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Proyecto Fin de Grado

INGENIERIA ELÉCTRICA

Design of the systems of an Electric Powertrain for a Formula Student

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Resumen

Ante los problemas que sufría el powertrain eléctrico del monoplaza Formula Student del equipo de la Universidad de Navarra, Tecnun eRacing, un rediseño del mismo era necesario, con el fin de conseguir un monoplaza fiable y competitivo.

Este proyecto recoge el trabajo realizado durante la temporada 2019-2020 sobre los sistemas que componen un powertrain eléctrico además de dar pautas de desarrollo para futuras temporadas. Por tanto, en este documento se definen los motores e inversores utilizados en el monoplaza, detallando la problemática de las últimas dos temporadas y proponiendo soluciones. Además, también se dimensionan todos los componentes intermedios del bus DC para poder conseguir la potencia máxima permitida por la normativa de la Formula Student Germany: 80 kW.

Por otro lado, el documento también recoge el sistema de monitorización de las baterías (BMS) del vehículo. Incluye las adiciones y rediseños realizados al módulo maestro para cumplir con la nueva normativa. Además, se detalla un nuevo diseño del módulo esclavo más moderno y con mejores prestaciones mediante el uso de componentes con estándares de automoción, junto con las pruebas realizadas. También incluye una guía con los pasos a seguir para poder configurar el inversor, acompañando cada paso con su respectiva fotografía del programa utilizado para la configuración.

Por último, este proyecto sirve el propósito de definir el método de trabajo que se ha de realizar en la fase de diseño para poder dimensionar y definir correctamente todos los componentes utilizados, evitando así problemas a futuro en el monoplaza.

Abstract

In response to the problems suffered by the electric powertrain of Tecnun University of Navarra's Formula Student single-seater racing car from Tecnun eRacing, a redesign of itself is necessary in order to achieve a reliable and competitive vehicle.

This project gathers the work carried out during the 2019-2020 season on the systems that compose an electric powertrain in addition to setting work lines for development in future seasons. Thus, in this document the motors and inverters used are defined, detailing the failures of the powertrain in the last two seasons and proposing solutions. Furthermore, the components that compose the intermediate DC bus are dimensioned in order to achieve the maximum power allowed by the Formula Student Germany rules: 80 kW.

On the other hand, this document also gathers the Battery Management System (BMS) of the vehicle. It includes additions and redesigns made to the master module for complying the new set of rules. In addition, a new slave module is designed and tested, more modern and with better performance by using components with automotive standards. Moreover, the document includes a guide for configuring the inverter, step by step and with a photograph of the program used for the configuration in each required step.

Finally, this project has served the purpose of defining the work line which should be followed in order to dimension and define correctly every used component, avoiding future problems in the vehicle.

Abbreviations

ADC: Analogic to Digital Converter

AIR: Accumulator Isolation Relay

AMS: Accumulator Management System

BMS: Battery Management System

CAN: Controller Area Network

CV: Internal Combustion Engine Vehicle

DoD: Depth of Discharge

DV: Driverless Vehicle

ECU: Electronic Control Unit

EMI: Electro-Magnetic Interference

EV: Electric Vehicle

FSG: Formula Student Germany

FSS: Formula Student Spain

GND: Ground

GUI: Graphic User Interface

HV: High Voltage

HVD: High Voltage Disconnect

IC: Integrated Circuit

IMD: Insulation Monitoring Device

ISO: International Standard Organization

LiPo: Lithium-ion Polymer

LV: Low Voltage

NC: Normally Closed

NO: Normally Opened

PCB: Printed Circuit Board

PMSM: Permanent Magnet Synchronous Motor

PWM: Pulse Width Modulation

SAE: Society of Automotive Engineers

SC: Shutdown Circuit

SCS: System Critical Signal

SoC: State of Charge

SPST: Single Pole Single Throw

TS: Tractive System

TSAL: Tractive System Active Light

TSMP: Tractive System Measurement Point

TSMS: Tractive System Master Switch

TVS: Transient Voltage Suppression

1. INTRODUCTION

We are living the change of an era. Now more than ever, there is a great awareness regarding the protection of the environment. Ecological movements and governments' new emission regulations regarding traditional internal combustion engine vehicles (CV) have made inevitable a transition to the electrification of the automotive industry.

This transition is happening a lot faster than it was expected, and so, the industry is determined to abandon the CVs and step into the field of the electric vehicles (EV). The principal car manufacturers and important electricity production, distribution and commercialization companies, as well as governments from all over the world, have made great economic investments and have started to participate in new global initiatives, such as the EV100 initiative, in order to accelerate this transition.

The racing and competition industry is no less committed to this transition. New competitions, such as Formula-E, have emerged in the last few years to push the I+D on electric vehicles. Same happens for the Formula Student competitions, in the last few years the organizers of this competition have encouraged the teams to focus in the electrification of the vehicles alongside the Driverless Vehicles (DV).

1.1 Formula Student

Formula Student is an international level engineering student competition which consists in the design, manufacturing and testing of a racing single-seater car. Teams are composed by students from different engineering disciplines (e.g. mechanical, electricity, electronics, etc.). Every year, each team can attend different competitions around the world, placed in many famous circuits.

These competitions are organized by the Society of Automotive Engineers (SAE). In Europe, many competitions are held during summer, such as Formula Student Germany (FSG) in Hockenheimring circuit or Formula Student Spain (FSS), held in the Circuit of Catalunya Montmeló. Furthermore, the competitions give the opportunity to many engineering students to acquire knowledge and formation in the field of the racing vehicles, and for many it is the first step into the electric vehicles field.

The competition is divided in three main categories: CV, EV and DV. Each category has two main event types: static events and dynamic events. The former consists in three events, Business Plan, Cost & Manufacturing and Design where each team has to defend and show the judges the design, documentation and decisions taken through the season, while the latter consists in five events, Skidpad, Acceleration, Autocross, Endurance and Efficiency, where the car competes in the circuit to obtain the best score possible within its category.

Before the dynamic events, each team must go through a technical inspection or scrutineering to verify that the designed vehicle is rule compliant and it is secure to pilot. This technical inspection is divided in five parts: mechanical inspection, accumulator inspection, electrical inspection, rain test, tilt test and brake test.

The team from Tecnun University of Navarra is Tecnun eRacing, which was born in 2017 from the union of the previous two teams from the university: Tecnun Seed Racing (EV) and Tecnun Motorsport (CV). From that point, Tecnun eRacing has manufactured two vehicles, the TER18 and TER19, and is still manufacturing the third prototype.

The team's philosophy and work focus are grounded in three principal features: Reliability, simplicity and effectiveness. In order to get a decent place in the competitions, participating and finishing the dynamic events are of paramount importance. The team has struggled to participate in the dynamic events due to problems in the electric powertrain and rule compliance. The focus should be pointed to the reliability of the electric powertrain, while being compliant with the competition rules.

Figure 1: TER18 and TER19

1.2 Motivation

This project arises from the necessity of Tecnun University of Navarra's Formula Student team to improve the reliability of the vehicle in the field of the electric powertrain focusing on the electronics inside the accumulator container.

The lack of reliability in the inverters and in the cell voltage and temperature measurements, imprecision in the voltage and current measurements in the battery and the compliance with the Formula Student Germany rules have not allowed the team to successfully complete the technical inspection in little time during competition, depriving the team from participating in all dynamic events in the last two years.

This has forced the team to redesign some critical systems in the electric powertrain which include the electronics of the accumulator container and the distribution of the inverters. In the last two years great progress has been made in this field, but still, a lot of research and development from the team is needed.

1.3 Project scope, objectives and structure

One of the objectives of this project is to document the knowledge acquired in the last three years by gathering the failures of previous designs, solutions, improvements for better performance and by stating future objectives and work lines the team should focus on when developing the electric powertrain of the vehicle. Every component selection and design has been justified either by the need to comply with the FSG 2020 rules or by past experiences of the team, positive and negative.

However, the main objective is to design and manufacture the systems of an electric powertrain with the premise that it has to be a reliable design for the team to be able to compete as it should, following the team's philosophy. To achieve this, each system explained in this project has followed the same structure: first, the respective system's features are briefly commented, the relevant rule set for that part is listed and if the respective system is a redesign of previous designs, the experiences and failures of them are documented, justifying the need for a new design. Afterwards, the new design is explained and justified. Finally, if applicable, the new design is tested. This will also help the team to set lines of work that will help to achieve good results (definition of the system, required rule set, previous experiences and justification of new designs).

Furthermore, the last vehicle manufactured by the team, has a maximum power of 48 kW. Another objective is to design the powertrain with 80 kW of power, the maximum permitted by the FSG rules. This objective will be taken into account for the selection and design of many components.

This document is separated in two fundamental parts:

- **Electric Powertrain:** the systems involving the electric powertrain, this is, motors, inverters, accumulator container and intermediate systems are explained.
- **Battery Management System:** the additions and redesigns regarding the BMS (master and slave) are explained.

2. STATE OF THE ART

The state of the art of the electric powertrain and BMS of commercial and Formula Student EVs will be analyzed in this chapter.

2.1 Electric Powertrain

An electric vehicle is a vehicle that uses one or more electric motors for propulsion. This vehicle can either be powered through an energy storage system such as electrochemical batteries, or through an electric generator to convert petrol into electricity for hybrid vehicles.

The electric powertrain is the most important part of an electric vehicle and consists of three main parts: the electric motors, the DC/AC inverters and a battery accumulator.

Depending on the vehicle and the use-case scenario, the vehicle can have one or more motors distributed in the front and rear axle of the car. These electric motors can be induction motors or Permanent Magnet Synchronous Motors (PMSM). The PMSM is the most usual choice for electric mobility since they are more efficient and have the highest torque density, therefore, they are the most interesting choice for lightweight, high torque and high autonomy vehicles.

On the other hand, an element which converts the stored or generated DC current to AC current is also needed: the DC/AC inverter. This device is the responsible for controlling the electric motors and one inverter per motor is needed.

Furthermore, in order to store the electric energy in EVs, a battery accumulator is used. The battery accumulator, accumulator container from now on, is the responsible for storing the electric energy needed for the propulsion of the vehicle. This can be done with many different storing elements, but the most used ones are electrochemical cells or electrochemical cells with supercapacitors.

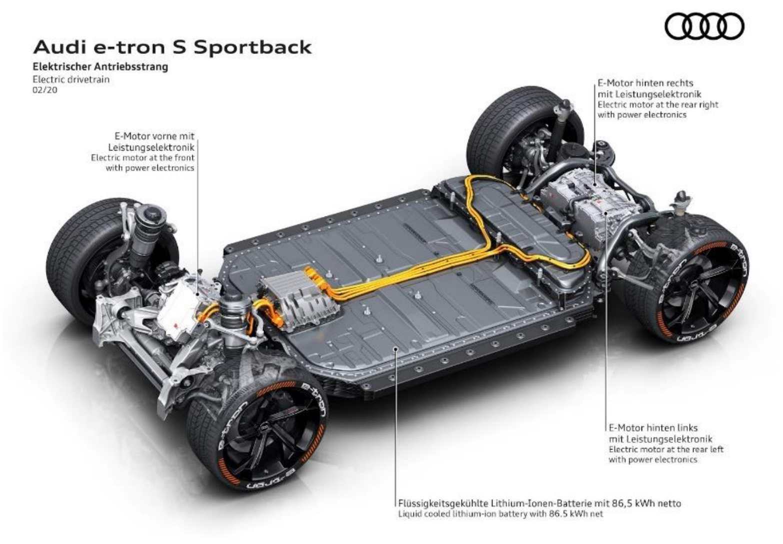

Figure 2: Powertrain of the *Audi e-tron*

In the case of Formula Student teams, there are many powertrain topologies. Regarding the electric motors, there are three main options: single rear motor with a differential, two independent rear motors or four independent in-wheel motors, being the most popular the last two. On the other hand, depending on the chassis and motor choice each team has either one or two accumulator containers, but using a single accumulator container is the most common option.

Using two independent motors or four in-wheel motors allow the teams to use a torque vectoring logic, thanks to the independence in the torque command of each motor. This gives a lot of advantage and greatly improves the handling of the vehicle, reducing the lap time of the car. Even though the four in-wheel motor option is the one used by the top teams and it is the ultimate objective for the design of the car, many teams still use the double rear motor topology.

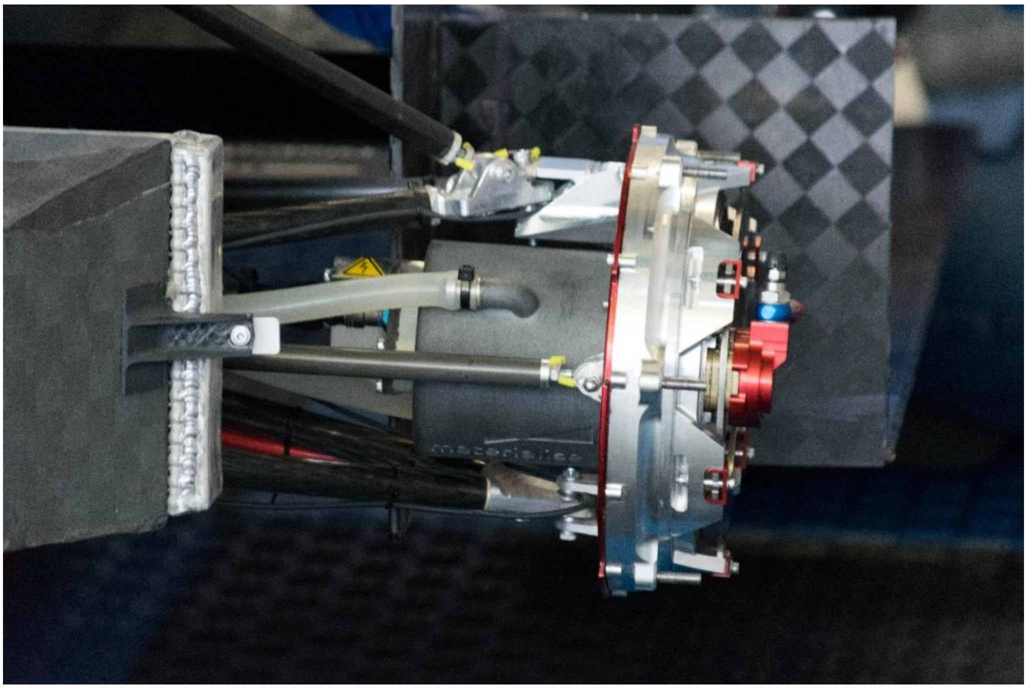

Figure 4: In-Wheel motor of a Formula Student

Figure 3: Powertrain of the KIT D19, Karlsruhe Institute of Technology

2.2 Battery Management System

The BMS is used to monitor the state of the battery cells, ensuring the right operation and the security of them. Many cell chemistries do not need any BMS system for their safety, such as lead-acid batteries used in current combustion cars for the low voltage system. This is not the case for most EVs, since they usually use Lithium-Ion Polymer (LiPo) cell chemistry.

The LiPo cells have a high energy density, they have no memory effect and have low self-discharge, so, these cells are light, small and loose very little charge if they are not used for a while. Despite these benefits, LiPo battery cells use flammable electrolyte, and so, a fault in the cell can cause an explosion or fire. These cells have a safe operation range between 3 V and 4.2 V, and if they are overheated or overcharged, they may suffer thermal runaway or rupture, which causes the electrolyte to be pressurized and so they can explode or catch fire.

For a safe operation, a system which monitors the operating ranges of the cells is needed: the BMS. This device needs to monitor the voltages of each battery cell in the accumulator container and their temperature If a value is out of range, the BMS must shut-down the battery and disconnect it from the load before it gets damaged. Furthermore, a BMS can have additional features, such as State of Charge (SoC) estimation, Depth of Discharge (DoD) estimation, cell balancing and current measurements.

The design of a BMS depends on the layout of the battery cells and their distribution, thus, there are different BMS topologies:

- **Centralized:** It is the most simple and cheap solution. Every cell is connected to the same PCB. This makes it difficult to use this topology in batteries with large number of cells, since a big wiring harness is needed.
- **Distributed:** This is the contrary of the centralized topology. A single cell is monitored with one PCB, denominated “slave” modules, and then it sends the measurements through a communication protocol (e.g. CAN bus, SPI, I2C, UART) to the “master” PCB.
- **Modular:** This topology is similar to the distributed topology, but the slaves used in this topology measure a stack of battery cells instead of a single cell. As in the distributed topology, the measurements of the cell stack are sent through a communication protocol to the master device. This topology is the most expensive, but the assembly is much simpler than the other two topologies.

There are many commercial solutions, such as the LTC6804 from *Analog Devices* or BQ76 series from *Texas Instruments,* used in the *Tesla Model S*.

2.2.1 BMS in Formula Student

In the 2019 FSS edition, 100 team attended the competition. Every year, it is expected for every team to present different solutions for their BMS system. Many teams design their own BMS since this allows the designer to design a specific BMS that fits perfectly in the system definition of their vehicle, designing a less bulky and optimized solution against a commercial one. On the other hand, there are teams which prefer to use a commercial solution as it is a plug-and-play solution. Examples of the commercial BMS are the Elithion Lithiumate pro (used previously by the team, distributed topology) or ORION (centralized topology).

The teams who design their own BMS usually select the modular topology. Among the characteristics for the design of the system, the most relevant choices are the communication protocol, current measurement method and the voltage measurement method. In figure 5, the BMS from Revolve NTNU team can be seen.

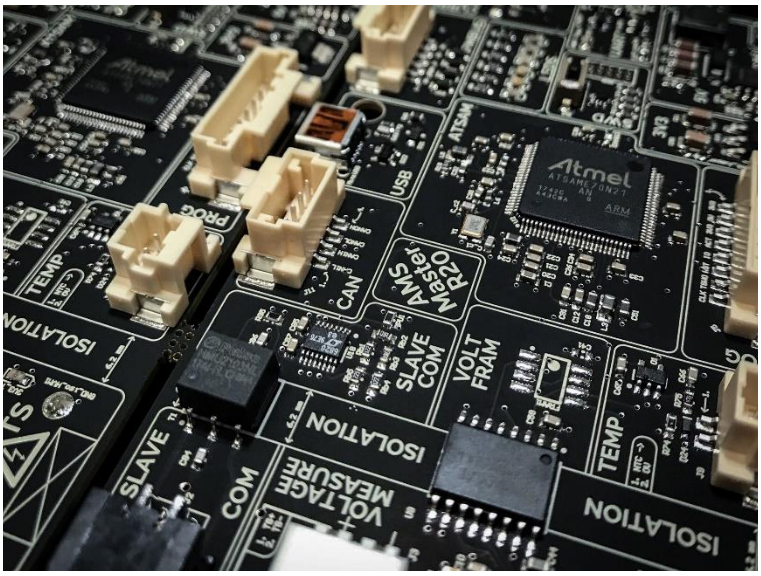

Figure 5: BMS from Revolve NTNU, *Trondheim NTNU*

The last BMS used by the team has been the BMS designed by Imanol Etxezarreta and Unai Echeverria and has been taken as reference. Some additions, changes and improvements have to be made due to the change in the FSG rules or problems in the operation.

3. ELECTRIC POWERTRAIN

The electric powertrain of the three cars manufactured by the team is composed of two independent PMSM with a gearbox attached, two DC/AC power converters, one per motor and a single accumulator container containing the batteries. In *appendix A*, schematics of the electric powertrain circuit can be seen. In figure 6, a picture of the current powertrain can be seen.

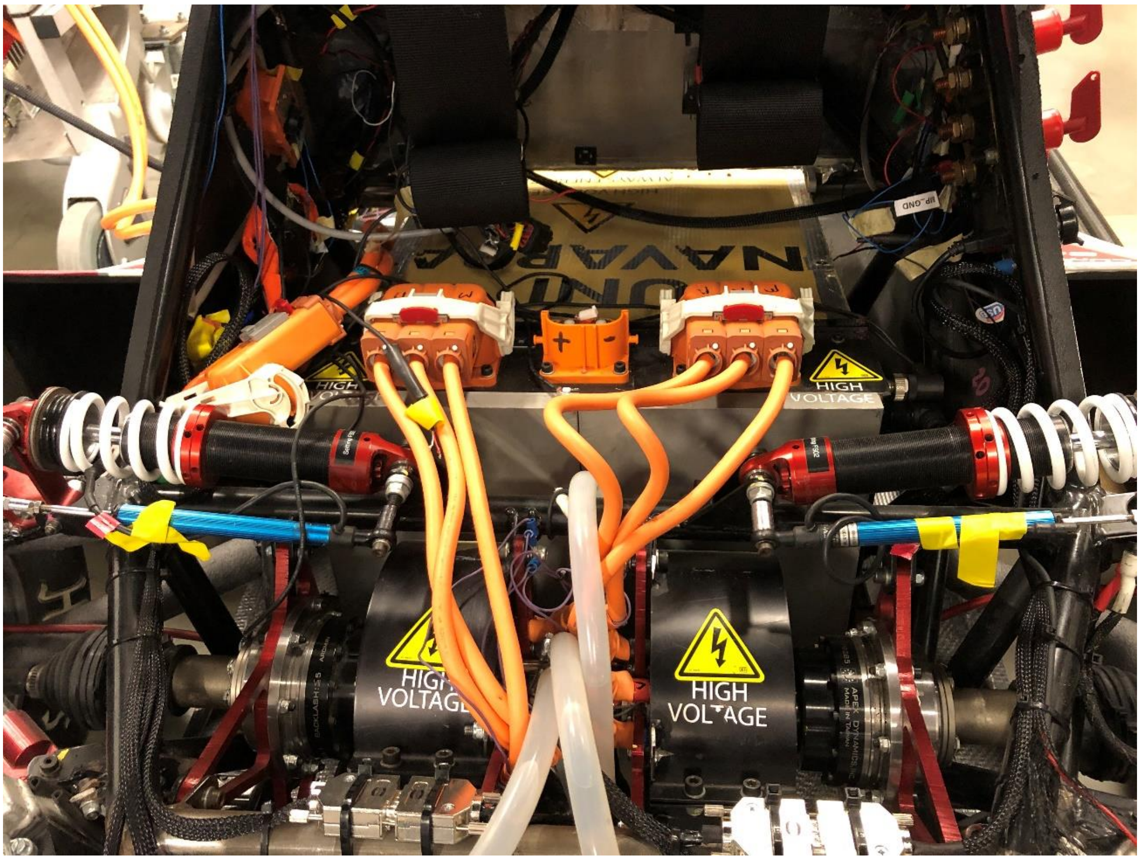

Figure 6: Powertrain of the TER19

The focus of the project is on the electronics of the accumulator container and the assembly of the powertrain rather than the powertrain itself, and so, the reasons and studies completed for the selection of the inverter and motor will not be covered thoroughly. Nevertheless, a description of the rest of used components is needed to understand the whole background and the system which the electronics will be assembled to. For this, a brief description of the actual inverter-motor topology will be made. In addition, the assembly of these components, the problems of this design and the systems inside the accumulator container will be explained.

3.1 Motor and Inverter

The used motors are the EMRAX 188HV from *Enstroj* and the inverters are the BAMOCAR D3 700-400 RS from *Unitek Industrie Elektronik GmbH*. Among other things, the main reason for using this inverter-motor configuration is that these two are tested together by the manufacturers, and so the inverter manufacturer can provide the team with better support and also the best configuration of the inverter, which is very helpful as a starting point.

Due to space restraints and weight reduction purposes, both inverters are placed inside the same container. Although both inverters are independent, they share the same DC link capacitors and DC bus through two long copper bus-bars, HV+ and HV-. The DC bus is then connected to both IGBT boards and afterwards, the motor connections are driven to a HV connector with more copper bus-bars. The mounting of the inverters can be seen in figures 7 and 8.

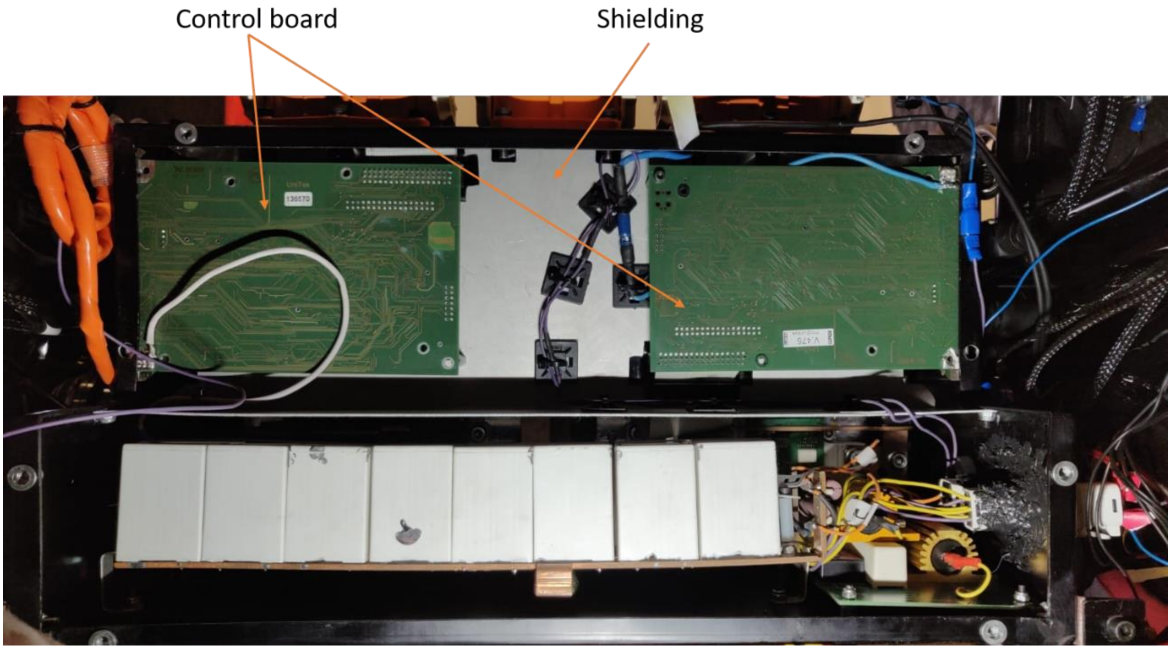

Figure 7: Inverter of the TER19. Control board and shielding

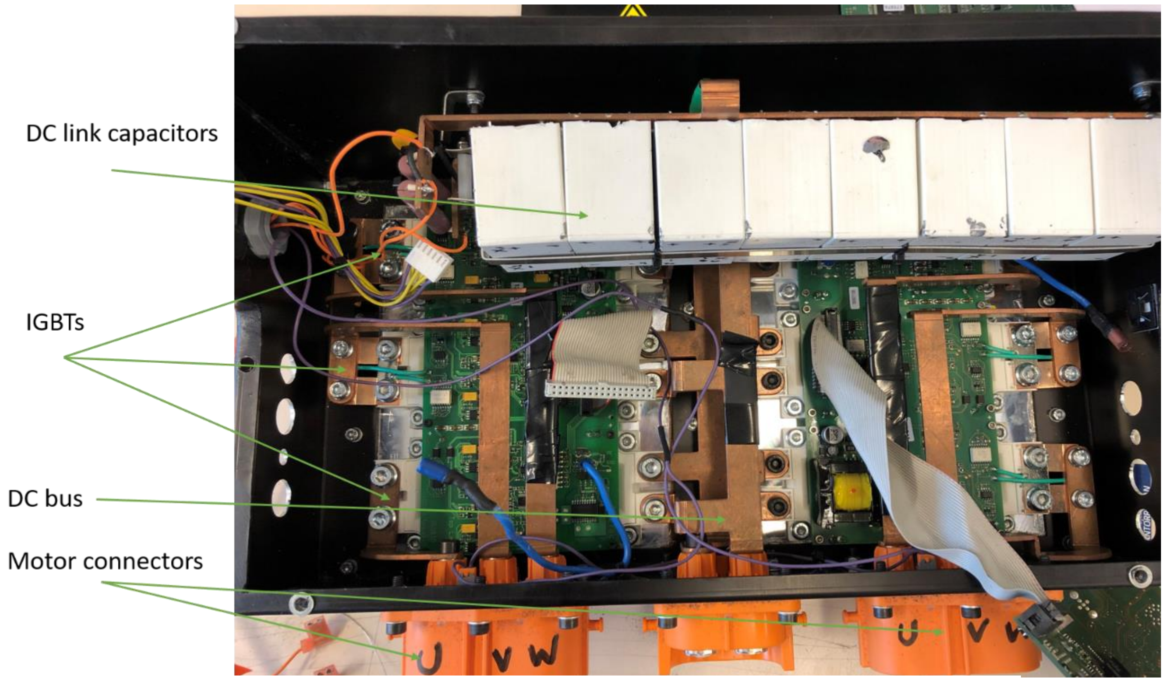

Figure 8: Inverter of the TER19. Power circuit

3.1.1 Electrical installation

The electrical connections needed for the control board from the inverter are separated in four connectors: control, motor feedback, CAN bus and RS232 for connections with a PC. The control connector withholds the supply and enable pins, the motor feedback connector withholds the motor temperature signals and resolver signals, the CAN bus connector withholds the two CAN bus connections and the RS232 connector withholds the connections needed to stablish communication with the PC for the parameter configuration. The connections needed for this use-case are:

Control Connector

In table 1, the mandatory signals are described. There are 4 pins in the connector just for the supply, two for 24V and two for GND. The other two signals, RFE and FRG/RUN, are two signals which can disable the inverter if the input value is 0 V. This serves as a safety feature. When the RFE signal is disabled, the rotating field will be blocked, and so, the motor will be free of torque. On the other hand, the FRG/RUN acts as an enable signal for the inverter, if it is disabled, the servo-drive is electronically disabled, this is, there will not be any PWM pulses. Also, the manufacturer specifies that when switching on the inverter, at least 0.5 seconds after the RFE has been enabled must pass to enable the FRG/RUN pin.

Control connector	
Name	Description
GND24	Auxiliary voltage ground
+24	Auxiliary voltage +
GNDE	Logic ground
+24v	Auxiliary voltage +
FRG/RUN	Enable
RFE	Rotating Field Enable

Table 1: Control connector of the inverter

Motor Feedback

One of the most important parameters for the motor control, is the position of the rotor. The position is measured by a position sensor, in this case, the Emrax motor incorporates a resolver. The manufacturers of the inverter and the resolver specify in their respective datasheets the connections of the resolver. In figure 9, the connections are defined. In figure 10, the position of the resolver in the motor axis can be seen.

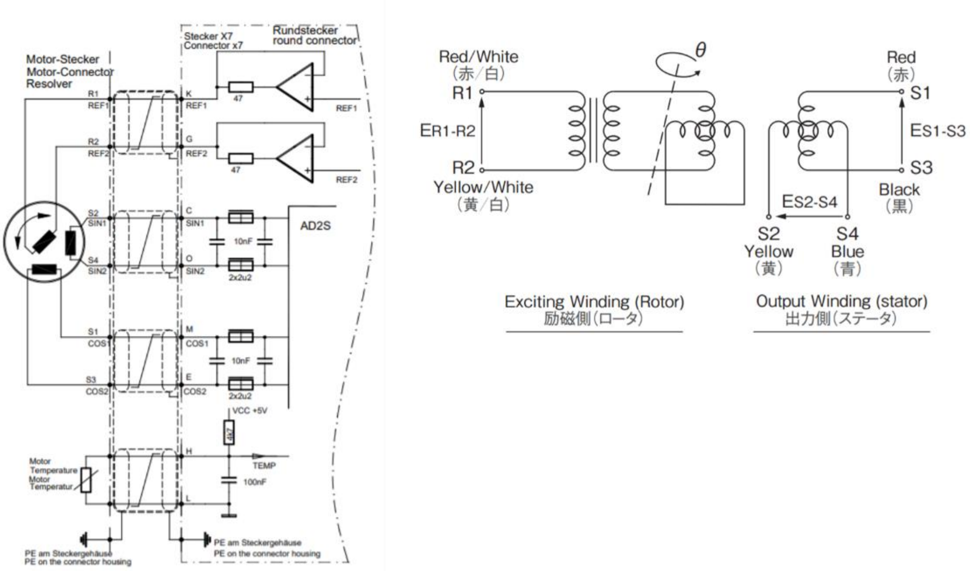

Figure 9: Connections of the resolver

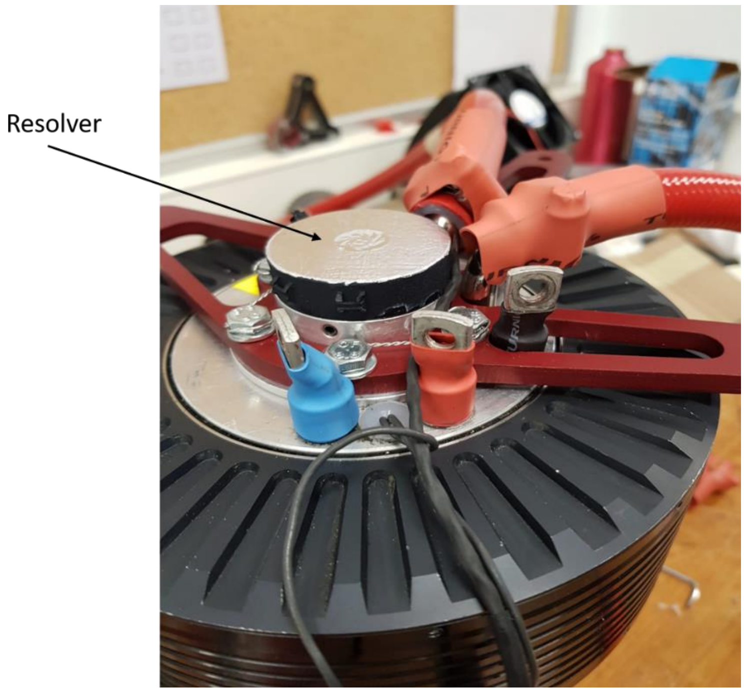

Figure 10: EMRAX 188HV with resolver

3.1.2 Setting of the parameters

Unitek provides a Graphical User Interface (GUI) for the configuration of parameters, called NDrive. If a computer with this program is connected to the inverter via the RS232 connector and the low voltage supply is switched on, different parameters of the inverter, such as switching frequency or maximum revolutions per minute, can be tuned. Every parameter is explained in the NDrive manual from *Unitek*. In figure11, a screenshot of this program can be seen.

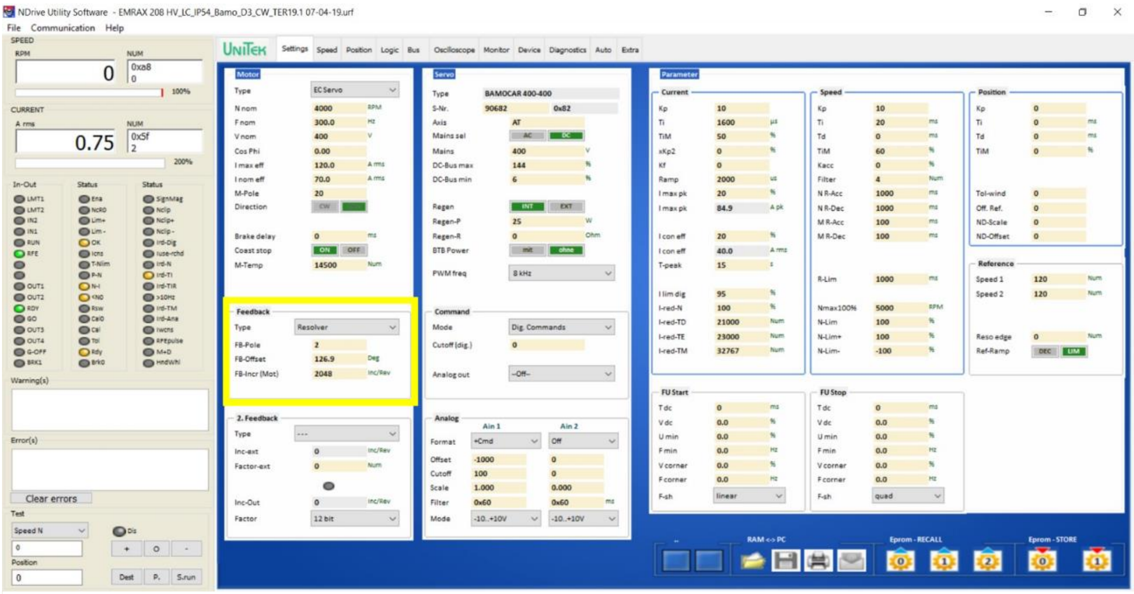

Figure 11: NDrive

Furthermore, in figure 11 the highlighted area shows the Feedback sensor parameters. The parameter that has to be configured every time the inverter or the motor is changed, is the offset of the resolver, which is measured in degrees. In order to obtain this parameter, an auto-tuning must be made, more about this process is explained in *appendix B*.

