POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Master's Degree Thesis

Low Voltage System of an Electric Formula SAE racecar. From engineering to production and integration.

Supervisors

Prof. Andrea TONOLI

Dott. Stefano FAVELLI

Candidate

Luca BORSELLO

OCTOBER 2024

Summary

In electric vehicles, the high-voltage systems is usually powered by a battery between 300 and 800 Volts, while low voltage systems (below 60 V) handles essential functions of the vehicle like powering Electronic Control Units, communication and safety lines, and all other service loads.

This thesis wants to summarize the experience and knowledge built in the last two years of Squadra Corse, in Formula Student championship, regarding Low Voltage System and its vehicle integration. After a first theoretical part regarding the main related topics like communication protocols, components ratings and Electromagnetic Interferences, the thesis covers the system specifications and design, passing through the choice of components, until the actual production of the complete system.

Particular attention is given to the design workflow and, consequently, to the production methodology used to standardize procedures and, at the end, validate the process.

During the last racing season, a failure analysis has been conducted to collect data, with the aim of discovering recurrent failing patterns and improve the reliability of future Squadra Corse prototypes.

Moreover, a preliminary study is conducted on the major future updates of the system, like the integration of a HV DC/DC converter to replace Low Voltage battery, investigating the main reasons behind the choices and exploring the available solutions.

Acknowledgements

"Un ringraziamento alla mia famiglia e alle persone con cui ho condiviso questi anni"

Table of Contents

Chapter 1

Introduction

1.1 Context

Low Voltage System is the electrical network grouping every electronic on-board component for what concerns both power supply and communication.

With the diffusion of Electric Vehicles (EVs), electrical systems of cars started facing new challenges. At first, electrical insulation respect to High Voltage (HV) components becomes fundamental; moreover, design choices about groundings, filters and Electromagnetic Interference reduction methods can have big impact on the system's final reliability. New solutions are experimented by car manufacturers to supply and protect Low Voltage System (LVS). [1]

First EV models inherited the majority of LVS components from previous generation combustion cars, usually powered by a 12 V battery. This solution allowed compatibility with previous on-board accessory components like windows motors, On-Board ECUs, Air Conditioning Systems and other LVS loads. [2]

Nowadays, higher voltages in service components are more common, in fact some very powerful plants (like HVAC) are directly powered from Tractive System (TS) battery to maximize efficiency. [3]

Automotive Racing is also following this trend with weight and space constraints, given by tight spaces and extreme environments being further challenges for integration and insulation of HV components. Moreover, extensive research is conducted on communication protocols to improve performance and increase reliability of the data. [4]

1.2 Formula Student Electric

Formula SAE is an international university engineering design competition initially proposed by SAE International. It involves the design and production of a race car, which is evaluated through a series of tests based on its design quality and engineering efficiency.

Established in 1981, the competition was designed to provide university students with an opportunity to apply their academic knowledge in a practical, engaging, and competitive setting.
Today, it is held globally, with numerous annual events organized either by SAE directly or by various national associations of automotive engineers and technicians.

Since 2017, Formula Student Germany, active as an official German Formula SAE event since 2005, has introduced its own version of the competition, renaming it "Formula Student". This version is based on the same concept developed by SAE but includes some minor regulatory variations.

Squadra Corse is the team from Politecnico di Torino that every year accepts the ambitious challenge to build a Formula-style electric race car prototype from scratch.

The team was born in 2004 and produced its first combustion model in 2005, which is also the year of its first appearance in Formula SAE competitions.

Since 2012, Squadra Corse only produces electric prototypes, according to the message of sustainability carried on both by the team and the Politecnico di Torino itself.

Formula Student competitions consist in both static and dynamic events, preceded by severe technical inspections that aim to verify the prototype's compliance with competition rules:

- **Pre-Inspections:** Drivers' equipment is checked and egress tests are conducted. All drivers must be able to exit to the side of the vehicle in less than 5 seconds with the driver in the fully seated position, hands in the driving position on the connected steering wheel.
- **Accumulator Inspections:** The HV battery pack is opened and single modules are examined; the PDU is also accurately inspected until matching rules standards.
- **Electrical Inspections:** Rules compliance of LVS and HV components in the vehicle are checked; every electrical safety feature is tested.
- **Mechanical Inspections:** The monocoque, suspensions, aerodynamics and their concerning data sheets are examined by the officials.

- **Tilt Test:** The vehicle is placed upon the tilt table and to an angle of 60°. There must be no fluid leaks and all wheels must remain in contact with the tilt table surface.

- **Rain Test:** The vehicle must be in ready-to-race condition. The Tractive System (TS) must be active during the rain test. Water will be sprayed at the vehicle from any possible direction. The water spray is similar to a vehicle driving in rain and not a direct high-pressure stream of water. The test is passed if the vehicle stays on while water is sprayed at the vehicle for 120 seconds and 120 seconds after the water spray has stopped.

- **Brake Test:** Lock all four wheels and stop the vehicle in a straight line at the end of an acceleration run specified by the officials without stalling the engine. During this procedure, officials also check ready-to-race sound and TSAL (Tractive System Active Light) illumination levels.

Figure 1.1: Technical Inspections at Formula Student Germany

Once technical inspections are all cleared, a team can proceed and take part to the dynamic events, which are:

- **Acceleration:** A straight 75 meters long acceleration test with standing start.

- **Autocross:** The vehicle is timed on a defined route (max 1.5 km) which is different for each event.
- **Endurance:** This is the longest event, with 22 km of track where time and energy efficiency is considered for the final score.
- **Skidpad:** With the aim of measuring the cornering capabilities of the vehicle completing one left hand and one right hand circle.

Also fundamental for the team's final score, static events are:

- **Engineering Design:** Each team must present a book with design choices about construction and assembly, from chassis to electronics, and defend their processes with judges from the industry.
- **Cost and Manufacturing:** Since usually race cars are very expensive, cost efficiency is measured in this event, both for bought and custom-made components.
- **Business Plan Presentation:** A team-related business plan is presented to demonstrate the possible economic profitability of the project.

Figure 1.2: SC24 at Formula SAE Italy 2024

At the end of competition, scoreboards are presented both for single events and for the overall classification.

Speaking about competition rules, these are very strict and mostly safety related.

The most recognizable safety device is the TSAL. Each model must have one, and its purpose is to indicate the state of the vehicle. In particular, a red flashing light must be present when the Tractive Sysem is activated, while a green light indicates that the vehicle is electrically safe. Both circuits are strictly regulated in competition rules. [5]

1.3 Motivation

Low Voltage System was often a source of reliability issues in Squadra Corse prototypes, hence the need of a study regarding a new design and production methodology to produce a complete new system from scratch.

Moreover, a full season gave the possibility to follow the whole process from the design to actual everyday usage.

Particularly, the documentation process and data collection were considered fundamental to track and understand errors, build internal knowledge about the products present in the market and to be able to evaluate different approaches to Formula Student challenges.

The target was the creation of standardized procedures for design and, specially, LVS manufacturing phases, to be able to track failures and to address them to specific points of the whole processes, allowing improvements on next iterations.

This thesis wants to be used as a starting point for future works regarding LV components and their modelling.

These works will be, at the end, the backbone of the design event, where the choice of every component in the model must be justified with calculations and motivations.

1.4 Thesis Outline

The thesis starts with an introduction to the general structure of an EV and, more specifically, of the SC24 prototype. Then, in the following section, the theory behind the main concepts topics to LVS design is presented with concepts like communication protocols and their physical implementations, linked to component ratings for usage in an Electric Vehicle.

In Chapter 3, a brief introduction to every component of SC24 LVS is followed by a description of the design and production processes. Documentation of standardized procedures is then presented.

In Chapter 4, production metrics are presented and a failure analysis on the system is conducted. Here the goal was to prepare the basis for a new iteration of design, describing the production timing and tools, while listing and analyzing all failures to find common root causes.

Conclusion and future works are discussed in Chapter 5.

Chapter 2

Background

2.1 Powertrain Architecture of SC24

BEVs are vehicles that use only the energy stored in a High Voltage battery pack to power the drivetrain. The battery pack is connected to inverters, which are responsible for driving the motors.

SC24 is a prototype race car that reenters in the BEVs category. The general structure of the powertrain is similar to commercial EVs, but there are some differences due to competition rules.

The powertrain is composed by a custom High Voltage battery pack and by AMK Formula Student racing kit for what concerns inverters and motors.

The HV Battery pack reaches 574 V maximum and has a 132 series 2 parallel configuration (132s2p). It is composed by Melasta pouch cells with 3.7 V nominal voltage. The pack provides 7.5 kWh nominal energy in total.

The AMK kit is composed by four 35 kWp 21 Nm peak motors that, in our case, are in-wheel motors. These electrical machines are liquid-cooled Synchronous-Reluctance with 5 poles pairs that go up to 20000 rpms. [6]

The four motors are driven by four inverters, included with the AMK kit, that have been repacked in a more compact and monocoque-friendly shape. This enclosure also allows the cooling of the power boards (inverter HV boards) with a metal coldplate connected to a liquid cooling circuit shared with the motors. The inverter assembly is placed beside the front of the battery pack, just behind the seat.

HV lines, which are orange according to regulations as they carry more than 60 V (see 2.2), count the HV+ and HV- lines and the four motor connection cables (from inverter to motors), which run on the inner side of the car.

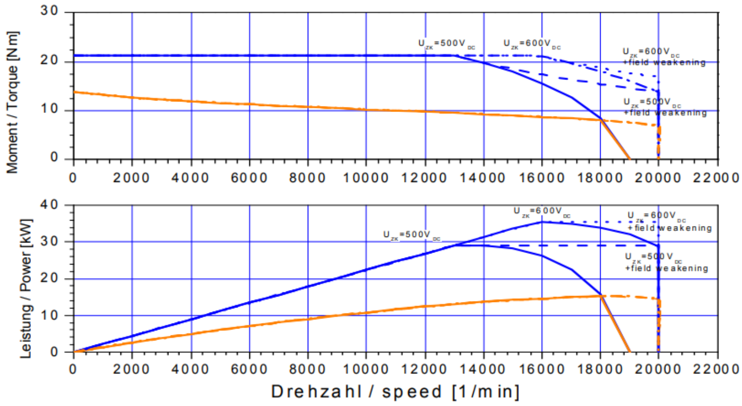

Figure 2.1: AMK Motor Characteristic

HV+ line goes directly from the TSAC to the inverter case, while HV- line enters the so called "derivation box", where the High Voltage Disconnect, an emergency device that opens the HV path in case of an emergency, is located. During races, the competition Data Logger is placed in the "derivation box" for current measuring. Finally, HV- line reaches the inverter case.

