115.5mm
	长度 Length(L)	≤140.5mm
	极耳中心距(D) Distance between 2 tabs	60.0±1.5mm
	极耳宽度 Tab Width(A)	40±0.2mm
	极耳厚度 Tab Thickness(C)	0.2mm
	极耳外露长 Tab Length(B)	30.0±1.5mm(含极耳胶，铝转镍)
	极耳胶外露长 Sealant Length(G)	0.5-3.0mm
	正封宽 Sealing Width（H）	13.5±0.2mm
	槽 1 Deep groove （E）	3.80mm
	槽 2 Deep groove (F)	----
重量 Weight		≤156.0g

Figure 4.8: Battery cell

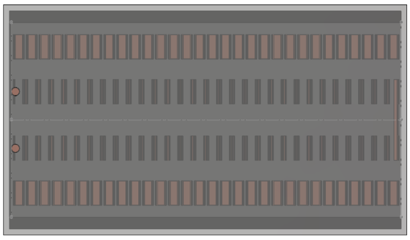
The CAD models of the battery pack are shown in the following. We visually cut the box open to show the inside structure. For the embedding of the battery pack in its surrounding, please refer to the 2.2.



(a) Battery pack (cut open)



(b) Battery pack from the side.



(c) Battery pack from the top

Figure 4.9: Battery pack schematics and drawings

Total amount thermistors: 40,040
BMS Thermistors: 8
Extern thermistors: 32

1: Thermistor Extern, 1.005: Thermistor BMS, 0: No Thermistor

- +

Group Nr.	Tap Nr.	Left (Cell N	Tap Wiring	thermistor	Cable Holes	Right (Cell Nr)		thermistor	Group Nr.	Tap Nr.
1	1,1	1	1	1,005		120	1	0	4,1	4
		2	2	0		119	2	1,005		
		3	3	1,000		118	3	1,000		
		4	4	0		117	4	0		
		5	5	1,005		116	5	1,005		
		6	6	0		115	6	0		
		7	7	0		114	7	0		
		8	8	0		113	8	0		
		9	9	1,005		112	9	1,005		
		10	10	0		111	10	0		
		11	11	0		110	11	0		
		12	12	0		109	12	0		
	1,2	13	1	1,005		108	1	1,005	3,1	3
		14	2	0		107	2	0		
		15	3	0		106	3	0		
		16	4	0		105	4	0		
		17	5	1		104	5	1		
		18	6	0		103	6	0		
		19	7	0		102	7	0		
		20	8	0		101	8	0		
		21	9	1		100	9	1		
		22	10	0		99	10	0		
		23	11	0	O	98	11	0		
		24	12	0		97	12	0		
	1,3	25	1	1		96	1	1	3,2	
		26	2	0		95	2	0		
		27	3	1		94	3	1		
		28	4	0		93	4	0		
		29	5	1		92	5	1		
		30	6	0		91	6	0		
		31	7	1		90	7	1		
		32	8	0		89	8	0		
		33	9	1		88	9	1		
		34	10	0		87	10	0		
		35	11	0		86	11	0		
		36	12	0		85	12	0		
2	2,1	37	1	1		84	1	1	3,3	
		38	2	0		83	2	0		
		39	3	0		82	3	0		
		40	4	0		81	4	0		
		41	5	1		80	5	1		
		42	6	0		79	6	0		
		43	7	0		78	7	1		
		44	8	0		77	8	0		
		45	9	1		76	9	0		
		46	10	0		75	10	0		
		47	11	0		74	11	0		
		48	12	0		73	12	0		
	2,2	49	1	1		72	1	1	2,3	
		50	2	0	O	71	2	0		
		51	3	0		70	3	0		
		52	4	0		69	4	0		
		53	5	1		68	5	1		
		54	6	0		67	6	0		
		55	7	0		66	7	0		
		56	8	1		65	8	0		
		57	9	0		64	9	1		
		58	10	1		63	10	0		
		59	11	0		62	11	1		
		60	12	1		61	12	1		

Figure 4.10: Schematic of battery pack

Temperature simulations for vacuum conditions.

For our heat simulations, we used the software of ANSYS. By vacuum conditions, we assumed the lack of gas flow, which eliminates the cooling heat flow from winds. The simulation tool solves the heat transfer equation $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$ by discretizing through Finite-Element-Methods.
Its results:

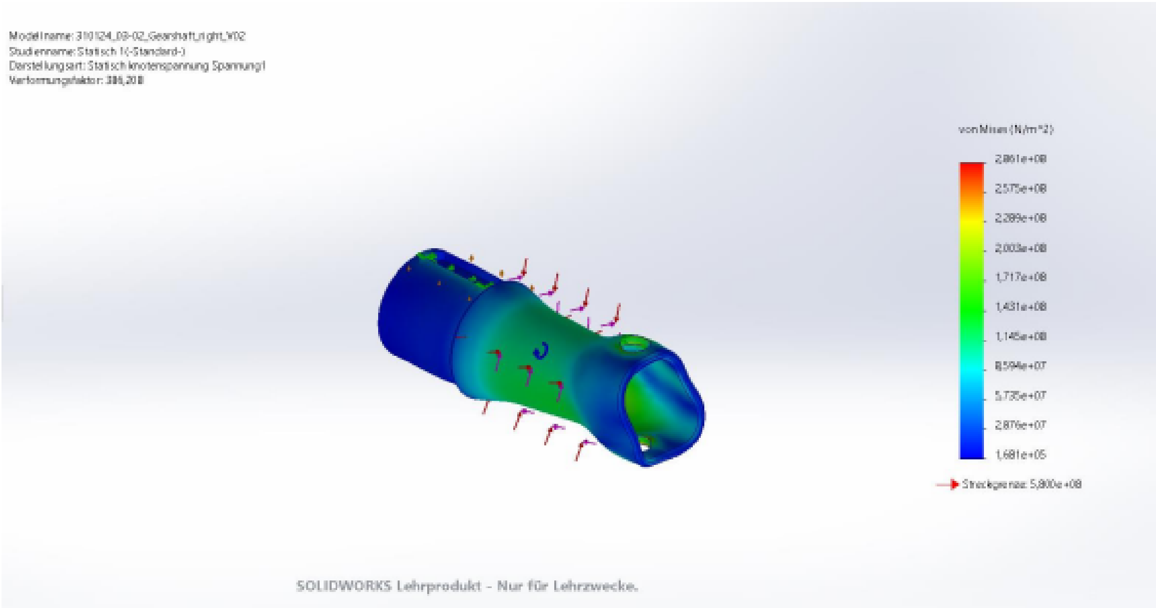


Figure 4.11: Simulation results

4.3.3 Electrical system characteristics

4.3.4 Interface with other system

Control systems of the boards

We configure the BMS prior to the competition, and do not plan to change any settings during the competition. It sends telemetry data over CAN and permits charging/discharging of the battery.
All the electric subsystems are located within the pod.

The physical connection matrix is as following:

From | To	LV Battery	HV Battery	BMS	Traction Inverter	Motor	Cooling System
LV Battery	-	-	Powers	Powers control system	-	Powers pump and control system
HV Battery	-	-	Connects to	Provides power	-	-
BMS	-	-	Controls	-	-	-
Traction Inverter	-	-	-	-	Propels	X
Motor	-	-	-	-	-	-
Cooling System	-	-	-	Cooling	Cooling	Cooling (implicitly)

Table 4.5: Physical connection matrix

The data connection matrix is as following. All communication between boards are via CAN, if not specified otherwise:

From \ To	LV Battery	HV Battery	BMS	Traction Inverter	Motor	Cooling System	Brakes Controller	Telemetry Unit
LV Battery	-	-	-	-	-	-	-	-
HV Battery	-	-	Discharge rate, voltage level	-	-	-	-	-
BMS	controls	controls	-	-	-	-	-	sends data
Traction Inverter	-	-	-	-	-	-	-	sends data
Motor	-	-	-	-	-	-	-	-
Cooling System	-	-	-	-	-	-	-	sends data
Brakes Controller	-	-	-	-	-	-	-	sends data
Telemetry Unit	-	-	updates limits	sends commands	-	sends target rates	sends commands	-

Table 4.6: Data connection matrix

4.3.5 Final system description

Battery Cells

High Voltage Network:
Our high voltage battery will make use of lithium-ion polymer technology. We use 120 pouch-format cells from Shenzhen GrePow Battery Co. Ltd rated at 45C maximum discharge that we plan to connect in series. The finished package (main battery pack) will be assembled by the team, helped by the ISEA institute of RWTH Aachen University. We are going to connect the 120 cells connected in series and that will have 1 parallel line. This will roughly have 504 Volt at max (using $120*4.2V = 504V$) which provides sufficient electricity to power the motor. The battery pack will provide up to 350 Amps of DC current available to the inverter. However, neither the inverter nor the motor is not rated for such high currents nominally, and we are not trying to use the full power of the battery pack.
Therefore, the maximum output current of the HV Battery will be rated at 120 A maximum (peak) and 74 A continuous. As the peak duration is at 120s, and our runs are at most 10s, we will set the limit of the inverter to 120A for the competition.

Company	Shenzhen GrePow Battery Co. Ltd
Model	GRP50B5140
Battery Type	Lithium Polymer Pouch Cell
Capacity[Ah]	6.1
Maximum voltage[V]	4.2
Nominal Voltage[V]	12
Cell configuration	1s
Max. discharge [A]	360
Max. discharge w/o cooling [A]	200
Weight per cell [Kg]	0.16
Dimensions per cell (L x W x H)[mm]	141 x 116 x 5

Table 4.7: High battery cell specifications

Battery Pack

The battery pack consists of two lines of 60 battery cells each that are connected in series, giving $120 * 3.7V = 444V$ nominal voltage. They are placed into a rigid rectangular container, with outputs being the power output, 120 wiring taps to the cells, and 40 thermistors (8 to the BMS, 32 to the telemetry device).