3.1.3 Problems

During the 2019 season, the inverter had numerous failures, damaging the IGBTs and needing a repair. After doing some research and asking the manufacturer about this design, the issue that most likely produced these failures seemed to be that the DC link capacitators were too far away from the IGBTs, and that the long copper bus-bars driving the DC bus were too large. In addition, the DC link capacitor values were also too low, the manufacturer suggested that each inverter should have their own DC link capacitors.

To solve this problem, a new inverter container design has been made during the 2020 season with the help of Jaime Jauregui, which is yet to be tested. In figures 12 and 13, this design can be seen.

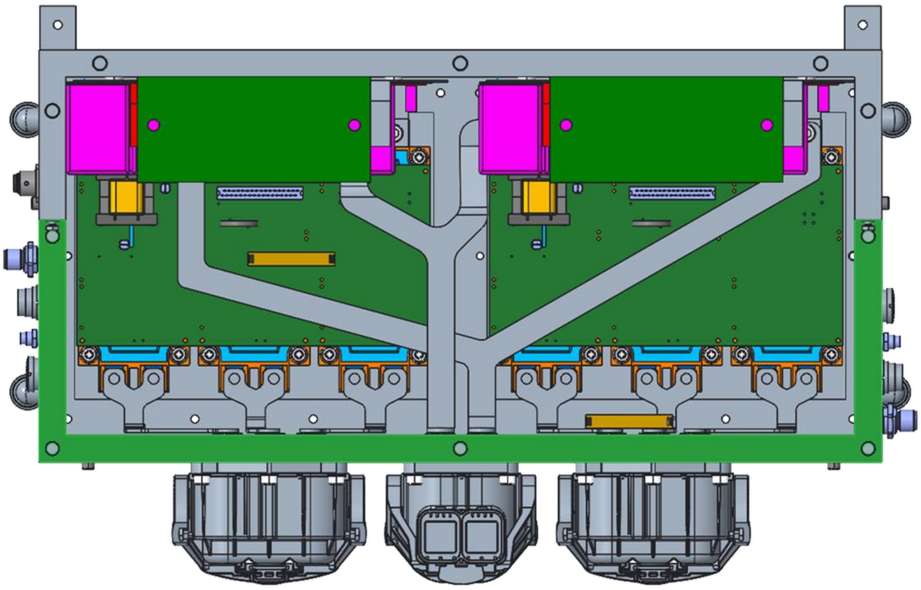

Figure 12: Inverter of the TER20. Upper view

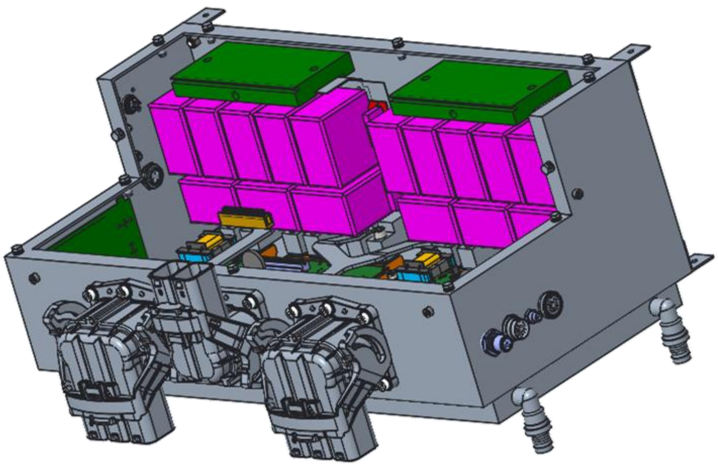

Figure 13: Inverter of the TER20. Perspective view

With this design, each inverter will have their own DC link capacitors, and are much closer to the IGBTs than in the first design. Even so, the bus-bars driving the DC bus are most likely still too large, if problems still happen because of this, using shielded cables or changing the distribution again could be a solution, so that the bus-bars are much smaller.

Another problem that happened during the 2019 season was that whenever the accumulator container's fuse melted, some IGBTs were damaged and needed to be replaced. The only protection the DC bus has, is the accumulator container's fuse. There is no protection between the inverter and the motors, so, the failure could have happened in a motor. Since there is no protection until the accumulator container, the overcurrent passing through the IGBTs could have been the reason why they were damaged. Protections between inverter and motor have not been placed due to space constraints, but it is strongly recommended to place a fuse for each motor phase, for example, in the bus-bars connecting the IGBTs with the motor connectors, with a fuse similar to the one in figure 14, which can be easily installed if there is enough space.

Figure 14: Fuse example

3.2 Accumulator Container

The accumulator container is the responsible for storing all the battery cells the vehicle needs alongside the electronics to monitor and control these battery cells. The accumulator container is one of the most important parts of the vehicle, from the point of view of the car's performance but also from the safety point of view and thus, this container is strictly regulated by the FSG rules.

The battery configuration has not changed since the 18th season due to the fact that the chassis of the vehicle has barely changed, and the space reserved for the accumulator container has been reduced. Even so, the configuration will be explained alongside future recommendations and problems that have been noticed with it.

In this chapter, the systems of the accumulator container and other components that directly affect the selection or design of the systems will be explained.

In figure 15 and 16, the actual accumulator container can be seen.

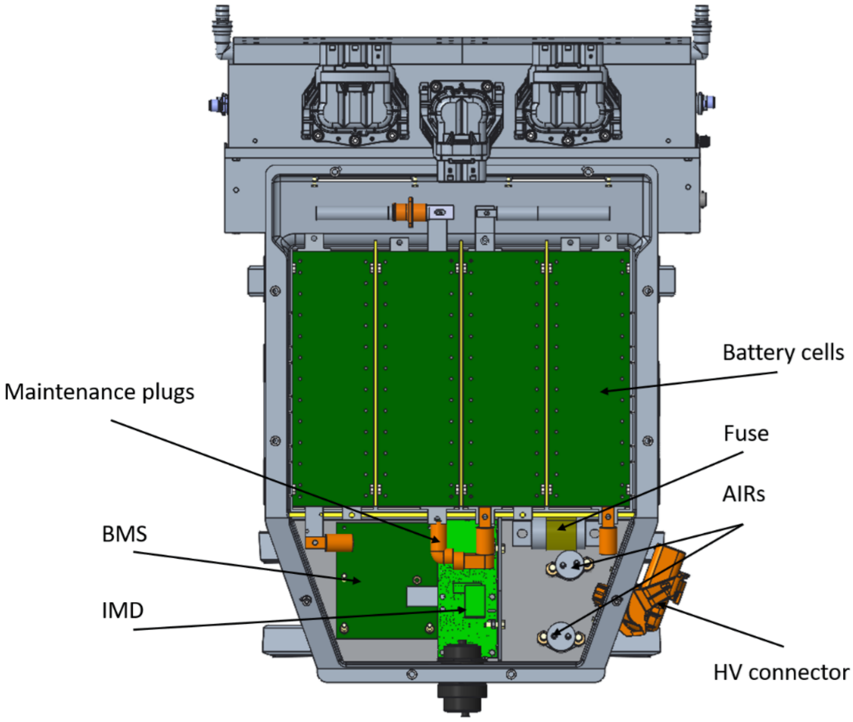

Figure 15: Detailed accumulator container

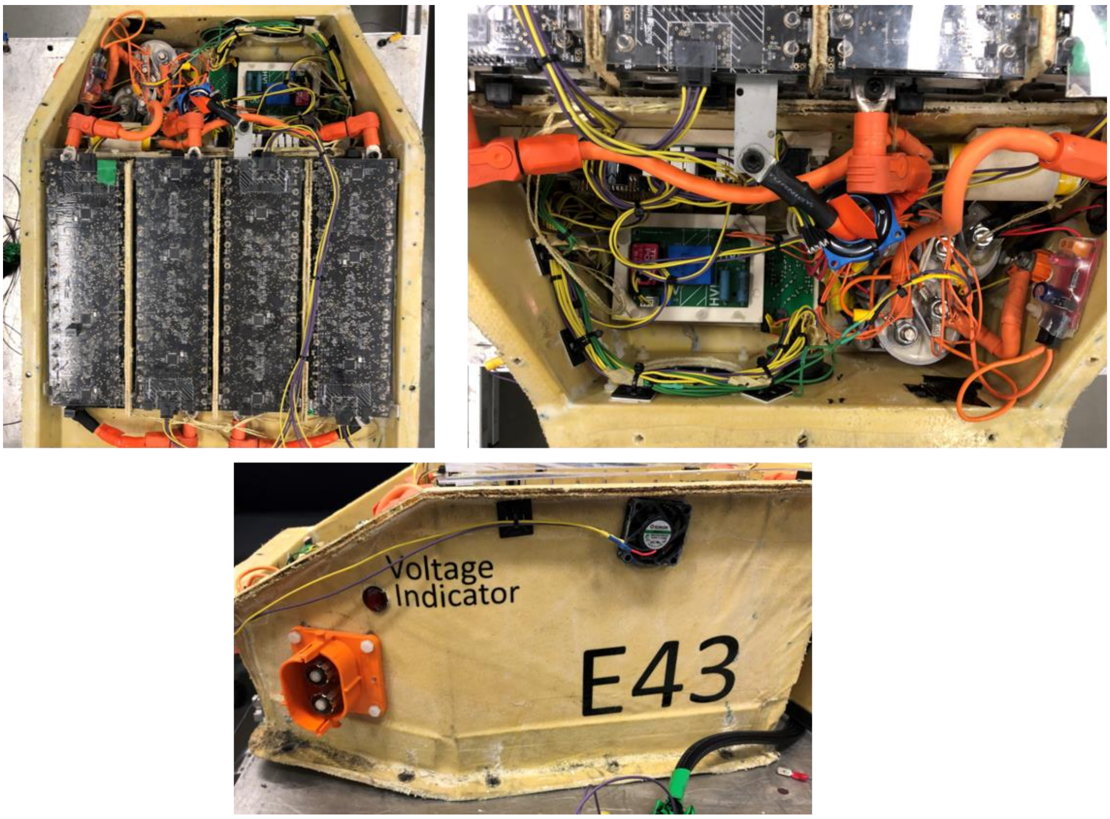

Figure 16: TER19 and TER20 accumulator container

3.2.1 Battery and assembly

The vehicle's battery is composed by lithium-ion battery cells with a $LiCoO_2$ chemistry. The battery has a configuration of 96s1p, this is, 96 cells in series and no cells in parallel. The battery cell used in this vehicle is the SLPBA375175 from *Melasta.* In table 2, the properties of this cell are listed.

SLPBA375175	
Nominal voltage [V]	3.7
Maximum voltage [V]	4.2
Cut-off voltage [V]	3
Capacity [Ah]	16
Max. Continuous discharge current [A]	240
Peak discharge current [A]	360 for 0.3 seconds
Max. Continuous charge current [A]	16

Table 2: Battery cell specifications

The configuration and assembly of the battery packs is restraint by the FSG rule listed below:

EV 5.3.2 *Each TS accumulator segment must not exceed* ***a maximum static voltage of 120 VDC, a maximum energy of 6 MJ****, see EV 5.1.2, and a maximum mass of 12 kg.*

As the rules state, each battery pack cannot have a voltage greater than 120 VDC and 6 MJ of energy. With this limitation the battery has been distributed in 4 battery packs, with 24 cells each. This configuration, per equation 1, gives an energy of 5.8 MJ and 100.8 V per stack.

$$Energy\ [J] = Voltage\ [V] x\ Capacity [Ah] x\ 3600 \frac{s}{h}$$

Equation 1: Energy of the accumulator container

Furthermore, this configuration will provide 403.2 V of maximum battery voltage, 288 V of minimum battery voltage and an energy of 6.45 kWh.

The cell tabs are connected by two aluminum bus-bars placed between two bolts and then pressed by two self-locking nuts. More about this connection method can be found in "*Diseño e implementación de la batería y del módulo esclavo del BMS para un vehículo eléctrico de Formula Student"* by Unai Echeverria. In figure 17, a CAD figure of the connections can be seen.

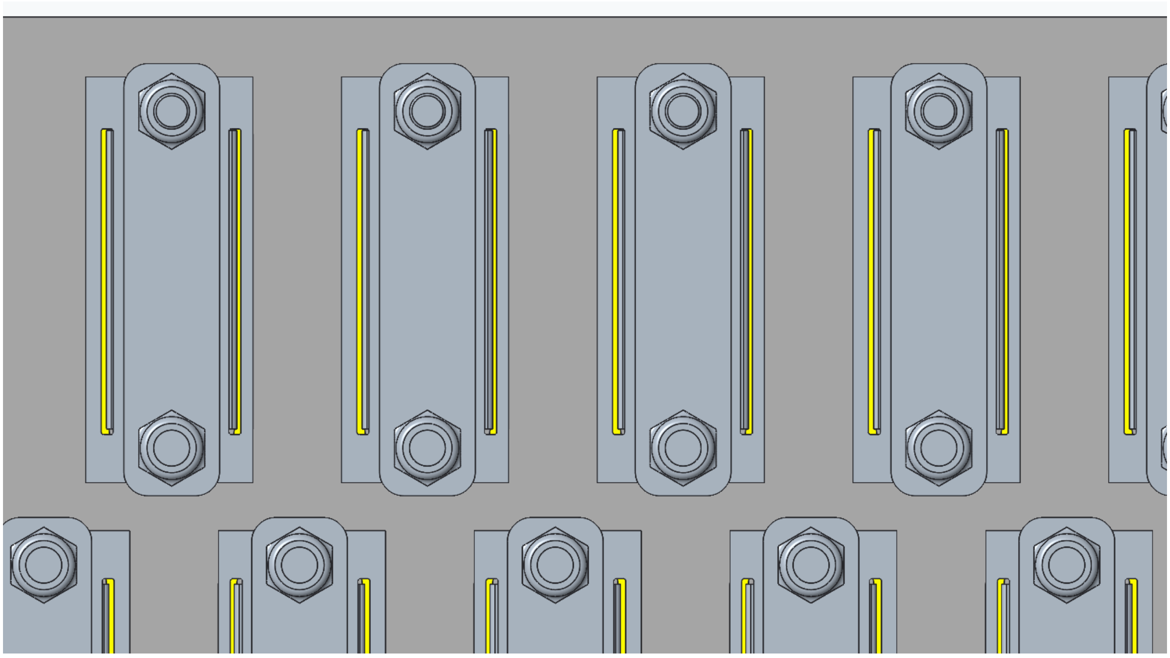

Figure 17: Cell connections

The major issue of this design has been the use of self-locking nuts for the connection between cells and the connection of the slave module of the BMS with the cells. If maintenance of the slave modules or the change of a cell is needed, all self-locking nuts must be removed. This kind of nuts can easily deform the bolt, making it impossible to re-introduce another nut. If this were to happen, the battery pack has to be fully disassembled and the bolt must be changed. This is very time consuming and can be dangerous since battery cells can easily be short-circuited between them when removing them as there is little space. This issue can be seen in figure 18.

Figure 18: Deformed bolt

3.2.2 Shutdown Circuit

The shutdown circuit is a safety line which drives important devices, such as the Accumulator Isolation Relays (AIR). The shutdown circuit, SC from now on, is made up of relays, shutdown buttons and interlocks, supplying the AIR's coils in the end of the line. The SC is a Low Voltage (LV) line of 24 V whose task is to shut down the supply of the AIRs in the event of a failure, disconnecting the battery from the rest of the vehicle. This is, if the SC is opened, the AIRs coils will not be supplied and they will open, since they are Normally Open (NO) type relays.

The specifications of the SC are defined in the FSG rules:

EV 6.1.1	*The **shutdown circuit directly carries the power driving the AIRs**, see EV 5.6, and the pre-charge circuitry, see EV 5.7.*
EV 6.1.2	*The shutdown circuit is defined as a series connection of at least two master switches, three shutdown buttons, the BOTS, see T 6.2, the IMD, the inertia switch, see T 11.5, the BSPD, see T 11.6, all required interlocks and the AMS.*
EV 6.1.4	*The Tractive System Master Switch (TSMS), see EV 6.2, must be the last switch before the AIRs except for pre-charge circuitry and hardwired interlocks.*
EV 6.1.5	*If the **shutdown circuit is opened, the TS must be shutdown by opening all AIRs and the voltage in the TS must drop to below 60 VDC and 25 VACRMS in less than five seconds**. All accumulator current flow must stop immediately. The action of opening the AIRs may be delayed by ≤250 ms to signal the action to the motor controllers and reduce the TS current before the AIRs are opened. The AIR supply must be abruptly switched off before reaching the minimum AIR supply voltage.*
EV 6.1.7	*All circuits that are part of the shutdown circuit must be designed in a way, that in the **de-energized/disconnected state they open the shutdown circuit**.*
EV 6.1.9	***Every system** that is required to or is able to open the shutdown **circuit must have its own, non-programmable, power stage to achieve this**. The respective power stages must be designed to be able to carry the shutdown circuit current, e.g. AIR inrush currents, and such that a failure cannot result in electrical power being fed back into the electrical shutdown circuit.*

In figure 19, a detailed schematic of the shutdown circuit of a Formula Student vehicle is shown.

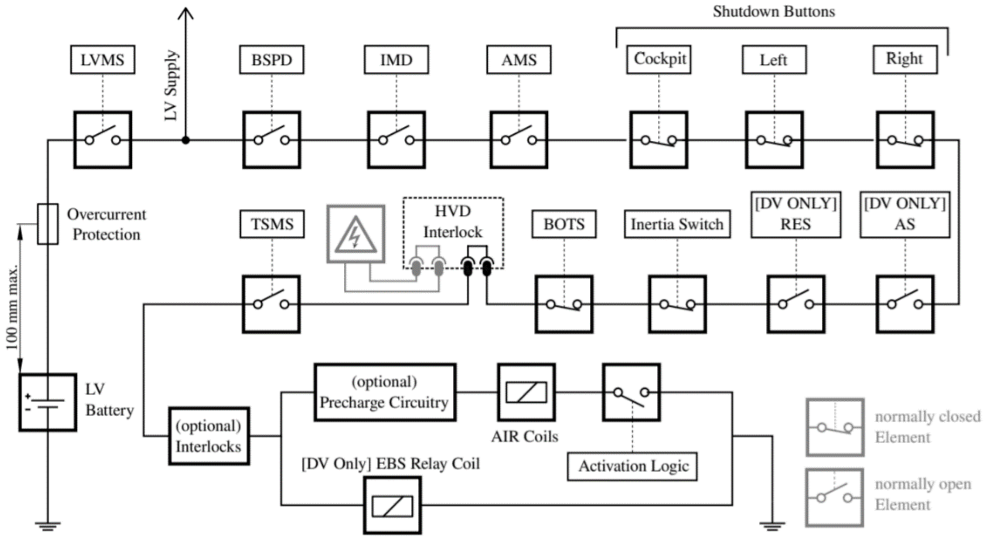

Figure 19: Shutdown Circuit example

The elements that matter for the study of the HV circuit, also known as Tractive System (TS), are the IMD, AMS (BMS), HVD, TSMS, AIR and interlocks from all the HV connectors in the vehicle. The IMD and AMS have their own power stage to open the shutdown circuit and will be covered in *chapter 4.1.1*. The High Voltage Disconnect (HVD) is a manual switch located in the HV circuit so that it can be opened manually. This is useful to disconnect the battery from the vehicle if the AIRs are stuck or to make maintenance to the vehicle with visual indication that the HV circuit is opened and that there is not HV present in the rest of the vehicle.

The HVD and the HV connectors have an interlock integrated in them so that the shutdown circuit can be driven into them, this way, if any connector is not correctly connected or fully disconnected, the shutdown circuit will remain opened and the closing of the AIRs will not be possible.

The Tractive System Master Switch (TSMS) is a manual switch located in the right side of the vehicle. This is the last switch the person responsible for switching on the car will manually activate and, as the rules specify, it must be the last element in the SC.

3.2.3 High Voltage Components

In this chapter, the HV components which are either inside the accumulator container or affect directly on the components inside the accumulator container will be explained.

Accumulator Isolation Relays

The AIRs are a mandatory feature in the vehicle as the rules state:

EV 5.6.2 ***The AIRs must open both poles of the TS accumulator****. If the AIRs are open, no TS voltage may be present outside of the accumulator container and the vehicle side of the AIRs must be galvanically isolated from the accumulator side, see EV 1.2.1.*

EV 5.6.3 *The AIRs must be mechanical relays of a* ***"normally open"*** *type. Solid-state relays are prohibited.*

Each accumulator container must have two AIRs, one for each battery pole. These contactors must be mechanical type NO relays which are powered by the shutdown circuit, so if there is any fault in the shutdown circuit, or the vehicle is powered off, the supply to the AIRs will be interrupted leading to their opening and disconnection of both battery poles.

When selecting the contactors, the rated voltage, rated current, isolation capacity and number of cycles must be considered. If the rated current is below the maximum current flow of the vehicle, the contacts will surely degrade and the contactors may not be able to open, as the contacts may get stuck. The contactors are of paramount importance to ensure the safety and reliability of the car, and so, the selected contactors will be oversized. So, the selected contactors must meet these principal specifications:

- Rated voltage ≥ 403.2V
- Rated current ≥ 240 A
- Coil voltage = 24 V

With these specifications, the contactor KILOVAC EV200 HAANA from *TE Connectivity* has been selected. In table 3, the characteristics of the selected contactor can be seen:

Contact arrangement	Form A SPST-NO
Rated operating voltage	900 VDC
Continuous carry current	500 A
Coil voltage	24 VDC
Mechanical life	1 million cycles
Mounting of power terminals	M8 Threaded rod

Table 3: AIR specifications

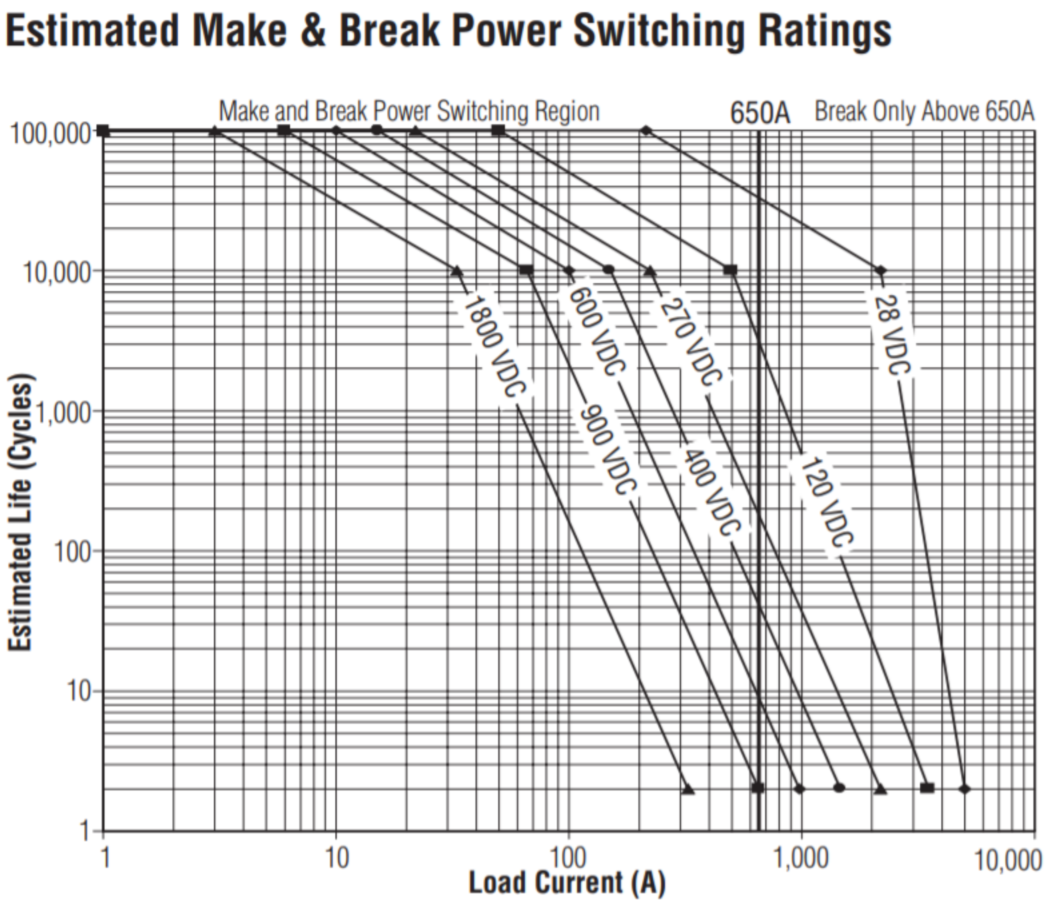

Figure 20: Estimated make and break power switching ratings from the AIR

For the Tractive System voltage of the vehicle (403.2 V) and maximum current (240A), the estimated life of the contactors is about 2000 cycles, which is quite enough for a formula student type vehicle.

In addition, this contactor has an extra feature which is very helpful for the safety systems of the car: auxiliary contacts. These auxiliary contacts serve the purpose of monitoring the mechanical state of the power contacts of the relay, this is, if it is open or closed, making it easy to detect if the relay gets stuck. This feature will be extremely helpful for the Tractive System Active Light, which will be covered in *chapter 4.1.2*.

High Voltage cables

The FSG rules specify a minimum requirements the high voltage cables must meet:

EV 4.5.5 All TS wires must be marked with wire gauge, temperature rating and insulation voltage rating or a serial number/norm printed on the wire if clearly bound to the wire characteristics for example by a data sheet.

EV 4.5.8 ***All TS wiring that runs outside of TS enclosures must be enclosed in separate orange non-conductive conduit or use an orange shielded cable****. The conduit must be securely anchored to the vehicle, but not to wire, at least at each end.*

EV 4.5.9 Any shielded cable must have the shield grounded.

The maximum power allowed by the FSG rules is 80 kW and the maximum current of discharge of the cells is 240 A, so, this current may be discharged when the battery is below 333V, thus, the wire section selected should be able to withstand this current. Although the wire will be selected for 240A, the current will never reach this current as it is the maximum current of the cells, it will be limited by software.

In addition, the wires must also have a shield if they are placed outside an enclosure. This is typical in electric vehicles, so electric vehicle suppliers offer a wide range of high voltage automotive cables. In figure 21, this kind of wires can be seen.

The selected cable has been a copper 35 mm^2 shielded cable, the FHLR2GCB2G from *Coroplast*. The maximum voltage this wire can withstand is 1000V, well above the battery voltage for this vehicle and the operating temperature goes up to 180°C. Furthermore, the manufacturer provides a graphic comparing the conductor's temperature against the continuous current of the wire for different ambient temperatures. Since the car will be competing in summer, in competitions such as Formula Student Spain in Montmeló, where the temperatures can go up to 40°C during the competition, this temperature may be taken as ambient temperature. So, for this ambient temperature, the wire can withstand currents up to 310 A until reaching the 180°C in the conductor, so this wire is valid for this application.

The selected cable could have also been a 25 mm^2 wire, but the current rating of the maintenance plug and the HV connector are much lower than the ones needed for this application with a 25 mm^2 wire. Using a 35 mm^2 wire, this problem disappears. Nevertheless, for a proper section selection, a thermal study inside the accumulator container with its cooling should be made. The graphic of the temperature can be seen in *appendix D*.

Figure 21: HV cable

Maintenance Plugs

If the battery segments were connected in series permanently, it would be dangerous to work with the segments, as the voltage would be very high. To solve this problem, maintenance plugs are placed in the poles of each battery pack, which allows the user to connect and disconnect the segments from each other and lower the voltage to be safer to work.

The FSG rules regarding this element are listed below:

EV 5.4.4 *Maintenance plugs must allow electrical separation of all TS accumulator segments, see EV 5.3.2. The separation must affect both poles of all segments including first and last segment.*

EV 5.4.5 *Maintenance plugs must:*

- ***not require tools** to separate the TS accumulator segments.*
- *be **non-conductive on surfaces** that do not provide any electrical connection.*
- *be designed in a way, that it is physically impossible to electrically connect them in any way other than the design intent configuration.*
- *be designed such that it is clearly visible whether the connection is open or closed. Electrically controlled switches must not be used.*

With these requirements, the SLPPB50BSO connector from *Amphenol Industrial* has been selected. These connectors are specially designed for electric or hybrid vehicles, battery management systems and energy storage amongst others. In addition, these maintenance plugs have a flammability rating of UL94 V-0, which is also needed for the battery segments. In figure 22, these connectors can be seen.

Figure 22: Maintenance plug

Furthermore, the manufacturer provides a graphic comparing the maximum operating current against the ambient temperature. The maximum temperature the cells can withstand is 60°C, so the ambient temperature will not go higher than this. With this temperature, the maximum current of this maintenance plug is about 260A, greater than the cells maximum discharge current (240A). In figure 23, in orange, the curves for the selected connector can be seen.

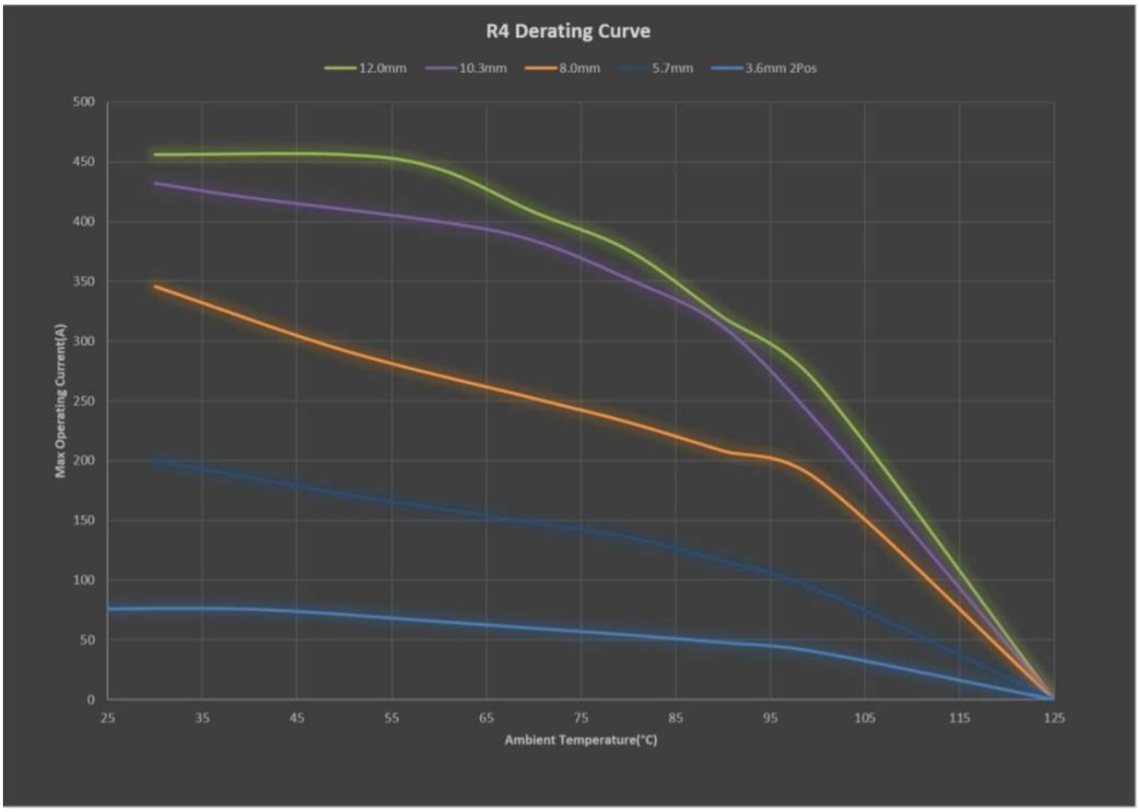

Figure 23: Maintenance plug derating curve

High Voltage Connector

A HV connector is needed in the accumulator container to plug it and unplug it from the charger or the vehicle. This connector must be able to withstand the maximum battery voltage and the maximum current. Furthermore, the connector must also include an interlock (also known as HVIL) to open the shutdown circuit when the connector is not connected. Then again, there is a wide range of HV connecters designed for electric mobility available in the market. The maximum battery voltage is 403.2V, and the maximum discharge current of 240A, with these requirements, the HVP800 connector from *TE Connectivity* has been selected. This connector withstands 850 VDC and 250A. In figure 24, the connector can be seen.

Figure 24:HV Connector. HVP 800

High Voltage Disconnect

There is a possibility for the HV to be touching the chassis, in that case, anyone who touches the chassis will electrocute themselves. Because of this, an element which disconnects at least one pole of the battery is needed, so that if this happens, the circuit can be opened quickly.

The FSG rules regarding the HVD are listed below:

EV 4.8.1	*It must be possible to* ***disconnect at least one pole of the TS accumulator by quickly removing an unobstructed and directly accessible element, fuse or connector****. It must be possible to disconnect the HVD without removing any bodywork. The HVD must be above 350 mm from the ground and easily visible when standing behind the vehicle. Remote actuation of the HVD through a long handle, rope or wire is not permitted.*
EV 4.8.2	*An* ***untrained person must be able to remove the HVD within 10 s*** *when the vehicle is in ready-to-race condition.*
EV 4.8.3	*A dummy connector or similar may be required to restore the system's isolation, see EV 4.5. The dummy connector must be attached to the push bar, see T 13.1, if not in use.*
EV 4.8.4	*The HVD must be clearly marked with "HVD".*
EV 4.8.5	***No tools must be necessary to open the HVD. An interlock is required****, see EV 4.5.10.*

The rules state that it must be an accessible element, which allows its removal without any tools and has to feature an interlock. With these premises, two connectors used in electric vehicles were chosen for analysis: the EM30MSD from *Hirose* and the MSDM2502 from *Amphenol Industry*. Both withstand currents up to 250A and greater voltages than the battery voltage, but since the HVD from Hirose is smaller, this has been the one selected. In figure 25, this HVD can be seen.

Figure 25: HVD. EM30MSD

Fuse selection

The components of the HVDC circuit must be protected from overcurrents or short-circuits since they are very expensive products. In order to select the right fuse, two things must be considered the maximum current of the elements placed in the HVDC circuit and the short-circuit current to know the maximum breaking current the fuse must have.

The current ratings of the HV elements are listed in ~~the~~ table 4:

Component	Continuous [A]	Max. current [A]
AIR	500	650
HVD	200	250[1]
Cable	-	280[2]
Connector	-	240[1]
Inverter	200	400
Maintenance plug	150[3]	260[2]
Cells	240	360 ≤ 0.3 seconds

Table 4: Current ratings of the TS components

The lower maximum current rating is set by the cells, in 240 A, while the lower continuous current rating is set by the maintenance plugs. In a vehicle, there is no continuous current, as the vehicle is always accelerating and decelerating, but even so, the fuse must blow in a certain amount of time if the continuous current value is overpassed. Regarding the maximum current rating, the fuse must blow in little time, since the components may get damaged if overpassed.