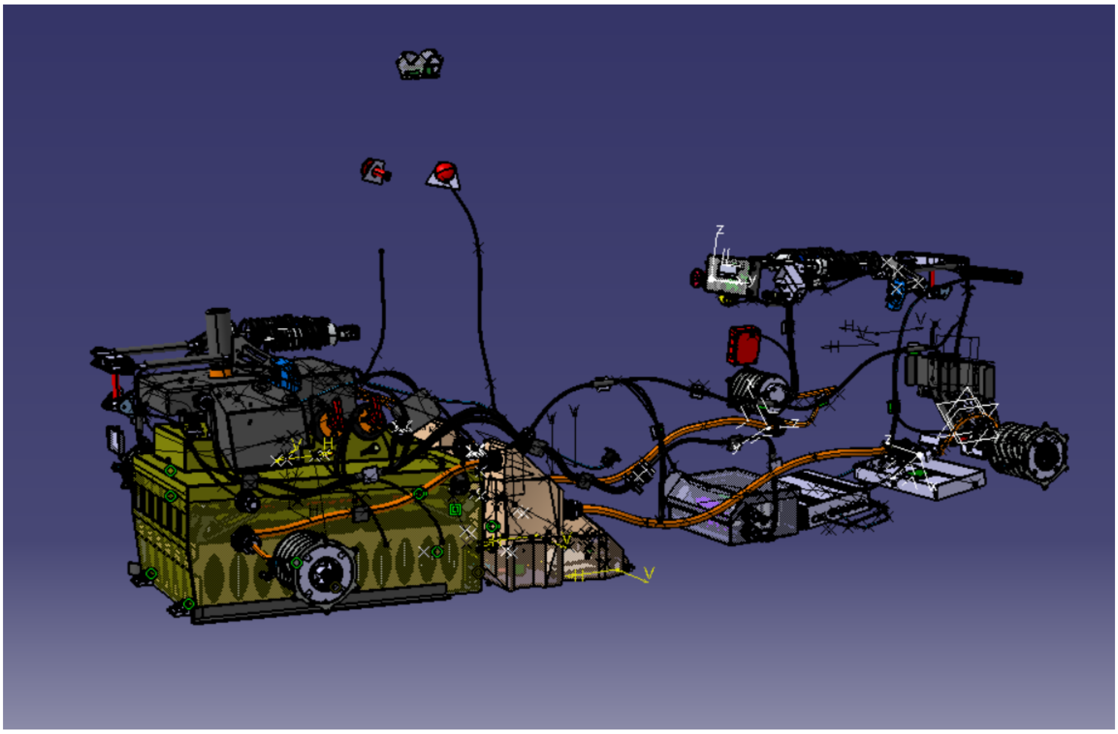

Figure 2.2: CAD Representation of SC24 Electrical System

Moreover, there are two additional HV lines for HV measurement points and one for racing Data Logger sensing.

Similarly to commercial vehicles, the DC bus is controlled by the Power Distribution Unit (PDU), that is placed inside the TSAC, and in our case, just over cells modules. Here two AIRs (power contactors) manages the two poles of the DC bus.

The precharge circuit, which limits the in-rush current, is located on a custom board (TLB Battery). Its schematic is reported below.

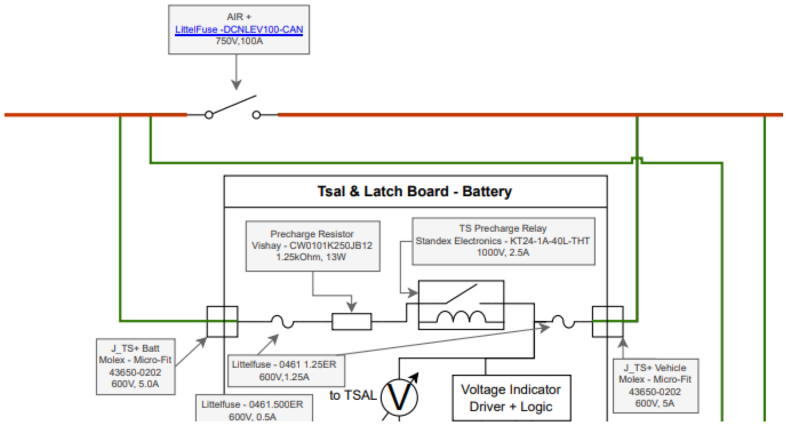

Figure 2.3: Precharge Schematic Detail

On the PDU is also installed the Insulation Monitoring Device (IMD) (BENDER IR155-3204 in our case), constantly measuring the electrical insulation between HV and LV Systems. Devices like this one are required by norms for commercial use; also Formula Student rules require one with an insulation of >500 Ohm/V related to maximum HV voltage (this is a common value also for OEMs). This board is connected to the HV BMS, which will trigger an error in case of insulation loss detection. [7]

A major difference respect to commercial vehicles regards the possibility to charge the battery. In fact, for competition rules constraints, the HV battery pack must be extracted and placed on a dedicated charging cart.

2.2 Components Ratings

Component manufacturers and OEMs use rating certifications to ensure that their products acheive standards and characteristics required by norms. Usually, tests are done by independent certification laboratories following normated procedures.

Moreover, for car manufacturers, components ratings provide essential information for verifying compliance, safety, and performance during the homologation process. They ensure that a product meets all the necessary standards to be legally sold, used, or marketed in specific regions or industries.

For Formula Student purposes, in the electrical area, Voltage, Current and Temperature are the three main ratings.

Voltage insulation rating is especially important in HV components and TS enclosures since competitions rules are very strict about electrical safety. Insulation capability is rated through standardized test procedures. Specifically, the most common in motorsport, for wires and other electrical components, are automotive, military and aerospace certifications.

Taking as an example the UL11028 certification, it guarantees 600 V insulation capabilities for wires. Usually, voltages values are referred to DC voltage or AC RMS value.

Temperature ratings are also important for the insulator resistance: the UL11028 certification ensures conductor protection up to 105°C. [8]

Current rating is often not reported, but wires producers usually provide a Current vs Heat chart, thanks to which designers can predict the wire heating and be compliant with temperature norms.

Another important set of norms in EV field regards the flammability of components. For example the UL94-V0, needed for some HV component also in FS competitions, requires that the component must pass a flame test with certain self-extinguishing time and no flame dripping. [9]

2.3 EMI in an Electric Vehicle

Electromagnetic Interferences (EMI) are disturbances, usually generated by electronic switching devices like power converters, that can seriously affect the reliability of electronic components.

This interference phenomena can propagate in different manners: conductive, capacitive, inductive and radiative. An interference path can be composed by one or, usually, by more of these mechanisms.

Conductive coupling happens when the source of noise is in direct electrical contact with the affected line or ECU. It can be again separated in "common-mode" and "differential-mode" for respectively in-phase and out-of-phase noise wave.

Capacitive coupling is related to capacitance between source and target. In this case the interference traduces in voltage variation between the two.

Inductive (or magnetic) coupling happens when the emitting device is coupled with the target by magnetic field, making waves transmission possible. The intensity of the coupling voltage depends on current variations and the mutual inductance between source and target.

At last, radiated coupling usually regards transmission in free air or vacuum of noise of higher-frequency signals in the microwave range. This type of EMI can be indicated with RFI. [10] [11]

In Electric Vehicles, the two main sources of noise are represented by the E-drive, including inverters and motors, and DC/DC converters. Moreover, since the available space is often reduced, HV cables run next to LV ones. This configuration has been previously modeled in literature as inductive coupling, testing with HV shielded cables.

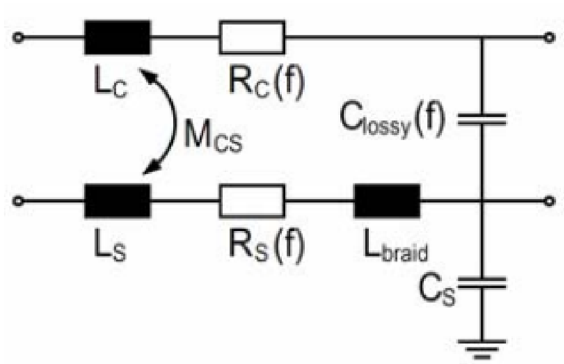

Figure 2.4: Modelling of a Shielded Wire

Crosstalk was measured and so the model was validated, allowing to calculate the impact on LV lines. [1]

To limit noise in LVS, automotive standards include dedicated norms for managing interference currents on single components, such as SAE J1113/41.

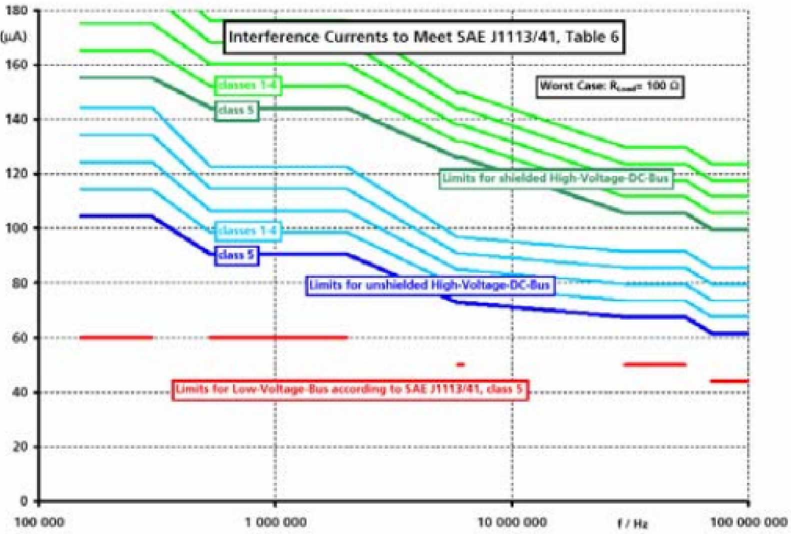

Figure 2.5: High-Voltage Bus Noise standards for Automotive Applications

Due to this phenomenon's intrinsic complexity, it is difficult to obtain quantitative analysis on single parts.

To this purpose, well defined EMC test methods and conditions are specified by international standard documents which are periodically updated by international committees.

Vehicle-level EMC tests are performed by placing a vehicle in a semi-anechoic chamber, a particular room whose ceiling and side walls are covered by electromagnetically absorbing materials and whose floor is made by a conductive material.

Absorbing materials on the sidewalls avoid reflection of radiated EM fields generated inside the chamber and prevent such fields from propagating outside of it. The same materials also avoid that externally generated fields affect the electromagnetic environment inside the chamber, where EMC measurements should be performed.

A conductive material is chosen for the floor in order to reproduce the electrical characteristics of the soil (e.g. roads), on which the vehicle operates in nominal conditions. Such a conductive material also provides isolation from the external environment, while it reflects (rather than absorbing) fields radiated inside the chamber.

Radiated emission tests on automotive components can be performed within a full anechoic chamber.

In this case, the component under test is connected to a standard setup, where the placement and the characteristics of the cables (including their termination impedances), the power supply/ground lines and of all the auxiliary equipment connected to the component are well defined and specified in the standard document.

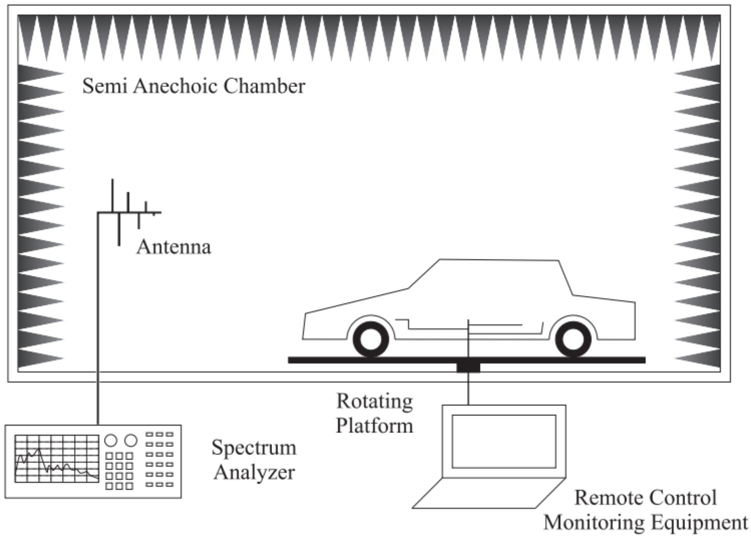

Figure 2.6: Semi-anechoic Chamber

A copper plane is placed below in order to reproduce the electromagnetic characteristics of the chassis of a vehicle. A receiving antenna, placed at a fixed distance from the testing component is employed as in full-vehicle tests to collect radiation.

EMIs are measured by a spectrum analyzer with the same method considered for vehicle-level EMI tests.