Therefore, we measure one third of all cell temperatures, which is above the EHW requirements. We use the thermistors NTCLE413E2103F102L from Vishay/BC. The thermistors are approximately equally spread across the box, with a slight focus on both ends and the middle of the pack, where we expect the highest heat transients. The external thermistors will be connected to the thermal (cooling) controller via the circuit that the manufacturer of the microcontroller, Texas Instruments, has proposed.[3] We will adapt the components of the circuit, providing an almost linear output voltage with temperature, to a higher temperature range (from 25-50 C to 0-60C).

Table 4.8: Thermistor parameters

Parameter	Value
Resistance at 25°C	10 kΩ
Tolerance	±1%
B-value (B25/85)	3435 K
Tolerance on B-value	±1%
Operating Temperature Range	-40 to 105°C

Table 4.9: Resistance Values of Thermistor

Temperature (°C)	RT (Ω)	R-TOL. (± %)	T-TOL. (± °C)	RMIN. (Ω)	RMAX. (Ω)
0.0	27,348	2.7348	-4.31	26,783	27,913
5.0	22,108	2.2108	-4.19	21,702	22,515
10.0	17,979	1.7979	-4.08	17,689	18,270
15.0	14,706	1.4706	-3.96	14,499	14,912
20.0	12,094	1.2094	-3.86	11,949	12,239
25.0	10,000	1.0000	-3.75	9,900.0	10,100
30.0	8,310.8	0.83108	-3.65	8,211.7	8,409.8
35.0	6,941.1	0.69411	-3.55	6,845.5	7,036.7
40.0	5,824.9	0.58249	-3.46	5,734.1	5,915.6
45.0	4,910.6	0.49106	-3.37	4,825.6	4,995.7
50.0	4,158.3	0.41583	-3.28	4,079.2	4,237.3
55.0	3,536.2	0.35362	-3.20	3,463.2	3,609.2
60.0	3,019.7	0.30197	-3.12	2,952.5	3,086.8

We add 4 holes to connect the cell taps and thermistors to the cells. They are marked in the layout of the battery box 4.10, and are visually shown in the following CAD image:

[3] Reference Design for Temperature Sensing with NTC Circuit, published by Texas Instruments, 2021. Visited on 12th March 2024

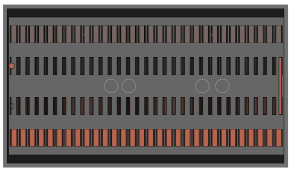


Figure 4.12: Openings for BMS cabling

Material Selection:

- Battery Case: It will be made of flame-retardant grades of ABS (Acrylonitrile Butadiene Styrene) because of its light weight and impact resistance.
- Vibration Protection Material: Neoprene foam will be used to damp against vibration that might damage the battery otherwise. It is chemically and thermodynamically robust.
- Cell Holder: Polypropylene (PP) will be used for pouch cell holders due to its lightweight, chemical resistance, and ease of molding. It provides good structural support and can be designed with features such as tabs or grooves to securely hold the cells in place.
- Thermal Interface Material: We are going to use aluminum foil, as well as materials from Würth Elektronik to increase the heat flow of the cells.
- Compression Protection Element: We will use Silicone Rubber due to its flexibility, durability, and robustness. It will provide cushioning against mechanical shocks and vibrations and hold the cells in place.
- Busbar: Busbar will be made of pure copper as it needs to transfer a high rate of discharge due to its low resistance.
- Thermal Protection Material: As we are depending on passive cooling of the battery, we will not use any thermal protection material to ensure the air passing through the cells maintains the operating temperature.
- Fire Retardant Material: A plate will be placed over the connections made of flame-retardant grades of ABS (Acrylonitrile Butadiene Styrene) to ensure the slow propagation of flame.
- Housing Sealing: Housing sealing will be made of the same grade of ABS as the casing to stop the ingress of air, water, and dust particles. The washer will be put between the joints to ensure complete sealing.

In conclusion, this is the specification of our high voltage battery pack. Table 4.10:

Battery Type	Lithium Polymer Pouch Cells
Capacity[Ah]	6.1
Nominal Voltage[V]	444
Maximum Voltage[V]	504
Cell configuration	1p120s
Max. discharge [A]	360
Max. discharge w/o cooling [A]	200
Weight [Kg]	23
Dimensions per cell (L x W x H)[mm]	500 x 285 x 210

Table 4.10: High Voltage Pack specifications

BMS

Our centralized battery management system, the Orion BMS 2, connected to the HV battery, protects it and improves its health and efficiency. It is an OEM product.
It acts by:

- Monitors every cell voltage in series
- Intelligent cell balancing (efficient passive balancing)
- Enforces min. and max. cell voltages
- Enforces maximum current limits
- Enforces temperature limits
- Monitors state-of-charge and pack health, internal resistance
- Controls discharging and charging
- Retains lifetime data about battery history

We include the relevant sections of the data sheet below: The input connections (cell taps) from the battery poles are grouped in 5 sections à 3 Groups à 12 cells, up to 180 cells in total. We will only use 4 sections, and 3 fully. Additionally, there are 8 thermistors measuring the temperature. As the Rules and Regulations of EHW require more, we added more thermistors that do not output to the BMS, but to the Sense and Control system.Refer to the wiring of the battery box for that (4.10).

4.3.6 Manufacturing process

Parts List:

Specification Item	Min	Typ	Max	Units
Input Supply Voltage	8		30	Vdc
Supply Current—Active (at 25°C)		< 2		Watts
Supply Current—Sleep (at 25°C, 12vDC)		450		µA
Operating Temperature	-40		80	°C
Sampling Rate for Current Sensor		8		mS
Sampling Rate for Cell Voltages		25	40	mS
Isolation Between Cell Tap #1 and Chassis / Input Supply	1.5			kVrms
Isolation Between Cell Taps #2+ and Chassis / Input Supply	2.5			kVrms
Isolation Between Cell Tap Connectors	2.5			kVrms
Digital Output Switching Voltage (Open Drain)			30	V
Digital Output Sink Continuous Current			175	mA
Cell Voltage Measurement Range	0.5		5	V
Cell Voltage Measurement Error (over 1-5v range)			0.25	%
Cell Balancing Current			200	mA
Cell Current (Operating)		0.5		mA
Cell Current (Low Power Sleep)		50		µA
Thermistor Accuracy		1		°C
Cell Voltage Reporting Resolution		0.1		mV

Table 4.11: BMS specifications

PCBs

Prototyping: Prototype PCBs are fabricated in the FabLab associated with our university. The FabLab grants access to PCB manufacturing equipment and materials for the rapid production of prototypes for initial testing and design validation. Once the PCBs are fabricated, they are assembled manually by our team members. Bigger PCBs are assembled in the facilities of the FabLab with the manual Pick and Place Machine and a reflow oven.
Production: We ordered our final PCBs from JLCPCB, a leading PCB manufacturing service. In addition to JLCPCB, we also collaborate with Würth Elektronik who produce PCBs in Germany, aligning with our goal of sustainability.

Batteries

Our phases of production followed this structure:

Component	Company/Product Name	Quantity	Mass [kg]	Size [mm]	Producer	Nominal Voltage
HV Battery Cell	GrePow	x2	9	151 × 65 × 96	Bought	12
Casing	Polycarbonate	x1	0.5	155 x 70 x 100	self-built	-
NTC Thermistor	Vishay NTCLE413E2103F102L	x40	0.03	1000 x 3 x 3	Outsourced	500

Table 4.12: Parts List - HV Battery

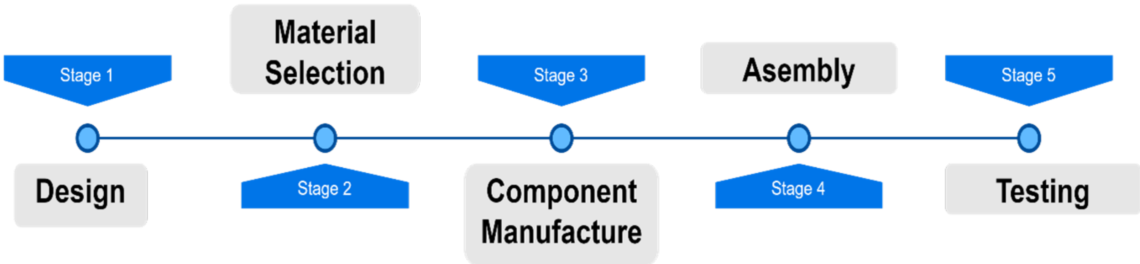


Figure 4.13: Stages of Production of Battery Pack

We produced the battery packs in cooperation with the ISEA (Institute for Power Electronics and Electrical Drives) at RWTH, whose experience helped us to assemble and design the parts more efficiently and more safely, as we had a considerable high voltage system.

The casing will consist of polycarbonate. Polycarbonate is a material that is durable, lightweight, and impact resistant. The problems with material degradation through UV emissions do not impact us substantially, as we cover the battery pack inside the shell for most of the time. We will have safety measures preventing too much exposure to UV radiation. Also, the degradation is mainly of cosmetic nature (https://link.springer.com/article/10.1007/s11668-020-01002-9).