On the other hand, the maximum short-circuit current that may happen is when the short-circuit happens right after the fuse between both battery poles. The resistance will be the series resistance of all the battery cells. Although in the datasheet the cell manufacturer specifies that the resistance of each cell is ≤1.5 mΩ, the testing data of the cells provided by the manufacturer actually shows that the cells used in this vehicle have all around 0.6 mΩ, so this resistance will be taken as valid. Per equation 2, the short-circuit current is calculated:

$$Icc = \frac{V_{bat}}{R_{bat}}$$

Equation 2: Short-circuit current

$$R_{bat} = 96\ cell\ x\ \frac{0.6\ m\Omega}{cell} = 0.0576\ \Omega$$

[1] *for 40°C ambient temperature outside the accumulator container. Derating curves in* appendix D
[2] *for 60°C ambient temperature inside the accumulator container. Derating curve in* appendix D
[3] *used with 35 mm² cables*

$$Icc = \frac{403.2\ V}{0.0576\ \Omega} = 7\ kA$$

With these specifications, the SPFJ070 from *Littlefuse* has been selected. This fuse will melt for a current of 150 A in about 200 seconds and 240 A in 2 seconds. The melting curve of the fuse can be seen in *appendix D*.

3.2.4 Current sensing

Current sensing of the battery may not seem critical, but it is of great importance to monitor the current being drawn from the battery for many purposes, such as protection or calculating the State of Charge of the battery.

The maximum continuous discharge current of the battery is 240 A, but the fuse will trip before reaching this value, so when the battery is discharging the cells are protected. The same cannot be said when the cells are charging. Although the discharge current is high, in lithium-ion cells the charging current is not usually high. In this case the maximum continuous charging current is 16 A, so the cells will not be protected with the fuse. For cell protection when charging, a current sensor is needed so that when the maximum value is reached, the BMS can open the AIRs and stop the charging process.

The most used methods in the automotive industry for electrical vehicles are shunt resistors and Hall Effect sensors. For very precise measurements, a shunt resistor needs to be used, but it is intrusive, non-isolated, expensive for its low tolerances, power dissipation is a problem and it needs low resistivity , what makes it difficult to measure small currents as the voltage drop will be very small. Anyhow, for high currents the voltage drop will not be very small, so the signal amplification for its reading is a great challenge. On the other hand, the Hall Effect sensor provides a very easy implementation, isolation, high linearity and integrated signal conditioning to measure positive and negative currents. The counterpart is that these sensors have offset currents and for sensors which the current rating is high, measuring low currents is difficult. Nonetheless, for a formula student vehicle, the accuracy is still very good.

The Hall Effect sensor is the most suitable option for this accumulator container, mainly because of the size of it and because it can be installed around any TS wire in the accumulator container easily.

The selected sensor for current measurement is the HTFS 200-P from *LEM*. This sensor is a Hall Effect sensor which provides galvanic isolation between the primary and secondary circuits. Its maximum temperature is 105 ºC and the case is made from UL94-V0 rating material, what makes it ideal for this application. Furthermore, the sensor has a V_{ref} pin which allows the user to introduce a reference for changing the slope of the transfer function so that it can be implemented in more microcontrollers.

The nominal current range of the sensor is ±200 A, it has an absolute maximum of 300 A and the accuracy of the sensor is of ±1%, so a precision of 2 A is obtained.

This sensor allows to measure positive and negative currents (discharging and charging). With 0 A, the voltage output will be equal to the reference voltage. If the battery discharges, the voltage output will rise from the reference voltage up to the supply voltage of 5 V, and if the battery charges the voltage output will decrease from the reference voltage down to 0 V.

As the microcontroller’s maximum input voltage for reading is 3 V, the maximum voltage for the maximum current should be less than 3 V. The manufacturer provides the transfer function of the sensor, which is shown in equation 3:

$$V_{out} = V_{ref} \pm (1.25 * \frac{I_p}{I_{pn}})$$

Equation 3: Current sensor output

The maximum current measured in this study will be 240 A, and a maximum of 3 V must be achieved in the output, so per equation 3:

$$3 \geq V_{ref} + 1.25 * \frac{240}{200}$$

$$1.5 \geq V_{ref}$$

Furthermore, the manufacturer also provides two functions to calculate the upper limit and lower limit of the output voltage depending on the reference voltage (figure 26):

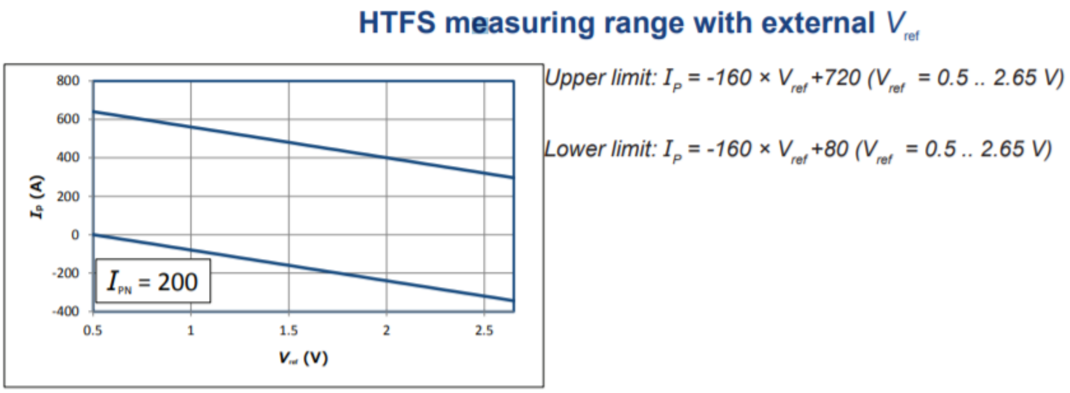

Figure 26: Current sensor measuring range in function of V_{ref}

With these equations and 1.5 V of V_{ref} the upper limit will be 480 A and the lower limit will be -160 A, more than enough for the range of current needed in this application. The circuitry needed for setting the V_{ref} and extra circuitry needed for the measurement will be explained in *chapter 4.1.3*.

3.2.5 Voltage Indicator

The AIRs may get stuck if the contacts are decayed and, if so, there can still be high voltage in the accumulator’s HV connector even if the low voltage is switched off. In order to increase the security for the worker who needs to disconnect the HV connector, an indicator must be placed in the accumulator so that it can be seen if it is secure to work. The FSG Rules regarding this feature are stated below:

EV 5.4.8 *Each TS accumulator container must have a prominent indicator, a voltmeter or a red LED visible even in bright sunlight that will illuminate* ***whenever a voltage greater than 60 VDC*** *or half the maximum TS voltage, whichever is lower, is present at the vehicle side of the AIRs.*

EV 5.4.9 *The indicator must be clearly visible while disconnecting the TS accumulator container from the vehicles. The indicator must be clearly marked with "Voltage Indicator"*

EV 5.4.10 *The indicator must be **hard wired electronics** without software control and directly supplied by the TS and always working, even if the accumulator is disconnected from the LVS or removed from the vehicle.*

As the rules state, the indicator must illuminate whenever a voltage greater than 60 V is present at the vehicle side of the AIRs, this is, in the HV connector of the accumulator. Furthermore, this indicator must be hard wired electronics and supplied directly from the HV batteries so that the indicator still works with switched off LV.

There are many possibilities for this circuit:

- Commercial DC-DC converter
- Self-built DC-DC Buck converter
- Voltage Divider
- Linear voltage regulator
- Analog voltmeters

This circuit is not critical for the vehicle's operation, so the solution must be as simple and fast as possible. Moreover, the solution must also be small as there is very limited space in the accumulator container. DC-DC converters are bulky, expensive and complicated if self-built. Voltage divider may be bulky because of the number of resistors needed to lower the voltage, and providing the current needed to the indicator may be challenging or power consuming. So, the simplest solutions are the linear voltage regulators and the analog voltmeters. As it has been aforementioned, the space in the accumulator is very limited, thus, the analog voltmeter would not be a valid option, so the linear voltage regulator is the selected solution in this project.

In figure 27, the circuit can be seen:

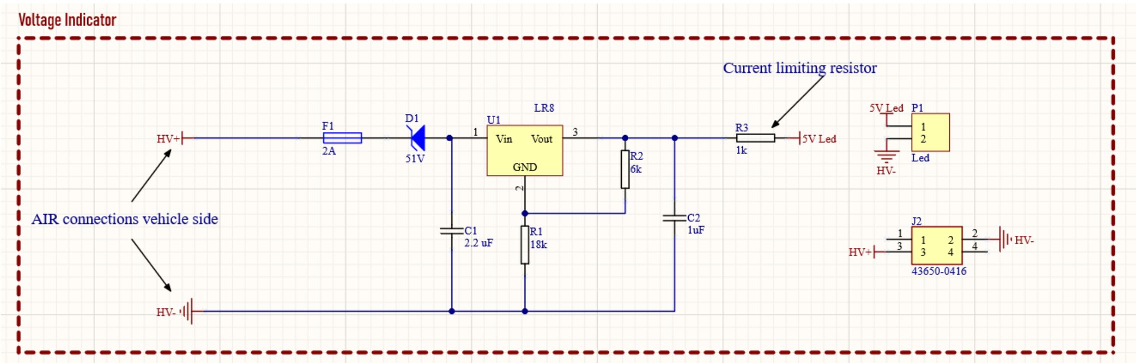

Figure 27: Voltage Indicator schematic

The problem with linear regulators is that they are linear, as their own name says, but the application requires that the regulator should not work until a voltage greater than 60 V is applied. To solve this problem, a Zener diode has been placed in an antiparallel position with a sufficient breakdown voltage so that when 60 V are applied in the input, the output can supply enough voltage to the LED so it can be lighted. The selected LED needs a minimum supply of 5 V, but while testing it could be proved that the LED would start to light at 2.2 V. In the datasheet, the Vout VS

Vin curve of the regulator is shown, and it can be seen that the input voltage needed to have around 2.2 V in the output is 5 V, and so the Zener diode's breakdown voltage needs to be 55 V maximum to ensure that with 60 V the LED will be lighted. Finally, a 2 A fuse is placed to protect the device in case of overcurrent.

3.2.6 High Voltage measurement circuit

For many applications and safety features of the vehicle, a HV measurement must be made in the vehicle side of the AIRs. The most common technologies used for voltage measurement in DC are voltage divider and Hall Effect sensors. In table 5, advantages and disadvantages of both methods are studied:

VOLTAGE DIVIDER	HALL EFFECT
ADVANTAGES	
Simple circuitry	Already isolated
Spare PCBs can be made	Very precise (1%)
DISADVANTAGES	
Galvanic isolation required → ↑€	Expensive sensors→↑€
Many resistors in series → ↑Area	High power dissipation on the primary coil
Low tolerance resistors → ↑€	Isolated DC-DC needed → ↑€

Table 5: Advantages and disadvantages between Hall Effect and voltage divider

The voltage divider method is a very simple one, with just a resistor ladder the voltage can be lowered into readable levels by the microcontroller (3 V), but galvanic isolation must be provided by some external component, such as a digital isolator, to be readable by the microcontroller and be rule compliant. Although it is easy to implement, for a precise measurement, low tolerance resistors must be used, which are usually expensive and depending on the voltage needed to be measured, a lot of resistors must be put in series due to power dissipation issues.

On the other hand, the Hall Effect option offers good precision and galvanically isolated measurement, so no other devices are needed for galvanic isolation, which is a big advantage. Despite this, Hall Effect sensors are very expensive, extra devices such as isolated DC-DC converters are needed which are also expensive and there is high power dissipation in the resistor needed in the primary coil.

All in all, because of the included galvanic isolation, the Hall Effect sensor was selected at first, but because of some unknown issue, in the transient regime when pre-charging, voltages with errors up to 7% were measured, so the pre-charge sequence would never finish. Due to this problem and time issues, the voltage divider option was selected in the end. Below, both circuits will be explained.

Hall Effect

The Hall Effect sensor selected at first is the LV-25-P voltage transducer from *LEM*. This sensor can measure up to 500 V with an overall accuracy of ±0.9%, very good linearity and has high immunity to external interferences. These characteristics make this sensor ideal for this application. Furthermore, it is made from UL94-V0 rating insulating plastic, so the sensor will extinguish any fire.

The operation of this sensor is very easy to understand, as it is similar to an AC transformer. The sensor has a primary and secondary coil. A small current limited by a resistor is driven from the voltage to be measured through the primary coil. The magnetic flux created by the primary current (Ip) is balanced by a complementary flux produced by driving a current through the secondary windings. A hall device is used to generate the secondary current which will have a relation with the Ip. Then, a resistor must be introduced in the secondary circuit so that the secondary current produces a voltage drop which can be measured by the microcontroller. In addition, an isolated DC-DC supply must be introduced to supply the hall device.

The manufacturer claims in the datasheet, that the primary resistor must be chosen so that, for the maximum voltage that will be measured, the primary current is limited to 10 mA. As the conversion ratio of the sensor (K_N) is 2500 to 1000, the secondary current will be 25 mA when the Ip is 10 mA.

As the maximum voltage of the battery will be 403.2 V, a resistor of 40 kΩ is selected to have $Ip_{nominal}$ ≈ 10 mA. The power which is going to be dissipated in the resistor will be

$P = 403.2V * 10mA = 4.032\ W$. As this is a critical feature of the vehicle, the resistors wattage will be oversized to ensure its correct operation, so two resistors of 20 kΩ tolerance will be placed, so the power dissipated in each resistor is about 2 W. The selected resistor is the 45F20KE from OHMITE with 5 W of maximum power dissipation and 1% of tolerance. Furthermore, a fuse has been also placed in the primary to protect the sensor if a short circuit happens in the DC bus.

On the other hand, the secondary resistor must be selected carefully. This voltage drop in the resistor when the maximum voltage is measured must be lower than 3 V, since it is the maximum voltage readable by the microcontroller. The selected resistor has 120 Ω, so the voltage drop with 403.2 V will be $25\ mA * 120\ \Omega = 3\ V$. Furthermore, the selected resistance must have very low tolerance, as low as 0.1% or 0.5% to have very little error in the measurement.

Finally, the isolated DC-DC supply must be chosen. The sensor operates with ±15 V and the current consumption is 10 mA plus the secondary current, so the DC-DC needs to be sized for the maximum Is, which is 25 mA. Then, the current consumption will be of 35 mA. The selected isolated DC-DC supply is the TEL 3-2423 from *TRACOPOWER* manufacturer. This DC-DC is able to supply 100 mA with ±15 V, with a 3 W output power. Again, this DC-DC is oversized, but another smaller DC-DC can be chosen, such as the TMA 1515D from *TRACOPOWER*, which is able to supply up to 35 mA.

To implement this sensor in the vehicle, a PCB has been developed. In figure 28, the schematic of the sensor will be shown. In figure 29, the PCB with the relevant components can be seen.

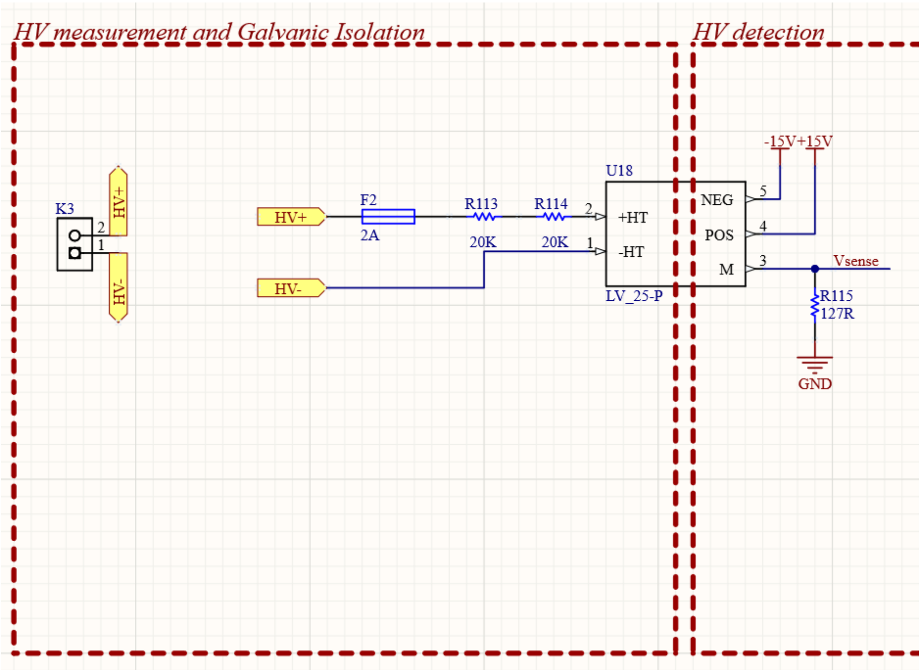

Figure 28: Hall Effect sensor schematic

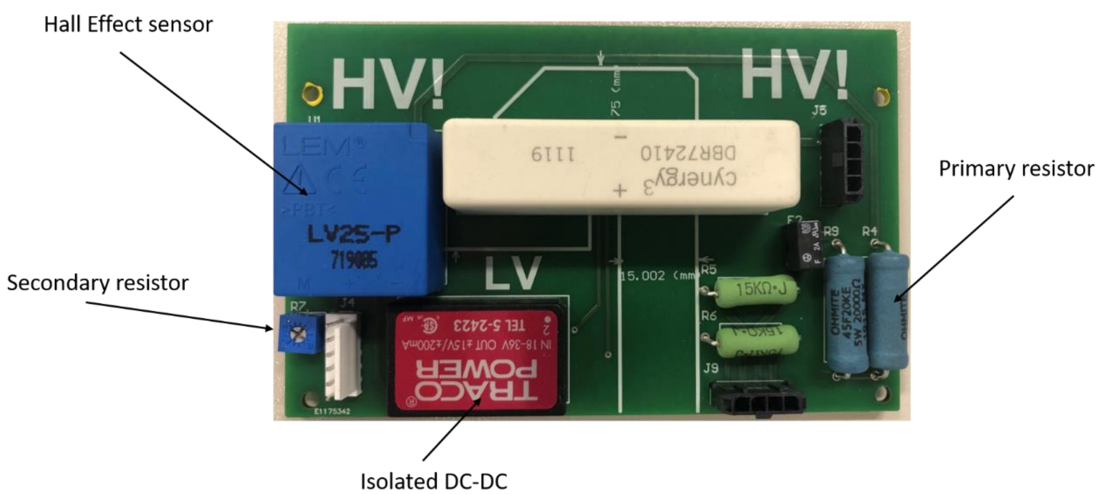

Figure 29: Hall Effect sensor PCB

Voltage divider

This circuit consists on a resistor ladder to lower the voltage and a digital isolator to provide galvanic isolation to the measurement and be readable by the microcontroller.

As the voltage to be measured is quite high, many resistors must be put in series. To select the package of the resistor, the number of resistors and the power that will be dissipated in each of them must be considered, until reaching an acceptable solution. Furthermore, the resistors need to have low tolerance to lower the error in the measurement as much as possible. This will increment the final cost of the circuit.

After studying many configurations, the optimum cost-size configuration was to place ten resistors of 20 kΩ in series and a final resistor of 1.5 kΩ. The final voltage of the voltage divider is given by the equation 4:

$$Vsense = \frac{E * R1}{Req + R1}$$

Equation 4: Voltage divider

Being E the voltage to be measured, R1 the lower resistor, and Req the equivalent of the series resistor. In this case, the voltage measured for the maximum battery voltage will be:

$$Vsense = \frac{403.2V * 1.5k\Omega}{(20k\Omega * 10) + 1.5k\Omega} = 3V$$

As it can be observed, the maximum voltage is equal to 3 V, so the microcontroller can perfectly measure this voltage.

The current drawn from the battery by the voltage divider will be:

$$Iconsumption = \frac{403.2V}{201.5k\Omega} = 2\ mA$$

The voltage drop in each resistor of 20 kΩ will be 40 V, which is not that high. The power dissipated in each resistor will be:

$$P_R = 40V * 2mA = 80\ mW$$

So, the selected resistor package must be able to dissipate this power. The selected resistor package is MELF 0204 which is able to dissipate up to 0.25 W.

As aforementioned, for the V_{SENSE} to be readable by the microcontroller, the signal must be galvanically isolated. For this, the dual channel digital isolator with integrated isolated DC-DC converter ADUM5202ARWZ from *Analog Devices* has been selected. The isolated DC-DC converter will provide the HV referenced part with a 5 V supply referenced to HV- which will be used by extra circuitry explained in *chapter 4.2.4*. Furthermore, the isolator provides 2.5 kV_{rms} isolation.

In figure 30, the schematic of the PCB is shown. The pin configuration of the isolator can be found in the datasheet of the component. Full view of the schematic can be seen in *appendix A*.

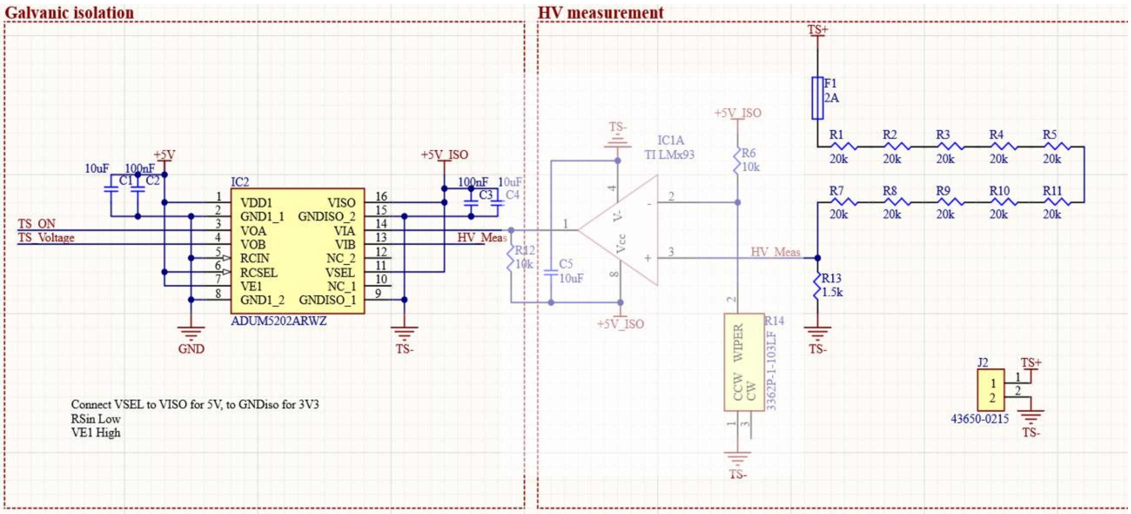

Figure 30: Voltage divider circuit schematic

Comparison

With both designs finished, a brief comparison between them will be made. If low tolerance resistors are used, high precision measurements can be made with the voltage divider. The current consumption drawn from the HV battery is of 2 mA for the voltage divider and 10 mA for the Hall Effect sensor, so the voltage divider circuit will take less energy from the cells. Furthermore, the hall sensor is quite big, and the primary resistor which needs to dissipate up to 4 W is also quite big, so this circuit will take more space, whereas the voltage divider circuit's geometry can be highly adaptable as it only consists of little resistors in series and a small IC. In addition, the Hall Effect sensor is quite expensive, 65 €, so fewer spare boards can be made because of its price.

3.2.7 Pre-charge

The inverters driving the motors need a bank of capacitors in the DC bus for a correct operation, as it stabilizes the voltage from the DC link of the inverters. As the current of a capacitor is directly proportional to dVc/dt, when the AIRs close, a big current spike is caused in the DC bus and so a resistor is needed in the circuit when the DC link capacitors are charged or otherwise the capacitors will be damaged.

A resistor is placed in series with the DC link capacitors to limit the current in the DC bus when the HVDC is connected to the inverters. This circuitry consists in a relay with a resistor placed in series to control when the resistor is being connected to the HV circuit. This circuitry is then connected in parallel to the negative poles' AIR so that when the capacitors have been pre-charged, the pre-charge circuitry is disconnected from the HV circuit.

The pre-charge circuit can be seen in figure 31.

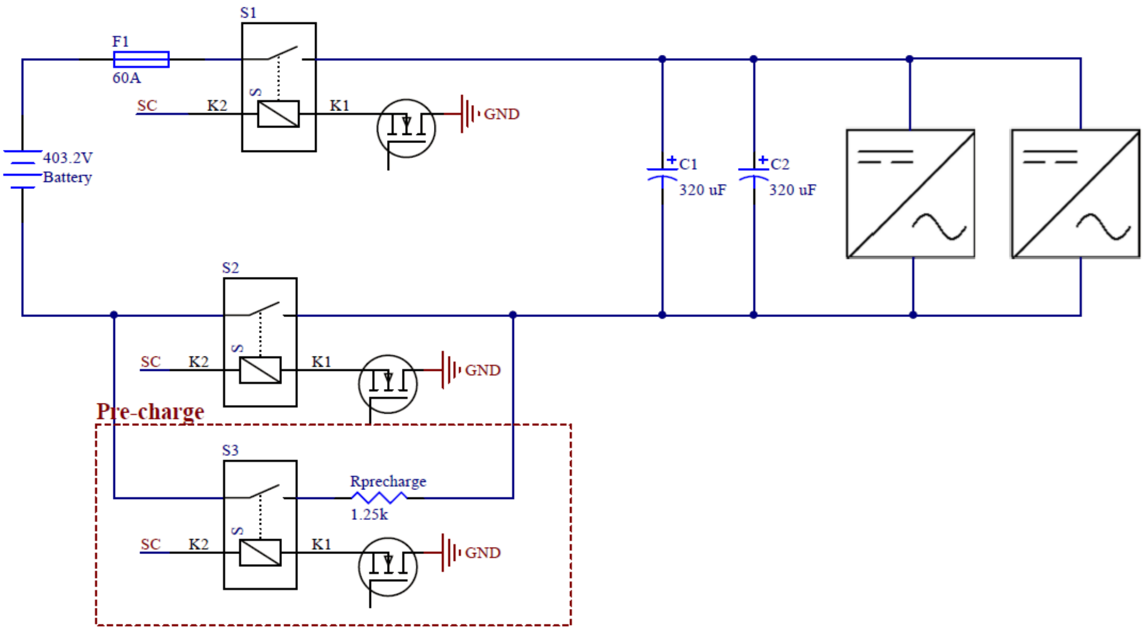

Figure 31: Pre-charge circuit schematic

The voltage across the DC link capacitors when pre-charging is given by the following equation:

$$Vc = Vbat * (1 - e^{\frac{-t}{RC}})$$

Equation 5: Capacitor pre-charge voltage

Vc: Voltage of the capacitors of the DC link

Vbat: Voltage of the HV battery

R: Pre-charge resistor

C: Capacitance of the capacitors

The FSG 2020 rules regarding the pre-charge of the vehicle are stated hereafter:

EV 4.10.4 *The mentioned states of the relays (opened/closed) are the actual mechanical states.* ***The mechanical state can differ from the intentional state****, i.e. if a relay is stuck. Any circuitry detecting the mechanical state must meet EV 5.6.2.*

EV 5.7.1 *A circuit that ensures that the intermediate circuit is* ***pre-charged to at least 95 % of the actual TS accumulator voltage*** *before closing the second AIR must be implemented. Therefore the intermediate circuit voltage must be measured.*

EV 5.7.2 *The pre-charge circuit must use a mechanical,* ***normally open type relay****. All pre-charge current must pass through this relay.*

As EV 5.7.1 specifies, the intermediate circuit (DC bus) must be pre-charged to at least 95% of the current accumulator voltage before closing the second AIR. To accomplish this task, the intermediate circuit voltage must be measured. This voltage measurement is made by using one of the circuits described in *chapter 3.2.6*.

When sizing this resistor, it is mandatory to consider the time the pre-charge sequence is going to take, the charging current and the power that will be dissipated in the resistor, as it will limit the choices of resistors and the size of it considerably. There are not many resistor choices in the market which withstand high power dissipation and offer relatively low resistances so that the pre-charge process is fast. So, the time of the pre-charge and the resistivity (and its maximum power dissipation) chosen must be changed iteratively until a resistor which fits the needed specification is found. To accelerate this process, a MATLAB script was developed to plot the pre-charge curves depending on the parameters.

With all these considerations, the resistor THS251K5J from *TE Connectivity* has been chosen. The DC link capacitor value is 640 µF, the maximum battery voltage is 403.2 V and the chosen resistor is 1.5 kΩ. With these parameters and as per equation 5, the pre-charge time until the 95% of the battery voltage is reached in 2.87 seconds and the maximum power dissipation is 27 W.

The THS251K5J resistor has a wattage of 12.5 W, but the manufacturer provides a power overload curve which shows how much time the resistor can withstand a certain power overload. For 3 seconds, the resistor is able to withstand 113 W, so even though the power rating is below the maximum power dissipated, the resistor can work with that overload in this application. The power overload graphic can be seen in figure 32.

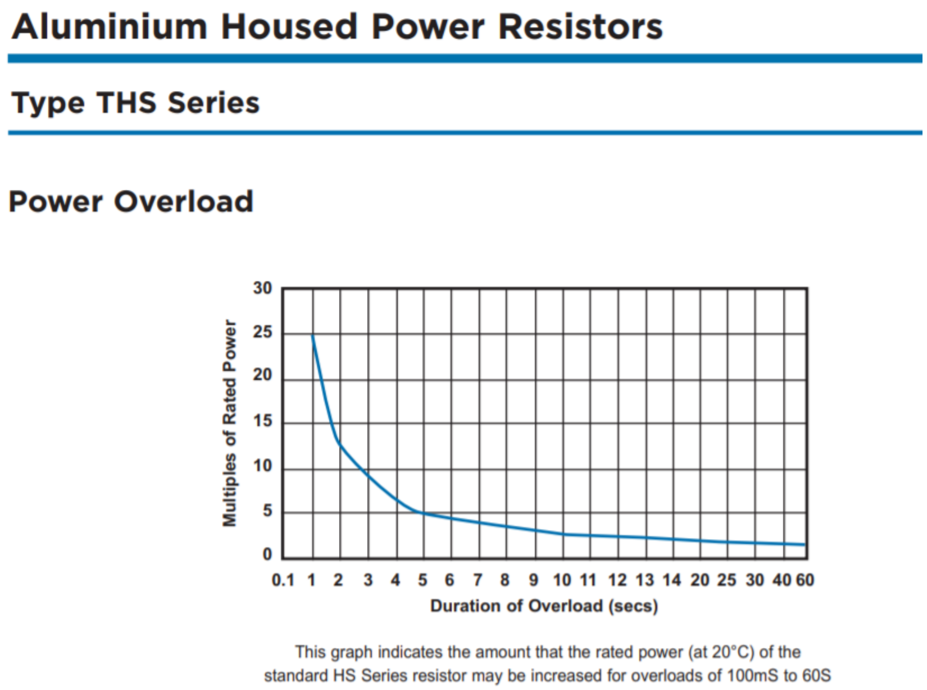

Figure 32: Pre-charge resistor power overload graphic

With these parameters, the pre-charge voltage, current and power curves can be seen in figures 33, 34 and 35.

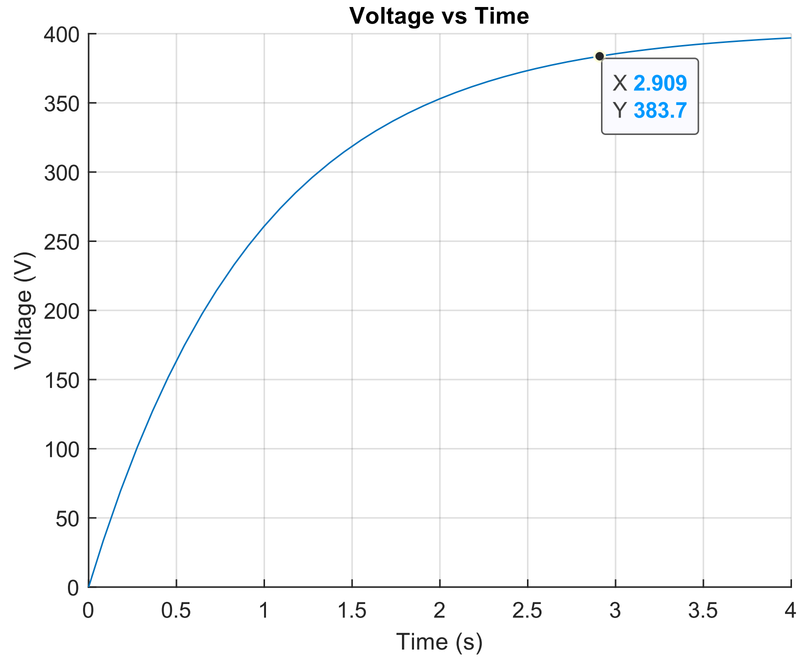

Figure 33: Pre-charge Voltage VS Time graphic

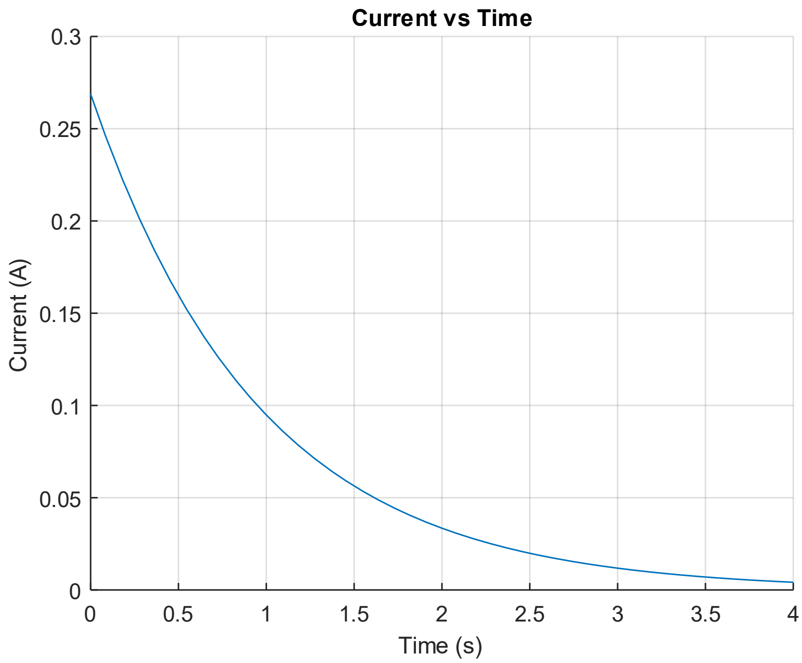

Figure 34: Pre-charge Current VS Time graphic

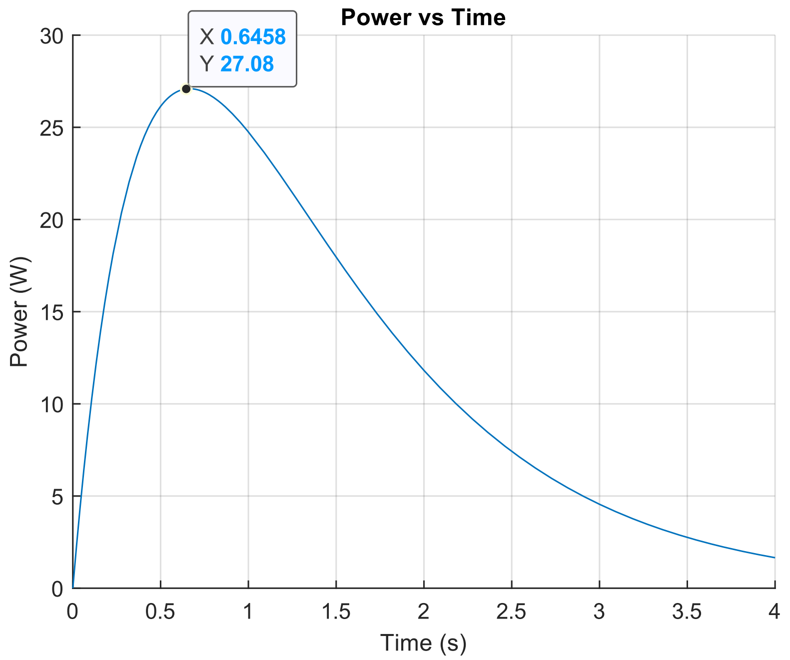

Figure 35: Pre-charge Power VS Time graphic

The relay must also be sized accordingly to the power that will be dissipated with the selected resistor, but it also has to be able to open the operating voltage of the battery. Furthermore, as EV 5.7.2 states, the relay must be a mechanical NO type relay, so solid-state relays are forbidden. With these requirements, a Single Pole Single Throw Normally Open (SPST-NO) relay is the most suitable for this application. With the current rating, power rating and voltage rating a relay can be chosen, but as the rules state, the mechanical state of the relay has to be monitored regardless of the intended state, this is, it is mandatory to detect if the relay gets stuck when it is intended to be opened. For this new feature, a relay with auxiliary contacts has been chosen to monitor the mechanical state of the relay, LEV100H5CNG from *TE Connectivity*. It has a voltage rating of 1000 V, continuous current rating of 100 A and a capability of 8 kV of isolation. Although this relay is massively oversized for its purpose, the auxiliary contacts make it ideal for the mechanical state detection. This feature will be covered in *chapter 4.1.2*.