Filtering techniques can be implemented to reduce effects on signals and communication lines. A decouplig capacitor is placed in parallel of the disturbing power device, very close to its power supply terminals. Thanks to such a capacitor, high frequency noises, most dangerous for EMI, are filtered.

2.4 Automotive Communication Protocols

2.4.1 LIN

LIN is a one wire communication protocol known for being a cheap solution; it is often used for service components like windows actuators or wipers. It uses a master-slave architecture with slave tasks responding to a master node. Speed is limited to 20 kbit/s, while the maximum package dimension is limited to 8 bytes.

In this protocol, only the master can initiate a message exchange, waiting for the slave's response.

The actual physical layer is controlled by a ISO 9141 compliant transceiver driving the line in case of transmission. In the dominant state, the line is shorted to ground, representing a bit "0", while the recessive state corresponds to the service battery voltage (up to 40 V) and represents a logical "1".

A single frame consists of a header (provided by the master task) and a response (provided by a slave task). The header contains a frame identifier, which uniquely defines the purpose of the frame. It is then transmitted by the slave task appointed for providing the response associated with the frame identifier.

The receiving node interested in these data reads the response, verifies the checksum and uses the data.

Moreover, LIN frames can be of four types: unconditional, event-triggered, sporadic or diagnostic. Unconditional frames are the standard ones, where just one slave task will respond to master request. For event-triggered, the appointed slave tasks transmit their signals in response to the triggering frame header (here collisions may occur and are solved by the master using a collision resolving schedule table). The last two types of frames are used for diagnostic and LIN slaves configuration. [12]

2.4.2 CanBus

CanBus is a two wire differential communication protocol.

The most diffused variant in automotive field is CAN 2.0 with speed up to 1 Mbit/s and max message payload of 8 bytes.

The two wires are twisted and two 120 Ohm resistance terminations are connected at the two ends of the bus.

Since there is no global schedule for transmission, the protocol has a distributed arbitration algorithm that identifies the winner using a dominance criterion.

Whenever two or more nodes start transmitting at the same time, a collision occurs. The first 11 bits of the identifier represent the priority of the message (at least one bit of the id must be a "1"). When a dominant and a recessive bit are simultaneously transmitted, the received bit is always dominant. In this case, the winner is the frame with more dominant bits at the beginning of the identifier.

Bus driving is provided by a transceiver with bit "0" dominant and bit "1" recessive, which are implemented with differential voltage between CAN High and CAN Low lines.

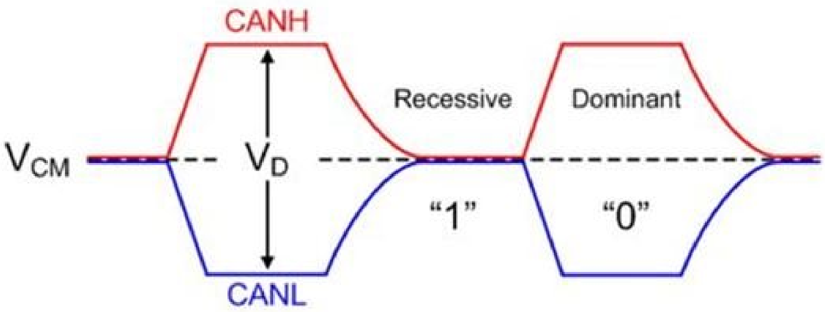

Figure 2.7: Bus Bit Representation

CAN protocol can manage different types of errors, like stuff errors, when after five identical bits the sixth does not change; bit errors, occurring when, after arbitration phase, a bit is different from the sent one or if a recessive bit is received when sending a dominant one.

There are also form, ACK and CRC errors, for respectively wrong value in a fixed slot, no ACK delimiter and for computed CRC different from the sent one. [12]

2.4.3 Automotive Ethernet

Automotive Ethernet targets devices requiring large bandwidth, like cameras and infotainment systems, while for safety critical applications manufacturers still rely on CanBus for its maturity.

This Ethernet specific relies on a different physical layer with respect to standard Ethernet. In particular, while standard Ethernet cables consist of four pairs of twisted wires, that are used for transmission (TX pair) or reception (RX pair), automotive Ethernet uses only one pair of unshielded twisted pair operating in full duplexity (simultaneous transmission and reception).

This specific is designed for shorter distances to save weight and cost on wiring harness.

Ethernet can provide higher speeds compared to CAN and LIN, starting from 10 Mbit/s with data field in one frame being from 46 to 1500 bytes.

The ECUs layout connection changes substantially by introducing Ethernet switches and hubs, dividing the car's network and connection in different sub regions. [13]

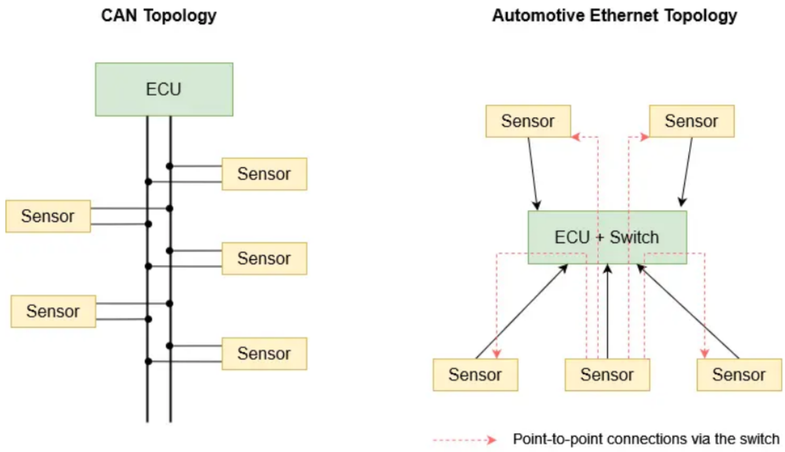

Figure 2.8: CanBus vs Automotive Ethernet High Level Connection Scheme

2.5 Commercial vs Motorsport Wiring Harness

Speaking about wiring harnesses, a series production model has quite few differences respect to a motorsport wiring.

The first difference regards the use of heat shrinks tubes on race harness to ensure protection against cuts, heat and chemicals. Usually, in mass production, electrical tape or corrugated plastic tubes are used to protect wires in order to lower the overall harness cost.

Also fixing methods are different: while a normal metal car body can easily handle fixing holes for wiring clips, adhesive bases are normally used to fix bundles to carbon fiber monocoque or, for heavier bundles, it is possible to add a fixing screw inserts to improve reliability and strength of the fixing method.

The last main difference lays between connectors. In the first case, wide plastic connectors are used, while in the second small and easily unlockable connectors are preferred. Connectors choice is treated in detail in Chapter 3.

These choices are mainly caused by the two different target in terms of weight, packaging, cost and service conditions. Commercial vehicles harnesses are in fact designed to tolerate less severe conditions in terms of vibrations and environment conditions, and not to be as easily replaceable.

While for motorsport it is expected for the process not to be automated, it is interesting to notice that a lot of work is still done by hand also for what concerns series production methods. In fact, only preparation phases, like wire cutting, are highly automated; the actual assembly phase is still manual but, because of the implementation of safety critical applications (like brake by wire), new patents and automation techniques are emerging to guarantee repeatable and reliable safety standards. [14]

Figure 2.9: Commercial vs Motorsport Harness

2.6 HV DC/DC Converter in EVs

DC/DC converters are essential electronic devices that convert DC source from one voltage level to another, ensuring compatibility between power sources and electronic requirement. These converters play a crucial role in systems where different components operate at varying voltage levels, such as in portable devices, automotive electronics, and renewable energy systems like solar panels or battery storage.

Automotive HV converters take the main battery voltage as input and, through high power gates (as IGBTs, SiC or GaNs), generate the desired output voltage (usually 12, 24 or 48 V) through switching duty cycle d. These devices are very efficient and, in most cases, bidirectional working as buck converter when draining energy from the battery and as boost when charging from LVS.
In particular, for ideal buck mode, duty cycle is retrieved as:

$$d = \frac{Vout}{Vin}$$

While in ideal boost mode the following relation is valid:

$$\frac{Vout}{Vin} = \frac{1}{1-d}$$

It has been shown that the output voltage is proportional to the duty cycle and input voltage. However, actual DC/DC converter circuits have practical limitations to prevent the duty cycle from covering the entire range from 0 to 100 percent. Subsequently, in slightly different architectures, the duty cycle is retrieved according to relative schematics.

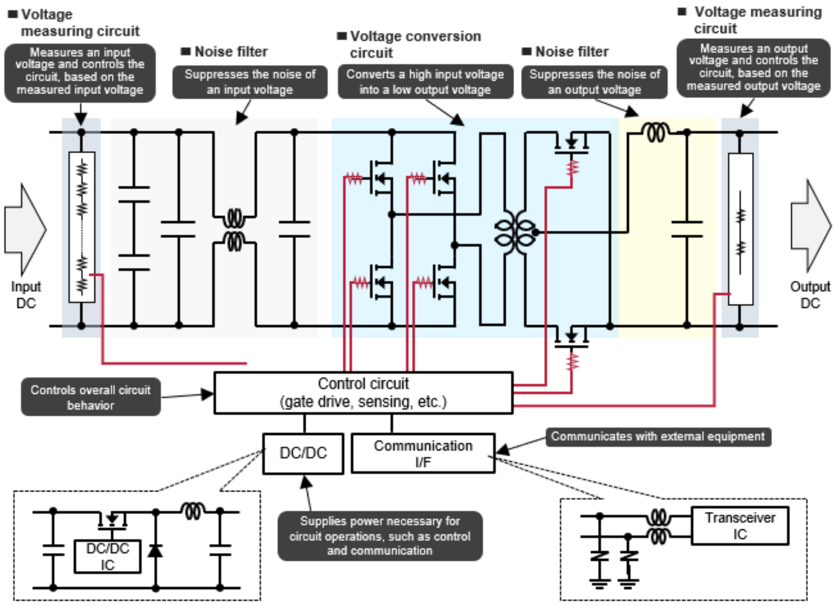

Figure 2.10: High Level Schematic of a Panasonic DC/DC Converter

Chapter 3

Design and Implementation

3.1 LVS Components and Functional Targets

Formula Student rules define LVS as every component below 60 V. In particular, in FS cars, it extends over the whole vehicle, comprehending all ECUs, service loads, driver interface and safety actuators.

Low Voltage System is powered by a custom 24 V nominal battery pack, composed by cylindrical cells with 3.6 V nominal in a 7 series 5 parallel configuration, providing 4.2 Ah.

The pack supplies all Electronic Control Units and few high power loads, like TSAC cooling fans, radiator fans and water pumps for the cooling system.

In this paragraph a brief introduction to each ECU's purpose is presented.

Low Voltage BMS is the custom ECU sensing cells voltages and temperatures and controlling the main power relay of LVS. In case of voltages or temperatures exceeding limits, the ECU can open the relay, cutting power to all other loads.

Just after the relay, there is the Low Voltage Master Switch, a manual switch whose presence is required by regulations, which is acting on LV main power line.

After the LVMS, the Fusebox acts as center point for LV power distribution. It consists of a custom board containing fuses and providing different voltages outputs. Unregulated 24 V (following the direct voltage coming from the LV battery) powers almost every ECU (see 3.1) and demanding loads, like fans and cooling pumps; then a dedicated 24 V line, rectified by a dedicated DC/DC, is used to power the LV boards of the inverters and the shutdown circuit.

The shutdown circuit is a safety line, similar to HVIL in commercial vehicles. It is mandatory for competition rules and runs through all HV connectors, emergency buttons and designated devices. This line also provides actual alimentation to

AIRs contactors. If the shutdown is open, contactors cannot be closed.