Assembly

- Stacking the cells: Insertion of the pouch cells into a holder/frame element, which brings the cells into a defined distance from each other, minimizes volume expansion during respiration, and protects the flexible cell housing from damage. We are stacking 60 cells in series in one stack and using 2 of these stacks in series.
- Connecting the cells: The cells are connected to each other in a series manner with the help of a busbar. Ultrasonic welding will be done to connect the cell tabs to the busbar.
- Connecting the BMS: The wiring diagram of the battery to BMS is given below:

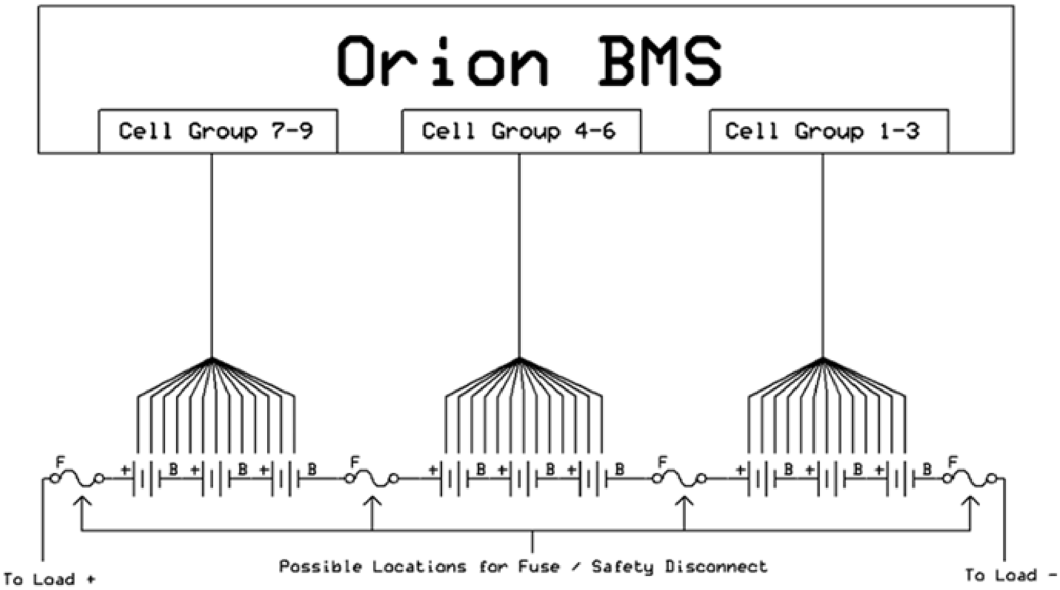


Figure 4.14: Example Connection Wiring of Battery to BMS with 108 Cells

We will have 4 round cuts on top of the battery pack to connect the BMS, which is mounted above the pack (but not to the pack! Refer to mechanical design), to the battery pack.

- Tensioning the Battery Cage Structure: We will use the stretch bands to tension the whole stack structure to reduce the expansion during the manufacturing process.

4.3.7 Testing

We started testing the BMS and we will test the cells, confirming the statements of the manufacturers and our simulations: This includes

- Capacity Testing: Measuring the total amount of charge a battery. We will identify outliers and not use them for the battery pack, but as spare ones.
- Voltage Testing: Measuring the voltage under load and no-load conditions, in comparison to the state of charge.
- Internal Resistance Testing: Measuring the resistance within the battery cells, observing high internal resistances that may indicate degradation or defects.
- Temperature Testing: Evaluating the battery's performance under different temperature conditions. We will include high temperature situations in this (<50C). Also, we will validate the temperature graphs we received from the manufacturer for the heat dissipation at 200A discharge, as well as our own simulations.

4.4 Safety and Risk Assesment

We will reduce the risks of the following events by the following to ensure the safety of the battery pack:

- HV System active without supervision from controllers: Emergency shutdown or HV device error shall disconnect the Accumulator Isolation Contactors and de-energize the HV system.

- Slight Overcurrent:A cell temperature and SoC based maximum current derating shall be implemented and communicated to the Traction Controller.
- Loss of Contact: Any loss of communication shall immediately trigger an emergency shutdown and bring the HV system to a safe state.
- Massive Overcurrent: A fuse will be installed in the line between the battery and the traction inverter.
- Insulation Error: LEDs that are visible through the shell will indicate closed connectors to the main battery pack as well as a positive (insulated) signal by the IMD and proper functioning of the low-voltage system.

4.5 Power Electronics

4.5.1 Overview

The power electronics of the Fermion comprises the following subsystems:

- Traction Inverter
- Precharge and Discharge circuits
- Insulation Monitoring Device
- MSD

Main requirements and design constraints

Our general design of this season is inspired by conventional modes of transportation, as we have not had the capacity to start developing a levitation system by this season Thus, we focussed on an electrical system that drives our friction-based motor with a high amount of acceleration, which is a problem that railway systems frequently face.

In between design and production phase, we received a sponsorship of Leadrive, a local startup for research on automotive power electronics. Therefore, our workload was eased, which turned out to be favorable because of our lack of team members in the electrical field. This has been a crucial constraint in the design and planning process of the electrical department since the last season. Only shortly before submitting the ITD, we were able to make an estimation of realistic goals for the new team.

This year, we would like to set the path for magnetic levitation in the future, relying on an active system inside the vehicles. This was taken into consideration when designing the power dimensions, keeping plenty of overhead for the future, which aligns with our goal of sustainability. By having reusable modules, the design process of the upcoming years will be simplified.

4.5.2 Electrical and mechanical design process

Our initial goal was to design our own traction inverter system, both the control and power stages. After receiving the sponsorship with Leadrive, who also sponsors another student team in Aachen that we collaborate closely with, we decide to put our own, limited sources to other projects temporarily.
This means that we have a automotive inverter, with slightly overdimensioned specifications, to work with. The DC link capacitor of the inverter is charged externally.

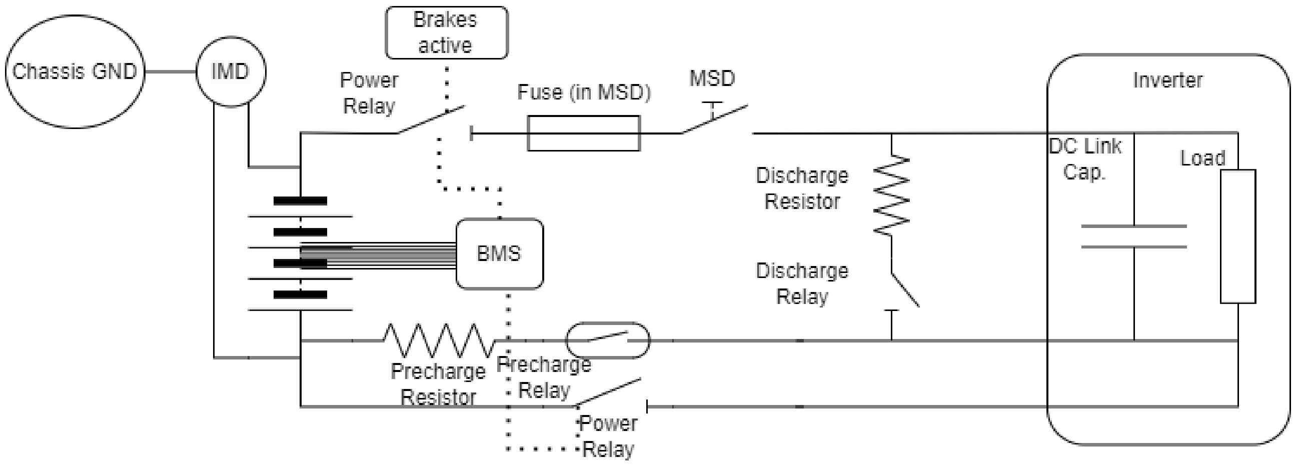


Figure 4.15: Schematic of our power electronics system

Precharge Circuit

The precharge circuit was based on an economic decision. Our pod is not made for a commercial purpose. Thus, fast pre-/discharge times are not highly prioritized. We designed with several different precharge resistors at levels from 50 Ohm to 10 kOhm, and simulated them. The results showed that the low-resistance circuits need very high-power components, which will dissipate a lot of heat and be a potential safety danger. However, we wanted to keep the charging times within reasonable times ($<$ 15 seconds), as well as the sizing. As the chassis-mounted precharge resistors rated at 50W were considerably smaller than at 100W, we chose to use them.
Deriving from Ohm's law by using the formula for power $P = U * I$, we get the equation $R = \frac{U^2}{P} = \frac{500V*500V}{50W} = 5000\Omega$. Simulating the circuit yielded favorable results. We simulated leaving both relays open for 2 seconds, then charging the capacitor with a 5k resistor for 8 seconds, then switching to the main power line by opening the respective relays. Due to financial reasons (due to the lack of available 5k resistors), we changed the value to 4.7k, which gave us many more favorable candidates. A quick estimation with $\sqrt{R*P} = \sqrt{4700\Omega * 50W} = 484.77V$ shows that this is still above our nominal voltage. Furthermore, we chose a resistor that can handle overpower for short amount of times (refer to final system description). At all time, the power ratings were abided as seen in the chart.
The objects of the simulation are as follows:

- C1: DC Link Capacitor
- R1: Precharge Resistor
- V2: Battery
- S1: Precharge Relay
- n003: positive wire of capacitor
- V(N003,N002)*I(R1): Power through the resistor
- V(N003)*I(C1): Power through the capacitor
- V(N002)*I(V2): Power through the battery

This gives us the following specifications of our precharge circuit:

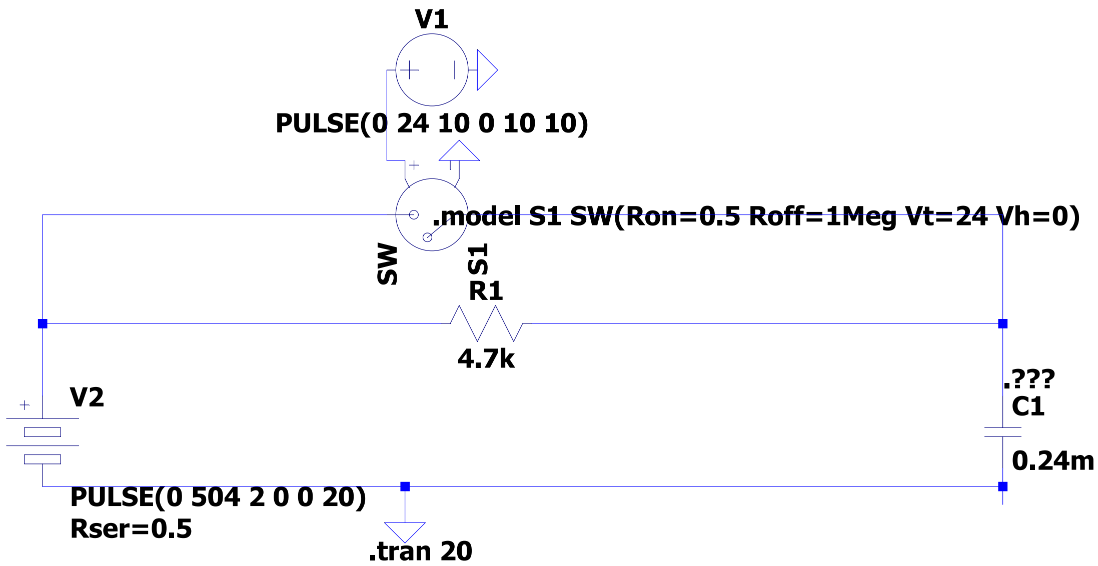


Figure 4.16: Precharge Circuit Schematic with 4.7k Resistor

- Time Constant (τ):

$$\tau = R \times C = 4700\,\Omega \times 0.24 \times 10^{-3}\,\mathrm{F} = 1.128\,\mathrm{s}$$

- Voltage across the capacitor at $t = 8$ seconds:

$$V(8) = 504 \times \left(1 - e^{-\frac{8}{1.128}}\right) = 503.58V, \Delta V = 0.42V$$

In our simulations, we see that the power through the circuit when switching to the main valve at t = 10s is not higher than 35 Watts, which is perfectly acceptable.

Discharge Circuit

It is convenient and advantegeous to use a discharge circuit when shutting of the system, tackling the safety hazard of a charged HV DC Link capacitor. We use the same resistor to discharge the capacitor. The power through the resistor is $\frac{444V^2}{4700\Omega} = 42W$, even with the maximum power, it is $\frac{504V^2}{4700\Omega} = 54W$, which the resistor can tolerate according to its data sheet. The time constant is $\tau = 4.7k\Omega \times 0.24 \times 10^{-3}\,\mathrm{F} = 1.128s$. This means that the capacitor is discharged to 1% of its voltage after 12 seconds. This is acceptable and in accordance with the recommendation of the producing company, Leadrive, who suggests a minimum of 4 seconds.

Present Schematics or logic diagrams of the boards.

We are not allowed to disclose information about the traction inverter, as it is an OEM product. We will treat it like a black box device. The same goes for the insulation monitoring device.

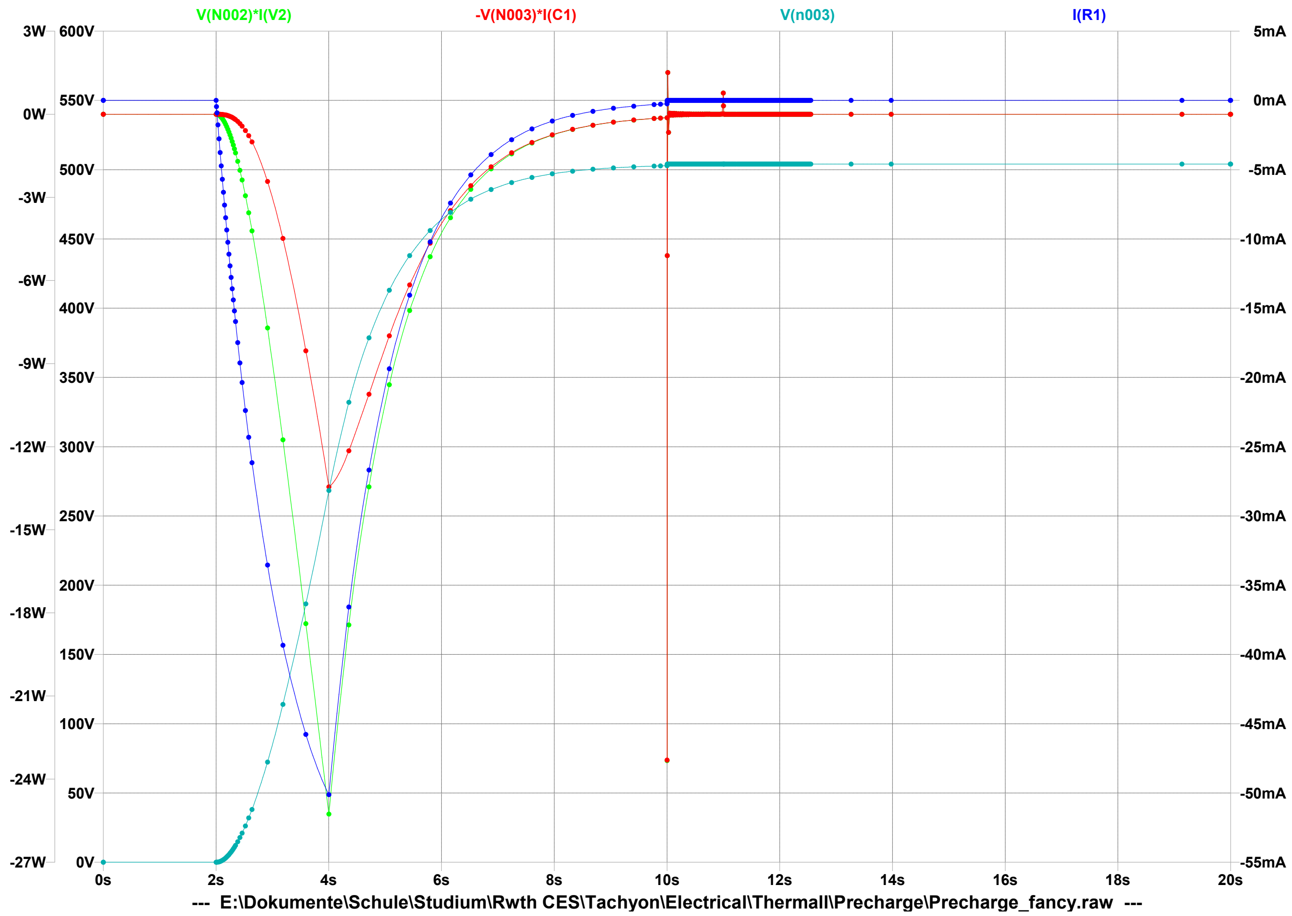


Figure 4.17: Precharge Circuit Simulation with 4.7k Resistor

(b) Present temperature simulations for vacuum conditions.

For our heat simulations, we used the software of ANSYS. By vacuum conditions, we assumed the lack of gas flow, which eliminates the cooling heat flow from winds. The simulation tool solves the heat transfer equation $\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$ by discretizing through Finite-Element-Methods.

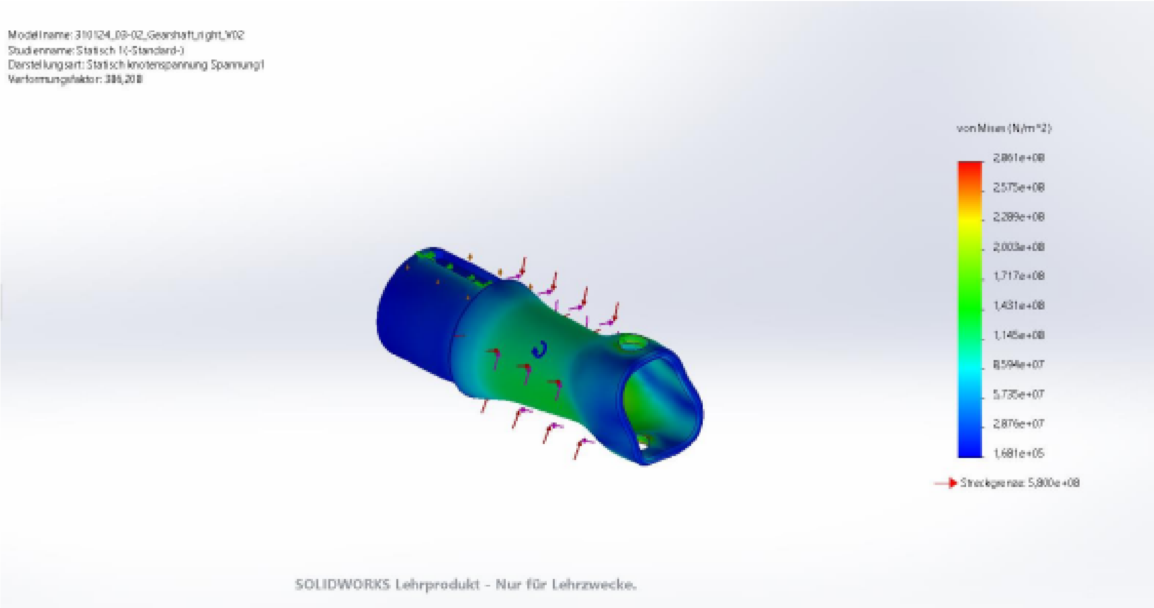


Figure 4.18: Simulation results

4.5.3 Description of subsystem control

(a) Briefly reference the control systems of the boards, which should be explained in the levitation or propulsion subsection respectively.

The precharge and discharge circuits are controlled via the relays. That is possible throough the Raspberry Pi 4 of the telemetry system, which also handles the CAN communication with the inverter of Leadrive. Furthermore, the HV relays are controlled by the Brakes controller to prevent braking and propelling at the same time. This is possible as we release the brakes by giving a constant power to the valves. At the same time, this will be required to close the relays.