3.2.8 Discharge

When the shutdown circuit opens due to a fault or a pressed shutdown button, the AIRs in the accumulator container will open, disconnecting the battery from the DC link capacitors. If the capacitors are not discharged, HV will still be present in the vehicle and thus the car will not be safe to work on. The discharge circuitry handles this situation.

The discharge circuitry consists in a resistor which is connected to the HV+ and HV- by a relay. The coil of the relay will be supplied by the shutdown circuit, so whenever the shutdown circuit is opened, the relay will be closed, allowing the discharge of the capacitors. Furthermore, the relay must be a SPST NC type relay, so that when the vehicle is off, the relay will be closed.

In figure 36, a schematic of the discharge circuitry is shown:

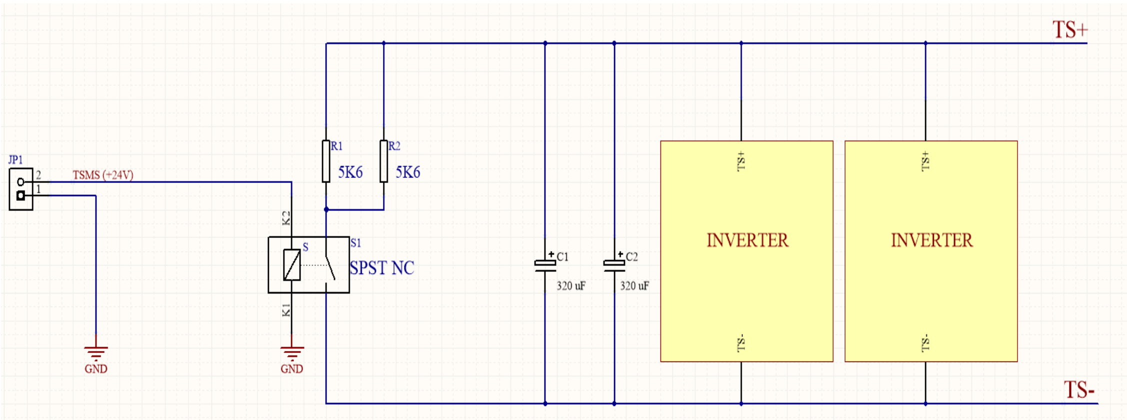

Figure 36: Discharge circuit schematic

The functions of the discharge circuitry are explained in the FSG Rules:

EV 4.9.1 *If a discharge circuit is required to meet EV 6.1.5**, it must be designed to handle the maximum TS voltage permanently**. After three subsequent discharges within 15s in total, the discharge time specified in EV 6.1.5 may be exceeded. Full discharging functionality must be given after a reasonable time with a deactivated discharge circuit.*

EV 4.9.2 ***The discharge circuit must be wired in a way that it is always active whenever the shutdown circuit is open**. Furthermore, the discharge circuit must be fail-safe such that it still discharges the intermediate circuit capacitors if the HVD has been opened or the TS accumulator is disconnected.*

EV 4.9.3 ***Fusing of the discharge main current path is prohibited**.*

EV 6.1.5 *If the shutdown circuit is opened, the TS must be shutdown by opening all AIRs and the voltage in the **TS must drop to below 60 VDC and 25 VACRMS in less than five seconds.** All accumulator current flow must stop immediately.*

As the rules state, the TS voltage must drop to below 60 VDC in less than 5 seconds and the discharge circuitry must be designed to handle the maximum power dissipation permanently (in case the resistor is always connected to the HV circuit). These restrictions will size the resistance and wattage of the resistor and the wattage of the relay. In addition, the rules also state that the discharge circuitry must be in such position that even with the HVD disconnected, the capacitors can still be discharged. To fulfill this statement, the discharge circuitry will be placed inside the inverter's housing.

Even though the rules permit the discharge to be in 5 seconds, the resistor will be chosen so that the HV circuit is discharged in less than 5 seconds. The maximum resistor to accomplish the 5 seconds is 4.1 kΩ.

With all these limitations, the best option is to use two resistors in parallel to withstand all the power dissipation continuously. The selected resistor has been a HS50 5K6 J resistor, with 5.6 kΩ of resistivity. The dissipated power with this resistor is 58 W, so 29 W will be dissipated in each resistor. Although the resistors wattage is of 14 W without a heatsink, the resistors wattage with a heatsink is of 50 W, enough for this application.

The heatsink for panel mount resistors such as the HS50 series are quite big, so another solution was reached: mounting both resistors to the inverter's housing aluminum box with thermal paste. The aluminum is a good material for heat transfer and as the area of the box is high, the heat is dissipated correctly. Even though this option was accepted by the scrutineers of the competition, a study of the heat transfer should be simulated and documented to prove in scrutineering that this option is valid. In figure 37, the discharge resistor can be seen.

Figure 37: Discharge resistor

In figures 38, 39 and 40, the voltage, current and power curves of the discharge can be seen.

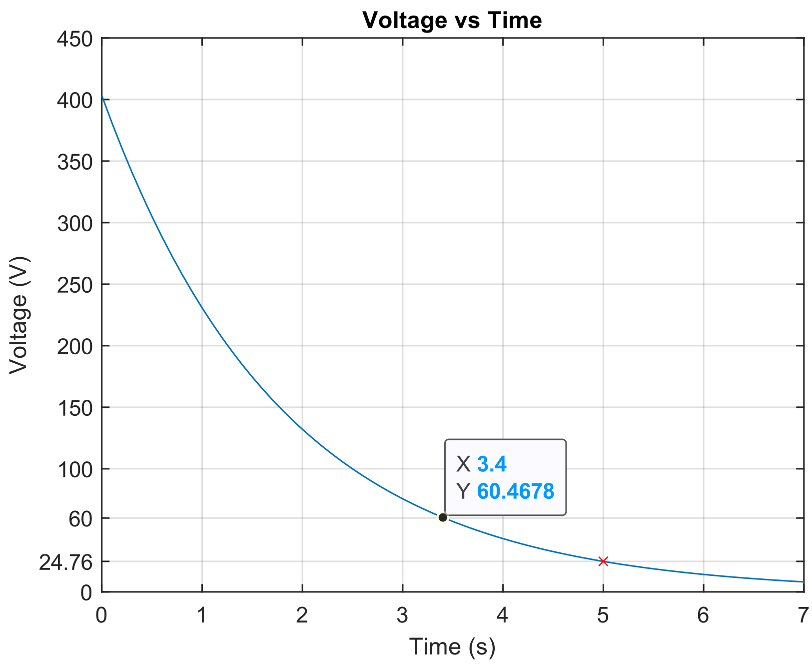

Figure 38: Discharge Voltage VS Time graphic

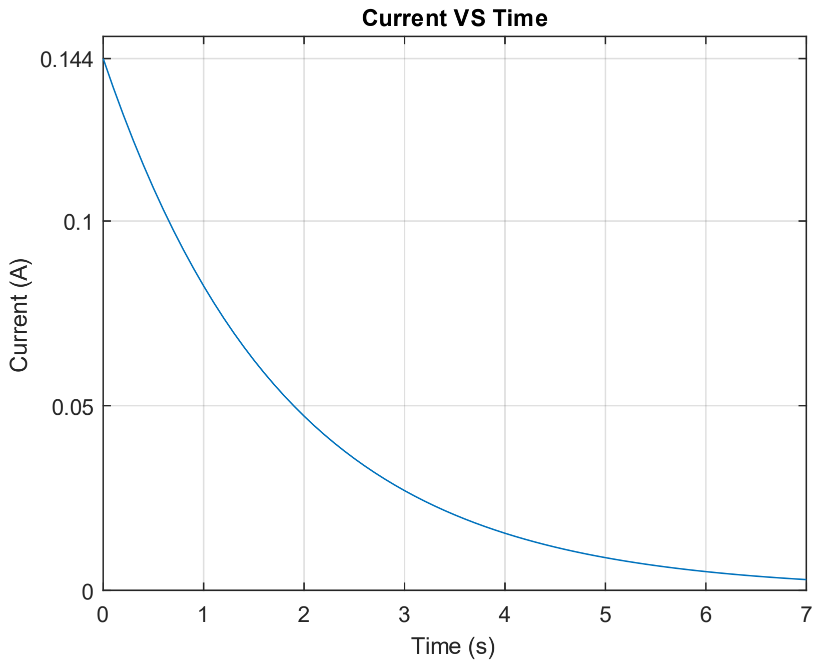

Figure 39: Discharge Current VS Time graphic

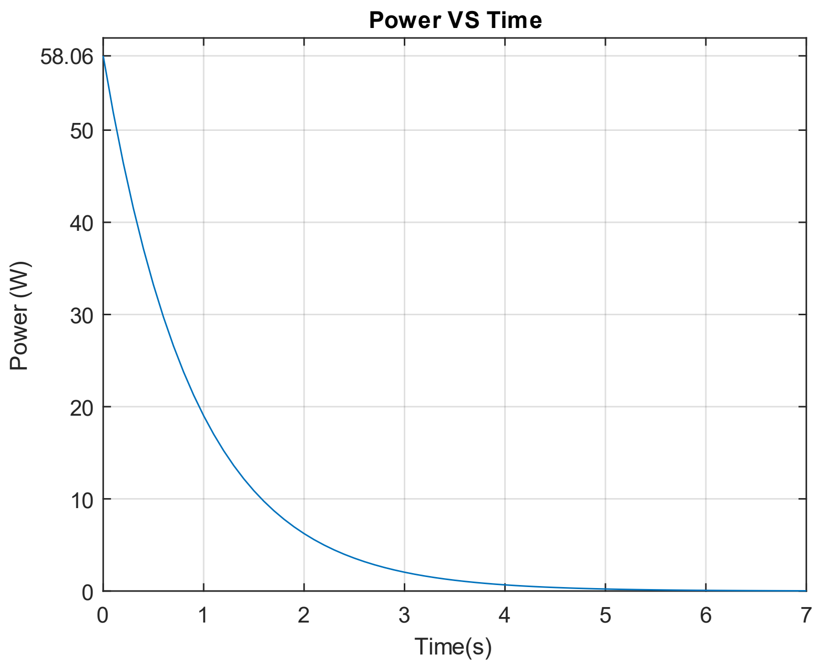

Figure 40: Discharge Power VS Time graphic

The relay should also be sized for the maximum power dissipation so the relay COTO-5504-24-1 SPST NC is selected, which can withstand up to 100 W of power dissipation.

3.2.9 Insulation Monitoring Device

The Insulation Monitoring Device (IMD), is an extremely important safety feature in the vehicle. The IMD's task is to monitor the insulation resistance between the HV conductors and the reference earth of the vehicle, the chassis. This device will detect any insulation failure between the TS and LV of the vehicle and will output a failure signal (0 V), helping to prevent the driver from getting any electrical shocks in the event of failure. Furthermore, this device is helpful to notice insulation failure due to water inside the vehicle. For instance, during competition in FSS, after passing the rain test, a bit of water entered the inverter housing, reducing the resistance between the HV and LV systems, so there was a failure until the water had dried out.

The FSG rules state some features the IMD must have:

EV 6.3.2 *The IMD must be a* ***Bender A-ISOMETER® iso-F1 IR155-3203 or -3204*** *or equivalent IMD approved for automotive use. Equivalency may be approved by the officials based on the following criteria: robustness to vibration, operating temperature range, IP rating, availability of a direct output, a self-test facility and must not be powered by the system which is monitored.*

EV 6.3.3 *The* ***response value of the IMD must be set to ≥500 Ω/V****, related to the maximum TS voltage.*

EV 6.3.4 *The IMD must* ***be connected on the vehicle side of the AIRs.***

EV 6.3.5 *One IMD chassis ground measurement line must be connected to the the grounded accumulator container. The other chassis ground measurement line must be connected to the main hoop. Each connection must use a separate conductor, rated for at least maximum TS voltage. An open circuit in any of this ground measurement connections must result in an opened shutdown circuit.*

EV 6.3.6 *In case of an insulation failure or an IMD failure, the IMD must open the shutdown circuit. This must be done without the influence of any programmable logic. See also EV 6.1.6 regarding the re-activation of the TS after an insulation fault.*

The rules specify that the IMD device has to be a specific model from *BENDER* and that its response value must be set to ≥500 Ω/V. In the case of this vehicle, the maximum voltage achievable is 403.2 V, so the response value must be set to at least 201.6 kΩ. To be safer, the response value has been set to 210 kΩ. If the insulation is OK, the IMD will output 24 V, and if the insulation is beneath 210 kΩ the IMD will output 0 V. This signal is needed to open the shutdown circuit and thus disconnecting the battery from the rest of the vehicle. The circuitry needed for this action will be explained in *chapter 4.1.1*.

Installation

In figure 41, the wiring diagram of the IMD is shown. Pins 1 and 2 are reserved for supply (24 V and GND), pins 3 and 4 are reserved for the reference earth of the vehicle and pin 8 is reserved for the IMDs state. As the rule EV 6.3.5 states, the two earth references must be connected to the accumulator container's fixing point (steel bolt to the chassis) and the main hoop of the car respectively. Furthermore, there are two more connections for the HV reference, these must be connected to the positive and negative pole of the battery, but in the vehicle side of the AIRs as EV 6.3.4 states. In figure 42, a typical application of the IMD is shown.

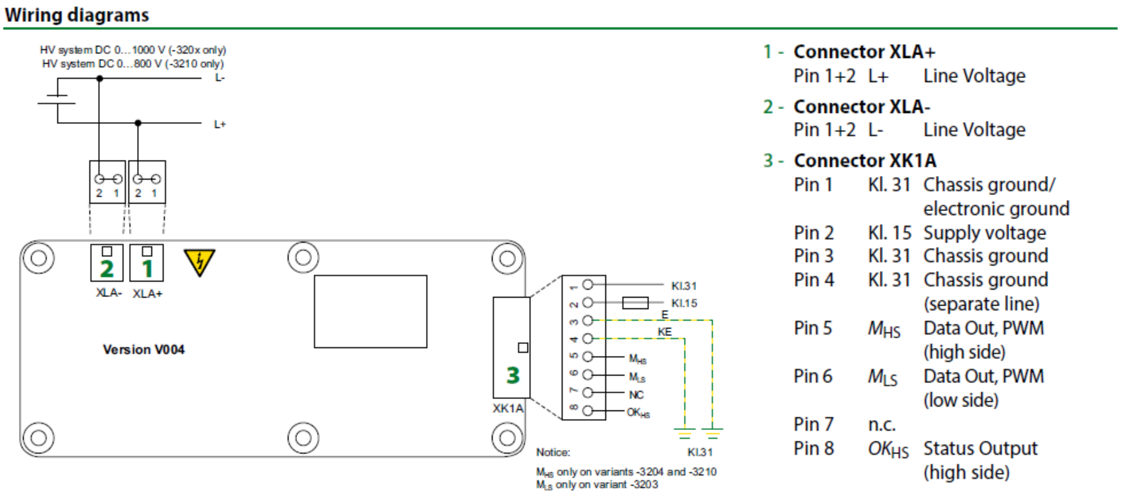

Figure 41: Wiring diagram of the IMD

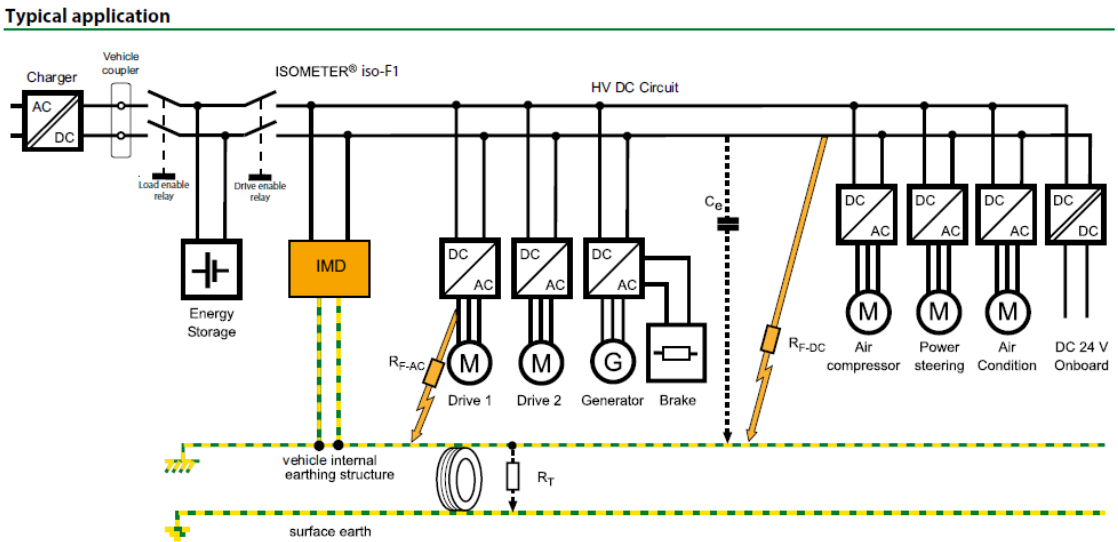

Figure 42: Connection of the IMD in the vehicle

4. BATTERY MANAGEMENT SYSTEM

The Battery Management System is in charge of monitoring the state of the battery cells that make up the HV battery and taking decisions upon their current state, such as opening the AIRs to disconnect the battery from the vehicle in the event of a cell discharge.

The BMS is one of the most important safety features in an electric vehicle, and as such, it must be secure, robust and fast for the correct operation and security of an EV.

The core functions of a BMS in a Formula Student EV are the following:

- Monitor the voltages of every battery cell and the temperature of at least 30% of the cells.
- Monitor the current drawn from the battery
- Control and monitor the pre-charge action of the of the HV circuit.
- Open and close the AIRs.
- Monitor other peripherals, such as the charging sequence or IMD.

Furthermore, there are other functions which can be fulfilled in other PCBs, but due to space restrictions the BMS board needs to contain them within. This is the case of the Tractive System Active Light (TSAL) for instance.

The BMS fulfills these tasks with a master module and eight slave modules, divided in 4 slave boards. The slave modules are in charge of monitoring the voltages and temperatures of the cells and send them to the master module via CAN bus. On the other hand, the master module processes all the information received by the slaves and takes decisions upon the state of the battery. It does so with the help of external circuitry, such as voltage measurement or insulation measurement with the IMD.

In the next chapters, the master module and the slave module will be described along with their original objectives.

4.1 Master module

The master module is based on the module designed by Imanol Etxezarreta in "*Design and fabrication of a BMS Master for a Formula Student car*", but many other features have been implemented due to rule changes, incorrect operation or just redesigned for better performance. The added or redesigned features are the shutdown circuit, the TSAL circuit, the current sensing, voltage sensing and CAN bus circuitry which will be explained in the next chapters.

4.1.1 Shutdown Circuit

The master module monitors the voltage, temperatures and insulation level of the battery cells and so, it needs to open the SC in the event of a single failure of these parameters.

First, the most important rules will be cited to understand the requirements of the BMS for the shutdown circuit:

EV 6.1.5 *If the shutdown circuit is opened, the TS must be shutdown by opening all AIRs and the voltage in the TS must drop to below 60 VDC and 25 VACRMS in less than five seconds. All accumulator current flow must stop immediately.*

EV 6.1.6 *If the **shutdown circuit is opened by the AMS or the IMD**, it has to be **latched open by a non-programmable logic** that can only **be manually reset** by a person at the vehicle who is **not the driver**.*

EV 6.1.7 *All circuits that are part of the shutdown circuit must be designed in a way, that in the de-energized/disconnected state they open the shutdown circuit.*

EV 6.1.9 *Every system that is required to or is able to open the shutdown circuit must have **its own, non-programmable, power stage** to achieve this. The respective power stages must be designed to be able to carry the shutdown circuit current, e.g. AIR inrush currents, and such that a failure cannot result in electrical power being fed back into the electrical shutdown circuit.*

EV 6.1.11 *All signals influencing the shutdown circuit are **SCSs**, see T 11.9.*

As the rules stipulate, the BMS needs to open the SC when there is a BMS fault or IMD fault with their own individual hardwired power stage and be latched open when this happens.

First, how the BMS fault and the IMD fault work will be explained:

IMD & BMS Fault

The BMS fault will happen when the voltage of any cell is not between 3.02 V and 4.18 V or if the temperature of any cell is above 50°C. When this happens, the microcontroller will output a logic high, but in order to activate its power stage, the signal must be inverted. This is achieved by the use of a NMOS and a pull-up resistor as shown in figure 43. If the BMS status is OK, the FLT_0 signal will be a logic zero, and thus the BMS_Fault signal will be 3.3 V. If the BMS status is fault the FLT_0 signal will be a logic high and thus the BMS_Fault will be 0 V.

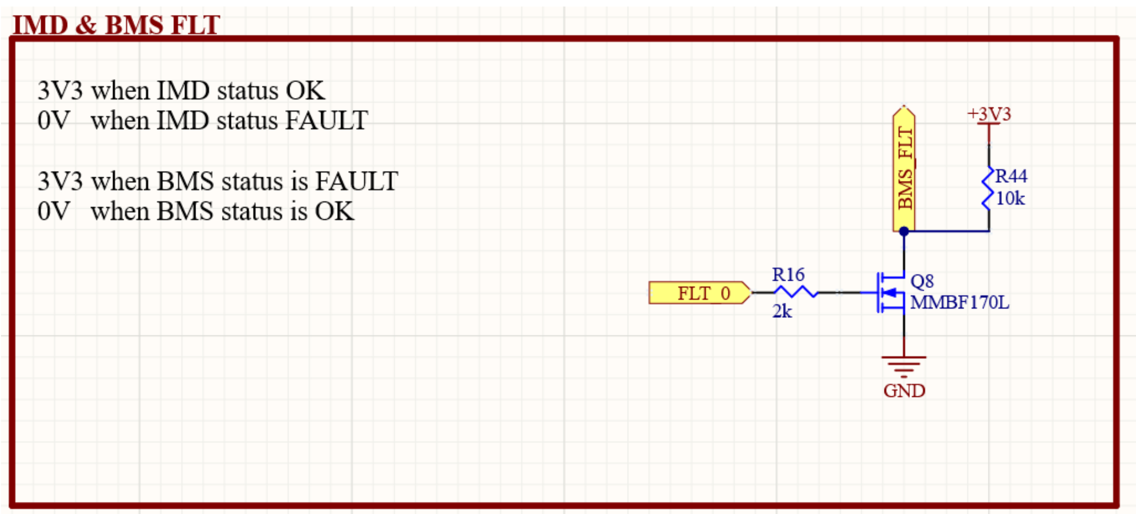

Figure 43: IMD and BMS fault schematic

The IMD fault happens as explained in *chapter 3.2.9*, if there is an insulation failure the IMD will output a 0 V and if there is not an insulation failure it will output 24 V. This signal is lowered by a voltage divider to 3.3 V to operate with it.

IMD & BMS Power stages

With the IMD and BMS fault signals aforementioned, the BMS must be able to open the shutdown circuit with and individual power stage for each fault, keep it latched open until the faults are restored and the power stages are manually reset. This is accomplished with the use of a latch type relay, logic circuitry and reset circuitry.

The circuit is shown in figure 44:

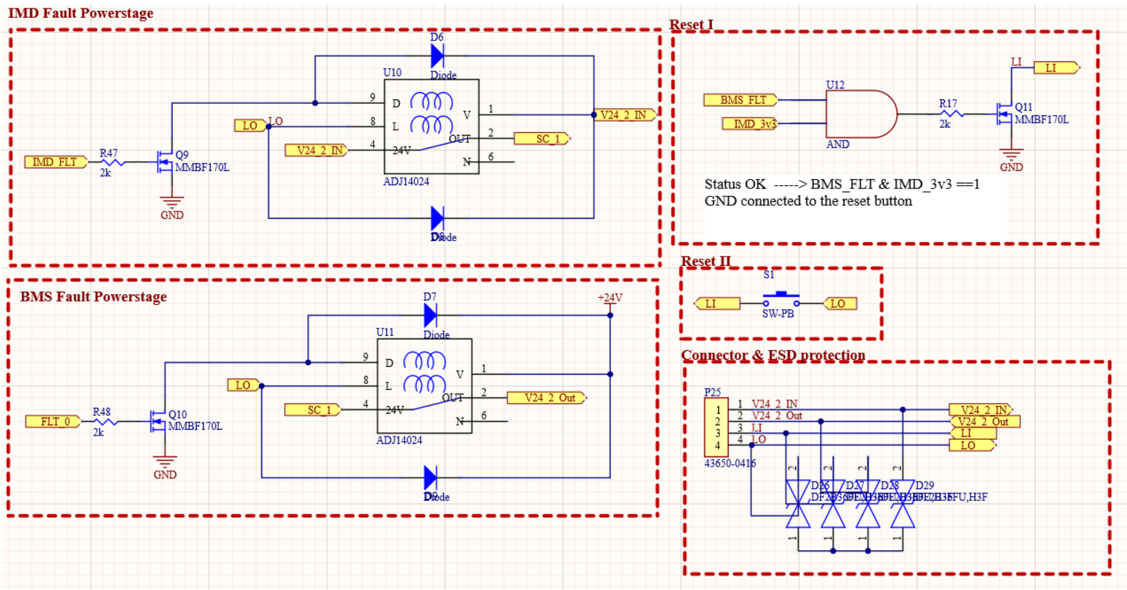

Figure 44: Latching circuit full schematic

A latch type relay will ensure that once the fault has been set, the relay will stay in that position until it is manually reset. The relay used is the ADJ14024 from *PANASONIC.* This relay features two coils, one for the SET and another for the RESET. When the SET coil is activated, the relay will remain latched in that position until the RESET coil is activated. In figure 45, the relay schematic can be seen.

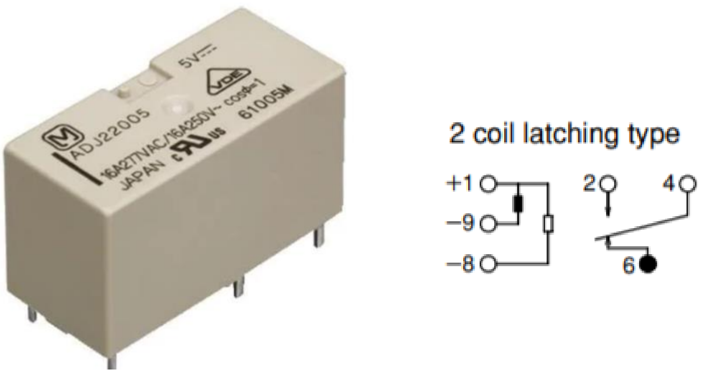

Figure 45: Relay schematic

The individual power stage consists in just one of these relays. Moreover, by putting two of these in series, one for the IMD fault and another for the BMS fault, the opening of the shutdown circuit is ensured if any of these were to fail. In figure 46 the power stages can be seen:

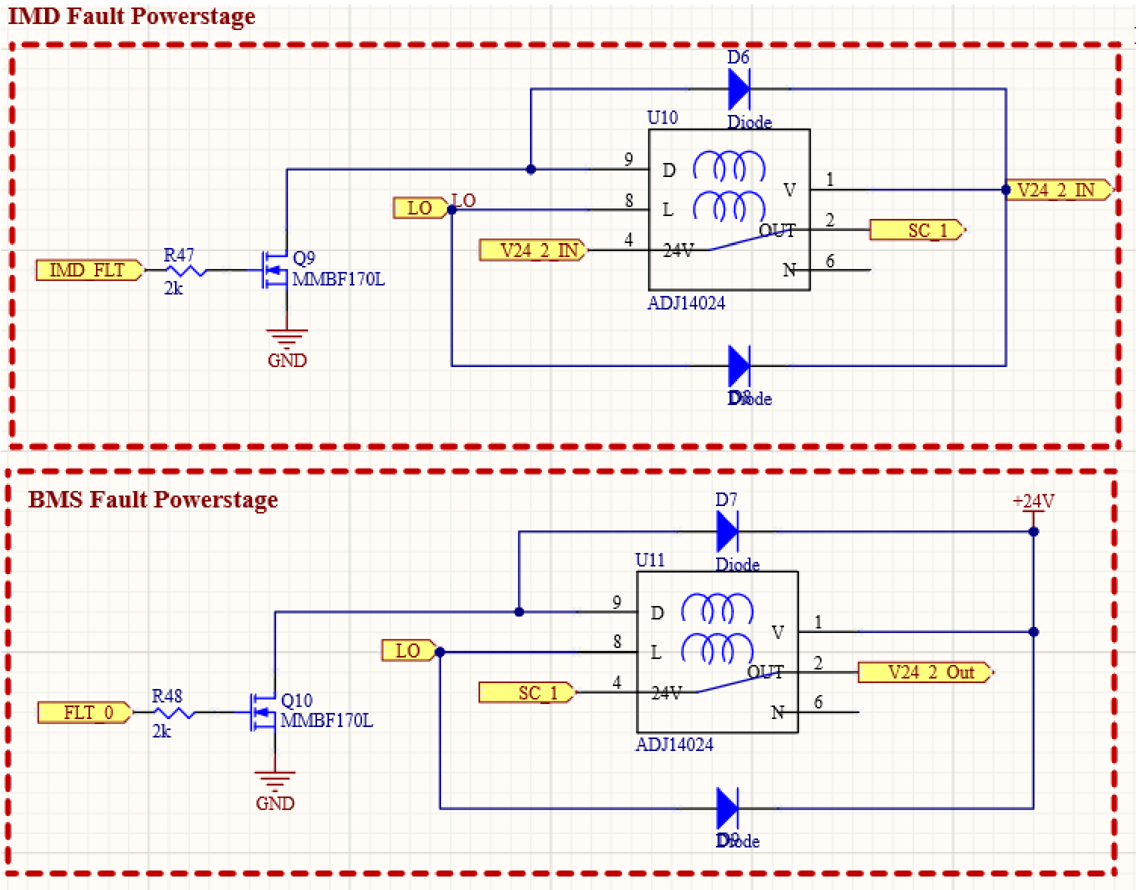

Figure 46: IMD and BMS powerstages

V24_2_IN is the shutdown circuit which enters the BMS and V24_2_Out is the shutdown circuit which exits the BMS, LO stands for “Latch Out”, which refers to the reset circuitry which will be explained later on. The SET coil is controlled by an NMOS. When the fault signal is a logic high, the NMOS is triggered and the coil is connected to ground, activating the coil. Then, the relay will be in position 6, opening the circuit. The diode provides a discharging path to the coil when the NMOS is opened so that the coil is not destroyed. As it can be seen in figure 47, the second relay in series has its coils supplied to 24 V of the LV supply rather than the 24 V from the shutdown circuit, the reason for this is that if the shutdown circuit is opened because of the IMD, and a momentary BMS fault occurs, as the coil would not be supplied, the BMS failure would not be detected, and thus the IMD relay could be reset and the shutdown circuit could be closed.

In order to reset the relay, the RESET coil must be connected to ground. This must be done through a reset button which needs to be placed in the side of the car where it is inaccessible for the driver. This button should be connected to ground on one side and to the coil on the other, but if the button is connected this way, the relay could be reset even if there is still a fault, which is very dangerous. To solve this problem, one side of the button is connected to the coil and the other one is connected to the logic circuit shown in figure 47.

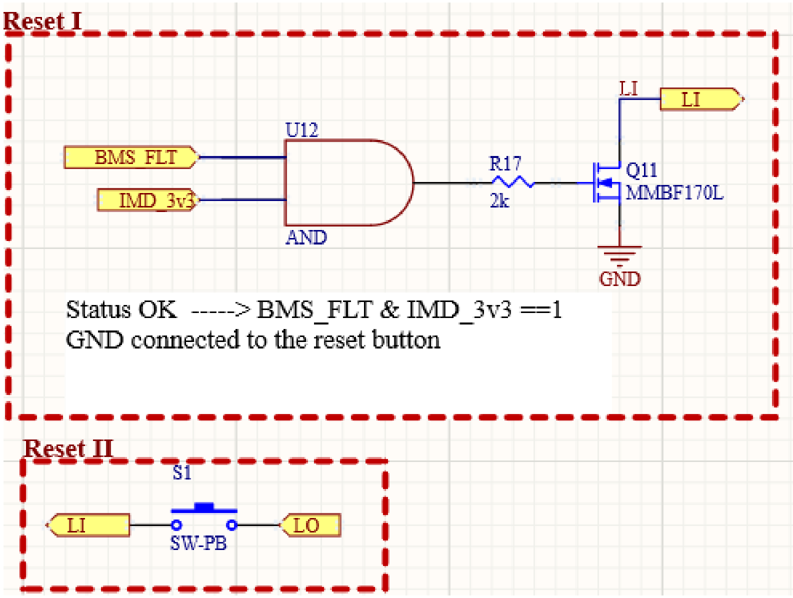

Figure 47: Reset logic schematic

With this logic circuit, the ground can be connected and disconnected from the reset button depending on the BMS and IMD fault signals, when both statuses are OK, the ground will be connected with an NMOS. LI and LO stand for "Latch In" and "Latch Out" respectively, referring to both ends of the button.

4.1.2 Tractive System Active Light

The TSAL is a passive security indicator (figure 48). It indicates if there is a voltage above 60 V outside the accumulator container and if there is a failure in the circuitry that needs to detect the voltage. The three states of the TSAL are:

- **Flashing red:** The TSAL will be flashing red between 2-5 Hz if the voltage outside the accumulator container is greater than 60 V OR any of the AIR is closed OR the pre-charge relay is closed.
- **Green:** The TSAL will be continuously lighted with a green color if none of the flashing red requirements happen and if there is no implausibility in the circuitry needed for detecting it.
- **Off:** The TSAL will be off if the safe state is entered. This happens if there is an implausibility in the circuitry needed for detecting the flashing red state, even if any of the requirements happen. For instance, this happens when the connector for detecting if the AIR is disconnected or short-circuited to ground.