Moreover, the shutdown controls the relay on the Discharge Board. This is another safety feature: when the shutdown is open, a resistance is put in parallel with the DC link of the inverter. In this way, if any energy is left, it is discharged.

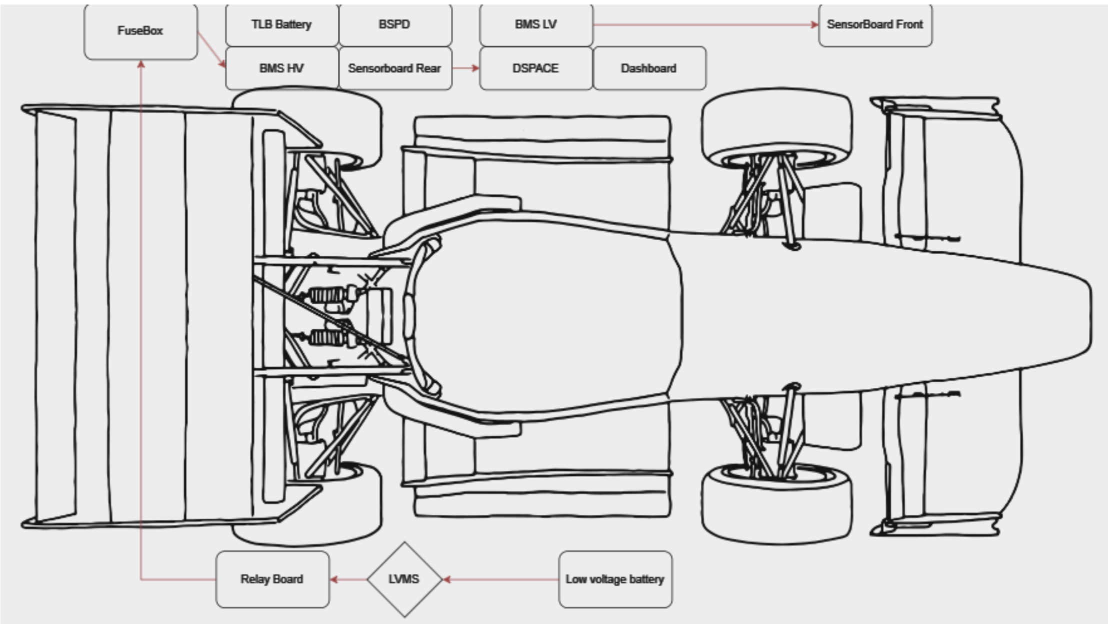

Figure 3.1: LV Battery Powered ECUs

Before moving on to other LV ECUs, it is important to notice how TSAL Green and Red LEDs are piloted. Both power supplies are placed on the high side, with TLB Battery providing power to the green light when DC BUS on AIRs vehicle side is below 50 V, and TLB inverter sensing DC link on the inverter, powering flashing red LEDs when it is over 60 V.

Proceeding with other ECUs, the BSPD is a custom safety-related board that will open the shutdown circuit in case of prolonged brake pressure and positive current exiting from the HV battery pack.

Another custom board is the SensorBoard: a sensor acquisition ECU. There are two SensorBoards in the vehicle: one at the front and one at the rear. As analog sensors and NTCs data are processed, they are shared through CanBus. These boards can also power LEDs as it happens for the brake light.

Then there is the SCanner, a CAN logging device with MicroSD card support and Ethernet connection.

The last custom board is the Dashboard, driving safety LED and powering a small

LCD display that shows real time information.

Finally, two more ECUs are present: IMU and DSpace MicroAutobox II. First one is SBG - Ellipse2-N-G4A3-B2: it takes inertial measurements and can be paired with a GPS antenna allowing to track car in coordinates. DSpace is the ECU on which the vehicle control algorithm runs.

Such a high number of ECUs in the limited space of a Formula Student race car presents significant integration challenges. Therefore, the LVS targets for the prototype primarily focused on creating a reliable and maintainable system, also compliant with FS Germany regulations in order to ensure smoother electrical technical inspections.

3.2 Design Procedure

The procedure starts with the definition and positioning of LVS components in the prototype. We decided to separate the wiring harness in six different bundles to be completely removable and replaceable in case of failure of one of them.

Then, every device power consumption is listed to correctly dimension each line. Location of components is fundamental also to define the four CanBus lines routing.

Then, pinouts from ECUs are recovered from PCB design and reported on Rapid-Harness nodes. Here, the first iteration of the electrical scheme is drawn.

Subsequently, the harnesses are drawn on CAD software (Catia V5 in our case) to check the feasibility of the project.

If the designed scheme is not doable for mechanical or integration issues, a new iteration begins.

At the end of the process, the whole system is defined on CAD for ECUs positioning and their enclosures, and for the whole wiring harness.

At this point, CAD models are used to get exact wires lengths to be reported on electrical schematics.

The process also comprehends the choice of wires, connectors and other production materials to allow a complete assembly and to ensure full competition rules compliance. Here in detail the single parts of the process.

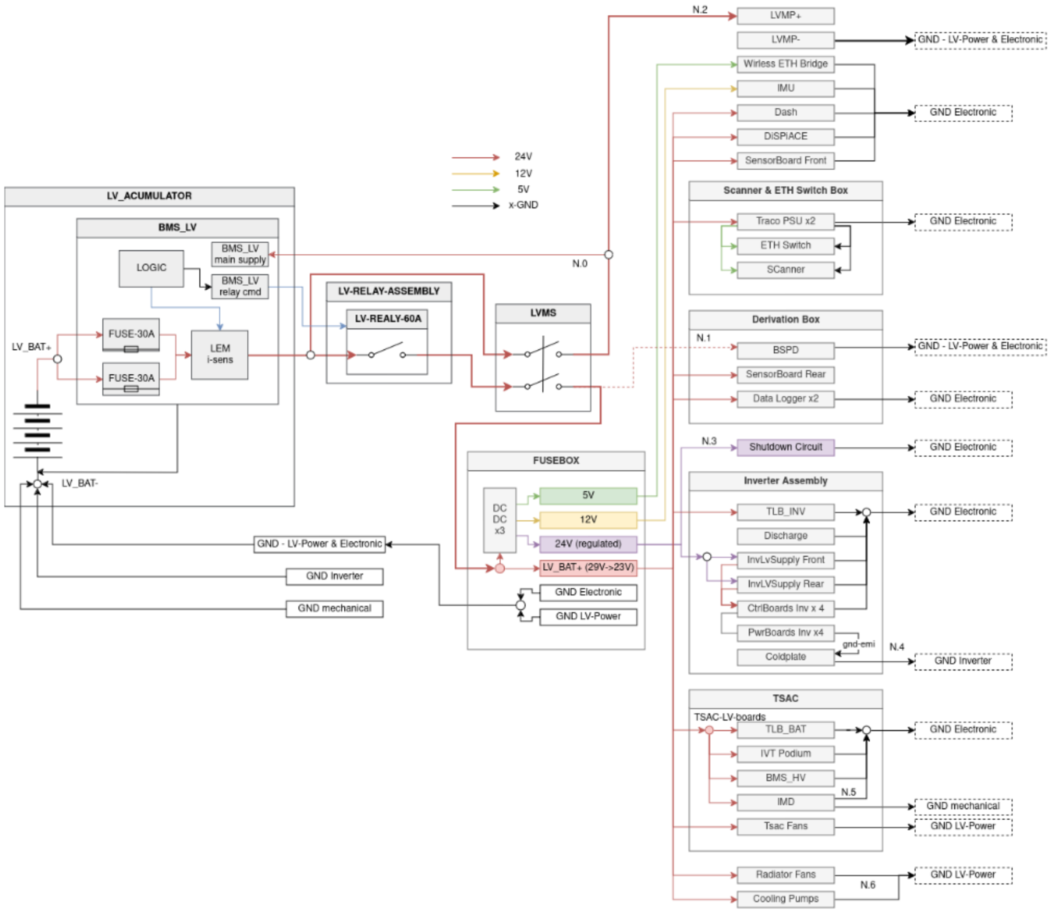

Figure 3.2: SC24 LVS Functional Level Scheme

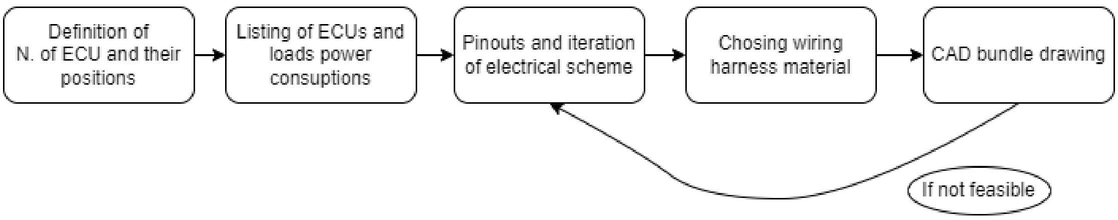

Figure 3.3: Design Procedure Scheme

3.2.1 Line Dimensioning

The use of heat shrink tubes in case of constant current can lead to wiring bundles heating, since heat dissipation is more difficult compared to the normal tape used for wiring or, in the extreme case, compared to a single wire in free air. [15]

Wires de-rating in a multi-conductor bundle is usually indicated by wire producer:

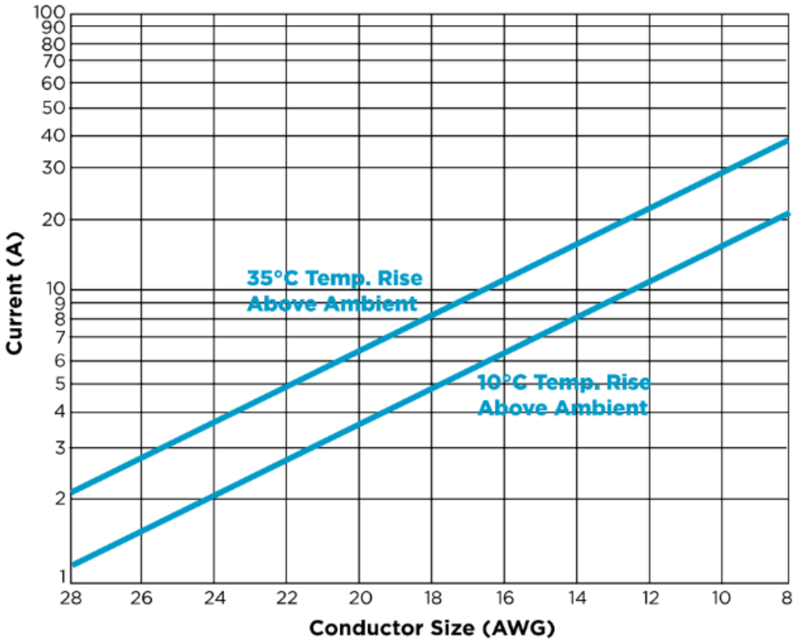

Figure 3.4: Wire Current capability

Current Ratings	
No. of Conductors*	**Factor**
1	1.6
2 to 3	1.0
4 to 5	0.8
6 to 15	0.7
16 to 30	0.5

Figure 3.5: Wire Conductors Coefficient

Bringing as an example LV charging wires, they must bring 10 A of continuous current being the only two wires in their bundle. Following the wire derating chart and considering conductors coefficient (3.5), the selected wire size is 16 AWG, since temperature can rise around 60°C, being 30°C the ambient temperature.

The same process is repeated for every load on LVS. The most adopted wire size is 22 AWG to facilitate and standardize production phases.

Here the process takes in account the conductor coefficient, that arrives up to 0.5 for larger bundles.

For the DSpace line, the expected consumption is 25 W, that correspond to 1.3 A with 19 V of LV battery (worst case), but since we are in a bundle with more than thirty wires, the current must be doubled to find the expected heating: 22 AWG presents almost no temperature changes.