4.5.4 Electrical system characteristics

Parameter	**MIN**	**NOM**	**MAX**	**Unit**	**Conditions**
Ambient Temp. for Operation (T_{AMB})	-40	-	90	°C	-
Ambient Temp. for Storage (T_{STO})	-40	-	85	°C	-
Relative Humidity	0	-	95	%	-
Flow Rate of Coolant (V_{CLNT})	8	12	16	l/min	Derating @ 8 $\sim$ 12 l/min
Inlet Temp. of Coolant (T_{CLNT})	-40	-	85	°C	Derating @ 65 $\sim$ 85°C
Cooling Inlet Pressure (P_{INLET})	-	-	2.5	bar	-
Pressure Drop between Cooling Inlet and Outlet (P_{DROP})	-	0.25	-	bar	$T_{\text{CLNT}} = 65°C$, $V_{\text{CLNT}} = 12$ l/min
Input Voltage (V_{DC})	260	600	850	V	Full operation @ $450 - 800$V
Input Current (I_{DC})	-	200	-	A	Continuous
Peak Input Current (I_{DCPK})	-	300	-	A	For max t_{PK} duration
Output Voltage (V_{AC})	-	400	-	Vrms	-
Output Current (I_{AC})	-	-	200	Arms	Continuous
Peak Output Current (I_{ACPK})	-	-	300	Arms	For max t_{PK} duration
Output Power (S_{AC})	-	135	-	kVA	Continuous
Peak Output Power (S_{ACPK})	-	200	-	-	For max t_{PK} duration
Peak Duration (t_{PK})	-	-	60	s	-
Input Voltage for Control (V_{BAT})	6	-	36	V	Full functional @ $8 - 32$V (control board)
Max. Efficiency (η)	97	-	-	%	-
Torque Control Accuracy (ϵ_{TRQ})	-	-	3	%	Torque $>$ 100Nm
	-	-	3	Nm	Torque $<$ 100Nm
Torque Control Speed (t_{TRQ})	-	-	100	ms	-
Speed Control Accuracy (ϵ_{SPD})	-	-	30	rpm	-

Table 4.13: 800V Single Inverter Specifications

4.5.5 Interface with other system

(a) Briefly reference the communication protocols or control mechanisms of the boards, which should be explained in the respective Sense and Control subsection.
All the electric subsystems are located within the pod.

The phsyical connection matrix is as following:

From | To	LV Battery	HV Battery	BMS	Traction Inverter	Motor	Cooling System
LV Battery	-	-	Powers	Powers control system	-	Powers pump and control system
HV Battery	-	-	Connects to	Provides power	-	-
BMS	-	-	Controls	-	-	-
Traction Inverter	-	-	-	-	Propels	X
Motor	-	-	-	-	-	-
Cooling System	-	-	-	Cooling	Cooling	Cooling (implicitly)

Table 4.14: Physical connection matrix

The data connection matrix is as following. All communication between boards are via CAN, if not specified otherwise:

From \ To	LV Battery	HV Battery	BMS	Traction Inverter	Motor	Cooling System	Brakes Controller	Telemetry Unit
LV Battery	-	-	-	-	-	-	-	-
HV Battery	-	-	Discharge rate, voltage level	-	-	-	-	-
BMS	controls	controls	-	-	-	-	-	sends data
Traction Inverter	-	-	-	-	-	-	-	sends data
Motor	-	-	-	-	-	-	-	-
Cooling System	-	-	-	-	-	-	-	sends data
Brakes Controller	-	-	-	-	-	-	-	sends data
Telemetry Unit	-	-	updates limits	sends commands	-	sends target rates	sends commands	-

Table 4.15: Data connection matrix

4.5.6 Final system description

Precharge and Discharge Circuit

We have a precharge circuit and discharge circuit for the DC Link Capacitor during the startup/shutdown phase to deal with the empty/charged capacitor. The design can be seen in this figure from above. We utilize the following relay: KT24-1A-40L-THT from Meder electronic and the following resistor WH50-4K7JI from TT Electronics. The circuits will be integrated into the battery casing. It shall be avoided that the discharge relay is activated while the HV relay connections are closed.

Parameter	Value
Model	WH50-4K7JI
Company	TT Electronics
Power Rating at 25°C	50 W
Resistance Range	4.7K Ohms
TCR (-55° to 200°C) for 10R	±25 ppm/°C
Resistance Tolerance Options	±5%
Isolation Voltage	3000 V DC or AC peak
Operating Temperature Range	-55 to +250°C

Table 4.16: Precharge (and Discharge) Resistor Specifications

Parameter	Min	Typ	Max	Unit
Coil Resistance	1.620	1.800	1.980	Ohm
Coil Voltage		24		VDC
Rated Power		320		mW
Thermal Resistance		80		K/W
Inductance		430		mH
Pull-In Voltage				VDC
Drop-Out Voltage	2.9		16	VDC
Contact Rating			100	mA
Switching Voltage			1.000	V
Switching Current			1	A
Carry Current			2.5	A
Contact Resistance Static		150	200	mOhm
Contact Resistance Dynamic				mOhm
Insulation Resistance	10			GOhm
Breakdown Voltage (40-50 AT)	3			kV DC
Capacitance			0.5	pF
Dielectric Strength Coil/Contact			7	KV DC
Dielectric Strength Contact/Contact		1.2		KV DC

Table 4.17: Precharge/Discharge Relay Specifications

Insulation Monitoring Device

The Insulation Monitoring Device that is mandatory for EHW participants, as well as Formula Students teams, is not built inhouse, after receiving the respective advice from the EHW technical jury. By reaching out to Bender, we received their device (Bender A-ISOMETER ® iso-F1 IR155-3204) through their Formula Students program. This device was approved for the FSE competitions. It is configured for a responding insulation resistance value of 500 kOhm between HV+ and Chassis, and between HV- and Chassis, following the guidance of approx. $500\frac{\Omega}{V}$. This takes into account that we might increase the dimension of our system in future designs. The calculation takes place with a DCP factor of 10, meaning that the detection value is calculated out of the mean of 10 measurements, which was suggested by the manufacturer.
Furthermore, we have the IMD set to detect undervoltage at 400V, which helps us do detect serious malfunctioning. This is a redundant feature that is also handled by the BMS. We do not expect our battery pack to ever fall under 400V.
The device is certified according to ISO16750. It will trigger a LED when there is no leak. Furthermore, we will read its outputs, which are a PWM signal, and a status binary output showing the proper working. Both the duty cycle and the frequency of the PWM contain relevant information. Both outputs furthermore require 2.2kOhm pull-down resistors.
The insulation monitoring device will measure directly from the high voltage battery pack output. We assume that the highest risk of leaks is at the output of the battery pack, as it is self-built, and not completely closed. Furthermore, it poses the greatest danger. The inverter might have a leak too. If it is connected to the battery, the IMD will detect the leak as well. If not, the (passive) discharge of the DC link capacitor would slowly reduce the risk.

Table 4.18: Insulation Monitoring Device Specifications

Parameter	Specification
Protective separation	Between (L+/L-) – (Kl. 31, Kl. 15, etc.)
Voltage test	AC 3500 V/1 min
Supply voltage U_S	DC 10 V...36 V
Max. operating current I_S	150 mA
Max. current I_k	2 A
Inrush current	6 A/2 ms
HV voltage range (L+/L-) U_n	DC 0 V...1000 V
Power consumption	$<$ 2 W
Response value hysteresis (DCP)	25 %
Response value R_{an}	100 kΩ...1 MΩ
Undervoltage detection	0 V...500 V
Load dump protection (-32xx)	$<$ 60 V
Measurement method	Bender-DCP technology
Factor averaging F_{ave} (output M)	10
ESD protection, contact discharge	10 kV (to terminals)
ESD protection, contact discharge	25 kV (indirectly to environment)
ESD protection (air discharge – handling of the PCB)	6 kV

Protections

MSD: We buy the manual safety disconnect from Amphenol (Amphenol MSDM6302 + Amphenol MSDF000R). This MSD can be opened without removing any parts of the Fermion as it is accesible by opening a lid of the shell. It can be opened with one hand - but only manually - and is rated for a temperature between -40°C and 70°C. There is a fuse built in the MSD. It is rated for 630A and 690V. The manufacturer recommends that the current be a third of the rated fuse current, which is $630A/3 = 210A$. [4]

Relays: We use one contactor at each side to open the poles of the High Voltage battery pack, controlled both by BMS and braking system. The ratings are well above our power limits.

Reverse polarity connection: The HV-IPT cables and connectors come from automotive standards and are rated for well above our power limits. Also, they are asymmetic, so that a reverse polarity connection is avoided.

4.5.7 Manufacturing process

Parts List:

High Voltage Interlock:

Cabling: The high voltage cables are all orange, and will be marked differently for high and low sides. We have the following

[4] Product Sheet EXCEL|MATE MSD Manual Service Disconnect, Amphenol PCD Shenzhen

Component	Company/Product Name	Quantity	Mass [kg]	Size [mm]	In-house/ out-sourced	Nominal Voltage
Inverter	Leadrive EV0019	x1	9	300 × 300 × 100	Bought	660
Cable AC	TE Connectivity	x3	0.5	-	Outsourced	1000
Cable DC	TE Connectivity	x2	0.5	-	Outsourced	1000
Connector AC	TE Connectivity	x6	0.5	-	Outsourced	1000
Connector DC	TE Connectivity	x4	0.5	-	Outsourced	1000
IMD	Bender IR155-3204	x1	0.2	140x60x15	Bought	1000
MSD Plug	Amphenol MSD6302	x1	0.6	106x104x100	Bought	690
MSD Receptacle	Amphenol MSDF000F	x1	0.1	-	Bought	690
Relay	MEDER KT24-1A-40L-THT	x3	0.1	10x3x13	Bought	24/1000
Contactor	Gigavac GV200	x2	0.4	73x80x56	Bought	24/800
Pre-/Discharge Resistor	TT Elec. WH50-4K7JI	x2	0.04	73 x 51 x 17	Bought	500

Table 4.19: Parts List - Power Electronics

PCBs

Our PCB Design follows the requirements of the printing company, which is either a prototype machine in the FabLab of our university, or JLCPCB, or Würth Elektronik. They are designed in Altium Designer, which checkes automatically for some errors.