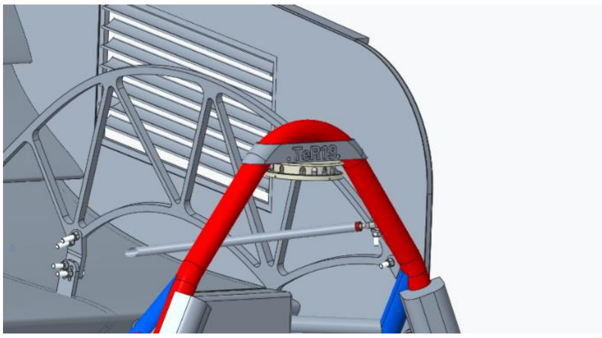

Figure 48: TSAL location in the main hoop

The most relevant rules for the TSAL to understand its functions are listed below:

EV 4.10.1 *The vehicles must include a single **TSAL that must indicate the TS status**. The TSAL must not perform any other functions. A TSAL with multiple LEDs in one housing is allowed.*

EV 4.10.2 ***The TS is active** when **ANY** of the following conditions are true:*

- *An **accumulator isolation relay is closed**.*
- *The **pre-charge relay**, see EV 5.7.2, **is closed.***
- *The voltage outside the accumulator container(s) exceeds **60 VDC** or 25 VAC Root Mean Square (RMS).*

EV 4.10.3 *The **TS is deactivated** when **ALL** of the following conditions are true:*

- *All **accumulator isolation relays are opened**.*
- *The **pre-charge relay**, see EV 5.7.2, **is opened**.*
- *The voltage outside the accumulator container(s) **does not exceed 60 VDC** or 25 VAC RMS.*

EV 4.10.4 *The mentioned states of the relays (opened/closed) are the actual mechanical states. **The mechanical state can differ from the intentional state**, i.e. if a relay is stuck. Any circuitry detecting the mechanical state must meet EV 5.6.2.*

EV 4.10.8 *The TSAL and all needed circuitry must **be hard wired electronics**. Software control is not permitted.*

EV 4.10.9 *A green indicator light in the cockpit that is easily visible even in bright sunlight and clearly marked with "TS off" must light up if the TS is deactivated, see EV 4.10.3.*

EV 4.10.10 *Signals influencing the TSAL and the indicator according to EV 4.10.9 are **SCS**, see T 11.9. The safe state for the TSAL is defined as TSAL non-illuminated. The TSAL has an active indication of absence of failures (continuous green illumination) and thus must not be illuminated for visible check, see T 11.9.5.*

EV 4.10.11 *The TSAL must be designed, that a single point of failure within the TSAL circuitry will not show an activated TS as deactivated TS according to EV 4.10.5*

EV 4.10.13 ***The voltage outside of the TS accumulator must at least be measured independently***

- ***across DC-link capacitors** in each housing with DC-link capacitors*
- *at the vehicle side of **the Accumulator Isolation Relays (AIRs)** inside the accumulator container*

If there is any implausibility between the independent voltage measurements, the safe state must be entered regardless of the relay states.

The rules determine the three different states any TSAL must have but also specify that the circuitry cannot be programmed but needs to be hard-wired. The TSAL circuitry is divided in two main parts, the logic circuit PCB and the PCB containing the LEDs. The logic circuit is also divided in 4 subsystems: the AIR detection, HV detection, logic circuitry for enabling the red or green light and the logic circuitry to turn it off. The PCB containing the LEDs is placed in the main hoop of the car, and its logic will be explained in table 6, but the PCB itself will not be covered in this project. The TSAL needs 3 signals: +5, GND and Enable_Red. If Enable_Red signal is a logic low, the TSAL will be flashing red, and if it is a logic high, the TSAL will be illuminated in green. To generate the Enable_Red signal, four signals are compared in a logic circuit. These four signals are: two signals for AIR detection, one for pre-charge relay detection and another for the HV measurement. Thus, the combinations of these signals will generate a logic low or high, enabling the flashing red or green state of the TSAL. Next, how these four signals are obtained is going to be explained.

The AIR and pre-charge relays have an auxiliary contact to monitor the mechanical state of the relays, which is really helpful for the TSAL circuitry. With these contacts, three different states must be monitored: closed, open, disconnected/short-circuit to GND. The latter is needed due to rule EV 4.10.10, which states that these signals are System Critical Signals (SCS). If a signal is an SCS, then, open circuits and short-circuits to GND must be detected, the complete definition of SCS can be found in rule T 11.9.

To differentiate these states from each other, each one is defined:

- **Closed:** When the contacts are closed, the measured voltage will be 3.3 V.
- **Open:** When the contacts are opened, the measured voltage will be 1.65 V.
- **Disconnect/Short-Circuit:** When the connector is disconnected or it is short-circuited to ground, the measured voltage will be 0 V.

This is achieved with the circuit in figure 49.

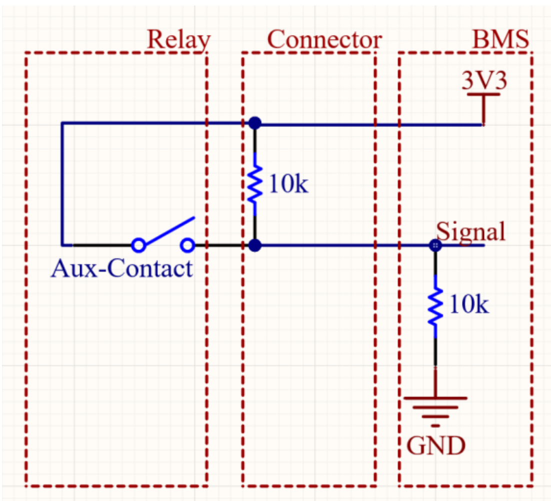

Figure 49: Auxiliar contacts of the AIR and pre-charge relay

The circuit needs to have a 10k resistor placed in the BMS board and another resistor placed in the connector, between the two wires of the auxiliary contact. When the contact is closed, the signal will be of 3.3 V, when the contact is opened, the resistors will set a voltage of 1.65 V, and when the connector is disconnected, the signal will be connected to GND through a 10k resistor, so a disconnection will be equal to a short-circuit to GND.

For detecting on which state the relays are, comparators are used. The signal from the auxiliary contacts are driven to the non-inverting pin of the comparator. A reference of 2 V is set by a voltage divider and driven to the inverting pin of the comparator. Thus, the comparator will output a logic high if the auxiliary contacts are closed (3.3 V ≥ 2 V) and it will output a logic low if the contacts are opened or disconnected (1.65 V/0 V ≤ 2 V).

The TS_ON_BAT signal seen in figure 50, which is obtained in the HV measurement circuit, will be a logic high if the voltage outside the accumulator container is greater than 60 V and a logic low if the voltage is below that value. This signal is obtained with the HV measurement circuit explained in *chapter 3.2.6*.

With these four signals and two logic gates, the enable red signal is obtained with the circuitry seen in figure 50.

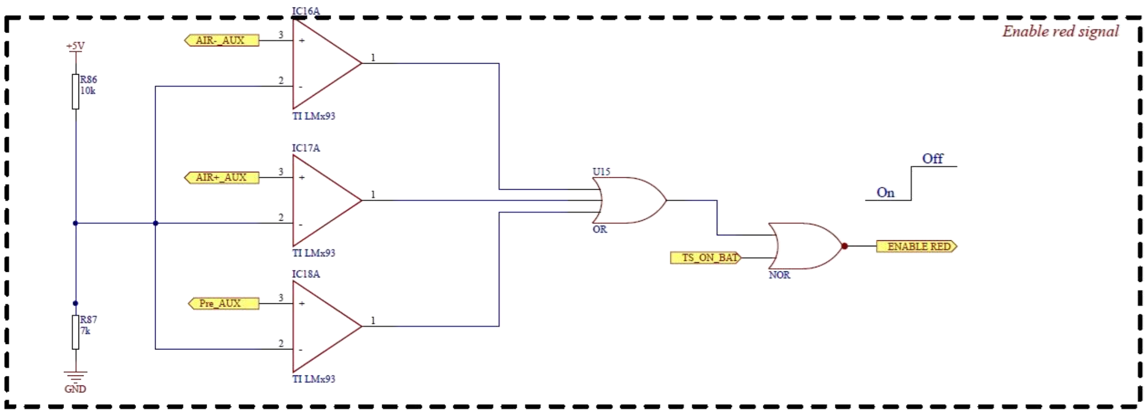

Figure 50: TSAL enable red schematic

Table 6, shows how the TSAL will act depending on the values of the four signals:

Relay	HV	Enable_Red	STATUS
0	0	1	Green
0	1	0	Red
1	0	0	Red
1	1	0	Red

Table 6: TSAL states

Furthermore, an additional circuit is needed for detecting any implausibility that may happen with SCS signals of the TSAL, this includes disconnection of any signal, short-circuits to ground or different measurements in the case of the two HV measurements needed.

To detect the disconnection or short-circuit of the relays' auxiliary contacts, comparators are used, but this time a reference of 1 V set by a voltage divider will be connected in the non-inverting pin and the signal to the inverting pin, so that when there is a short-circuit, the comparator outputs a logic high. Afterwards, an OR gate is used, so that if only one contact has an implausibility, the OR gate will output a logic high. In figure 51 the circuit can be seen.

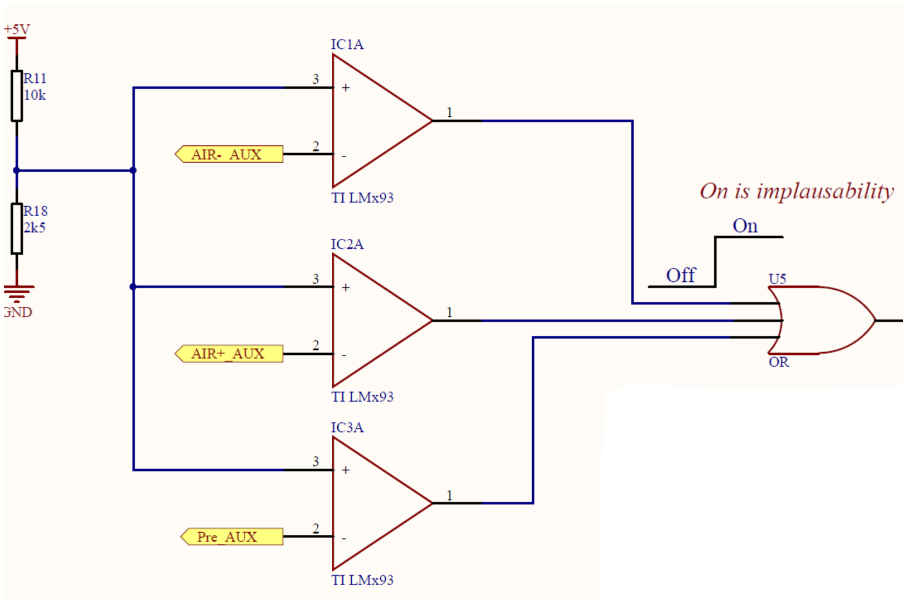

Figure 51: TSAL auxiliar contact implausibility circuit schematic

Regarding the voltage measurement implausibility, two options may arise: disconnection of the signal wire or different measurements of the sensors. The former is detected with the use of comparators and the latter with an XOR gate. In figure 52 the disconnect detection can be seen.

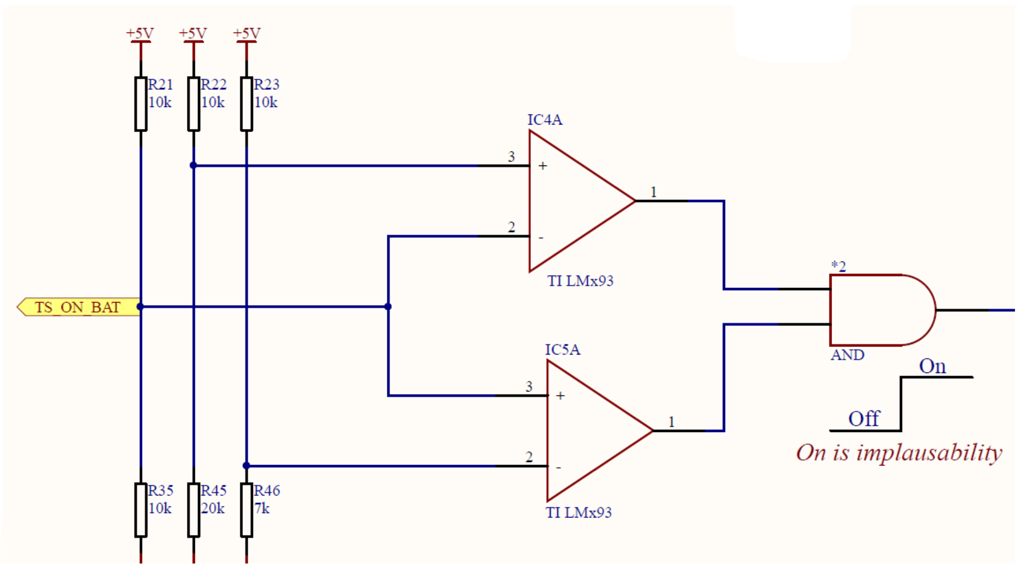

Figure 52: TSAL HV measurement connector implausibility circuit schematic

There are three references set with a voltage divider. The first one is connected to the HV measurement signal, so that if the wire is disconnected, the value will be of 2.5 V. The other references are of 3.3 V and 2 V. Because of the design of the HV measurement circuit, the signal will only be 0 V or 5 V if the voltage is greater than 60 V. If the signal value is either of these, the AND gate will output a logic low, but if the signal is disconnected, the TS_ON_BAT signal will be 2.5 V, and so the AND gate will output a logic high. The same circuit is used for the measurement made in the inverter enclosure and the accumulator container.

On the other hand, the XOR gate circuit can be seen in figure 53.

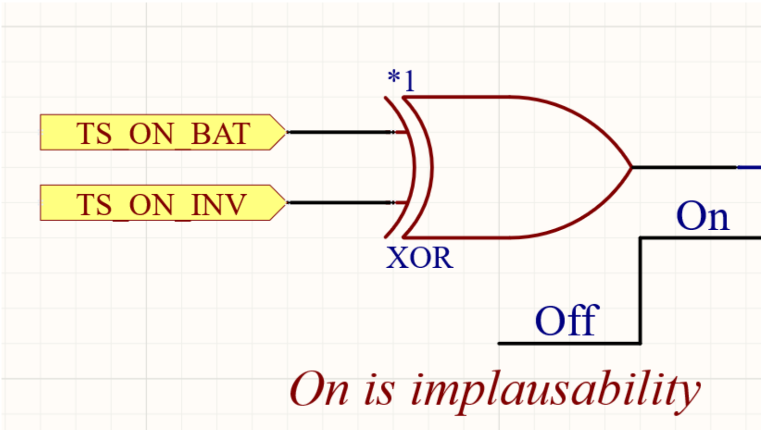

Figure 53: TSAL HV measurement signal implausibility circuit schematic

The truth table of an XOR gate is the next:

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Table 7: XOR truth table

So, if one of the sensors measures that there is no HV and the other one measures otherwise, the XOR gate will output a logic high, whereas if both measure the same, it will output a logic low.

With these three signals, the auxiliary contact implausibility, the disconnection of the HV measurement signal and the different measurements' implausibility, an extra logic circuit is needed to turn the TSAL off. In figure 54 the circuit can be seen:

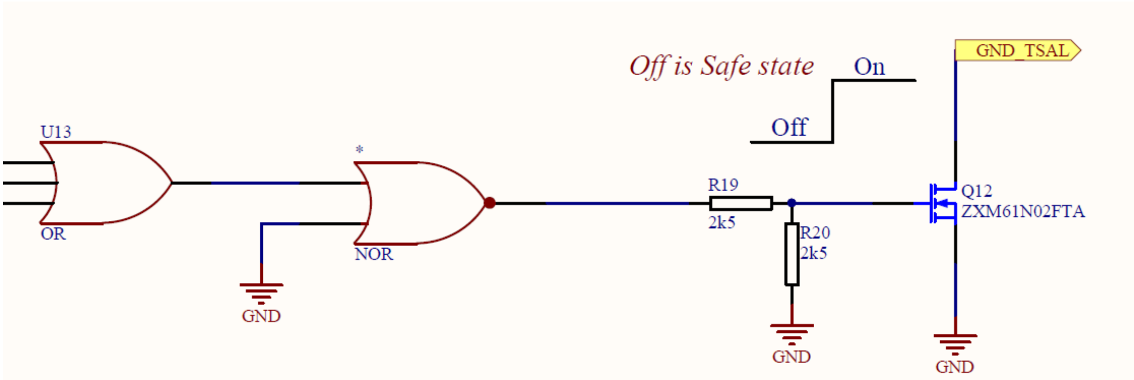

Figure 54: TSAL implausibility circuit

The three signals obtained before are driven to an OR gate and then to a NOR gate to invert the signal. Afterwards, there is a NMOS which supplies the TSAL board, the signal obtained from the NOR gate will determine if the NMOS is closed or opened and thus if the TSAL is active or off. If any implausibility signal is a logic high, the NMOS will be off. In addition, the OR and NOR gates can be replaced by just a three input NOR gate, but as there were not any three input NOR gates available in the workshop, the first ones were used. The whole TSAL circuit can be found in *appendix A*, and the schematics for the PCB design are inside the BMS master schematics in appendix E.

4.1.3 Current sensing

The sensor selected for the current sensing, the LEM HTFS 200-P requires some extra circuitry defined in the datasheet of the sensor. First, a circuit for providing the needed voltage reference is needed. The simplest option is to select a voltage reference component such as the ISL21010CFH315Z-T7A from *Intersil*, which provides a 1.5 V reference output with ±0.2 % of precision, but if the voltage reference needs to be changed so that it can fit other current ranges, depending on the configuration of future accumulator containers, this cannot be done.

To add this versatility, a voltage divider is used to set the reference voltage, so that by changing just one resistor, the reference voltage can be adjusted. Alas, the V_{ref} pin has little output impedance and the datasheet specifies that this pin needs to sink or source a maximum of 2.5 mA. Because of this, the voltage divider needs a buffer to provide high impedance between the voltage divider and the V_{ref} pin, so that the buffer is the one providing the current. In figure 55, the resulting circuit is seen.

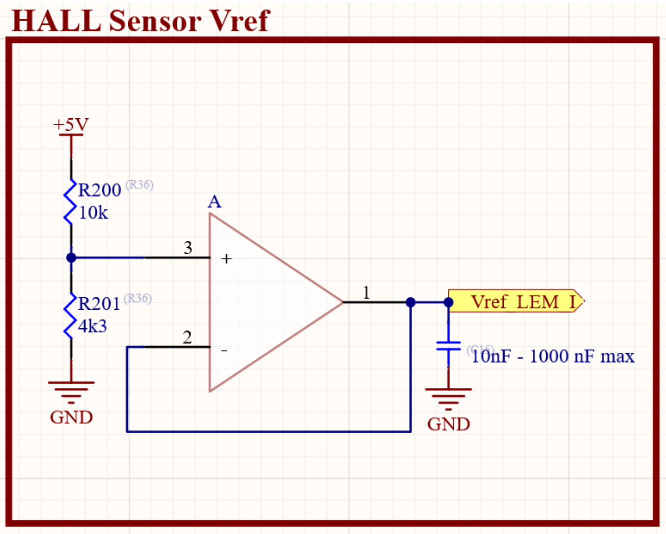

Figure 55: Hall sensor V_{ref} schematic

Furthermore, the datasheet also states that some capacitors should be used on every pin of the sensor for a correct operation, as it can be seen in figure 55. In addition, a Zener diode is placed for overvoltages and a pull-up resistor is also used so that if the sensor is disconnected, the measurement will be greater than the maximum current of the cells, and the AIRs can be opened.

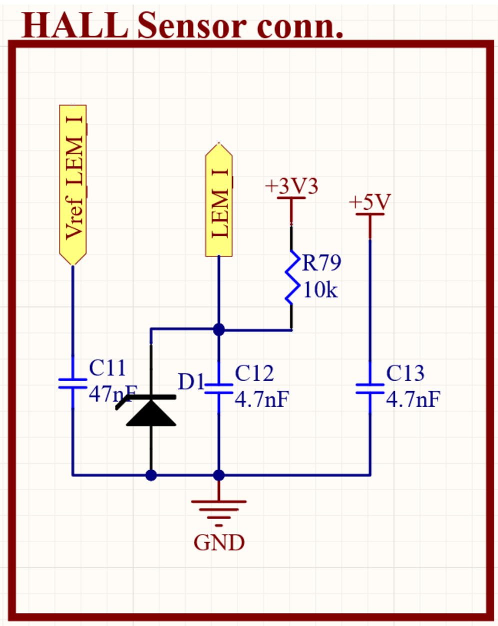

Figure 56: Hall sensor filters and protections

4.1.4 Voltage sensing

The voltage measurements needed for the pre-charge sequence are made with the voltage divider method designed in *chapter 3.2.6*. The measurement obtained with the resistive ladder, is used for two features of the board: the pre-charge sequence and the TSAL. The former is required for closing the second AIR when the inverter's DC link capacitors have been charged up to 95 %, so this signal must be an analogic signal ranging from 0 V up to 3 V, whereas the latter, should be a digital signal, this is, a logic low or a logic high of 5 V for the TSAL circuitry.

Obtaining the analogic signal, is as simple as connecting the measurement directly to the digital isolator so it can be read by the master module's microcontroller, but to obtain the digital signal, a comparator is used with a reference set by a voltage divider in the inverting input. For the TSAL circuitry, a logic high is desired when the voltage measured is above 60 V, so per equation 4, 60 V will be measured as 0.447 V. This voltage must be introduced as a reference in the inverting input of the comparator, for that, a voltage divider with a variable resistor is used to regulate the reference voltage to the voltage needed. Then, the measurement is driven to the non-inverting input of the comparator, and so, if the signal measured is above the set reference, the comparator will output a logic high, and then this signal will be driven to the digital isolator. In figure 57, the comparator circuit can be seen.

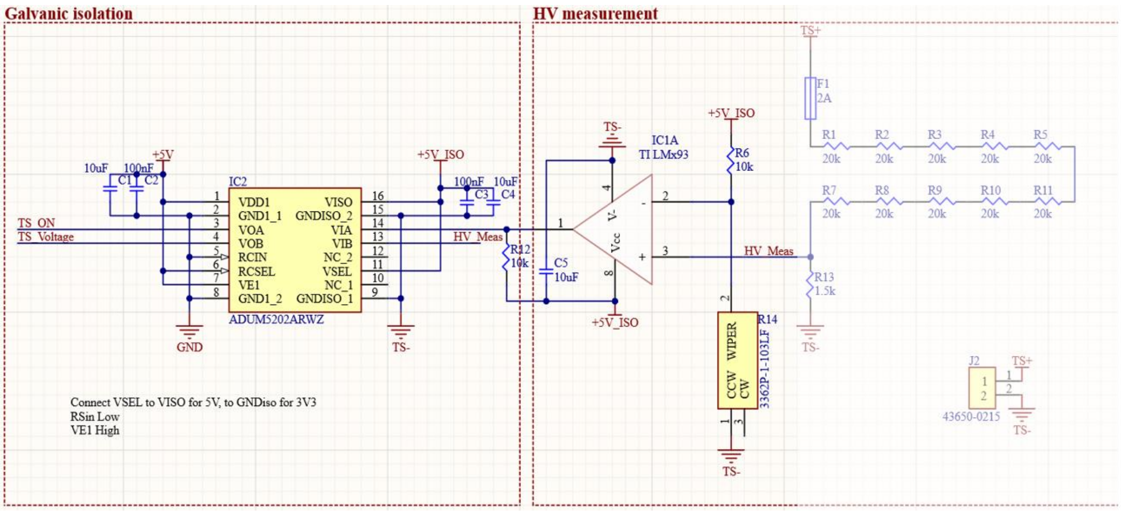

Figure 57: HV Measurement full schematic

4.1.5 Controller Area Network

The Controller Area Network (CAN) is a serial communication protocol which efficiently supports distributed real time control with a very high level of security. In automotive electronics, ECU, sensors, anti-skid-systems, etc. are connected using CAN with bitrates up to 1 Mbps. At the same time, it is cost effective to build into the vehicle body electronics in order to replace the wiring harness in many applications.

The development of the CAN bus started in 1983 at Robert Bosch GmbH and was officially released in 1986 at the Society of Automotive Engineers (SAE). This protocol has many variants, but in 1993, the International Organization for Standardization (ISO) released the CAN standard ISO11898 1, 2 and 3 in order to standardize its use in the automotive field. The ISO11898-2 standard is the one used in the vehicle and the components used for the CAN bus in the vehicle. This standard specifies the interconnect to be a single twisted pair cable (shielded or unshielded) with 120 Ω of characteristic impedance. Resistors equal to the characteristic impedance of the line should be used at both ends of the cable to prevent signal reflections. Furthermore, if additional filtering is desired, the termination resistor can be split in two resistors with a capacitor connected to ground. This kind of termination improves the electromagnetic emissions behavior of the network by eliminating fluctuations in the bus common-mode voltages at the start and end of message transmissions. In figure 58, a typical CAN bus architecture can be seen.

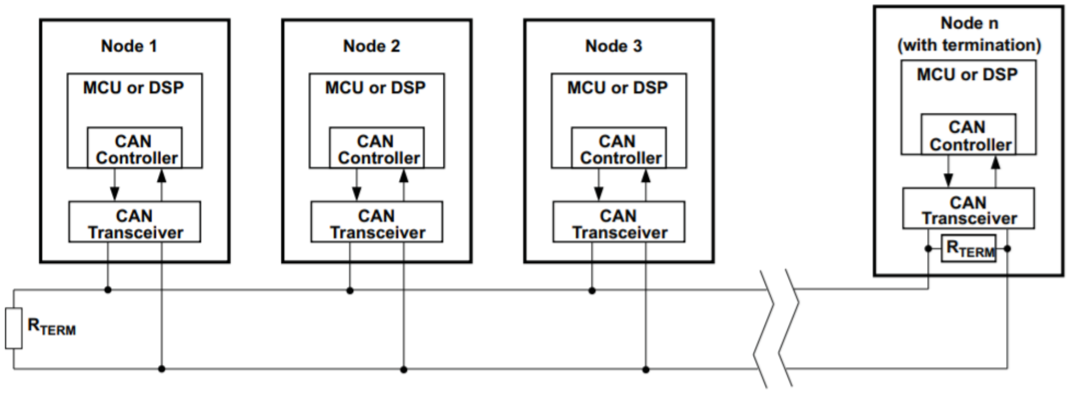

Figure 58: Typical CAN bus arquitecture

In figure 59, the terminations of the CAN bus can be seen. If the split termination with the capacitor is placed, the values of the resistor and capacitor should be selected to obtain a cut-off frequency of 1MHz if the bus bit rate is of 1 Mbps. With equation 6, the capacitor can be calculated:

$$fc = \frac{1}{2x\pi x60\Omega xC_{SPLIT}} = 10^6$$

Equation 6: Cut-off frequency of an RC filter

$$C_{SPLIT} = 2.65\ nF$$

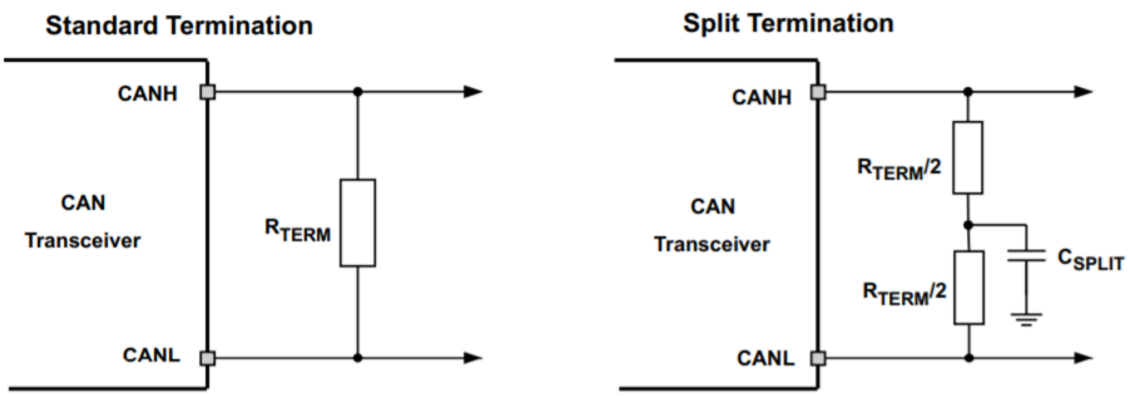

Figure 59: CAN bus split termination

In addition, before connecting the microcontrollers to the bus, a transceiver is needed in between to adequate de microcontroller levels to the bus levels, as it can be seen in each node in figure 58. For additional protection and filtering, an isolated CAN transceiver can be used, which prevents noise currents on the bus. With these characteristics, the ISO1050DUB from *Texas Instruments* has been selected as the CAN transceiver. It provides an isolation of 2500 V_{RMS} and bit rates up to 1 Mbps.

In the circuit designed for this module, extra filtering devices, such as common-mode chokes have been placed since they were recommended by many manufacturers. Moreover, to add extra protection to the transceiver in case something happens to the bus, a Transient Voltage Suppression (TVS) diode has been placed to protect the transceiver from voltage spikes. In figure 60, the final circuit schematic can be seen.

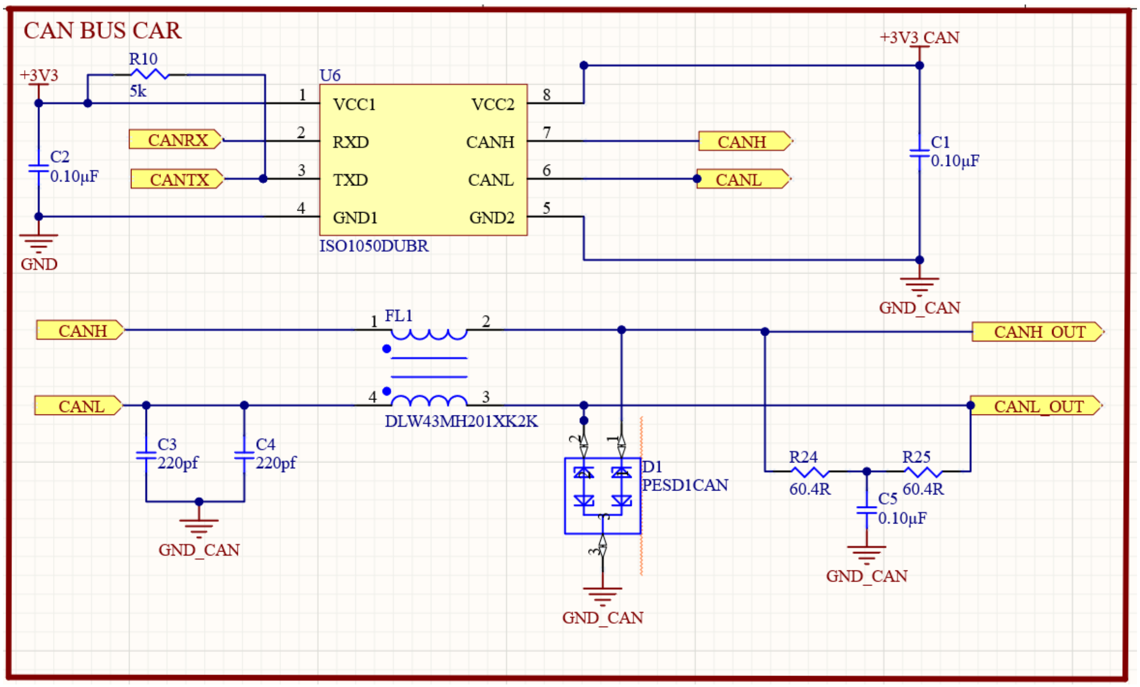

Figure 60: CAN bus schematic

As it can be seen in figure 60, both sides of the transceiver have different supplies to achieve the required isolation. This isolated supply is achieved by using an isolated DC-DC converter, in this case the TME2433S from *TRACOPOWER*, which converts the LV supply of 24 V to +3.3 V with an isolated reference.

4.1.6 Layout and PCB design

The master module is divided in two boards, the microcontroller board and the master board. The master module designed by Imanol Etxezarreta featured the LAUNCHXL-f28377S development board from *Texas Instruments*, but since this board has been discontinued from the market, the newest model has been chosen, the LAUNCHXL-f28379D. This option has been chosen above integrating the microcontroller in the master board because of the great experience the team has had using these boards, as no problems have been encountered when using them. Nevertheless, as a future line objective, the team should try to implement this microcontroller into a self-developed board, but as the objective of all electronic devices in the vehicle for now is to ensure its correct operation and robustness, the development board is the better option, since it is just a plug-and-play device and a replacement can be easily made. The development board can be seen in figure 61.

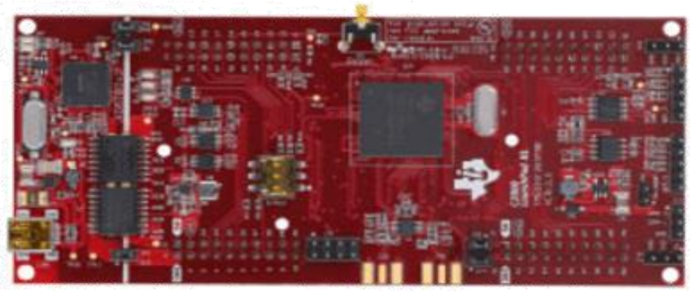

Figure 61: LAUNCHXL - f28379D

The master board contains all the circuitry that has been explained in the chapters above. It is the responsible of all low voltage electrical connections inside the accumulator container, as well as the communications. For this purpose, the PCB can be separated in different submodules, as it can be seen in figures 62 and 63.

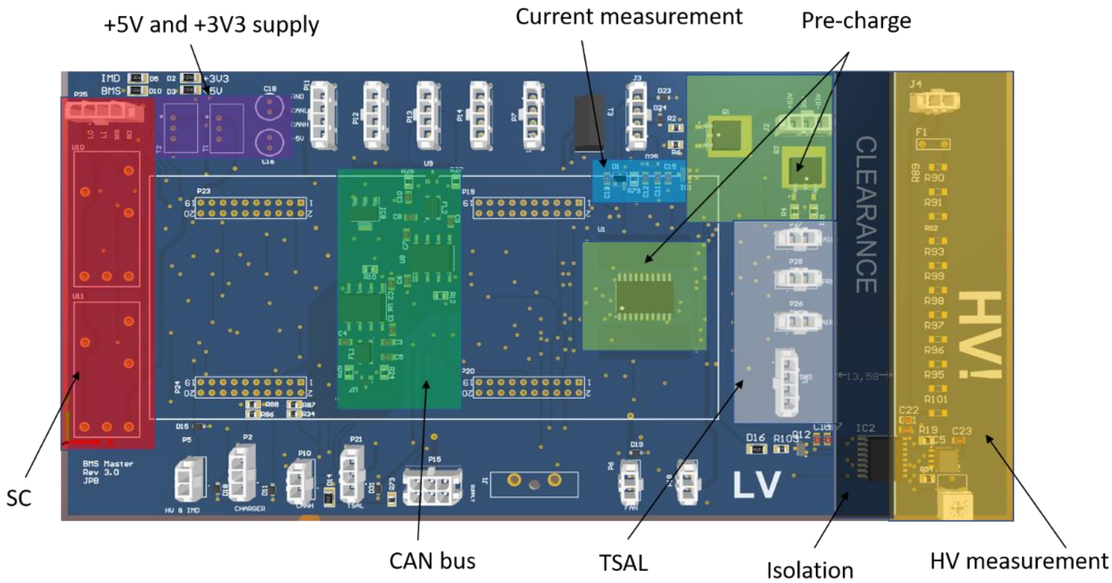

Figure 62: BMS master PCB. Top view

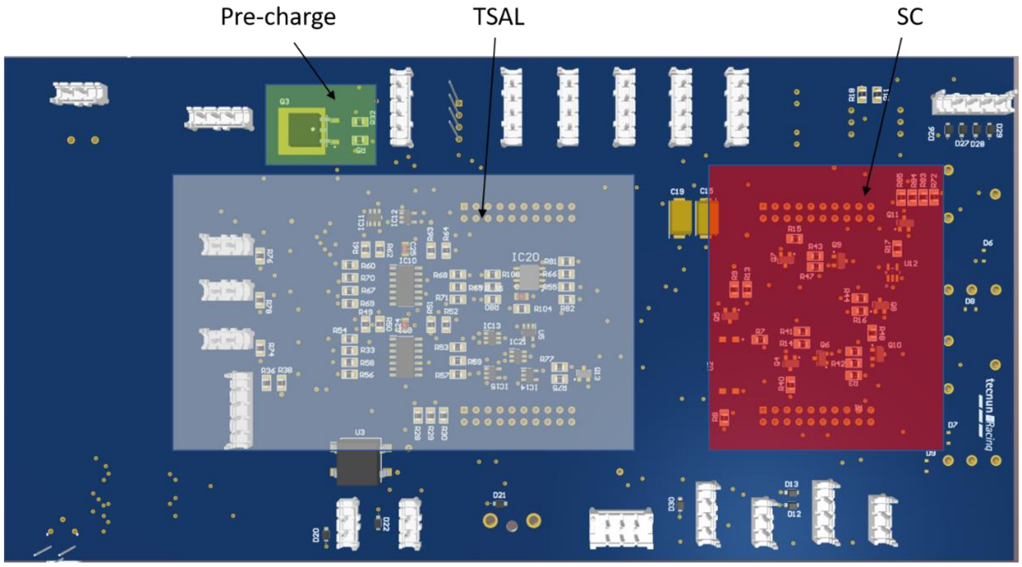

Figure 63: BMS master PCB. Bottom view

Furthermore, in order to increase the robustness against EMI or other kind of noises, a ground plane has been placed as it can be seen in figure 64. This ground plane alongside a power plane, simplifies the routing of the PCB, since the power and ground connections do not need to be routed together. Moreover, as the can bus has its own isolated reference, a plane with the isolated ground has been placed beneath the CAN bus circuitry, which has increased the reliability of the CAN bus substantially in the vehicle overall. This plane can be seen in figure 65.