DSpace is the most powerful ECU in SC24. For other ECUs the choice could be more extreme, with smaller diameters wires, but would also require a validation of all production procedures for different gauge size. Details on production in paragraph 3.3.

3.2.2 CanBus

CanBus was chosen for his intrinsic robustness, that lies within its differential communication protocol.

Moreover, our goal was to follow the SAE J1939 standard to reduce noises on the bus as much as possible. In fact, for our speed of 1 Mbit/s, the maximum number of ECUs connectable to the bus, the number and value of termination resistances and the lengths of the whole bus and single stubs were designed according to standard. In particular, the maximum bus length of 40 meters was respected, as the most extended bus in the vehicle is 23 meters long.

There is also a limit of 1 meter for stub length, for this reason the bus is passing through every ECU connector avoiding stubs wherever is possible.

Those lines are shielded to be protected against irradiated and capacitive EMI. The shielding process was designed to have only one end of the metal braid connected to ground, following SAE standard. This way, the GND potentials of two adjacent ECUs are not shorted. [16]

SC24 is equipped with four CAN lines, all starting from DSpace ECU (with termination resistance). The first two lines are dedicated to the inverters and each line has only two node.

The third bus is dedicated to TSAC (called "HVCB"), along with HV BMS, its sensor, the Dashboard and the SCanner ECU.

The last Bus is the most extended. It is named Main CanBus (MCB), passing through SensorBoards, BMS LV, Dashboard, Scanner and TLB Battery.

The longest stub present in the vehicle is the service port. This port has been called CSC (CanBus Service Connector), and uses a sealed RJ45 female connector to easily connect to MCB and HVCB. The same connector was placed on the charging cart to standardize the needed tools, such as a custom RJ45 to db9 cable and a PEAK Can adapter for computer connection.

However, during the season, external ECUs are used for testing purposes. For this reason, we also designed two CAN expansion port on the MCB. The choice was to place those on the two SensorBoards, to access the bus both form the front and the back of the vehicle.

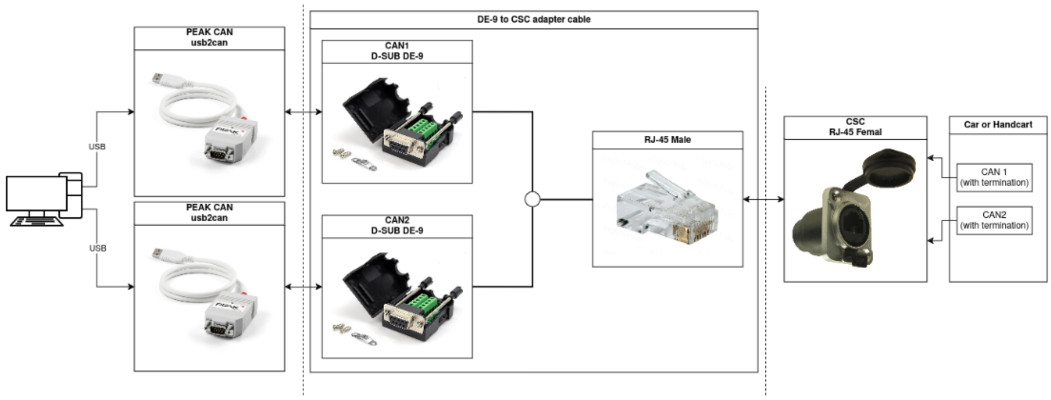

Figure 3.6: Can Connection Tools Schematic

3.2.3 Grounding Approach

The grounding of an electric race car equipped with carbon monocoque can be done in many different ways.

The simplest way would be connecting all GND to the chassis, but the chosen approach in this case was to separate the three main ground lines - "Inverter ground", "Mechanical ground" and the so called "Electronic ground" - as much as possible.

All three lines are connected to the negative terminal of the LV battery at the end of the path, but the idea was to keep them as separate as possible.

The noisiest line is, of course, the inverter line, which uses the inverter's coldplate as ground star point. Also the four motors PE are connected to this line through shieldings of three phases cables. This GND is also used by inverter and outboard motors connectors. These ones are electrically insulated from the chassis by means of plastic masks. In fact, the carbon chassis with the main hoop (main metal rollbar of the prototype) represents the mechanical GND.

The last GND ground line is the "Electronic ground", dedicated to supply lines to every ECU. The main purpose was to protect GND reference of the ECUs from the conducted EMI generated by inverter and motors, and also to avoid dangerous ground loops between different systems as much as possible.

Analog sensor lines follow the same principle with alimentation and ground reference coming from the sensing ECU and being as short as possible.

GND Inv	GND Mech	GND Elect
Inverter Coldplate	Chassis	ECUs
Motors	LV chassis connectors	Fan
	Seat	Pumps
	TSAC	

Table 3.1: Grounding Groups

3.2.4 Connectors

The market offers a vast variety of connectors coming from different environments, like automotive and aerospace ones.

Furthermore, there are three main sub category: in-line, panel and PCB connectors.

In our case, the main parameters taken in account during the decision process were: voltage rating, contacts layout, material, water insulation and cost.

Voltage rating is fundamental for HV components. For plastic PCB connectors, the choice was to have one multi-purpose cheap connector and one rated 1000 V for boards with HV connection, in our case respectively Molex Nanofit and Microfit series.

For wider and more populated panel connectors, Mil-spec series was chosen. These are from the same series of HV ones: metal circular connectors that become waterproof once heat shrinks are closed. Mil-spec circular connectors can come in different packaging and materials, from heavy duty applications to lightweight motorsport series.

Figure 3.7: Complete Mil-spec Connector Disassembled

In our case, the choice fell on D38999 series III [17]. Those connectors are still light but not as light as motorsport ones. They are a good compromise between weight and cost.

Circular plastic connectors were also taken in consideration, but were discarded because of the high mating and un-mating cycles needed in our application.

Another possible choice was represented by automotive grade plastic connectors, the most used in commercial vehicles. However, they were dropped due to higher weight and their large size.

Moreover, being consistent with connectors series allowed us to reserve less budget for the tools needed to assemble the connectors and to facilitate stocking operation of contacts in production and repair phase.

	Advantages	Disadvantages
Mil-spec	Durability	Weight
Race-spec	Size, Weight	Cost
Circular Plastic	Cost, Weight	Durability
Automotive Plastic	Cost	Size

Table 3.2: Connector Type Comparison

3.2.5 Design Tools

As cited before, two main tools are used for the design and production phase: RapidHarness and Catia V5.

The first one is used for drawing electrical schematics. These ones are called harnesses (3.20) in the program, and different harnesses can be joined to compose the entire car system (3.21). The software permits to insert all types of wires and connectors (with related contact) to subsequently generate a complete Bill Of Material ready for production. Each connection is marked with a wire size and color, then a name is placed in the connection's notes, while wire twisting is assigned in the wire section. The tool also allows to indicate the location of splices, which are the wires joining points.

The wiring harness tool of Catia V5 is used to draw every bundle inside the model. Connectors are imported on CAD assembly and act as endpoints for the bundle model.

An online tool is used to calculate the bundle thickness to be inserted in Catia, then the esteem is enlarged by 10 percent as a safety margin. [18]

Bundles bending radius is a very complicated measure to retrieve: rules of thumb suggest an increasing multiple of the diameter as bundles size increases. [19] Bending radius must be set on every bundles, since the tool will automatically calculate if the route is feasible.

Additionally, since wiring bundles are fixed in the prototype using adhesive bases, these are represented by a specific part on Catia. Bases are designed with electrical properties, so wire bundles can pass through them with the correct direction. Adhesive bases with heat shrinks are also modeled on Catia, with 6 centimeters of tube (most frequent case in production) to simulate real scenario.

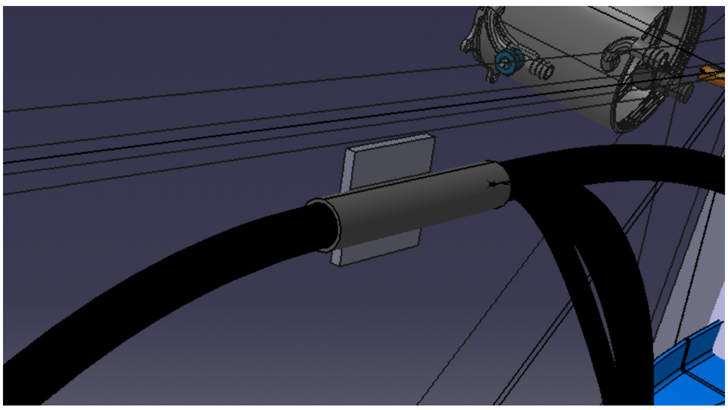

Figure 3.8: Adhesive Base with Heat Shrink Model

3.3 Harness Production

Production is a very critical phase, in fact a repeatable and reliable process is needed to ensure the quality of each task.

At first, RapidHarness loom schematics are used as main reference for the production. They are printed and then disposed on wiring tables. Nails are used, in the place of harness forks (that were not available), in branch-points, in splices and in connector nodes. RapidHarness tables are placed next to splices and connector nodes, indicating all wires needed on that nail.

Another possibility regards printing in-scale schematics, but it would require a longer process in drawing loom disposition, since schematics would need layout modification to allow wire disposal. A third option would be using RapidHarness cutlist tables and pre-cutting wires at right length, but in this case a different assembly procedure would be needed.

The first step of the process regards the wire positioning following schematics connections. Each wire is laid down on the table and marked with a label.

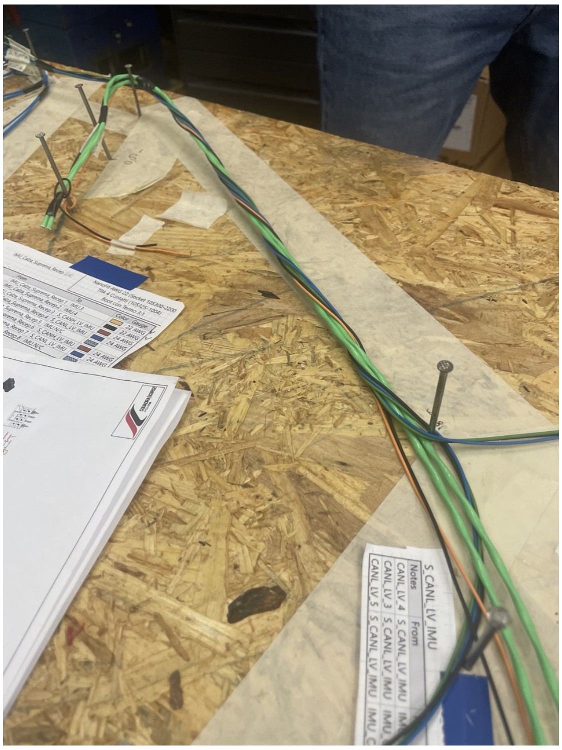

Figure 3.9: Wiring Assembly Tables

To facilitate bending and harness construction operations CAN shielded cables are placed at the center of the bundle (see 3.9). Wires are regularly wrapped with a round of electrical tape to ensure bundle geometry.

When all the wires of a bundle are completed, a continuity check is conducted to verify the correctness of the work. If passed, the check is reported on respective labels of nails.