Prototyping: Prototype PCBs are fabricated in the FabLab associated with our university. The FabLab provides access to PCB manufacturing equipment and materials, enabling the rapid production of prototypes for initial testing and design validation. Once the PCBs are fabricated, they are assembled manually by our team members.

Production: We ordered our final PCBs from JLCPCB, a leading PCB manufacturing service. In addition to JLCPCB, we also collaborate with Würth Elektronik who produce PCBs in Germany, aligning with our goal of sustainability.

Inverter

The inverter is a product from Leadrive used as an OEM product in automotive and mobility industry.

Support from Leadrive: The development of the inverter system is supported by Leadrive, a company specializing in advanced inverter technology. Their expertise significantly contributes to the optimization of our propulsion system. Collaboration with Formula Student Team of FH Aachen: Additionally, we collaborate with the Formula Student Team of FH Aachen, benefiting from their practical experience in electric vehicle design and inverter application. This partnership enriches our project with valuable insights into inverter integration and performance enhancement.

4.5.8 Testing

We started testing software.

4.6 Sensing and Control

4.6.1 Overview

Our S&C subsystem consists of :

- Control Boards:
  - Braking Controller
  - Thermal (Cooling) Controller
  - Telemetry Controller
- Telemetry Device:
  - CAN Bus
  - Telemetry Transceiver
  - Network Transceiver
  - GUI/Logging system

In this section, the main components of the sensor network and software architecture shall be described, as well as their basic functionality. A special focus shall be made on how safety mechanisms are implemented in these systems. Extensive design descriptions are expected for, if applicable:

4.6.2 Control Boards

Introduction

Overview of all control boards (Brakes, Thermal, Telemetry):

- Brakes Controller:
  The brakes board controls the pod's friction braking system. It drives the solenoid valves that are connected to the braking mechanisms. The board's design engage the brakes by default for safety, releasing them only when all safety criteria are met, which come from the sensors and user commands. It utilizes a Texas Instrument C2000 series microcontroller.

- Thermal (Cooling) Controller: The thermal board drives the coolant pump via a PWM to a MOSFET bridge, adjusting the pump speed based on the feedback from temperature and flowrate sensors in the cooling loop. The system design also includes continuous monitoring of temperatures at multiple (critical) areas of the Fermion to detect overheating.

- Telemetry Controller: The telemetry board is the pod's communication system, facilitating bidirectional data exchange between the pod and the user device, typically a laptop. It is responsible for sending commands to the pod and receiving diagnostic and sensor information in return. The system uses the CAN bus for communication in the pod.

Our Sense&Control system includes three main boards:
For the Braking Managament System **TO BE ADDED**
The Thermal Management Controller is responsible for cooling the Traction Components, i.e., Motor and Traction Controller. The actuator is the coolant pump which is controlled with the feedback of the temperature of coolant in the cooling loop (Refer to Diagram for Visualisation). The Pump Speed is controlled via PWM to the MOSFET Bridge. The PWM duty cycle is simply calculated from a lookup table that is referenced to the temperature difference between target and actual temperatures. The only safety feature to be developed is to issue an emergency stop signal to HV Systems in the event the coolant temperature exceeds a critical temperature.
Finally, the Telemetry Unit is responsible for receiving commands from, and transmitting diagnostic and sensor information to the commanding PC. The Telemetry unit then receives and broadcasts information as well as commands on the CAN bus as a Master Controller to all the slave devices.
Diagram with the connection of all boards with NAP and control station:

The telemetry system connects to a Network Access Point, which is the Rocket M2 as proposed by EHW. It transfers to the control station, which will be a team member's commanding PC (user device).

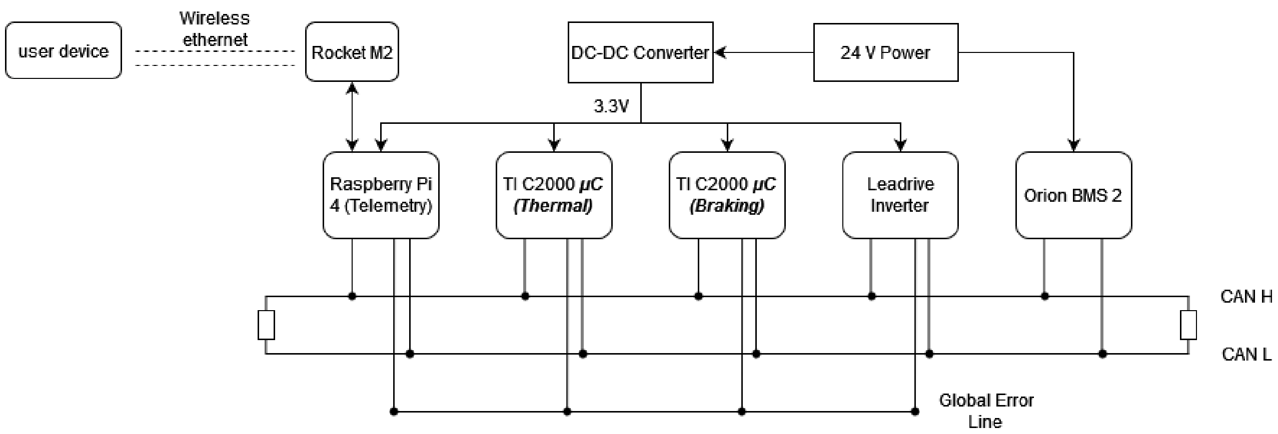


Figure 4.19: Overall Structure of the Telemetry System

The implementation of the hardware architecture goes as follows:

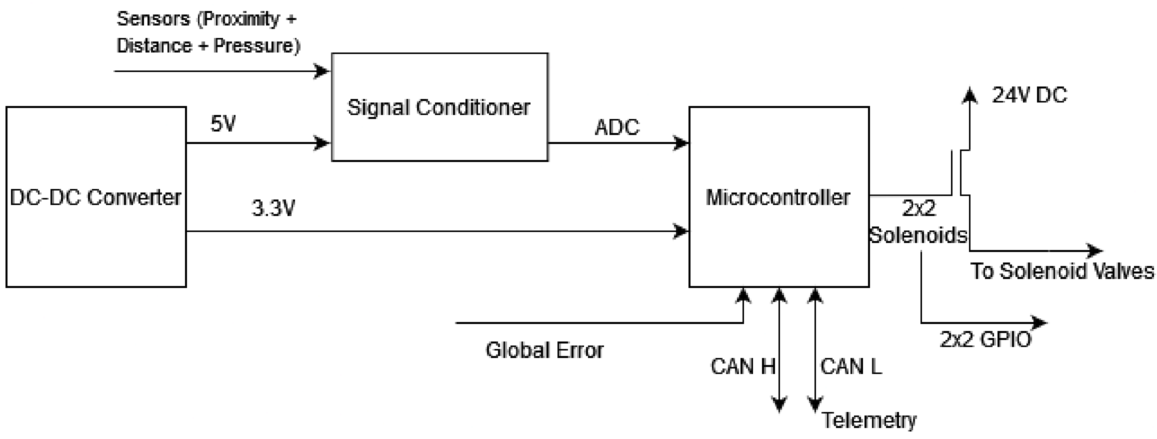


Figure 4.20: Brakes Controller Schematic

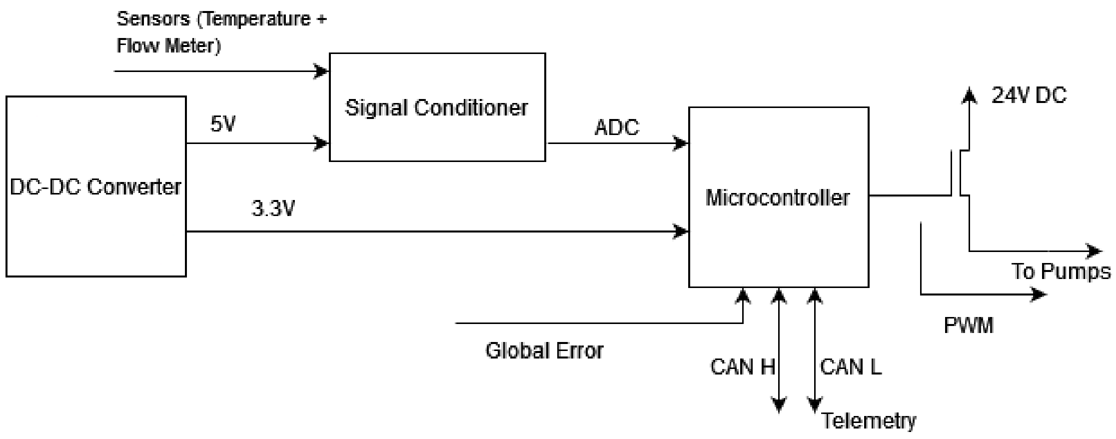


Figure 4.21: Thermal Controller Schematic

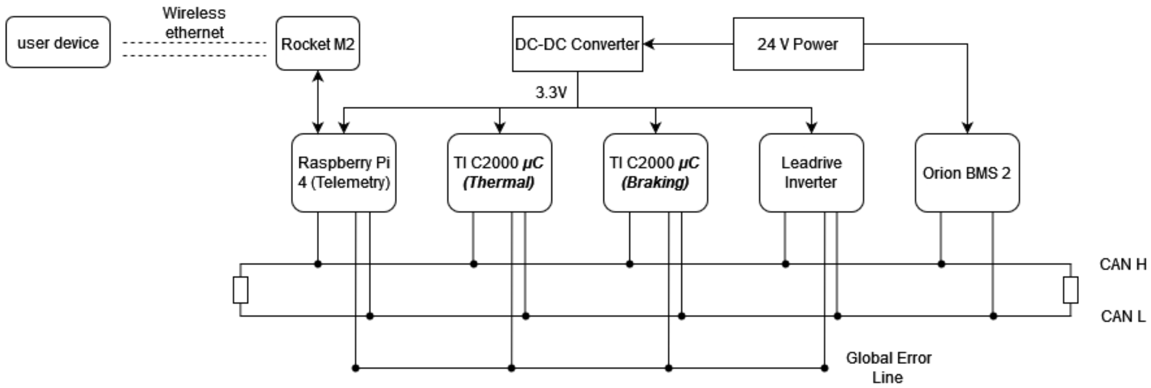


Figure 4.22: Telemetry Unit Hardware Architecture

Communication protocols used:

- Control Area Network (CAN): CAN was implemented as the inter-board communication protocol. This decision is inspired by the automotive industry, where CAN has been used for decades as a robust and physically reliable protocol. To add to that, many of our OEM devices (only) support CAN communication. CAN Description.