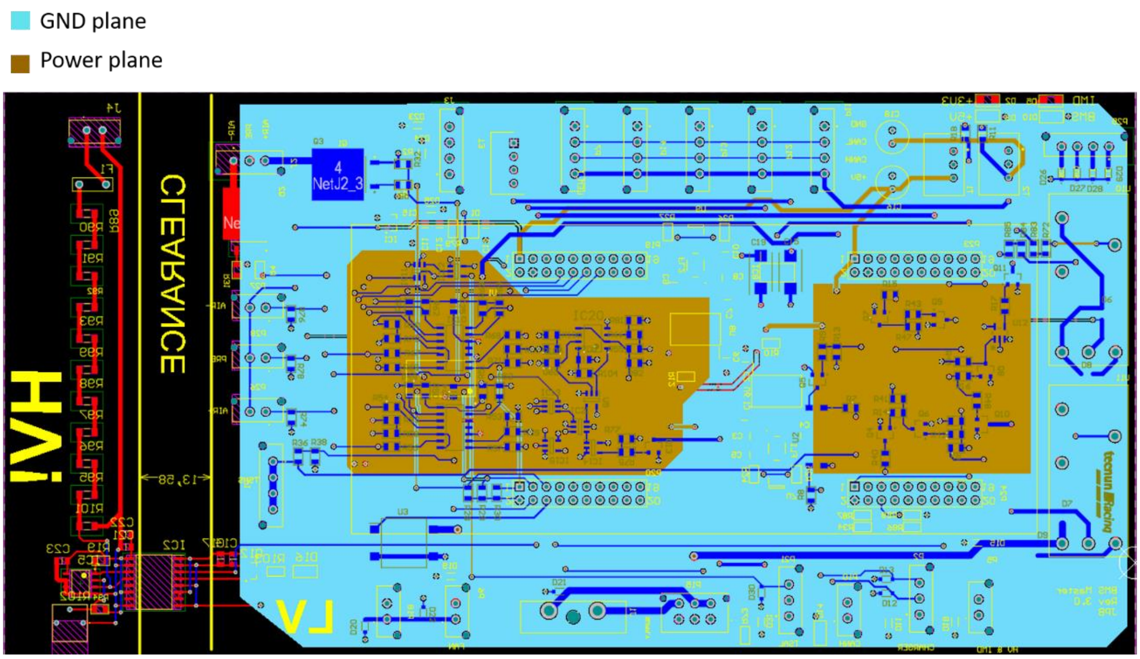

Figure 64: BMS master. Planes. Bottom view

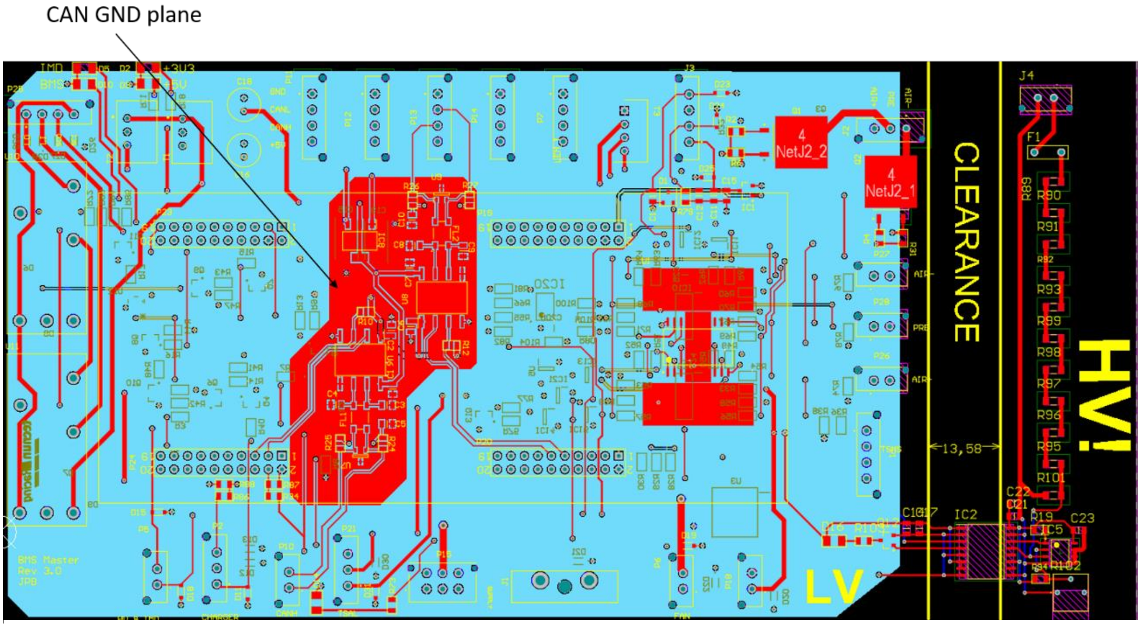

Figure 65: BMS master PCB. Planes. Top view

Finally, the microcontroller board and the master board are assembled with four male headers in the master board and four female headers in the microcontroller board. The final assembly can be seen in figure 66.

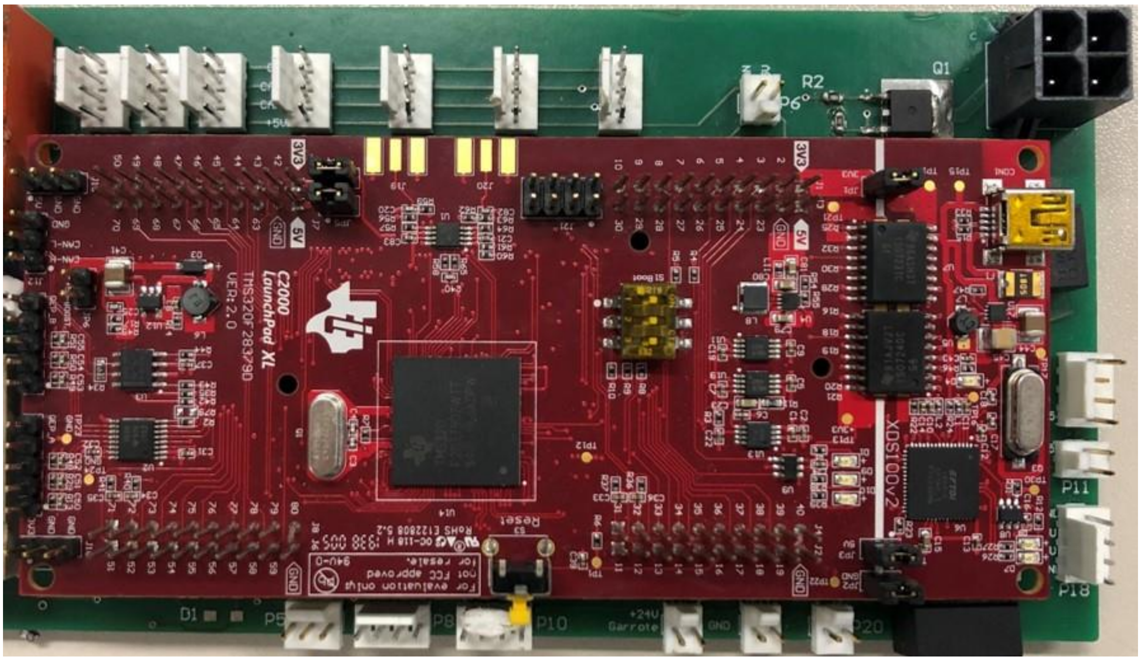

Figure 66: First prototype of the BMS master. Assembly of the LAUNCHXL – f28379D

4.2 Slave Module

The slave modules must be able to measure 24 cell voltages and at least 8 cell temperatures. In addition, the slaves must also be able to communicate with the master module via a communication protocol. Also, a communication timeout needs to be detected as these signals are SCS. Furthermore, the cell balancing is also a very important feature, in order to finish the endurance race, the cells being balanced will definitely help to achieve it because all the available energy of the cells can be used. All in all, these are the four core functions the slave modules must provide.

The FSG rules regarding this feature are listed below:

EV 5.8.2	*The AMS must continuously measure* ***• all cell voltages*** *• the TS current* ***• the temperature of thermally critical cells*** ***• for lithium based cells: the temperature of at least 30 % of the cells equally distributed within the accumulator container(s)***
EV 5.8.3	*Cell **temperature must be measured at the negative terminal of the respective cell and the sensor used must be in direct contact** with the negative terminal or less than 10 mm along the high current path away from the terminal in direct contact with the respective busbar. It is acceptable to monitor multiple cells with one sensor if this requirement is met for all cells sensed by the sensor*
EV 5.8.4	*The **maximum cell temperature is 60 ◦C** or the limit stated in the cell data sheet, whichever is lower*
EV 5.8.9	*AMS signals are **System Critical Signals**, see T 11.9.*

The team has designed its own slave modules since the 2017 season, since they can be more versatile than commercial solutions. In the next chapter, the previous slave module will be briefly explained so that it can be understood the motive behind the new design of the slave modules.

4.2.1 Previous design

The slave modules used the 2018 and 2019 season were designed by Unai Echeverria. In this chapter, the design will be briefly explained, and the motives to design a new slave module will be explained.

The voltages and temperatures of the cells are read by three microcontrollers using their included ADCs, and then the information is sent via CAN bus to the master module. Each slave board is divided in three modules, one for each microcontroller. The whole board measures the voltages of 24 cells and the temperature of 9 cells. In addition, it includes a passive balance feature which can balance the cells at 175 mA. Next, the measurement methods will be explained.

In figure 67, the voltage measurement method is shown:

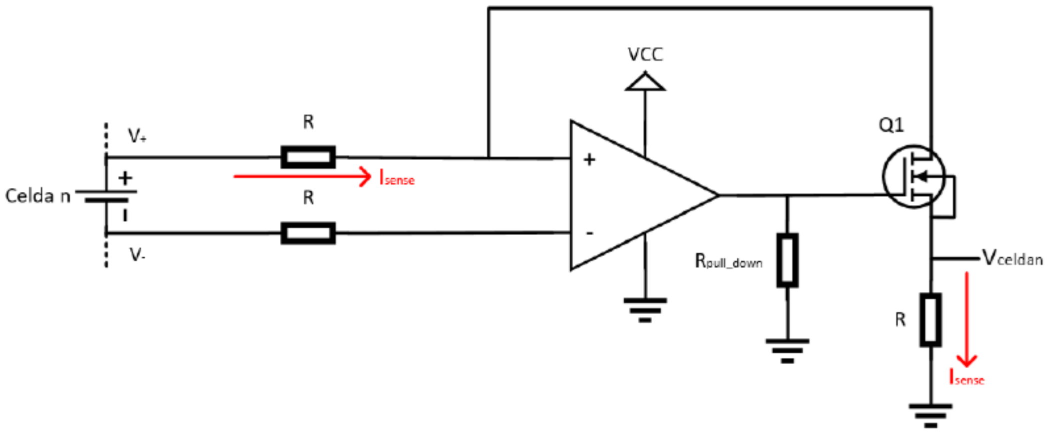

Figure 67: Voltage measurement

The voltage measurements are made with a differential amplifier, one for each cell, so at least 4 resistors are needed per cell, as it can be seen in figure 66. The NMOS is placed to avoid any consumption from the cells when the vehicle is switched off.

This method was simulated and tested, and the results were satisfactory, but with time, the vibration of the vehicle would lose the bolts needed for the cell connections a little bit and the cell would plug in and out constantly, so, the NMOS or the operational amplifier resulted damaged. This required taking out the board, replacing the damaged components and mounting the board back in, which is time consuming and difficult due to the space restraints. This may have happened because the components used were not designed for automotive or battery use.

The temperature measurements were made using the MCP9701A sensor from *Microchip*. This sensor has worked fine, so revolutions do not need to be made for this task. Although the temperature measurements are not a problem, the number of temperatures measured is very low even though it is rule compliant. The temperature of a battery cell is critical, as they are very flammable if a temperature of 50 °C is overpassed.

4.2.2 Objectives

The main objective is to solve the reliability issue the previous modules had after a long use, and use components designed for battery and automotive applications, since these have been tested in harsh environments, have automotive standards. Furthermore, since they have been developed in the past few years due to the growth of the electric vehicle, they are almost state-of-the-art components and are widely used by prestigious brands such as *Tesla*.

The new slave modules must also be compatible with the old modules, so both can be used. This will be helpful if spare battery packs are needed in case of damaged modules need to be replaced fast or to use them in future projects such as the electric powertrain test bench. Moreover, the CAN bus protocol is recommended as the team has a lot of experience with it, and it will not be a source of trouble. This will restrain the communication protocol and the supply of the board. The communication protocol must be the CAN bus protocol and the LV supply of the board must be of

5 V. To implement the CAN protocol, a microchip is needed, regardless of which components are used.

Furthermore, the number of temperature measurements must also be increased in order to rise the safety feature of the board. To set a numeric objective, 50% of the cell temperatures will need to be measured. Moreover, the precision from the previous design is of ±2°C, so the new design's precision should be same or more.

In addition, the voltage measurement precision should at least be the same as the previous design (±8.4 mV), but an improvement can be made using the aforementioned components, so a target ±5 mV will be set.

Regarding the cell balancing, the balance current objective will be at least the previous design's balance current (175 mA) or higher.

All in all, the objectives of the new design are gathered in table 8.

Communication protocol	CAN bus @ 1 Mbps
Temperatures measured	≥ 48
Balance current [mA]	≥ 175
Voltage measurement precision [mV]	±5
Temperature measurement precision [°C]	≥ ±2

Table 8: BMS slave module objective specifications

4.2.3 Definition of the system

Before starting the design, the measurement methods and components need to be selected. The previous design offered good measurements, so a similar design could be made selecting components for battery and automotive applications. Nonetheless, improvements can hardly be made following this design.

A very good alternative to this design, is the use of Integrated Circuits (IC) designed for battery driven applications in electric vehicles, ideal for this use-case. The implementation of a digital IC will increase the reliability of the system, reduce the number of total components and thus, reduce the needed space in the board.

As a future line objective, the communication protocol between master and slave should be the one used by the ICs instead of CAN bus. There would not be the necessity for having a microchip and so, less components would be used, decreasing the cost of the module and decreasing the needed space. This will affect in the IC selection, even though the design for this season will be using a microchip with CAN bus.

A preselection of ICs has been made according to the characteristics of the battery in table 9.

	BQ76PL455	LTC6804	MC33771
Cells per IC	16	12	14
Series cells	256	100	882
Temperature sensors	8	5	7
Shut-down consumption [µA]	40	4	40
Operation consumption [mA]	8	1.5	5.4
Total measurement error [mV]	0.75	0.3	0.8
Sampling time [ms]	2.5	0.290	0.00943
Communication protocol	UART	SPI/isoSPI	SPI/isoSPI

Table 9: Battery monitoring IC comparison

Looking at table 9, the most suitable option is the LTC6804 from *Analog Devices*. This IC has the exact amount of cells if we use two ICs per board in a stack (12 + 12 = 24 cells), they can be stacked up to 100 cells, the current consumption is the lowest, the accuracy is the best and the sampling time is also the fastest. On the other hand, it only has 5 additional analog inputs for temperature sensors, so if 8 ICs are used, a total of 40 cell temperatures could be read, less than wanted. A microchip is needed for CAN bus communication with the master module, so this problem could be solved by using the microchips ADC, but then these signals have to be isolated, and digital isolators must be introduced in the board, increasing the cost of the board and space. So, for this reason, the BQ76PL455 IC from *Texas Instruments* has been selected. It is capable of reading 8 cell temperatures, so a maximum of 64 cell temperatures can be measured if 8 ICs are used. Furthermore, the communication protocol is UART instead of SPI, which is easier to implement, and although the sampling time seems to be quite lower than the rest, the code of the microcontroller needs about 20 ms to run, so this will not be a problem.

This IC is an integrated battery monitoring and protection device, designed for high-reliability automotive applications. The integrated high-speed, differential and isolated communication interface allows up to 16 devices to communicate with a host via UART interface.

This device monitors voltages and temperatures but is also able to detect several different faults, such as overvoltage, undervoltage, overtemperature and communication faults. Furthermore, it also features a secondary thermal shutdown for the protection of the IC.

For the monitoring purpose, the IC features high performance 14-bit ADC for cell voltages and eight auxiliary analog inputs for temperature sensors, both with a voltage range of 0 V to 5 V. It is designed for robust hot-plug performance, so the reason suspected to be damaging the old design of slave modules would not damage the slaves anymore. Furthermore, the IC includes an open wire detection feature, if this detection is run cyclically in the code, disconnections can easily be detected, which is a must for Formula Student technical inspection.

The topology of the slave module will be a master-slave topology, two ICs and a host microcontroller will be placed in each slave board, they will be connected in a daisy-chain topology to the host microcontroller. The operation of this IC is simple: the host microcontroller needs to send a wake-up signal to the IC (a pulse) and if the IC is supplied by the battery cells, the IC will be available for starting communications with the host microcontroller. So, in order to communicate with it, a wake-up signal, low voltage supply and two UART signals are needed.

4.2.4 Voltage sensing

For the battery cells used in this application, the cell voltage can vary from 3 V up to 4.2 V in normal operation, but the voltage can go above that limit or below the limit, for example, if two battery cells are short-circuited.

The IC's ADC input ranges from -0.3 V to 5.5 V. The ADC has a resolution of 14-bit so, the voltage resolution per ADC is of 354 µV (equation 7), almost insignificant.

$$Voltage\ resolution = \frac{5.5 + 0.3}{2^{14} - 1} = 354.03\ \mu V$$

Equation 7: Voltage resolution

The cell connections go through an RC filter among other systems before entering the ADC, in figure 68, the filters and protections used for every cell connection can be seen.

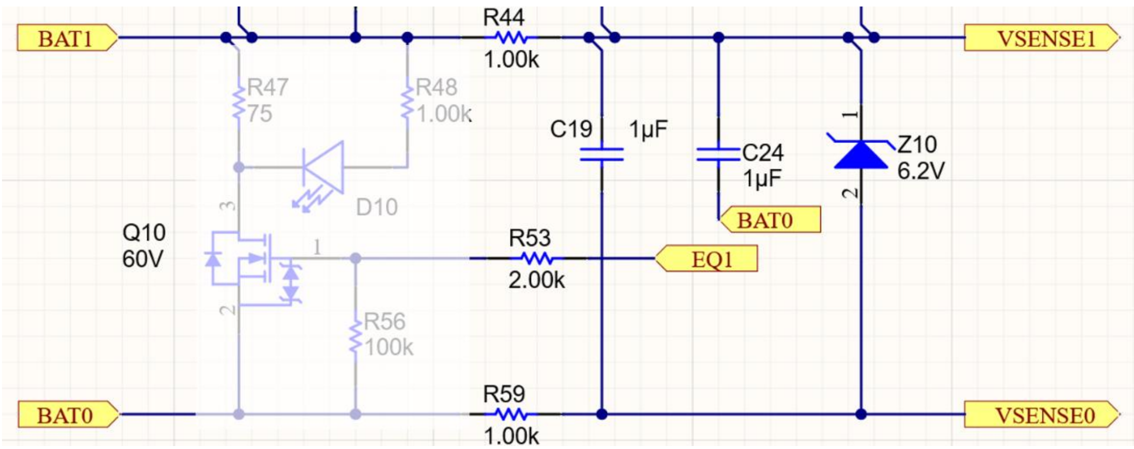

Figure 68: Battery connections. Filters and protections.

This filter is the recommended by the manufacturer in the datasheet, but the RC values need to be changed depending on the overall environment that surrounds the board to have optimum performance. The resistance recommended is a 1 kΩ resistor and the capacitor of 1 µF, these values give a cut-off frequency of 159 Hz (equation 6) so if these values of resistor and capacitor are changed, they should be changed upon this cut-off frequency as a reference.

$$f_c = \frac{1}{2x\pi x1000x1x10^{-6}} = 159.15\ Hz$$

4.2.5 Temperature sensing

The FSG rules state that at least 30% of the cell temperatures need to be monitored and that the sensor used for this measurement must be in direct contact with the negative cell terminal. To achieve this, at least 29 cell temperatures need to be measured, but the goal set was to measure at least 48, half of the cells.

Because of the mounting of the slave board, there will be a distance between the board and the cells, so for the selection of the temperature sensor, a through-hole sensor is needed. Furthermore, the sensor must also have a minimum accuracy of ±2°C. After searching the market, a very standard sensor was found, the LM35DZ from *Texas Instruments*. This sensor is a PTAT sensor, whose principle for the measurement is to output the forward voltage drop in a silicon diode, which is temperature dependent and its coefficient is given by the manufacturer. The package of the sensor is T0-92-3, and its size is enough to reach the respective negative cell terminal. In figure 69, an image of this type of sensor can be seen:

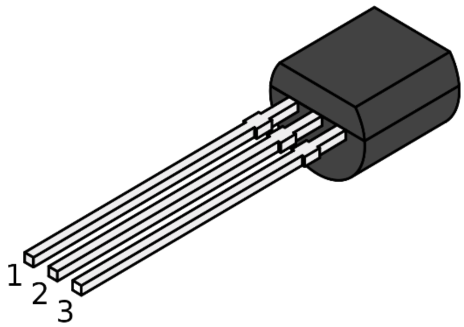

Figure 69: TO-92-3 package

The working temperature of the sensor is between 0°C and 100°C, which is enough for the cell temperatures since the maximum temperature the cell can withstand according to its datasheet is 60°C. The sensor gain is of 10 mV/°C, so the maximum output voltage the sensor will have is 600 mV. In order to make it easier to measure the output voltage, a non-inverting amplifier is used to make the output voltage range be between 0 V and 5 V, for that, the circuit in figure 70 is implemented.

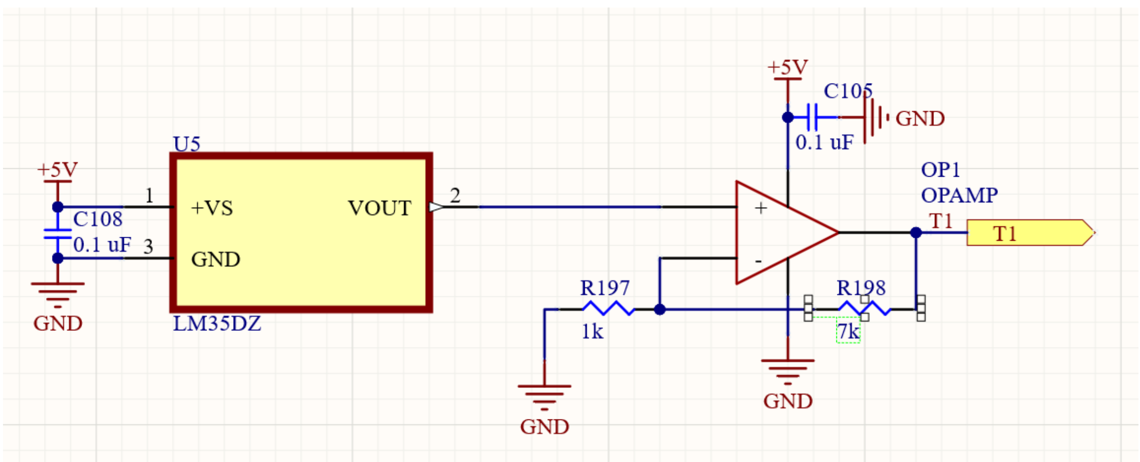

Figure 70: LM35DZ sensor signal conditioning

The amplification needed is about 8, the amplification the amplifier provides is 1+R198/R197, so the resistors selected are 7k and 1k. This will also provide a protection for the IC in case the sensor gets short-circuited. In addition, two capacitors have been placed in the supplies of the operational amplifier and sensor for filtering noise and add robustness to the circuit.

Finally, to make sure there is a good contact between sensor and cell tab, thermal paste needs to be added in the junction to reduce thermal resistivity in the contact. In figure 70 this can be seen.

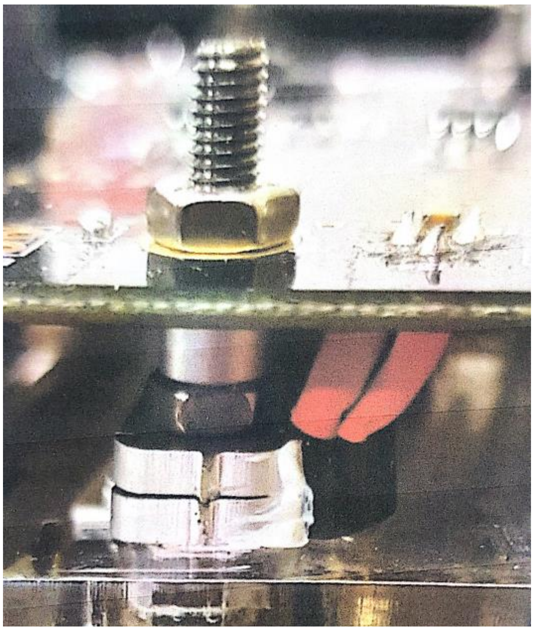

Figure 71: Temperature sensor with thermal paste

4.2.6 Cell balancing

The battery cells may unbalance due to different conditions. Although the discharging or charging current is the same if all the battery cells are connected in series, each cell has a different capacity value and internal resistance, this causes unbalancing of the cells in time. As charging-discharging cycles increase, the unbalancing also increases, so when discharging, one cell is going to be the first to be discharged. On the other hand, when charging, one cell is going to be the first to be fully charged. So, the energy stored by the of the cells will not be used in the discharge process and the cells will not be charged to their full storage capacity in the charging process.

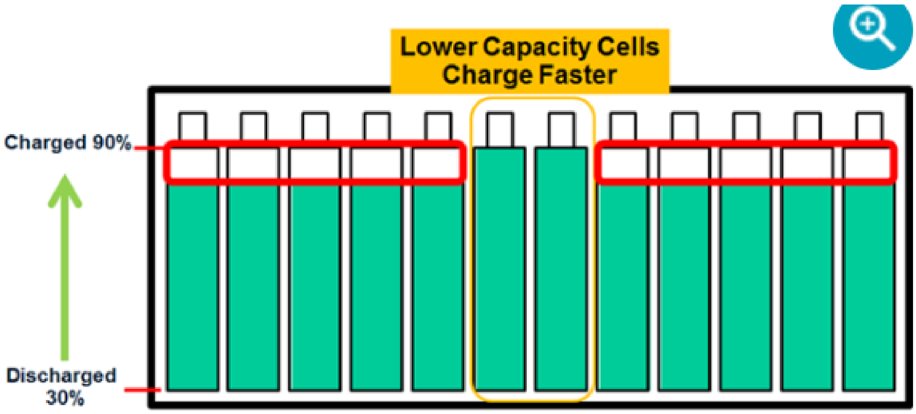

Figure 72: Unbalanced cells charging process

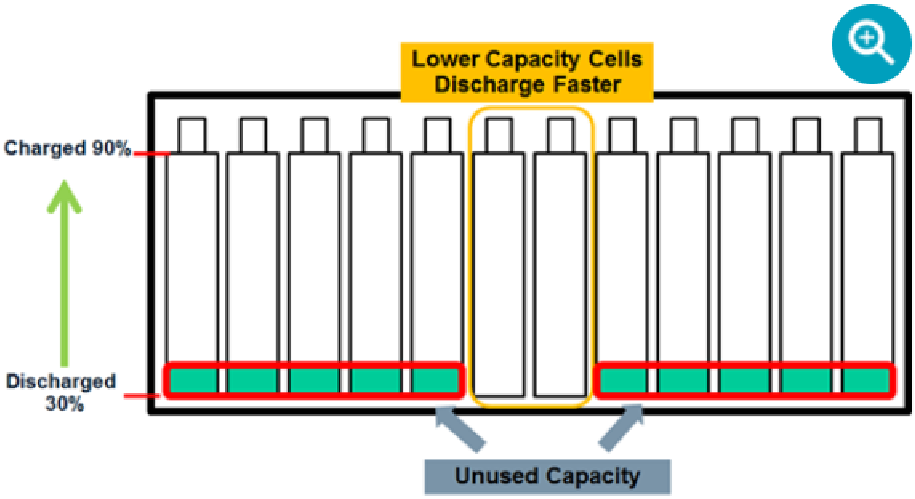

Figure 73: Unbalanced cell discharging process

If the autonomy of the vehicle is to be harnessed, the cells must be balanced as much as possible to increase the available energy of the battery. Furthermore, balancing will maintain a healthy battery SoC. This will require to add external circuitry to balance the cells. For this task, two options are available, passive or active balancing. The former results in all cells having a similar SoC by "burning" the excess energy in a bleed resistor which is placed in parallel with the cell and is connected and disconnected from it, whilst the latter redistributes the charge between the cells during the charging or discharging process, increasing the autonomy of the battery even in the discharging process.

This IC incorporates the passive balancing feature with external NMOS or active balancing with external ICs such as the EMB1428Q from *Texas Instruments*. The active balancing requires bulky and expensive components depending on the balancing technique, such as coils or capacitors. As the space in the accumulator container is very limited, the passive balancing option is the only available option.

When selecting the bleed resistor, the resistance value will not only determine the balancing current but also the package and size of the resistor for the needed power dissipation, but the higher the power dissipation, the pricier is the resistor. So, a compromise between space, current and price must be achieved. Logically, a higher balancing current will mean lower balancing time, so this parameter should be maximized.

In addition, the charging time should also be considered when selecting the resistor. If the charging process is much shorter than the balancing process, e.g 24 hours, the balancing circuit should be redesigned. The charging time of the battery is about an hour.

In table 10, a comparison between different resistors in the market is shown:

Resistance [Ω]	18	15	11	10
Current [mA]	233.33	280	381.82	420
Max Power[W]	1	2	2	2
Power [W]	0.98	1.176	1.60	1.764
Price [€]	0.348	0.553	0.5	0.346
Total price [€]	33.408	53.088	48	33.216
Price increase [%]	100	158.91	143.68	99.43
Balance time 5% [h]	3.429	2.857	2.095	1.905

Table 10: Bleed resistor comparison

Normally, when a cell reaches the 4.2 V, the least charged cell is about 4 V, so there is a difference of 5 % capacity between them and thus, the balance time will be the time to balance this 5 % of difference, not the whole capacity. As table 10 shows, the best option would be the 10 Ω resistor, but the power dissipation when the cell is charged to 4.2 V is quite high (1.76 W). Although the resistor can withstand the power dissipation, if many resistances were balancing at the same time, the total power being dissipated would be high and could be challenging to cool the batteries. For this reason, the next better option would be the 15 Ω resistor, but it is 58 % more expensive than the 18 Ω resistor, and as the module is intended to be cheap since the budget is very limited, the 18 Ω resistor is chosen. Still, if the budget were not a problem, the 15Ω resistor could be easily implemented and the balancing time would be considerably reduced.

For connecting and disconnecting the bleed resistor, an NMOS is used, one per cell. This NMOS needs to handle a V_{DS} voltage of 5 V maximum, and an I_{DS} current of at least 250 mA. With these requirements, the 2V7002KT1G from *ON Semiconductor* is chosen, which is also recommended in the IC's datasheet.

Finally, a LED is placed so that in can be seen which cells are discharging. This will help to the identification of problems, for example, when a transistor is damaged, and so the cell is always discharging unintentionally.

In figure 74, the final balancing circuit can be seen:

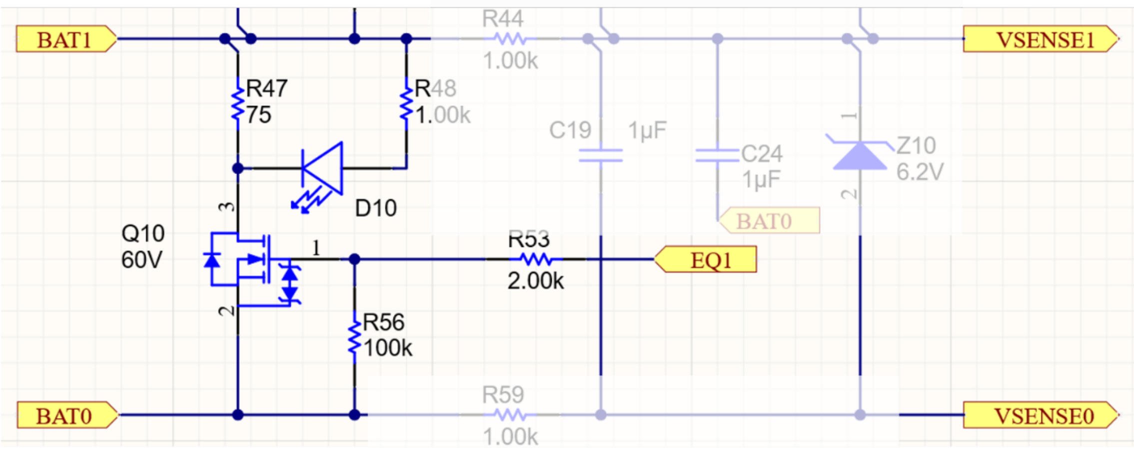

Figure 74: Battery connections. Balancing circuit

In figure 74, the balancing circuit in the PCB can be seen.