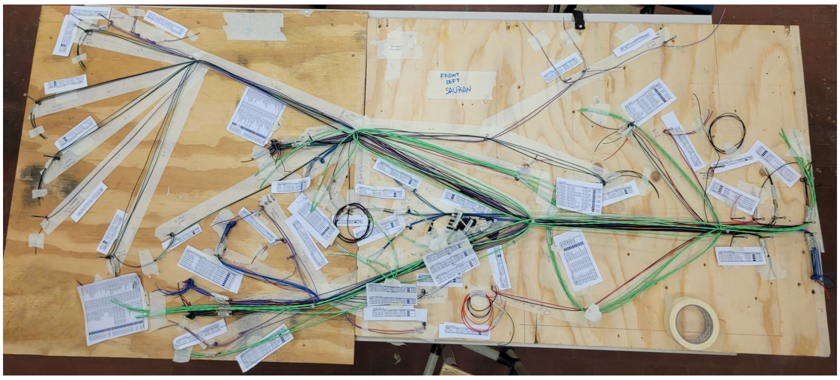

Figure 3.10: Front Left Loom before Heat Shrinks

Then, splices are crimped. We chose a specific manual procedure, to be repeatable and less prone to failure. In particular, Parallel Type Splices method was used following the NASA-STD-8739.4A standard. Transparent adhesive heat shrink is closed on crimped splices with some extra space left on both wire ends (see 3.12).

In this way, stress is distributed between splice and epoxy of the shrink tube, while clear shrink allows an easier visual quality control. In particular, both wire cores must exceed the splice to ensure a complete connection. [20]

Successively, splices lines are retested to prove the electrical connection.

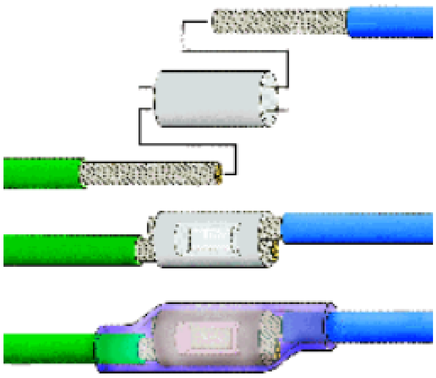

Figure 3.11: Detail of NASA-STD-8739.4A Regarding Splices

Figure 3.12: Example of a Completed Splice

Heat shrinkable tubes are then inserted and closed on branches. Adhesive heat shrinks are successively placed and closed on intersections to fix the harness shape and to seal ramification points. In this last part, adhesive tubes are cut 6 cm long in particular branch points that have been previously selected on CAD.

Figure 3.13: Heat Shrinks Tubes before Heating

The next step regards connectors. Here the procedures can differ a lot, depending on the connector typology. Plastic connectors are usually the easiest, if the correct tools are used.

The wire is stripped by some millimeters, following the producer's drawing, then the contact is positioned in the tool and crimped. When all terminals of one node are completed, the connector is assembled.

Mil-spec connectors need little more attention, since they are usually more contact dense and present smaller sized contacts. The overall connector procedure is similar, but contact crimping must follow a standard process (like the previously cited NASA one [20]).

There are two options for the connector assembly, which can be inserted with or without service loops. These are wire loops to be placed just before the connector that provide extra wire slack, facilitating the insertion and extraction of contacts.

Both solution were experimented, and led to the conclusion that for wider wires, service loops can become a problem, since their dimension can impede connectors accessory mounting, like back-shells and boot adapters. For high density connectors, they instead represent a valid solution.

3.4 Vehicle Integration

At this stage, every E&E component is ready for the final assembly. After surface preparation, adhesive bases are placed as reported in the CAD model, then the bundles are fixed to the bases by means of zip ties. (3.17)

Successively, ECUs are mounted inside their enclosures, fixed in place and connected to wiring harnesses. Then, every other electronic component like sensors, buttons and additional switches are fitted into the chassis and connected to their respective ECU.

Speaking about enclosures, most of them are made of FDM 3D printed PETG (a plastic resistant to UV rays); while for enclosures containing HV components or boards with HV parts, Formula student rules imposes requirements in terms of material and conductivity.

In fact, "TS enclosures mus be made of a grounded solid layer made of at least 0.5 mm thick electrically conductive material, aluminium or better, having a resistance below 300 mΩ, measured with a current of 1 A, to LVS ground and able to continuously carry at least 10 % of the TS accumulator main fuse current rating or be fully made out of electrically insulating materials having an isolation resistance of at least 2 MΩ, measured with a voltage of 500 V. The enclosure must be rigid and must prevent possible mechanical penetrations." (EV 3.1.1).

In our case, Onyx and ULTEM were the main choice for TS enclosures, so we reentered in the second case of fully insulated material. Taking as example ULTEM, enclosures have a minimum wall thickness of 3 millimeter and, with this FDM material having 10^{15} Ohm/cm, the rules limit is respected with margins.

Mechanical integration required coordination with the chassis division in order to follow and reproduce CAD model in each detail. The longest process regarded firewall connectors: their housing was drilled from supports of the carbon fiber firewall seat starting from a connector mask. (3.14). Another challenge was the grounding of metal parts of the firewall and conductive parts of driver harness mounting points. Since EV 3.1.1 requirements must be met also in terms of conductivity and connection method, metal parts of the sets needed extra ground connection.

In addition to connectors, on the firewall seat frame, an Ethernet panel connector dedicated to racing Data Logger was also mounted, to facilitate data download.

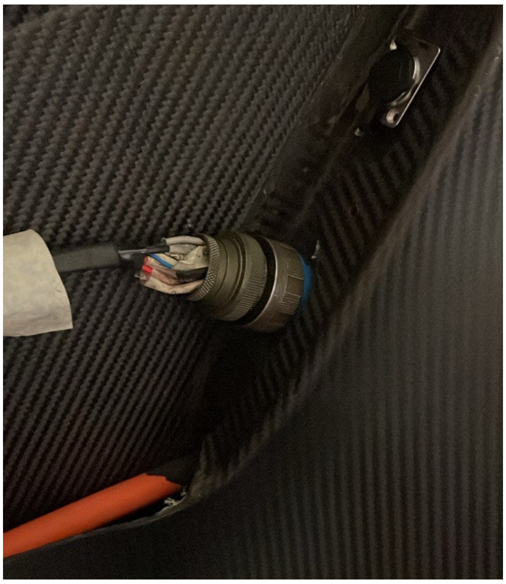

Figure 3.14: Connector on Firewall Seat Frame Detail

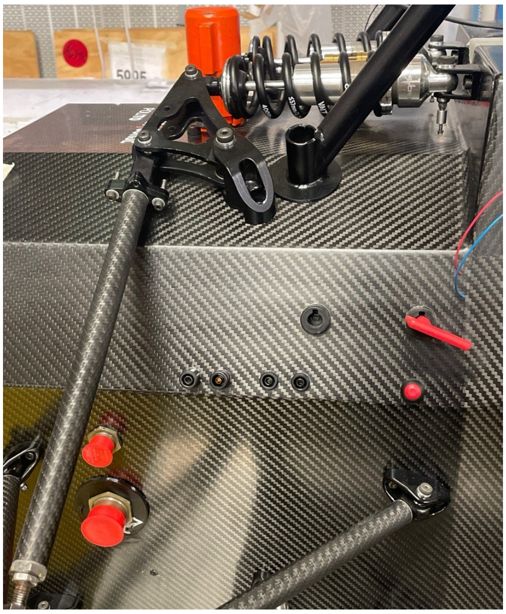

Figure 3.15: Electrical Switching Zone Preparation

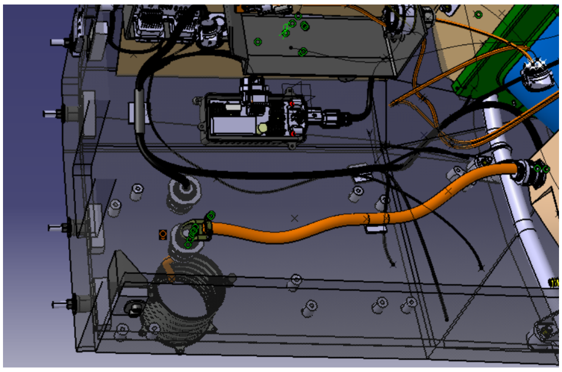

Figure 3.16: Rear Left Loom CAD Design

Figure 3.17: Rear Left Loom

3.5 HV DC/DC Implementation

Implementation of this component in FSAE prototypes is an open debate point.

While a LV battery pack provides a simple solution in terms of integration and rule compliance, it needs to be recharged frequently and requires a dedicated BMS.

DC/DC converter would solve charging problems, allowing packaging to be redistributed along the vehicle.

Weight saving is another important point, as LV Battery pack weights 3.1 kg, while DC/DC converter for racing applications are around 600 grams.

For the dimensioning process, low voltage consumptions have been analyzed to ensure a constant and sufficient supply during the endurance event, being this the most power demanding dynamic event.

For the actual setup, the maximum consumption is about 630 W, with 150 W estimated for the LV electronics and 120 W for the cooling pumps. Half of the power is required by fans, in our case for cooling purpose.

Another advantage of HV DC/DC converter is, in fact, to have a separate 48 V outlet for higher power load with lower currents, allowing smaller dimension of cables and saving ulterior weight.

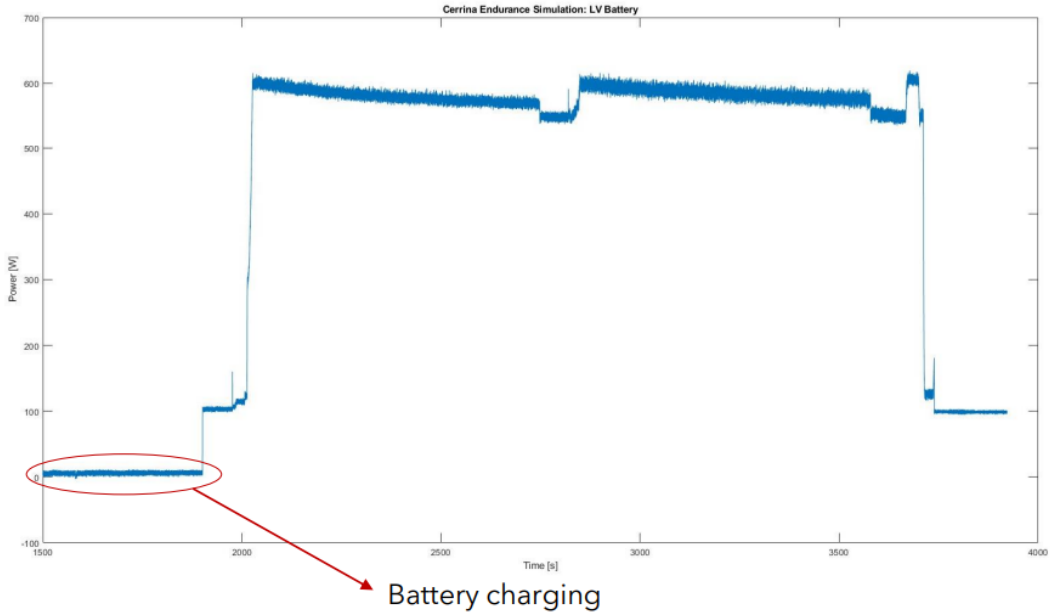

Figure 3.18: SC24 LV Power Log during Testing

FSG rules allow placing HV DC/DC inside the TSAC, as stated in EV 5.4.3, and do not prohibit HV connection on battery side of AIRs. This configuration would allow a complete removal of LV battery pack, even if a temporary LV pack would be needed for car service when the HV battery pack is not present.

Figure 3.19: BrightLoop HV DC/DC

Galvanic insulation must be ensured with three time the maximum TS voltage or 750 V, whichever is higher (EV 1.2.1), so in our case we are looking for components with insulation higher than 1800 V.