- TCP/IP: Used to transmit data between the Telemetry Unit and command PC. We transmit wirelessly via UDP between the Rocket M2 and the command PC.
- Serial Peripheral Interface (SPI):
- Inter-Integrated Circuit (I2C): Multi-device communication protocol used for connecting sensors. Uses Master-Slave-Architecture.

4.6.3 State Machine of the Vehicle

We use different states in each component. Generally (and in the main control of the pod), we have the following structure of states:

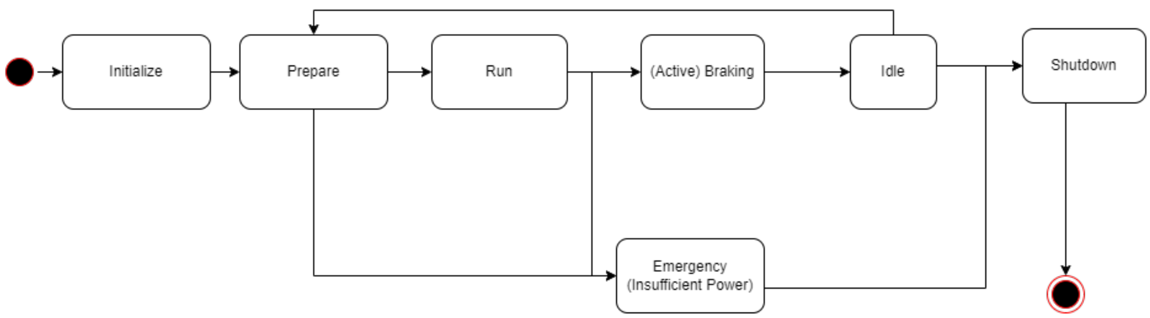


Figure 4.23: Overall State Chart

Because of layout reasons, we decided to give the transitions and actions seperately:

- Transitions requires:
  - Initialize:
    * Prepare: When all systems have been powered on. Controllers automatically enter this state.
  - Prepare:
    * Emergency: Run conditions not met, which may be
      · Insufficient initial Brake Pressure
      · Overheat
      · IMD trigger
      · Global Error Line Trigger
      · Undervoltage
      · Manual Interruption
    * Run: Prepare finished without incidents.
  - Run:
    * Emergency: Safety hazard, such as
      · Insufficient Brake Pressure/Pressure Leak
      · Overheat
      · IMD trigger
      · Undervoltage
      · Global Error Line Trigger
      · Manual emergency

- Braking:
  - Idle:
    - Speed = Zero
- Idle:
  - Prepare:
    - Manual decision
    - Requires: No emergency condition
  - Shutdown:
    - DC Link almost discharged
    - Speed = Zero
- Emergency:
  - Shutdown:
    - Safe shutdown conditions
    - DC Link almost discharged
    - Speed = Zero

4.6.4 Code Architecture and Class Diagram

For each system respectively was the following software architecture implemented: Concerning the rulebook, we point out that the brakes controller checks for air pressure before and during running, while the thermal system checks for overtemperature, especially when temperatures are increasing. However, our simulations show that this is very unlikely to happen.

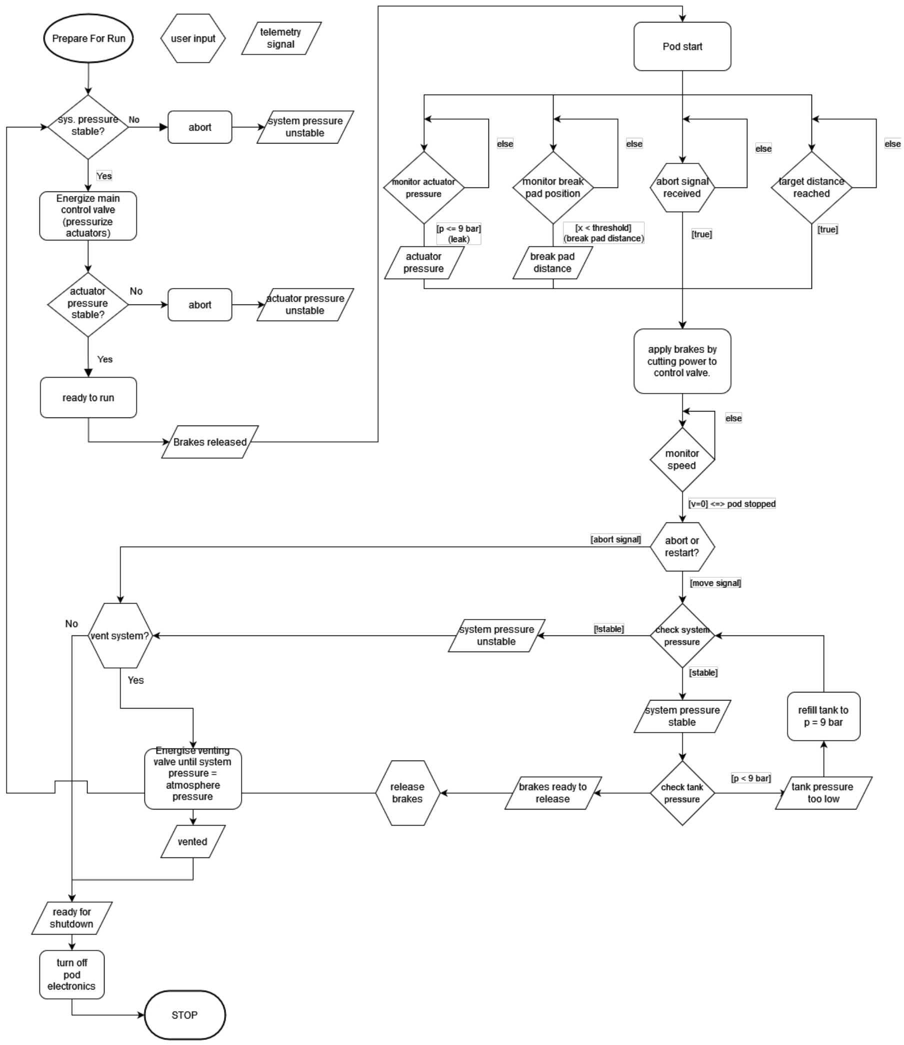


Figure 4.24: Brakes System Software Architecture

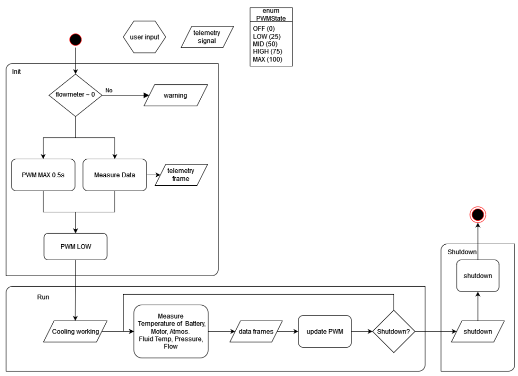


Figure 4.25: Thermal System Software Architecture

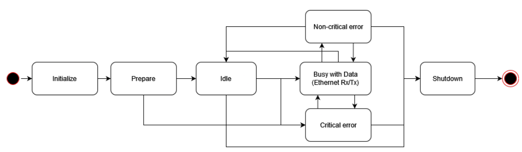


Figure 4.26: Telemetry Unit Software Architecture

4.6.5 Control Boards/Units in the Vehicle

1. Brakes Controller

   (a) Requirements of the board. Parts List: The complete part list can be found in this table.

Component	Company/Product Name	Quantity	Mass [kg]	Size [mm]	Producer	Nominal Voltage
NTC Thermistor	Vishay NT-CLE413E2103F102L	x40	0.03	1000 x 3 x 3	Outsourced	500
Coolant Pump	Pierburg	1	1	-	Sponsored	12
Speed Sensor	Festo	x2	0.01	-	Sponsored	12

Table 4.20: Outline of Components of the Thermal Controller

   (b) Hardware Rationale (HW design and concerns).
   Critical points: Safety. The brakes should engage by default, and only release when all safety criteria are met. The board should be designed to be fail-safe, and process information and requests quickly. Our brakes controller's hardware design documentation is uploaded (non-publicly) online, to view for the reader. We show only the schematic here.