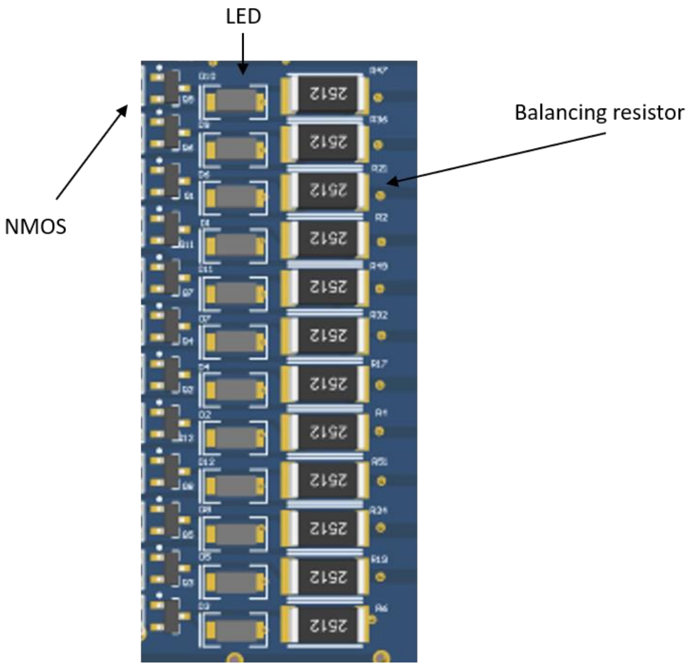

Figure 75: Balancing circuit in the PCB

4.2.7 Low Voltage

The slave module needs a low voltage zone in order to communicate with the master module, which is supplied by the low voltage system of the vehicle. The purpose of this zone is to wake-up the IC and receive the voltage and temperature readings via UART and bounce them via CAN bus to the master module, for that a microcontroller and a CAN transceiver are used.

The selected microcontroller is the PIC18F4680 from *Microchip*. This microcontroller has the CAN bus feature and its voltage levels are 0 V to 5 V, which is needed to communicate with the IC, these are the main reasons why this microcontroller was selected. Nonetheless, it is also small, it can be configured to the needed frequency for the CAN bus (40 MHz), it has enough ADC if additional temperature sensors are wanted to be placed and has little power consumption (55 mW). Furthermore, the team has also the knowledge to use this microcontroller effectively. For the correct operation of the microcontroller, a crystal oscillator must be placed to achieve the required 40 MHz frequency.

Regarding the CAN bus circuitry, it is the same as the one used in the master module. An isolated CAN transceiver is used along with the needed filters and isolated DC-DC supply in order to adequate the voltage levels to the master module's levels.

To supply this zone of the board, a connector is placed in the edge of the PCB. This connector drives the low voltage supply (+5 V and GND) and the two CAN bus wires. In figure 75, this zone can be seen in detail.

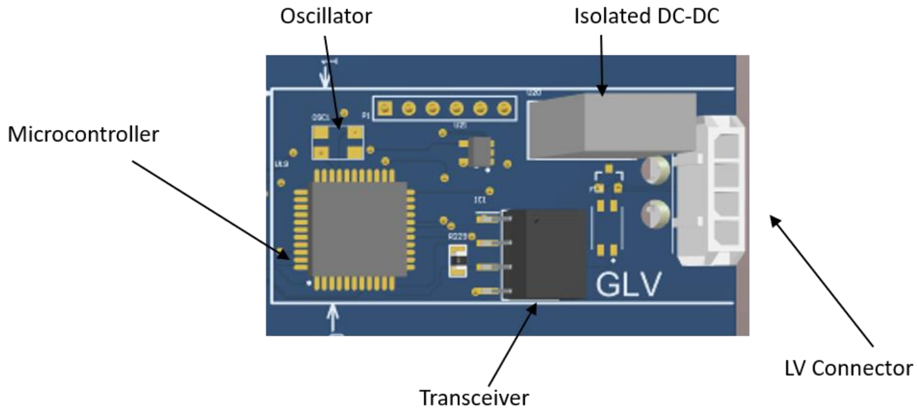

Figure 76: Low Voltage zone in the PCB

4.2.8 Galvanic Isolation

The FSG rules state the situations where galvanic isolation is required:

EV 4.3.5 ***If TS and LVS are on the same PCB, they must be on separate well defined areas of the board, meeting the spacing requirements in table 5****, each area clearly marked with "TS" or "LV". The outline of the area required for spacing must be marked. "Conformal coating" is referring to a coating insulator, solder resist is not a coating. If integrated circuits are used such as opto-couplers which are rated for the respective maximum TS voltage, see EV 1.2.1, but do not fulfill the required spacing, then they may still be used and the given spacing does not apply for this integrated circuit.*

Voltage	Over Surface	Through Air (Cut in board)	Conformal Coating
0 V DC to 50 V DC	1.6 mm	1.6 mm	1.0 mm
50 V DC to 150 V DC	6.4 mm	3.2 mm	2.0 mm
150 V DC to 300 V DC	9.5 mm	6.4 mm	3.0 mm
300 V DC to 600 V DC	12.7 mm	9.5 mm	4.0 mm

Table 5: Spacing required between TS and LV.

EV 4.3.7 ***All connections from a TS component to external devices, such as laptops must include galvanic isolation****, see EV 1.2.1.*

As EV 4.3.7 states, all connections from a TS component to any device, such as a laptop, need to be galvanically isolated. The low voltage zone, as it is connected to the master module and can be connected to a laptop for the programming of the microcontroller, needs to be galvanically isolated.

This isolation can be divided in two different parts, the electrical isolation and the physical separation. The rule EV 4.3.5 states that in every PCB where HV and LV are present, spacing of at least 12.7 mm is required between these two according to the voltage of the vehicle. Even though this spacing can be reduced by using an insulation coating for PCBs, as there is enough room, the spacing will be of 12.7 mm.

On the other hand, an electrical isolation is required for the UART communication protocol and wake-up signal for the IC. These signals are isolated with the use of digital isolators. In the case of the UART, the ISO7021 dual-channel digital isolator is used. This isolator has ultra-low current consumption, 3000 V_{RMS} of isolation and up to 4 Mbps of speed, which is more than enough as the UART has a maximum of 1 Mbps in this use-case.

Regarding the isolation of the wake-up signal, this is achieved using the same isolator used in the voltage measurement circuit described in <u>*chapter 3.2.6*</u>, the ADUM5202.

In figure 77, the galvanic isolation schematic can be seen, whereas in figure 78, the isolation zone of the PCB can be seen.

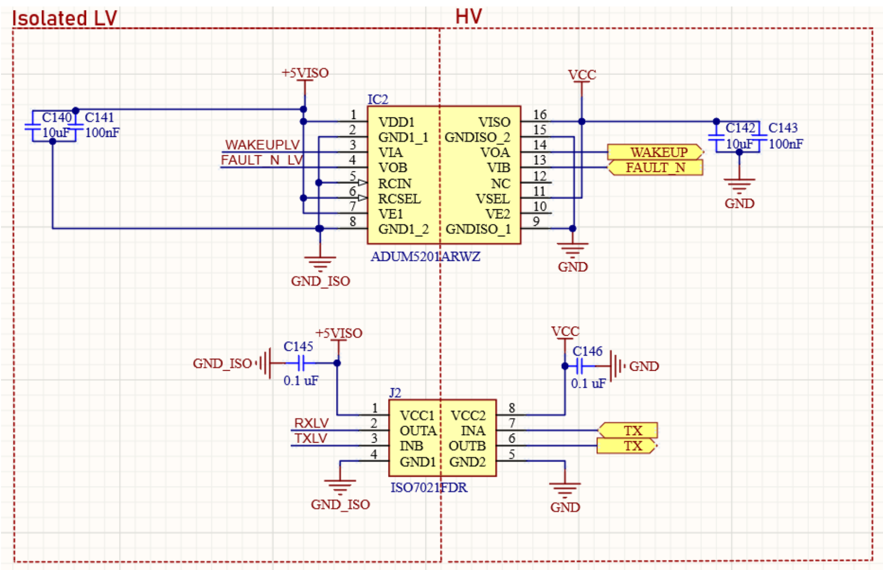

Figure 77: Galvanic isolation schematic

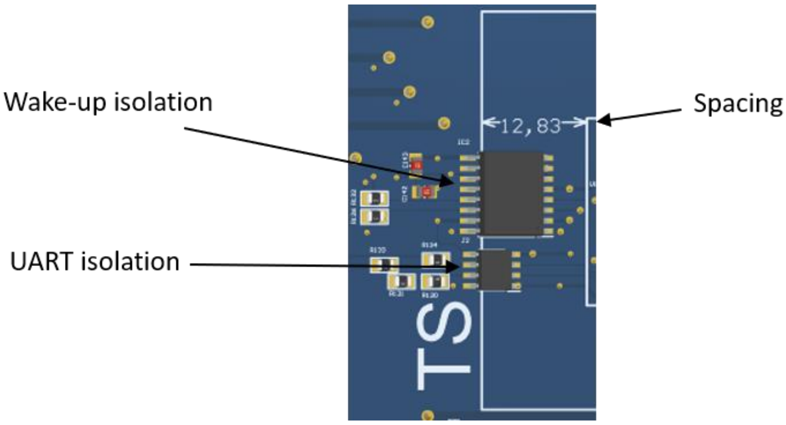

Figure 78: Galvanic isolation in the PCB

4.2.9 Layout and cell stack integration

One of the objectives of the slave board was to be compatible with the old slave boards and battery packs. This defines the dimensions of the PCB. Each board must handle 24 cells in series, and so, 25 holes of 3 mm of diameter (24 positive cell tabs + the most negative cell tab) are needed. Then, the board is introduced in the battery pack by introducing the holes in the bolts of the pack, and in order to avoid loosening due to the vibrations, the last nut must be a metallic self-locking nut. Furthermore, each cell connection has a dedicated fuse to protect the circuits in case of a short-circuit between cells. In 79, the PCB integration in the cell stack can be seen.

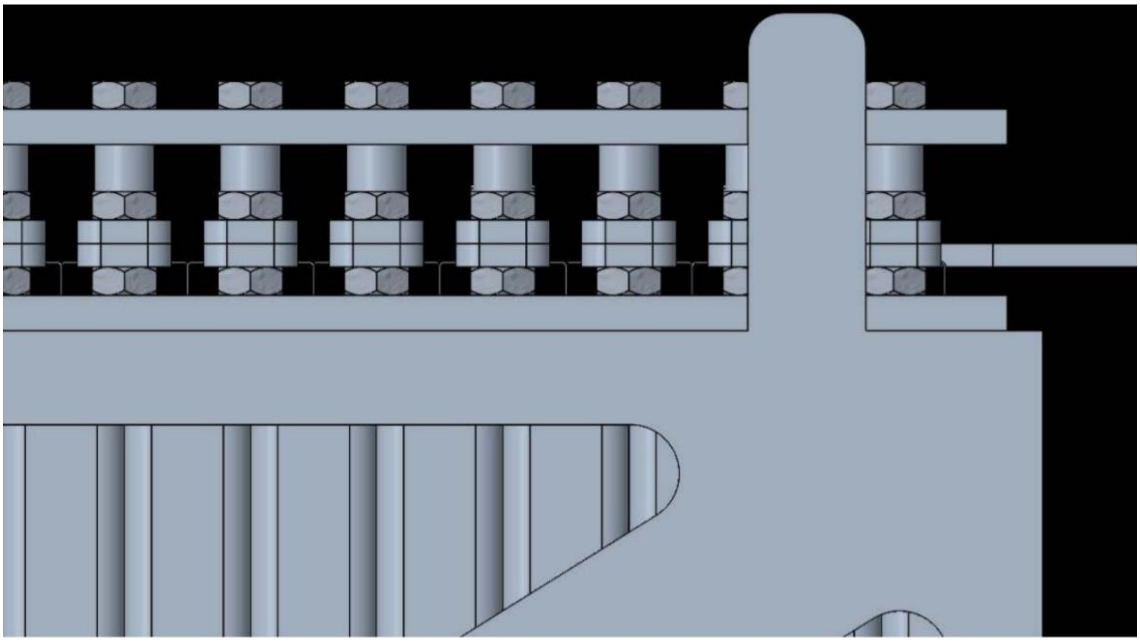

Figure 79: Cell stack integration

The PCB is separated in 5 zones: the low voltage zone, first module, second module, cell connections and isolation. In figure 80, these zones can be seen highlighted. Each slave board will have two modules, this is, two ICs. Then these two ICs will be connected in a daisy-chain topology to the host microcontroller located in the low voltage zone, but before this, the signals coming from the IC are galvanically isolated.

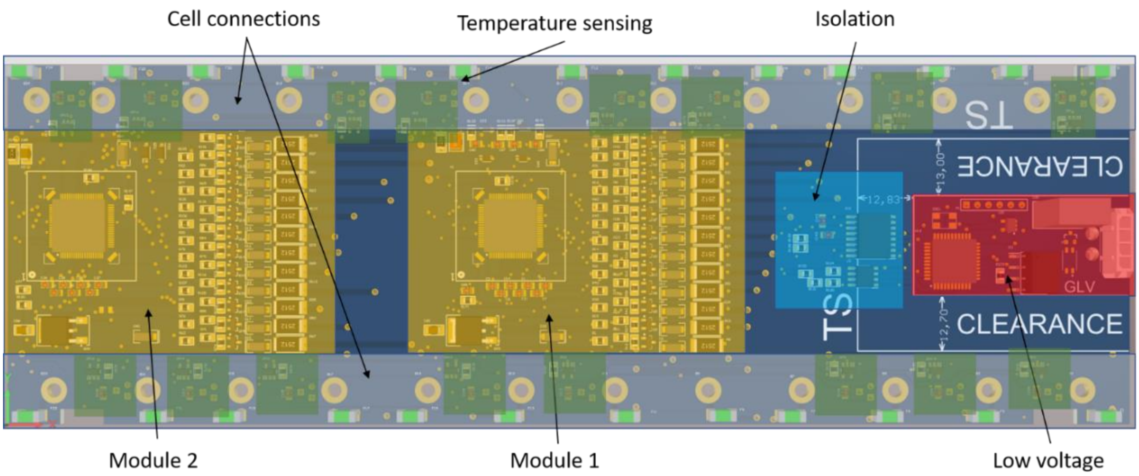

Figure 80: Detailed BMS slave PCB

4.2.10 Testing

When testing this kind of boards, where the hardware is just as important as the software, both must be tested thoroughly. Even so, if one of them is badly designed, it may lead to confusion. If the board is not working as it should because the hardware is not okay, the designer does not know if the problem is the hardware or the software. Because of this, the first step is to design the software and test it.

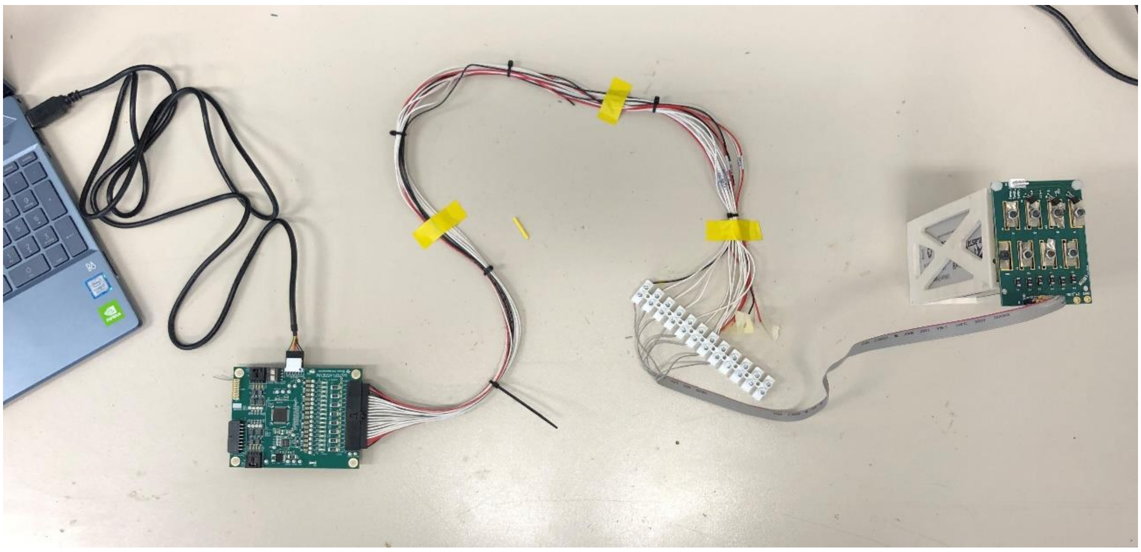

Figure 81: BMS slave module test bench

The configuration of this IC is done by sending commands via UART from the host microcontroller to the IC. These commands are in the datasheet, but there are a lot of commands which are not crucial for the proper operation of the IC. Furthermore, each command also has its variants depending on the number of ICs in the board. In order to get these commands correctly, a good testing platform is needed. *Texas Instruments* has its own evaluation board for this IC, the BQ76PL455EVM. In addition, the manufacturer also provides the client with a GUI for the testing of this evaluation board. This GUI offers the user the possibility to introduce manually the commands and see the response of the IC to this command.

For the test, a low voltage battery of 6 cells in series which was developed by the team was used. First, the voltages from these cells were recorded with the GUI to know if the readings were okay when testing the commands. The voltage readings from the GUI can be seen in figure 82.

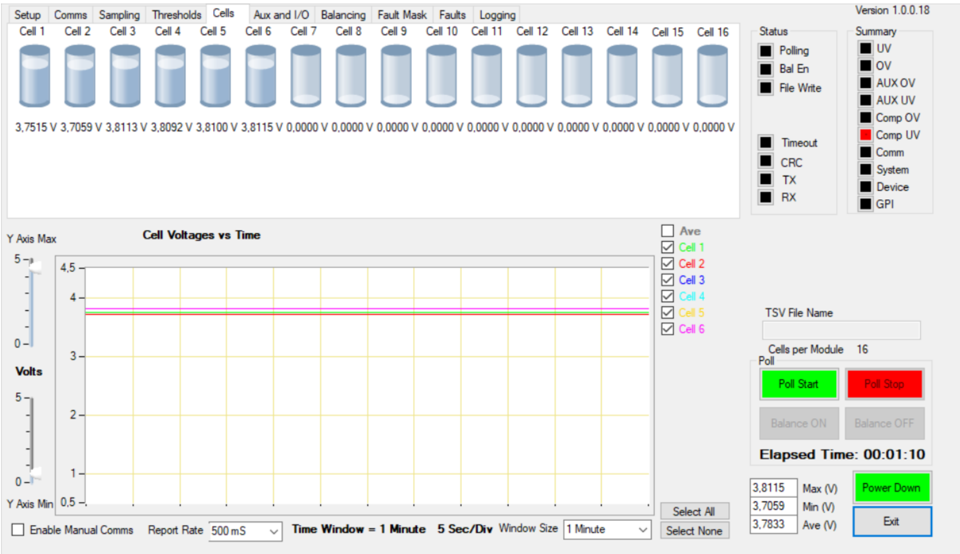

Figure 82: Voltage measurements from the GUI

Afterwards, the manual commands were tested. Many iterations were needed until the voltage readings were achieved, but eventually, the sequence and the commands were successfully achieved.

The next step would be to manufacture the slave module and test the software using the microcontroller from that board but since the manufacturing of the board has not been possible and another board with the same microcontroller used was not available, the whole software has been developed and tested on the development board from *Texas Instruments* used for the master module of the BMS, the LAUNCHXL-F28379D. Since a future objective for the team should be to implement this slave module using the master module's microcontroller, this is a very logical procedure, which will not just serve for the testing of this IC, but also to gather knowledge on the programming of this device in C code.

When using the f28379D microcontroller, it will not be possible to use the GUI from the evaluation module, and so, another method for visualizing the readings from the IC is needed. For this, the readings of the voltages are sent from the evaluation module to the f28379D via UART, then, the readings are bounced to the CAN bus of the microcontroller. Next, the CAN bus is connected to the CAN network interface used in the vehicle, the VN1630 from *Vector*, so the CAN bus can be visualized in a computer. In figure 83, the voltage readings can be seen.

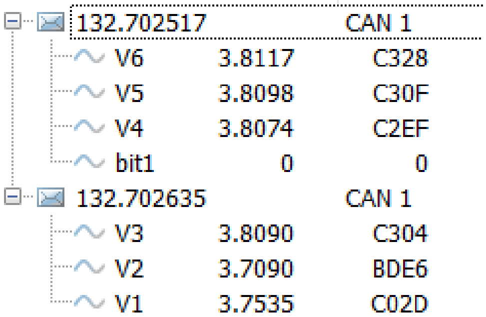

Figure 83: Voltage measurements from CANoe

The results obtained from the GUI and from the f28379D are almost equal, so the designed software has been validated.

Once the crucial features of the IC are achieved, more features can be tested, such as the cell balancing feature. For this, the same procedure was followed, first the commands were tested with the manual command window from the GUI, once they were validated, the commands were implemented in the f28379D software. When the cells are balancing, LEDs from the balancing lights are lighted on the evaluation module for visual confirmation. In figures 84 and 85, the manual command window from the GUI and the visual confirmation of the cell balancing can be seen.

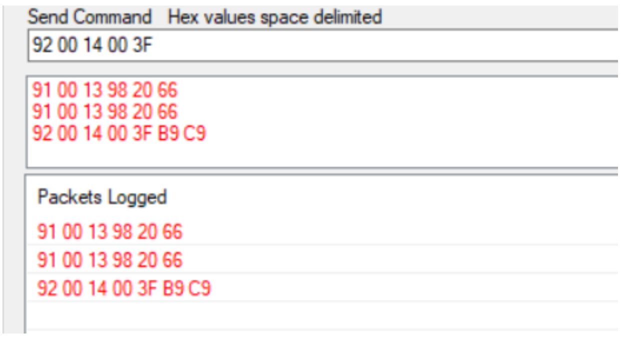

Figure 85: Manual command window

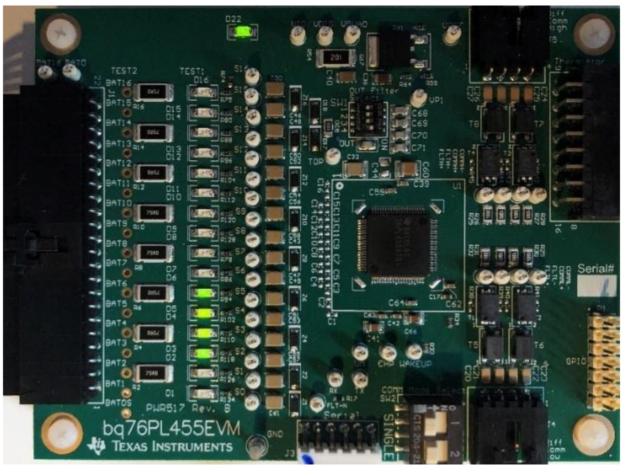

Figure 84: Cell balancing in the evaluation module

Furthermore, another feature the design must have, is a detection of a timeout from the communications, for example, when the TX or RX wire from the UART is disconnected. So, the test was as simple as disconnecting one of the two wires from the f28379D board, and as expected, the microcontroller detected the timeout and set the cell voltages to 0 V. This feature is of paramount importance for the safety of the driver, since if the communications are disabled, the BMS will not know the actual state of the battery cells and thus it must not be possible to run the vehicle in these conditions. Moreover, this is one of the multiple tests that the scrutineers will make to pass the accumulator container scrutineering in the competition.

4.3 Software

In this chapter, the software changes in the master module, the software used for the test bench of the slave modules and the battery interface will be explained.

4.3.1 Master module

The code implemented in the master module is the same as the one developed by Imanol Etxezarreta, but changes and new implementations have been made due to changes in the ECU's programming and new additions to the FSG rules for this season. Just like Imanol's code, this one has been implemented in Simulink.

One of the additions due to the change in the ECU's programming has been the pre-charge action. The problem with the old software was that, if the SC was opened by a shutdown button, when the button was released the BMS would pre-charge again without any additional action. This has been solved with the code that can be seen in figures 86 and 87.

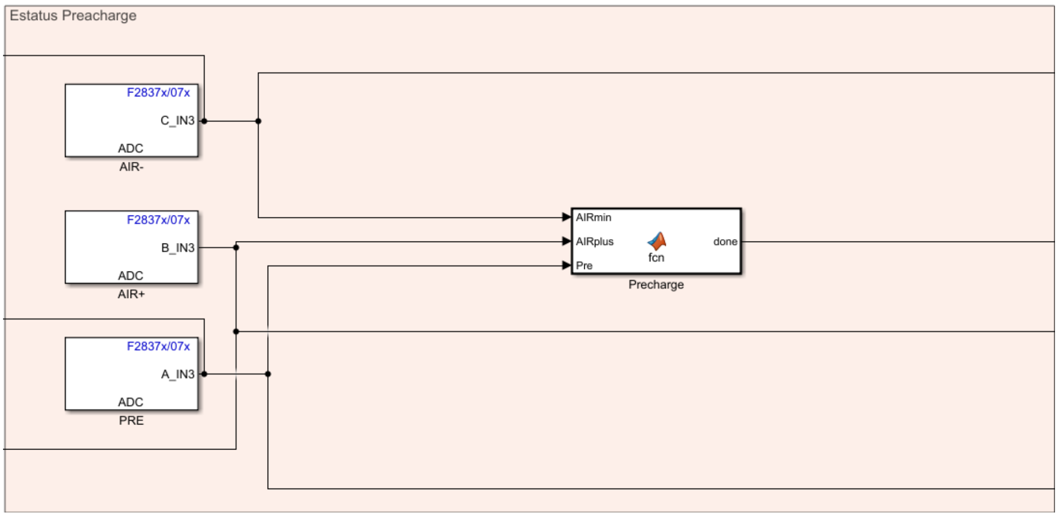

Figure 86: Pre-charge status

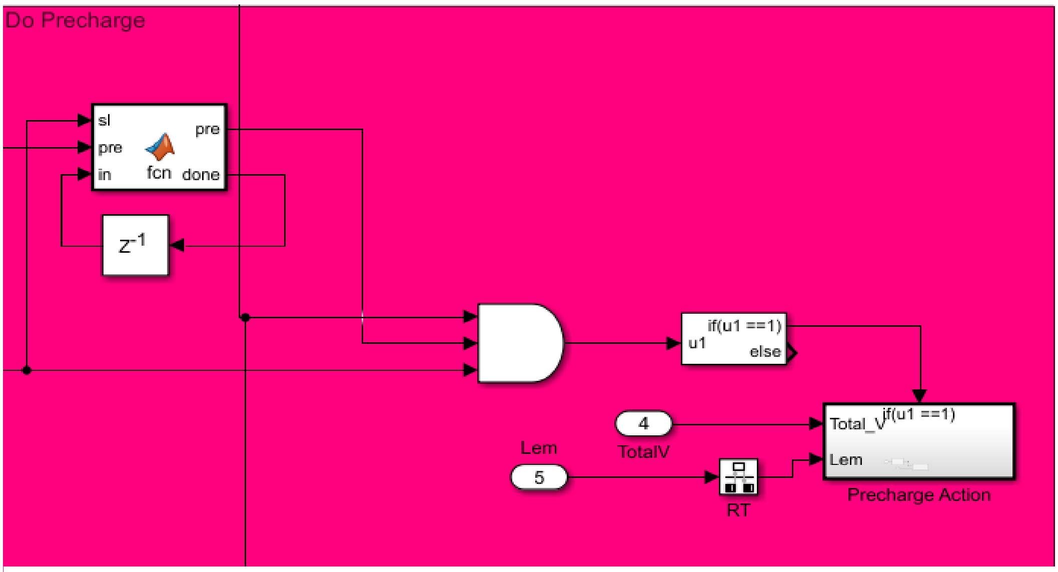

Figure 87: Pre-charge command code

To understand this code, first the pre-charge sequence will be explained. When the vehicle is ready to start, the driver pushes a button to start the pre-charge sequence. When pushing this button, the ECU will send a high pre-charge flag to the BMS to give the order to start the pre-charge sequence.

In figure 86, the mechanical state of the AIR and pre-charge relay is read by the ADCs to determine the status of the pre-charge sequence, this is, if it is still pre-charging or if it has finished. If the pre-charge sequence has been completed, the "done" signal will be set high. In figure 87, pre-charge action is activated or deactivated, to activate it, three things must happen:

- The SC must be closed. This is the "sl" signal.
- The pre-charge sequence must be low. This is the "done" signal.
- The pre-charge flag must be set high by the ECU. This is the "pre" signal.

To solve the problem, a MATLAB function has been coded. In this function, the pre-charge flag is set low if the SC is opened and the pre-charge sequence has been completed, regardless of the ECU sending a high for the pre-charge flag. If the function is setting the flag low while the ECU is sending a high flag, the control of the pre-charge activation is given to the BMS rather than the ECU. Once the ECU sends a low and the SC is opened, the control is given back to the ECU. With this, a failure in the ECU's programming will not affect the control of the pre-charge sequence, which could be dangerous if the pre-charge is done without additional action.

Furthermore, if the CAN bus connector is disconnected, the BMS must realize it and open the AIRs by setting a BMS fault. When the CAN bus is disconnected, the microcontroller will keep reading the last value that was sent in the bus. To detect this, the ECU sends an incremental signal with each cycle of the code, then, the BMS compares the actual signal with the signal from 10 ms before, if these two signals are the same it will mean that there has been a CAN bus timeout and the BMS fault is set. In spite of this, when the accumulator container needs to charge, there is a problem: for charging, the accumulator is taken out of the vehicle, and the pre-charge and charging commands are sent via CAN bus with the CANoe program in the PC, so the incremental signal coming from the ECU no longer exists. But CANoe has a functionality that converts the PC in another

CAN bus node, and so, "imaginary messages" can be sent with the program, thus, the problem is solved. More about this can be found in *appendix C*.

4.3.2 Slave module

The code developed for the slave module is the one implemented in the test bench for the testing of the slave modules software. This code has been developed using Code Composer Studio, an integrated development environment that supports *Texas Instruments* microcontrollers for C code. Even though the software has been developed in Code Composer Studio, another code for the PIC18 microcontroller is being also developed. The full code can be seen in *appendix F*.

First, the code hierarchy will be explained to understand the code sequence (figure 88). The IC needs a wake-up signal when it is supplied to step out the shut-down state. This signal will be a logic low. Then, some parameters of the IC need to be configured before starting the measurements. These parameters include baud rate of UART, address, fault clearance, etc.

In this case, the baud rate of the IC is set to 250 kHz since it is the standard for the device. The address set for the IC is the 0x00, it does not matter the address for this use-case scenario, but this is recommended for systems where many ICs are placed in a daisy-chain configuration, so that the ICs are addressed in order (first IC 0x00, second IC 0x01…). Then, some faults and transmissions have to be disabled, and afterwards, the sampling configurations are set to the standard values, which can be found in the IC's datasheet.

Once the device has been configured, the user needs to command the IC to sample the readings and request to send them via UART. If this is done in an infinite loop, the IC will be sampling and sending every cycle of the code. The full list of commands can be seen in table 11.

For the visualization of the voltage and temperature readings, the f28379D microcontroller receives the UART messages containing the measurements and bounce them via CAN bus, then, the CAN messages can be visualized in the PC. This will be covered in the next chapter.

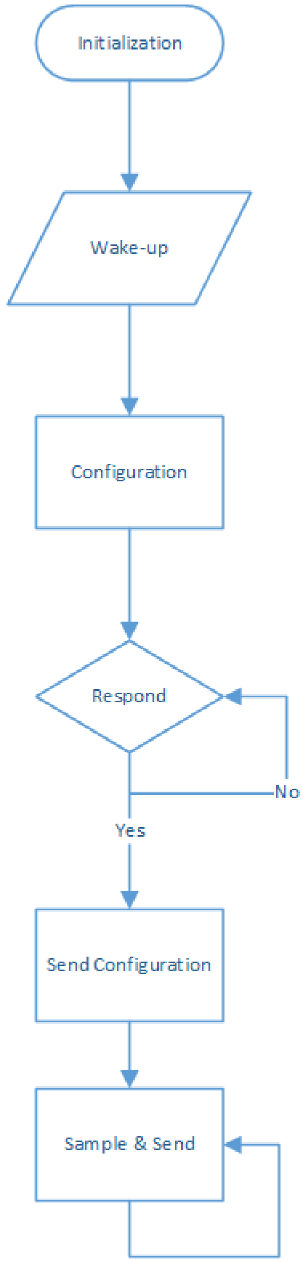

Figure 88: BMS slave code flow chart

	B1	B2	B3	B4	B5	B6	B7	CRC		
Set baud rate	F2	10	10	E0				3F	35	Configuration
Autoadress1	F1	0E	10					54	5F	
Autoadress2	F1	0C	08					55	35	
SetAdress IC	F1	0A	00					57	53	
Disable High Side receiver	92	00	10	10	20			B4	00	
Disable low side transmitter	92	00	10	10	C0			B5	88	
Clear fault IC	92	00	52	FF	C0			59	AC	
Initial Sampling Delay	91	00	3D	00				3C	6C	
Sample period	91	00	3E	BC				3D	2D	
Oversampling rate	91	00	07	00				2E	CC	
Clear and Check Faults 1	91	00	51	38				10	BE	
Clear and Check Faults 2	92	00	52	FF	C0			59	AC	
Clear and Check Faults 3	81	00	51	00				15	AC	
Select num cells 1	91	00	0D	07				69	AE	Sample & read
Select num cells 2	94	00	03	01	FC	03	C0	50	A5	
Read	81	00	02	20				28	84	

Table 11: BQ76PL455 Command list[4]

4.3.3 Battery interface

Apart from monitoring the cell voltages and temperatures, these measurements must be visualized in a PC. The program used to visualize the CAN bus messages, CANoe from *Vector*, incorporates a panel designer feature to design a panel based on the CAN bus messages. This panel is divided in three tabs: General, Voltage and Temperature.

- **General:** general information about the battery is shown, such as the current battery voltage, current, maximum voltage and temperature and minimum cell voltage.
- **Voltage:** this tab shows every cell voltage in the battery alongside the balancing status.
- **Temperature:** this tab shows the measured temperatures for the battery cells.

In figures 89, 90 and 91, this panel can be seen.