The perfect candidates are devices like "BrightLoop DCDC SP": this model weights 616 grams in air cooled version, with 3000 V insulation (respecting the FSG limit). Moreover, this device has two separate power outlets, individually controlled through CAN, with voltage ranging between 0 and 59 V. [21]

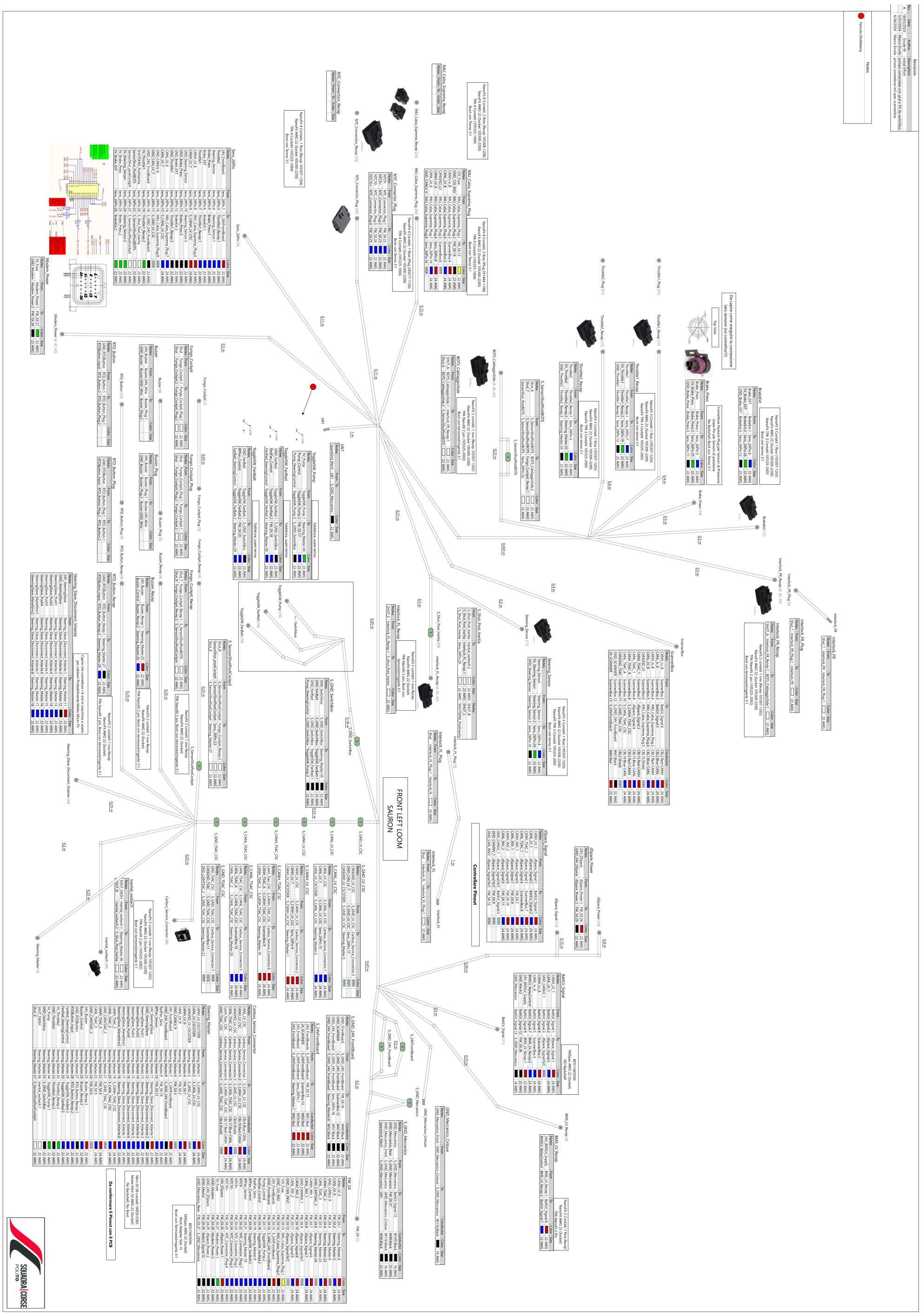

Figure 3.20: Front Left Loom Schematics

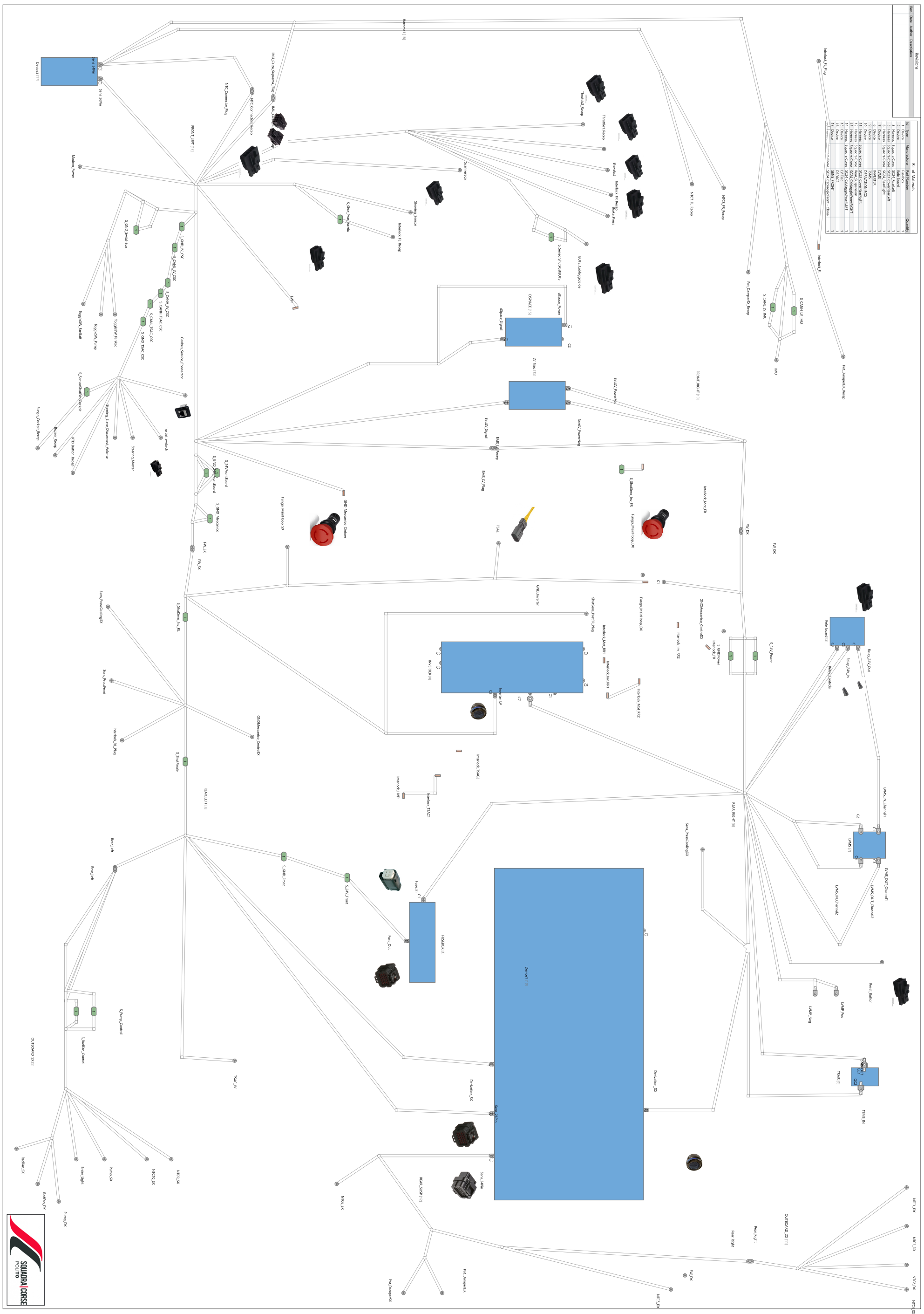

Figure 3.21: SC24 Complete System

Chapter 4

Results and Discussion

4.1 Production Metrics

This section wants to summarize the main production metrics for future design iteration purposes. Harness production phase was planned to have a group of three-to-four people working eight hours a day. One person was always entirely dedicated to quality control.

Bundles preparations required an entire month of work, including benches setup and connectors assembly. Integration phase required two people a day, but lasted for about two whole months. Esteemed time previsions for bundles production were generally respected, but integration phase lasted, at the end, longer than planned.

Speaking about production material, here the main numbers are presented, considering the whole assembly process.

Four type of non adhesive heat shrink tubes were used, 3-1, 6-2, 12-4, 24-8 while adhesive ones are only 3-1, 6-2 and 12-4, each of these tubes have a shrinking ratio of 3:1. In addition, bigger tubes with a higher shrinking ratio (6:1 and 4:1) were used for branches points.

The majority of the wires were 22 AWG, representing the 93% of total (4.1) in-vehicle conductors.

Three sizes of open barrel splices were used. Heat shrinkable splices were tested for smaller wires, but poor mechanical resistance resulted in their eventual discard.

Despite the effort to standardize connector connections, a total of 10 connectors types (Mil-spec d38999, TE Superseal, Molex Nanofit, Molex Microfit, Molex Megafit, Molex Squba, Delphi, Zif Connector, MCON and Duraclick) have been used, mainly due to non-custom ECUs and sensors. Problems arose when dedicated tools were not available, sometime resulting in functioning but mediocre crimping job.

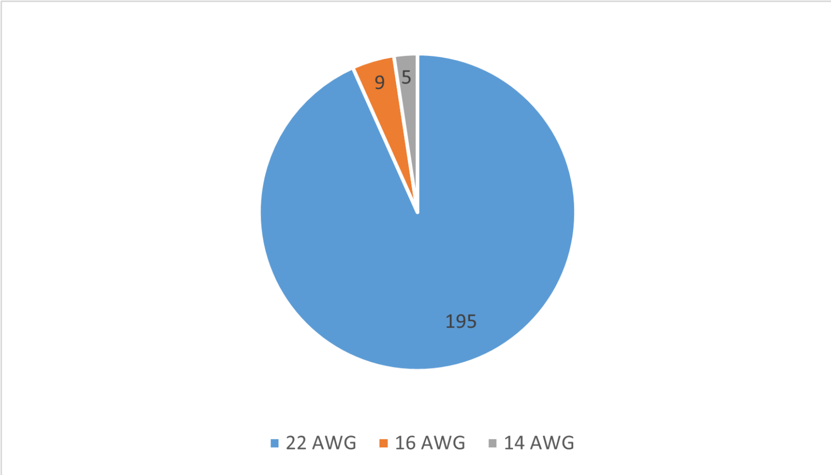

Figure 4.1: Total Wire Usage

4.2 Failure Analysis

LVS design was validated by both testing and racing seasons, with overall good results. However, all the failures that occurred are reported in detail in this paragraph. Moreover, failures are divided in categories to track recurrent patterns with the aim of identifying root causes.

CAD simulation were overall respected, but in some locations the calculated bending radius was not applicable due to the higher local rigidity of adhesive heat shrinks on branches. There were some discrepancies regarding bundle length in some branches at the rear of the vehicle, resulting in some extra centimeters not allowing an easy mating of connector to ECUs. In this case, the excess of the wire bundle is relocated if possible; otherwise, connector procedure must be re-assembled after shortening the cable.

Another integration issue regards the use of too small and bad positioned wire-to-PCB connector on some ECUS. In this case, the mating and un-mating process damaged the wires creating failure points. This is a problem that needs a complete iteration of the ECU to be permanently solved.

Dangerous issue occurred during the first turn-on of the prototype, with LVS not turning on. The issue was caused by wrong pinouts of the Fusebox supply connector reported on wiring scheme from PCB designing tool. The error corresponded to shorted poles of LV battery on the PCB causing the popping of the fuse on LV

BMS.