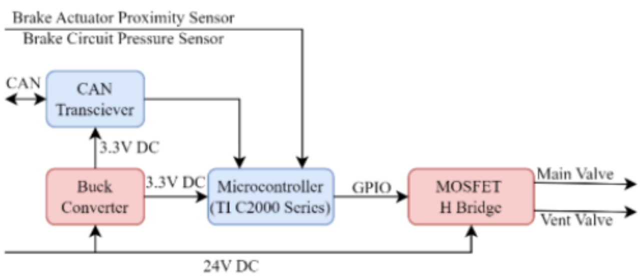


Figure 4.27: Brakes Controller Hardware Schematic

   (c) Firmware Rationale (Internal State machine and design concerns). No stuck loops. Real-life transport scenario: Re-release of brakes is possible.
   What concerns the state flow of the system, it can be described as follows:

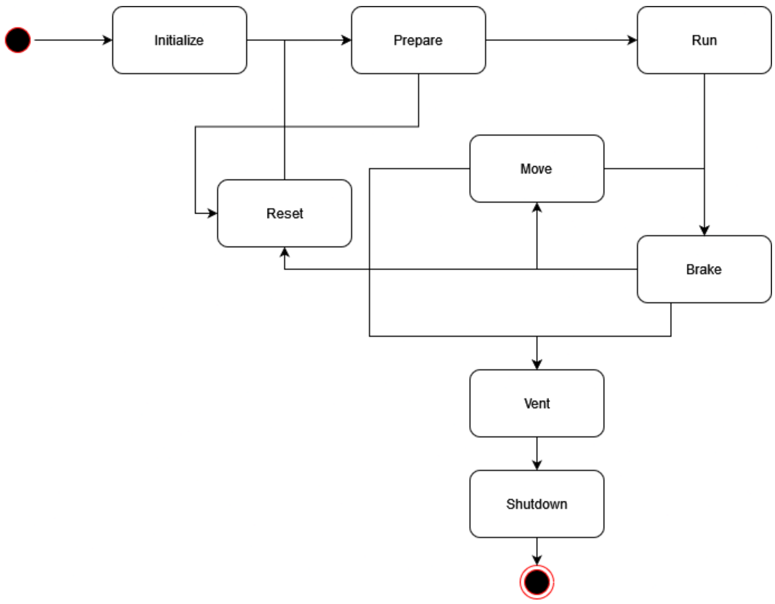


Figure 4.28: Brakes Controller Internal State Machine

(d) Testing and validation plan.

2. Thermal Controller

(a) Requirements of the board.
Should drive the coolant pump. The control algorithm, planned as a PID controller, is to be implemented, but not necessary. We can let the thermal system run on a on-off scheme, which is less effective, but easier.

Component	Company/Product Name	Quantity	Mass [kg]	Size [mm]	Producer	Nominal Voltage
Microcontroller	Texas Instruments F280039C	1	-	-	-	-
Multiplexer	Texas Instruments	8	-	-	-	-
NTC Thermistor	Vishay NTCLE413E2103F102L	x40	0.03	1000 x 3 x 3	Outsourced	500
Coolant Pump	Pierburg	1	1	-	Sponsored	12
Speed Sensor	Festo	x2	0.01	-	Sponsored	12
Heat Conductors Muster	Würth	2	-	-	-	-

Table 4.21: Components of the Telemetry Controller

(b) Hardware Rationale (HW design and concerns). Simplicity. The brakes controller design was big. The thermal controller is mainly gathering sensor data, such as temperature sensors, and flow rate, and controlling the pump. The pump is a simple on-off device, and the (fine) temperature control is not critical. We set that

50 C shall not be exceeded in the batteries (which is not cooled by the liquid cooling system), while traction inverter and motor shall stay under 60 C. If we require a fan for the battery, it will be controlled by the BMS.

(c) Firmware Rationale (Internal State machine and design concerns).

(d) Testing and validation plan.

- Test maximum volume (mass transfer) power of pump.
- The temperature sensors should be tested for their accuracy and deviance.
- The control algorithm should be tested for its effectiveness, and delay due to mechanical and thermodynamical factors.
- Test flow system sensors for accuracy and deviance.
- Test maximum cooling power of pump. This testing scenario will not be used during the competition.

3. Telemetry Controller

(a) Requirements of the board. Parts Lists

Part	Manufacturer	Description
Raspberry Pi Zero 2 W	Raspberry	Microcontroller for telemetry
Raspberry Pi 4 B	Raspberry	Computer for telemetry
MC3479	Memsic	3-Axis Accelerometer
RS485 CAN HAT	Waveshare	CAN adapter for RPI4B

Table 4.22: Telemetry System Parts List

(b) Hardware Rationale (HW design and concerns).

(c) Firmware Rationale (Internal State machine and design concerns). The design concerns were:

- Process data transmission from CAN line to the GUI in the user device. CAN bus simulations with CANoe have shown that the transmission speed is sufficient to not to stall the line. The data is transmitted more often than at 2 Hz.
- Process command transmission to the CAN line from the GUI in the user device in less then 100ms. With measuring transmission speeds of 10ms, this is not a concern.
- The system should be able to handle the data from the sensors and the commands from the user.

The state flow of the thermal system can be described as such:

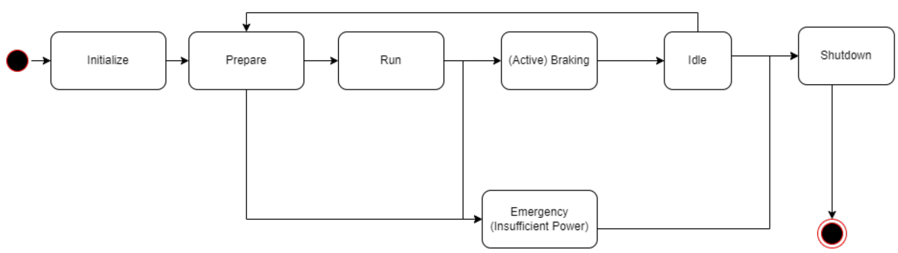


Figure 4.29: Thermal Controller Internal State Machine

(d) Testing and validation plan.

4.6.6 Communication and Navigation

Communication

For communication, we use our telemetry system, transmitting bidirectionally telemetry data and commands to the pod. The telemetry system uses the CAN bus, which is a robust and reliable protocol that will not be explained further, presuming that the reader is already familiar with it.
The VCU, in this sense, is a Raspberry Pi 4B, which is connected to the CAN bus via a RS485 CAN HAT. Through its connectivity abilities, we can connect to a Wireless LAN system for (necessary) remote control. We use the Rocket M2 as a transmitter. A short estimation of scales of speed between electromagnetic fields and the speed of common ground transportation modes show that we have not reached the speed where the Doppler effect of the signals play any significant role, so we do not take that into consideration. We use the open-source GUI system of Swissloop and plan to develop our own data logging system as an addition. The addition we plan to add to the GUI system are the following:

- (Cosmetic) adaption to the Fermion, including
  - the battery pack layout for both batteries
  - the thermal system data
  - acceleration data
  - check for abnormal situations (out of range values) and carrying out safety procedures, consisting of:
    - LV or HV Battery temperature or voltage out of range:
      - Go into emergency state and shutdown
    - Temperature in motor or inverter close (10C) to operational limit:
      - Set cooling pump to maximum. Limit current to inverter.
    - Temperature in motor or inverter over operational limit for more than 1 second:
      - Assuming that previous state has been reached already, cut power to HV.
    - Brakes pressure out of range:
      - To emergency.
    - Speed too high:
      - Apply brakes.
    - IMD leak:
      - To emergency. Proceed only with safety equipment (gloves, glasses, boots)
    - Latency of GUI too high/heartbeat missed:
      - After second time: Emergency
- Time Counter since start of run
- More informative audiovisual feedback

Navigation and Control

Our navigation system does not incorporate railway-like switches, nor GPS due to the track's short length. Instead, the pod solely uses an accelerometer and speed sensors to measure the velocities of both the front (guiding) wheel and the back (propulsion) wheel, determining the pod's dynamics. This also includes vibrations.

In this iteration, we have clearly defined competition rules, and hence stick to simple acceleration/velocity/distance curved. In the future, we plan to implement a more complex navigation system, including a system that can compute the acceleration/speed automatically, which is a more realistic use case.
Our sequence of the run is as follows:

- Start sequence:
  - Initialize:
    - Start Telemetry System
    - Start BMS
    - Start Cooling System at 0
    - Start Braking System
    - Send signal to GUI
  - Prepare:
    - Start Inverter (KL30)
    - Open precharge relay (5s)
    - Open HV relay
    - Close precharge relay
    - Every individual system checks preparations
- Run sequence:
  - Start Cooling System at 50
  - Release Brakes
  - Propel inverter to target speed
  - Wait for errors or stop signal
- Brake sequence = Decelerating = Emergency Braking:
  - Open precharge relay and HV relay and open valves (with same signal)
  - Wait until speed is zero
- Shutdown sequence:
  - HV relay is opened
  - Check:
    - Speed Zero
    - Acceleration next to zero
    - Brakes Vented
    - Thermal Pump down
  - Inverter shuts down (Turnoff KL30)
  - Brakes are shut down
  - BMS is shut down
  - Cooling system is shut down
  - Telemetry system is shut down

Design requirements

The Telemetry Devices possesses the following properties and constraints:

Constraint/Specification	Value
Operating Voltage	24 V
Mass	< 200 g
Budget	< 500 €
Range	0.2 Km LOS
Communication Frequency	2.4GHz

Table 4.23: Specification of the Telemetry Unit Constraints

To allow the correct transmission of information, the following CAN signals should be sent by the Telemetry unit to all the Slave devices:

Device	Command
Traction Controller	Target Speed or Torque
Battery Pack/Raspberry Pi4	Emergency Disconnect
Thermal Management System	Manual Pump Control
Brakes Controller	Brake Engage/Manual decision Command

Table 4.24: Devices and their commands

Device	Signal
All	Emergency / Error Messages
Traction Controller	Speed, Phase Currents, Inverter Module & Motor Temperature
Battery Pack	Pack Voltage, Pack Current, Cell Temperatures, SoC
Thermal Systems	Temperatures

Table 4.25: CAN signals received by the devices

All the above signals shall be transmitted to the command PC over wireless ethernet.

4.7 Additional considerations when writing the document for specific subsystems and sourcess

Sources:

- BMS System Reliability
- Insulation Monitoring Device