LVS suffered of EMI problems on CanBus when inverters started switching, especially at zero torque with 0.5 duty cycle. CAN errors began to increase dramatically, not allowing a clean communication on the bus despite the fact that CAN shielding was planned and connected. Worst problems were noticeable on MCB, since it is the longest bus with the largest number of ECUs. Small PCBs with Y-type capacitors (capacitors type that fails as open circuit for safety reasons) were added on DC-link to filter common-mode interference using cooling coldplate as ground star. [22]

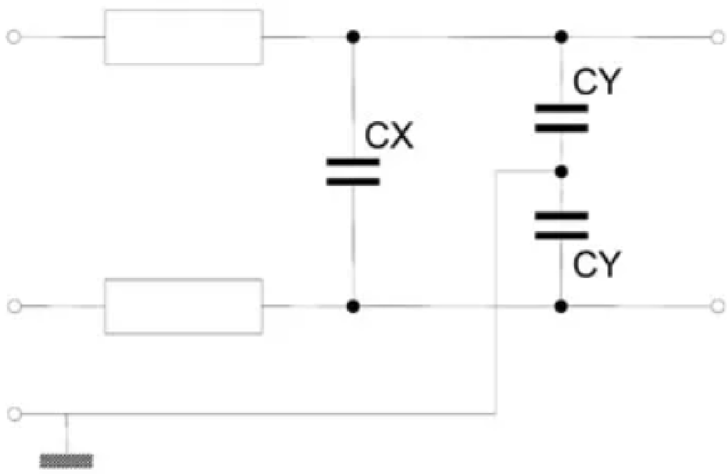

Figure 4.2: Generic Y-cap Schematics Configuration

However, the modification was not completely resolutive since ground reference was not good enough and we were not able to have a complete shield since our inverter case is made of plastic.

Additionally, in-service failures occurred. Usually, pinches or cuts on wiring harness represented the cause (see 4.3). The problem manifests with loss of a sensor, open CanBus or with impossibility to close the shutdown (HVIL) circuit.

Again, the cause of the problem needs to be addressed to the design phase, where serviceability and harness protection in the interested zone have not been taken enough in account.

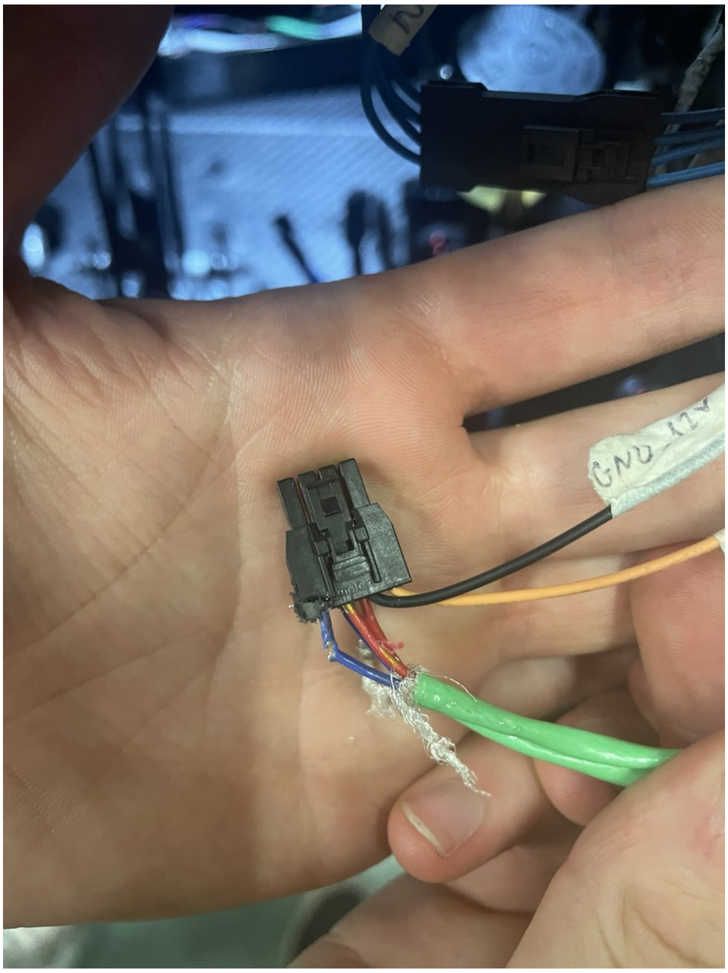

Figure 4.3: Harness Failure after Maintenance

Issues regarded compliance with EV 3.1, in fact 300 mOhm resistance was exceeded in firewall fixing points and next to motor metal parts. The adopted solution to pass technical inspection was to use stranded wires, with eye or blade terminals, to create direct connection to lower resistance points in the prototype like main hoop, in the case of firewall bolts.

Moreover, better solution can be studied during the design phase, integrating conductive elements in mechanical design or planning grounding points on metal custom part.

Last important point of failure was waterproofing LVS. During a very wet event (FSG Endurance) SC24 wouldn't turn back on after driver's change, indicating loss of insulation (IMD). It was a real error since water entered from one of TS measuring points, shorting HV+ and the chassis' honeycomb(LV ground).

A Failure Mode and Effects Analysis (FMEA) has been conducted on most common issues. The Risk Priority Number is calculated multiplying probability, impact and detection coefficients, each of them ranging between 1 and 10 basing on how severe the situation is.

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN
Wiring harness	Too long loom branches in some vehicle locarion	Impossibility to mount ECUs, no extra space for slack	4	Error in production, wiring assembly	1	Test fit in final chassis	1	4
Wiring harness	Wire To PCBs connections damagind wires when mounting and dispounting ECUs	Sudden malftuctioning of vehicle	7	Bad Desing, maintenance procedures not taken in account	4	Visual inspection, continuity check, vehicle test	3	84
Fusebox	Initial vehicle assembly	Vehicle not turning on, main LV popped	8	Error in pinouts reporting	1	Wiring schematics	7	56
Wiring harness	Cuts, oil leaking on harness	Sudden malftuctioning of vehicle	8	Damage during mechanical maintenance	6	Visual inspection, continuity check, vehicle test	3	144
Canbus	Strong EMI disurbances when inverters powered on	CANBUS ECUs in bus-off, general lagging response of the car	8	Error in pinouts reporting	1	Oscilloscope, Canbus datalogging	7	56
Groundings	Missing reliable connections to LV ground	Car not passing Electrical Insections during races	4	Not grounding friendly mechanical design	5	Multimillimeter test	3	60
HV insulation	Water entering inside the vehicle and inside TS enclosures	Car stopping, IMD error lighting	8	Broken sealing, too weak seal	1	IMD, Insulation tester	3	24

Figure 4.4: FMEA Table on LVS

At the end of the analysis, the need of more effort towards a robust implementation of the LVS emerged.

At first, mechanical protection of the harness, especially in frequent maintenance locations, needs to be improved.

Then, the complete ECUs layout needs to be revised with the goal of improving integration in terms of mechanical mounting points and connectors positions. Furthermore, waterproofing ECUs and buttons need to be taken more into account.

Chapter 5

Conclusions and Future Works

In conclusion, this work wants to represent a first iteration of a complete LVS design. The system showed his overall reliability during the 2024 racing season, but there is still margin for improvements, as adopted solutions can be further validated with numerical approaches.

At first, anechoic chamber tests, conducted on full vehicle and with electronics powered, would be very useful to gather further data on the type of EMI in our application.

Then, mechanical tests, like traction test, on harness and procedures can be run to validate more extreme solutions.

It is worth to notice that, in both this and the previous seasons, ECUs integration testing was performed on the vehicle when all wiring harness was assembled. This is a big limit to custom ECUs iteration process, hence the need of an off-board test bench, reproducing the complete LVS system, to allow a faster iteration process and a controlled environment for testing.

Acronyms

BEV
: Battery Electric Vehicle

BMS
: Battery Management System

CAN
: Controller Area Network

ECU
: Electronic Control Unit

EMC
: Electromagnetic Compatibility

EMI
: Electromagnetic Interference

HV
: High Voltage

HVIL
: High Voltage Interlock Loop

LIN
: Local Interconnect Network

PDU
: Power Distribution Unit

SAE

Society of Automotive Engineers

TLB

TSAL Latching Board

TSAC

Tractive System Accumulator Container

List of Tables

List of Figures

Bibliography

[1] S. Guttowski, S. Weber, E. Hoene, Wore John, and Herbert Reichl. «EMC issues in cars with electric drives». In: Sept. 2003, 777–782 vol.2. ISBN: 0-7803-7835-0. DOI: 10.1109/ISEMC.2003.1236706 (cit. on pp. 1, 11).

[2] URL: https://www.vicorpower.com/resource-library/articles/automotive/48v-systems-goodbye-12v (cit. on p. 1).

[3] URL: https://www.ti.com/lit/wp/szzy015a/szzy015a.pdf?ts=1724485758479&ref_url=https%253A%252F%252Fwww.google.com%252F (cit. on p. 1).

[4] URL: https://brightloop.fr/products/hv-lv-dc-dc-converters/dcdc-sp/ (cit. on p. 1).

[5] URL: https://www.formulastudent.de/fileadmin/user_upload/all/2024/rules/FS-Rules_2024_v1.1.pdf (cit. on p. 5).

[6] URL: https://www.amk-motion.com/amk-dokucd/dokucd/en/content/projekt/doku-cd_html5/topics/amk_automotive.htm (cit. on p. 7).

[7] URL: https://www.ti.com/lit/ug/tidudj6b/tidudj6b.pdf (cit. on p. 9).

[8] URL: https://iq.ul.com/awm/stylepage.aspx?style=11028 (cit. on p. 10).

[9] URL: https://www.amade-tech.com/it/guide-on-ul94-horizontal-vertical-burning-flammability-test/#Evaluation_Criteria_for_Classificaton_V-0_V-1_and_V-2 (cit. on p. 10).

[10] URL: https://en.wikipedia.org/wiki/Electromagnetic_interference (cit. on p. 11).

[11] URL: https://resources.system-analysis.cadence.com/blog/msa2022-emi-types-and-coupling-methods (cit. on p. 11).

[12] Crovetti P. *Slides of couse Electronic Systems for Vehicles*. 2024 (cit. on pp. 14, 15).

[13] URL: https://www.keysight.com/blogs/en/tech/educ/2024/automotive-ethernet (cit. on p. 15).

[14] Huong Giang Nguyen, Marlene Kuhn, and Jörg Franke. «Manufacturing automation for automotive wiring harnesses». In: *Procedia CIRP* 97 (2021). 8th CIRP Conference of Assembly Technology and Systems, pp. 379–384. ISSN: 2212-8271. DOI: `https://doi.org/10.1016/j.procir.2020.05.254` (cit. on p. 17).

[15] URL: `https://aboveboardelectronics.com/documents/Alpha-Wire-Catalog.pdf` (cit. on p. 23).

[16] Eugene Knowles and Lee Olson. «Cable Shielding Effectiveness Testing». In: *Electromagnetic Compatibility, IEEE Transactions on* EMC-16 (Mar. 1974), pp. 16–23. DOI: `10.1109/TEMC.1974.303318` (cit. on p. 24).

[17] URL: `https://www.souriau.com/en-en/products/connectors/circular-connectors/d38999-series-iii-connectors` (cit. on p. 27).

[18] URL: `https://www.rbracing-rsr.com/22759_diameter_shielded.html` (cit. on p. 28).

[19] URL: `https://www.nexans.nl/en/business/Building-Territories/Building/Distributors/Bending-radius.html` (cit. on p. 28).

[20] URL: `https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/nasa-std-8739.4a.pdf` (cit. on pp. 30, 32).

[21] URL: `https://brightloop.fr/products/hv-lv-dc-dc-converters/dcdc-sp/` (cit. on p. 36).

[22] URL: `https://www.mouser.com/pdfDocs/doc191_CMFiltDesign.pdf` (cit. on p. 41).