[4] Values are in hexadecimal format

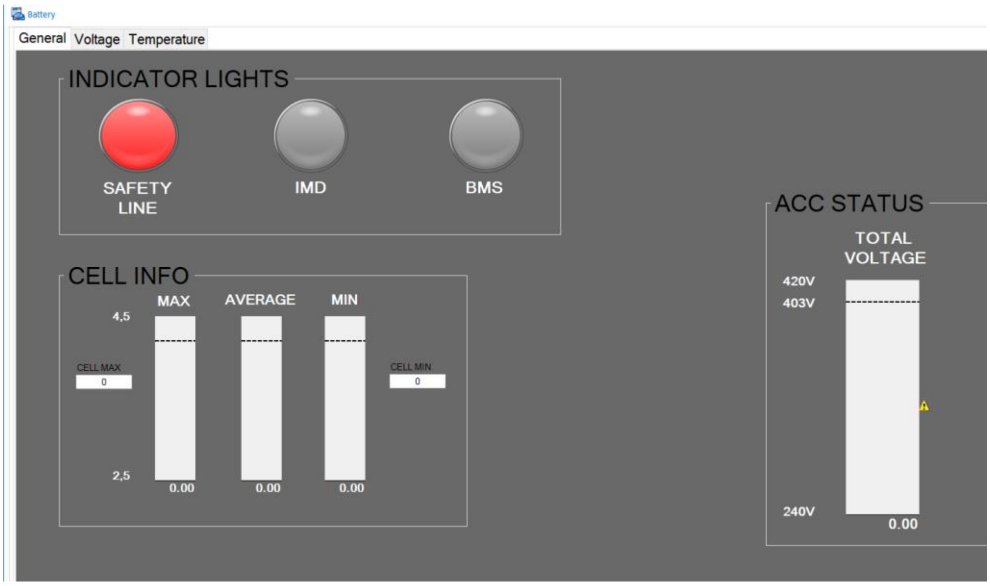

Figure 89: Battery interface. General tab

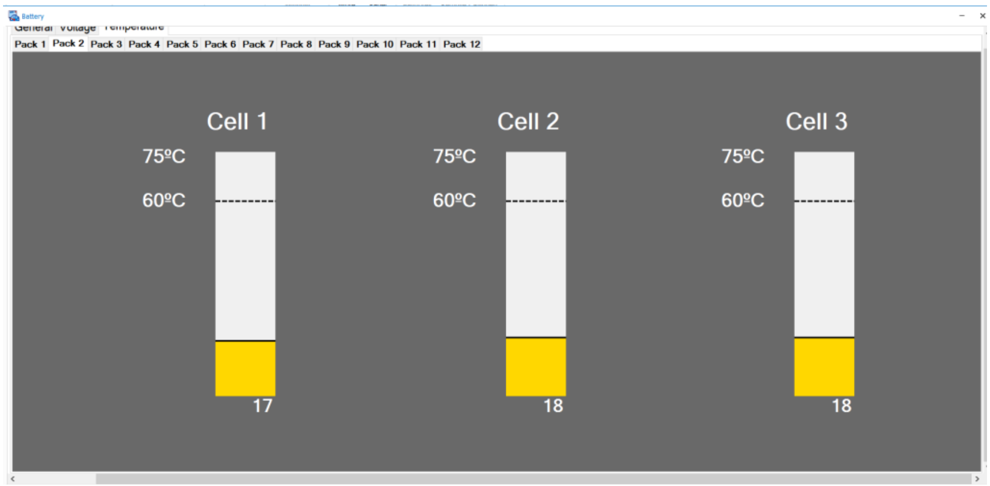

Figure 90: Battery interface. Temperature tab

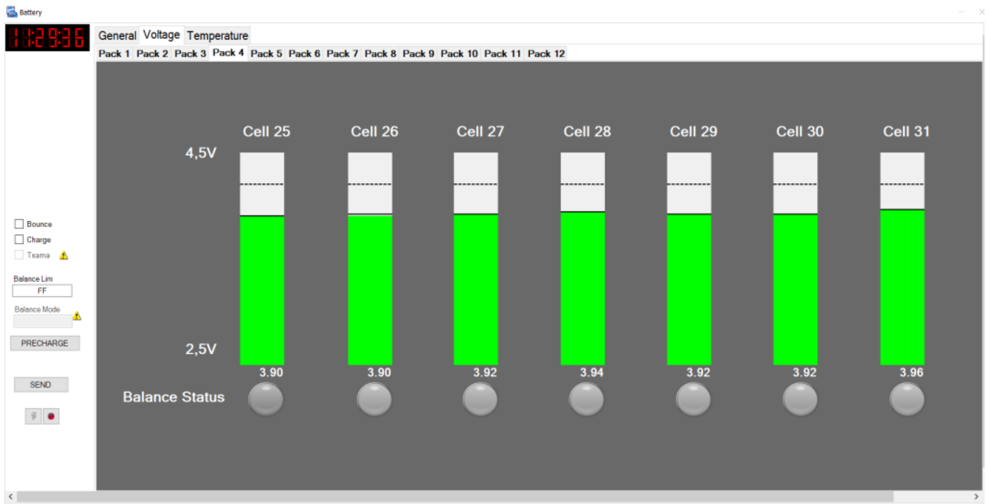

Figure 91: Battery interface. Voltage tab

5. FUTURE LINES

Although many problems have been solved and many upgrades have been made in many systems, there are still several improvements to be made in order to have a reliable vehicle and increase the performance of it.

Regarding the slave module, the microcontroller should be removed as its only purpose is to bounce the UART of the ICs into the CAN bus. Although this microcontroller can be used to measure the 100 % of the cell temperatures, this can also be made with external ADCs that incorporate a communication protocol, such as UART. The removal of the microcontroller will reduce costs and PCB area needed.

Furthermore, the slave module has to be manufactured and tested to validate the design. The testing of it should start with the basic functions of the IC, such as the voltage and temperature measurements and continue with more features the IC incorporates, such as the undervoltage or overvoltage flag.

Regarding the master module, this design accomplished the needed reliability and performance, alongside the compliance with the FSG rules. Still, improvements can be made, as for example, implementing the microcontroller in the master module PCB, which would make the module to be more compact. In addition, a lot of work should be made in the software area, as there is a lot of room for improvement. Simulink is a great environment for programming since it is very visual and the user does not have to worry about microcontroller registers or configuration as it is a very user-friendly environment, but the improvement of software is very limited, for example, to use global variables. Moreover, the UART communication needed to configure the ICs from the slave modules cannot be programmed in Simulink, as it does not support many UART communication blocks. Because of this, the implementation of the master modules software in C code is highly recommended and should be the main objective once reliability issues have been eliminated from other systems in the vehicle. First tests for the implementation of the C code have been made this season and more precisely in the slave module test bench.

On the other hand, the cell connections should be made in a different manner, as it has been shown how the actual system damages the bolts used for the connection of the cells and have to be replaced. Furthermore, the contact between the cell tabs with this system is not optimal and heat can be dissipated due to bad electrical contact between them. These issues can be solved by using systems such as the one used in the TSR 17 but with proper positive locking and screwing the cell tabs together with a bolt instead of pressing them with two bus-bars.

In addition, with the actual cell configuration, the 80 kW of power cannot be achieved in the entire voltage range of the battery. The maximum discharge current of the cells will be exceeded at 333 V, so there will be a significant range where the maximum power will be below 80 kW. Furthermore, even though the manufacturer of the cells assure that the cells will not degrade if currents near the maximum discharge current are drawn from the battery, it is strongly recommended that the maximum current discharged is lower than the maximum discharge current rating of the cell, most importantly for safety reasons. This design problem can be solved by adding a parallel cell branch, building a 96s2p configuration, so that the current drawn from each branch is half the total current, allowing the battery to supply 80 kW through the whole voltage range. It is not that easy though, the volume needed to place double the cells would increase dramatically and another cell model would need to be selected with lower capacity (still greater capacity overall because of the 2p configuration, but they are smaller), which would take a great amount of the budget.

Finally, but not less important, the inverter's design must be tested and protections need to be added for proper operation. This will avoid many problems in the long term. To hold the test in a test-bench is highly recommended, since it is faster than testing it with the vehicle, apart from being a more secure environment. This will help the team to get the optimum inverter configuration and validate different designs rapidly to increase the overall reliability.

6. CONCLUSIONS

The principal objective of this project was to design a reliable powertrain while being rule compliant. One of the problems for the lack of reliability was the inverter. Although it has not been possible to test it yet, the design and fabrication is already done, it only has to be assembled. Nevertheless, the new design has taken into account the recommendations made by the manufacturer, so no problems should be expected, but still testing must be done.

A previous version of the BMS master module has been tested, incorporating all features except the HV measuring system. The module has been tested with the vehicle and no problems were observed so far, it has performed all its duties perfectly and with no reliability issues. Furthermore, the rule compliance part has been verified by making the tests done in the technical inspection of the competition, which have been successfully accomplished.

Even though the tested module did not incorporate the HV measurement system, a separate board was built for testing it, and as expected, there were no problems with the measurements and the precision was also increased.

Regarding the BMS slave module, although it has not been possible to manufacture it yet, the software has been fully tested, obtaining satisfactory results. Nonetheless, a solid basis for the slave module has been left to continue working on it, a design has been developed and the software just needs to be adapted for the microcontroller used. The next step should be to manufacture it, test it and understand its functionality.

Furthermore, the electric powertrain systems and components have also been dimensioned to achieve a power of 80 kW, with the weak point being the cell configuration. Nevertheless, the steps for achieving this have been set, once the cell configuration is changed, this power can be achieved in all the voltage range of the battery.

Finally, this project has also served the purpose of documenting all the work done this season regarding the electric powertrain, justifying the decisions taken in each moment and stating previous failures, which will be helpful to avoid repeating the same mistakes again for future team members.

7. BUDGET

The budget associated to the project is detailed below:

7.1 Assets budget

Quantity	Reference	Description	Price (€)	
				Total
1	-	BMS slave components	146.28	146.28
4	-	PCB BMS slave	107.33	429.32
1	-	BMS master components	127.40	127.40
1	-	PCB BMS master	81.76	81.76
1	LAUNCHXL - F28379D	Development board	32.67	32.67
1	-	PCB Discharge components	63.64	63.64
1	-	PCB Discharge	40	40
2	HS50 5K6 J	Discharge resistor	3.36	6.73
1	-	Voltage Indicator components	3.44	3.44
1	-	PCB Voltage Indicator	60.40	60.40
1	HTFS 200 P	Current sensor	14.13	14.13
96	SLPB375175A	Battery cell	53.89	5173.69
16	SLP P B 50B SO	Maintenance Plug	13.74	219.90
8	HVP 800	HV Connector	53.72	429.75
1	EM30MSD	HVD	74.52	74.52
1	SPFJ070	Fuse	89.48	89.48
1	LEV100H5CNG	Pre-charge relay	107.11	107.11
1	THS251K5J	Pre-charge resistor	2.22	2.22
2	EV200HAANA	AIR	115.85	231.40
2	BAMOCAR D3 700-400	Inverter	2541.74	5083.47
2	EMRAX 188HV	Motor	2695.45	5390.91
4	-	Methacrylate Pack	46.93	187.70
Total assets				17996.21

Table 12: Assets budget

7.2 Expendable equipment budget

Quantity	Reference	Description	Price (€)	
			Per Unit	Total
768	-	Fasteners	0.08	61.50
26	-	LV wiring (meters)	0.18	4.80
2.6	FHLR2GCB2G 35	HV TS wiring (meters)	21.03	54.69
1	-	Solder Tin	16.60	16.60
384	-	Cell connections busbars	1.19	456.99
2.4	FHLR2GCB2G 16	HV motor wiring (meters)	12.09	29.02
18	-	Inverter busbars	11.96	28.70
Total expendable equipment				652.31

Table 13: Expendable equipment budget

7.3 Non-expendable equipment budget

Equipment	Acquisition fee (€)	Depreciation period (years)	Monthly depreciation fee (€)	Usage time (months)	Depreciation (€)
PC	826.45	5	13.77	9	123.97
Welder	35.54	3	0.99	9	8.88
Electric tools	107.44	6	1.49	9	13.43
VN163 Vector	998.35	4	20.80	9	187.19
Total equipment					333.47

Table 14: Non-expendable equipment budget

7.4 Software budget

Software	Acquisition fee (€)	Depreciation period (years)	Monthly depreciation fee (€)	Usage time (months)	Depreciation (€)
Matlab	1652.89	5	27.55	9	247.93
Office	123.14	5	2.05	9	18.47
Altium Designer	5987.60	1	498.97	9	4490.70
Vector CANoe	82.64	1	8.33	9	74.97
Windows 10	119.83	5	2	9	17.98
Total software					4850.05

Table 15: Software budget

7.5 Labor budget

Task	Length (hours)	Price (€)	
		Per unit	Total
Student	300	3.12	936
Supervisor	50	50	2500
Total labor			3436

Table 16: Labor budget

7.6 Budget summary

The global budget of the project is shown below, which amounts to #thirty-seven thousand six hundred twenty-eight point forty nine euros#

Budget line	Amount (€)	
	Partial	Cumulated
Assets	17996.21	17996.21
Non-refundable equipment	652.31	18648.52
Equipment	333.47	18981.99
Software	5852.85	24834.84
Labor	3436	28270.84
Indirect Costs (10%)		2827.08
Total without VAT		31097.92
Total with VAT		37628.49

Table 17: Budget summary

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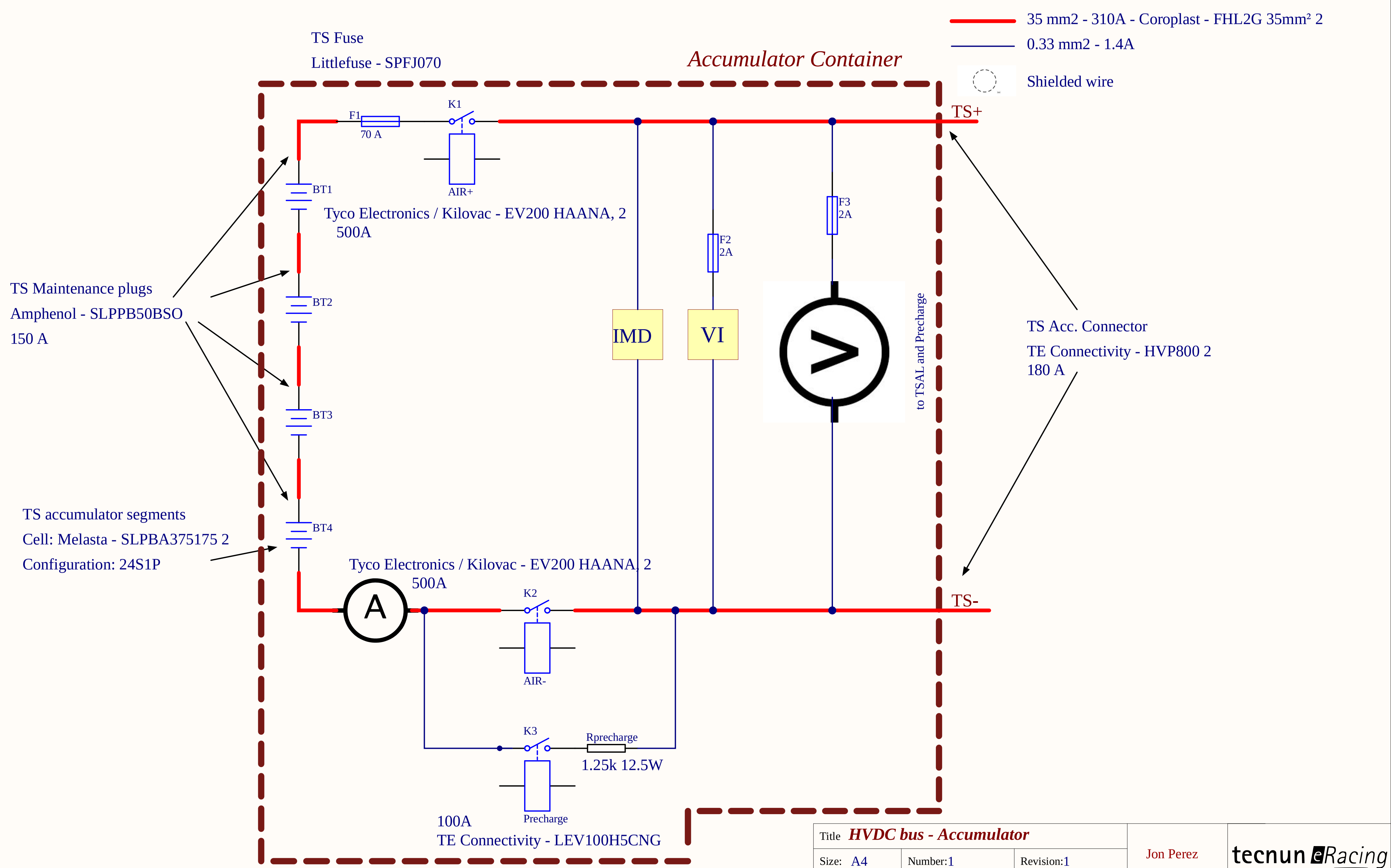
APPENDIX

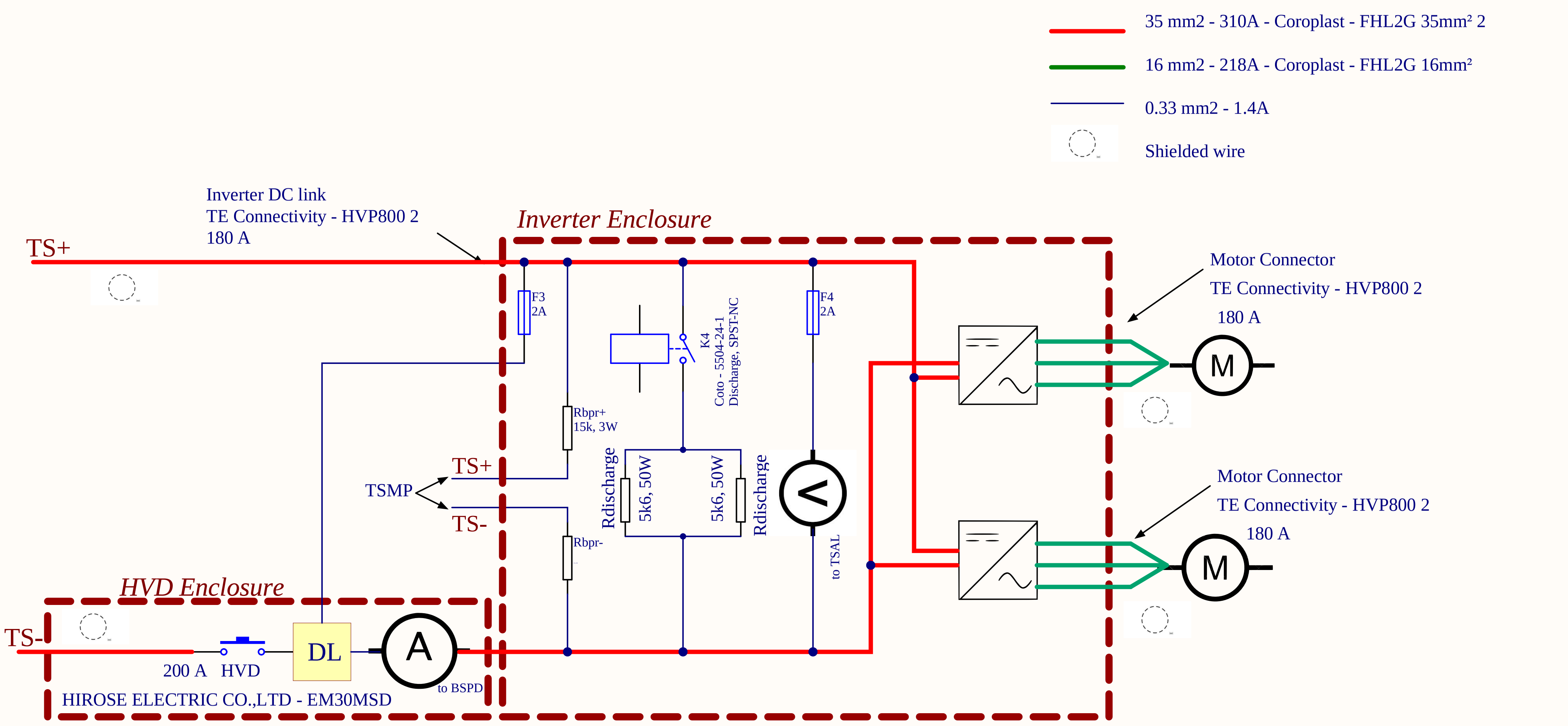
Appendix A: Schematics

In this appendix the following explanatory schematics are provided:

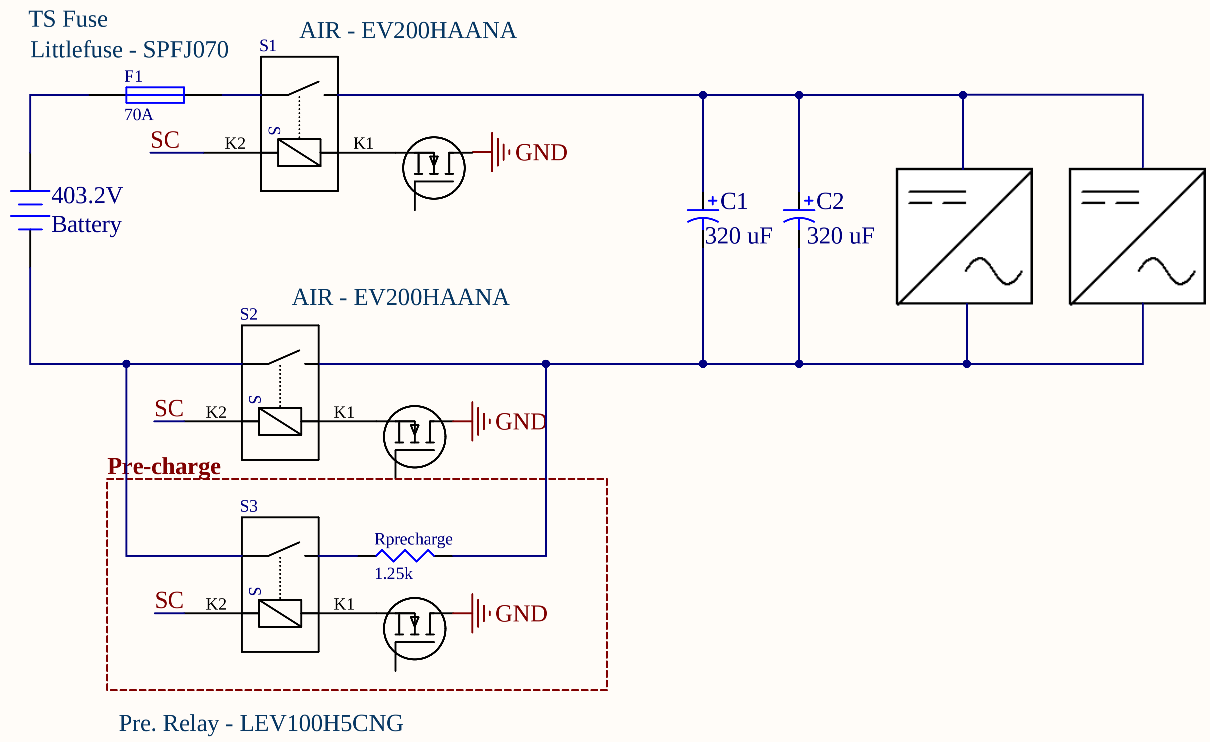
- HVDC bus – Accumulator
- HVDC bus – Vehicle
- HVDC bus - Pre-charge
- HVDC bus – Discharge
- TSAL 1
- TSAL 2



Title *HVDC bus - Accumulator*			Jon Perez
Size: A4	Number:1	Revision:1	
Date: 19/06/2020	Time: 12:31:33	Sheet1 of 6	



Title **HVDC bus - Vehicle**			Jon Perez	tecnun eRacing
Size: A4	Number:1	Revision:1		
Date: 19/06/2020	Time: 12:27:58	Sheet 2 of 6		



Title	*HVDC bus - Pre-charge*		Jon Perez	tecnun eRacing
Size: A4	Number:1	Revision:1		
Date: 19/06/2020	Time: 12:24:41	Sheet3 of 6		

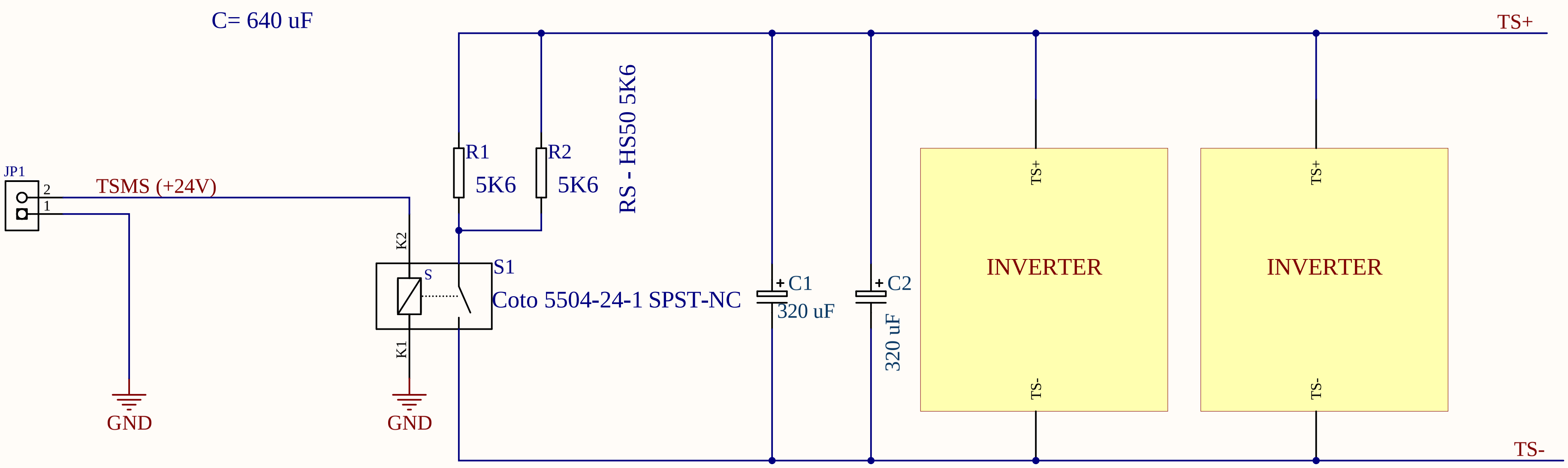
Umax = 403.2 V

Pmax = 58W

R = 2800 ohm

C= 640 uF

Tdis = -RC*ln(60/403.2) = 3.41 seconds



The power dissipated in each resistor will be 58/2 = 29 W
The resistors are rated for 50W on a heatsink and 14W without heatsink.
For power dissipation, the resistors will be mounted with thermal paste to the inverters' aluminum box

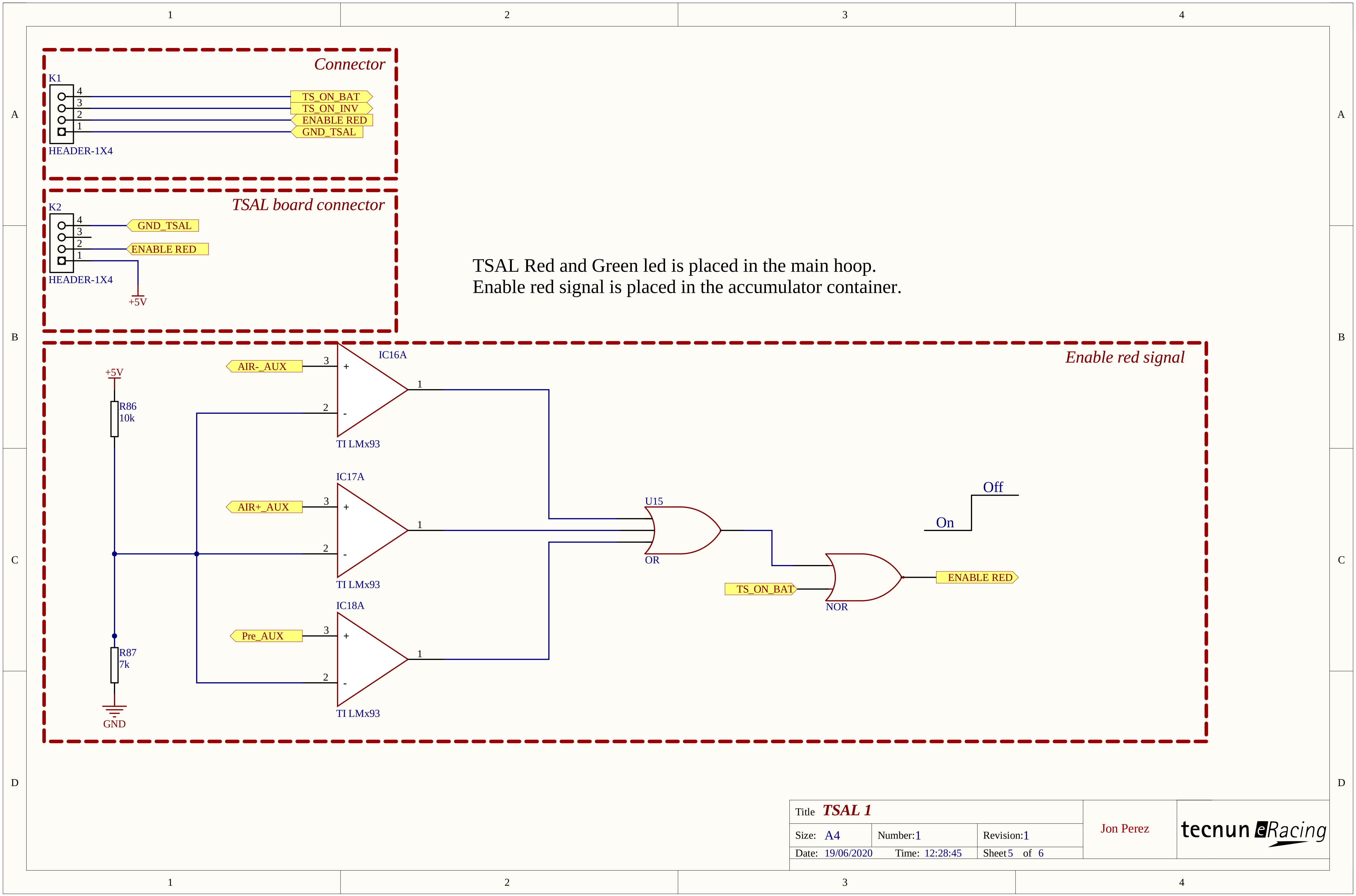
Title **HVDC bus - Discharge**

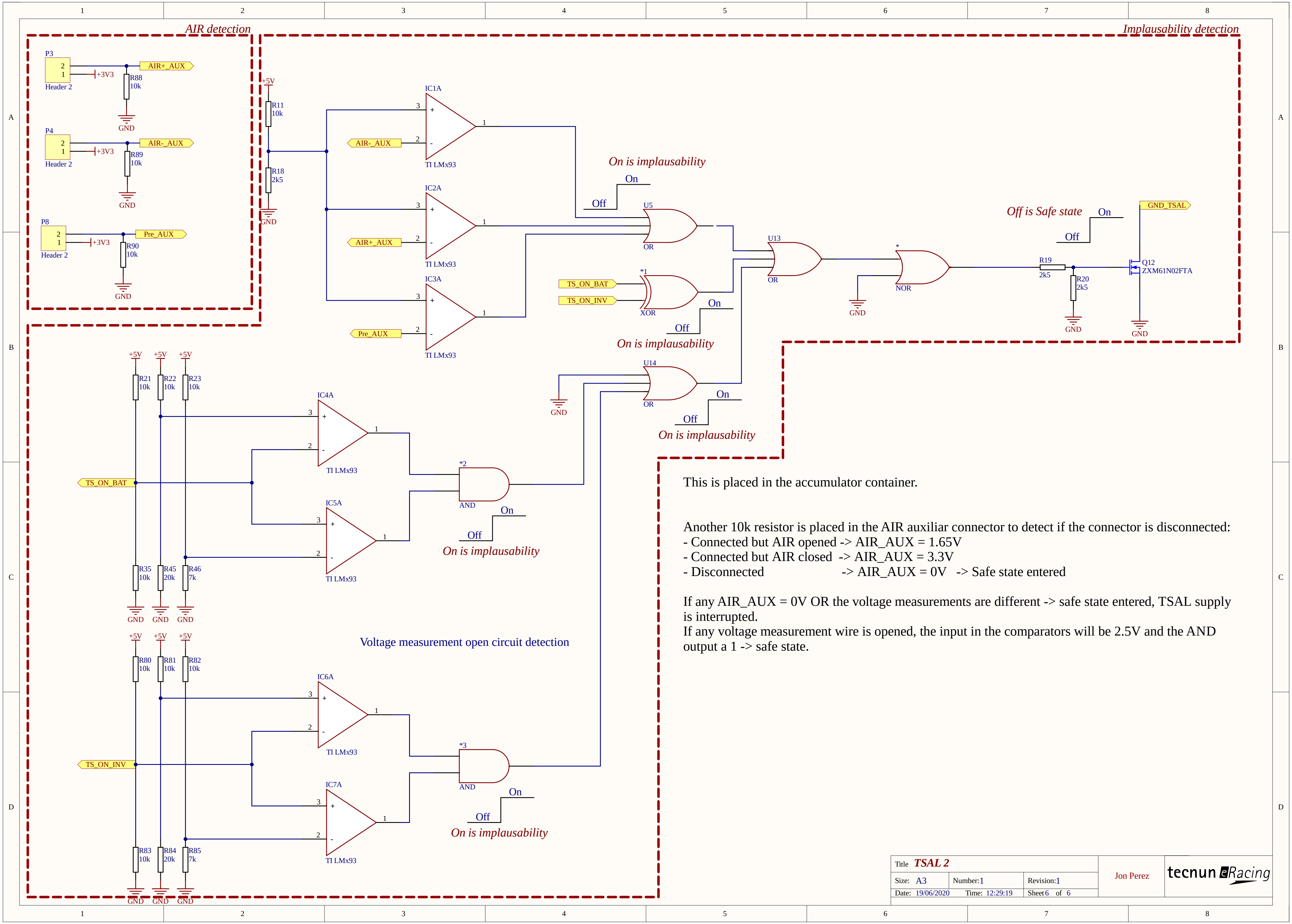
Size: A4 | Number:1 | Revision:1

Date: 19/06/2020 | Time: 12:26:32 | Sheet 4 of 6

Jon Perez

tecnun eRacing


Connector
K1
HEADER-1X4
TS_ON_BAT
TS_ON_INV
ENABLE RED
GND_TSAL
TSAL board connector
K2
HEADER-1X4
GND_TSAL
ENABLE RED
+5V
TSAL Red and Green led is placed in the main hoop.
Enable red signal is placed in the accumulator container.
Enable red signal
+5V
R86
10k
R87
7k
GND
AIR-_AUX
AIR+_AUX
Pre_AUX
IC16A
IC17A
IC18A
TI LMx93
TI LMx93
TI LMx93
U15
OR
NOR
TS_ON_BAT
ENABLE RED
On
Off
Title TSAL 1
Size: A4
Number:1
Revision:1
Date: 19/06/2020
Time: 12:28:45
Sheet5 of 6
Jon Perez
tecnun eRacing


AIR detection
Implausability detection
P3
Header 2
+3V3
AIR+_AUX
R88
10k
GND
P4
AIR-_AUX
R89
P8
Pre_AUX
R90
+5V
R11
10k
R18
2k5
IC1A
IC2A
IC3A
TI LMx93
On is implausability
On
Off
U5
OR
U13
XOR
NOR
TS_ON_BAT
TS_ON_INV
U14
Off is Safe state
GND_TSAL
R19
2k5
R20
2k5
Q12
ZXM61N02FTA
R21
R22
R23
R35
R45
20k
R46
7k
IC4A
IC5A
AND
Voltage measurement open circuit detection
R80
R81
R82
R83
R84
R85
IC6A
IC7A
This is placed in the accumulator container.
Another 10k resistor is placed in the AIR auxiliar connector to detect if the connector is disconnected:
- Connected but AIR opened -> AIR_AUX = 1.65V
- Connected but AIR closed -> AIR_AUX = 3.3V
- Disconnected -> AIR_AUX = 0V -> Safe state entered
If any AIR_AUX = 0V OR the voltage measurements are different -> safe state entered, TSAL supply is interrupted.
If any voltage measurement wire is opened, the input in the comparators will be 2.5V and the AND output a 1 -> safe state.
Title TSAL 2
Size: A3
Number: 1
Revision: 1
Date: 19/06/2020
Time: 12:29:19
Sheet 6 of 6
Jon Perez
tecnun eRacing

Appendix B: Auto-tuning of the inverter

The BAMOCAR D3 inverter provides a functionality to automatically configure or set some of the parameters. These configurations include adjustments and calibrations. However, the most used function will be the autotuning of the motor feedback sensor offset angle (FB – offset parameter in NDrive), called "phasing – rotating" in the *NDrive Manual*.

This function provides the automatic reading of the rotor offset angle for synchronous motors (FB – offset parameter in NDrive). Furthermore, this function will also help to check if the motor phase connections (U, V, W) are correct.

First, the hardware must be prepared:

1. The motor must be running free.
2. The inverter's LV supply must be connected.
3. The inverter must be supplied with the HV from the batteries.

Afterwards, the software needs to be prepared:

4. Connect the RS232 connector to the PC.
5. Open NDrive → Communication tab → Baud rate → select 115200.
6. Communication tab → select the COM port until the right one is found (this depends on the USB or RS232 port of the PC).
7. Load the .urf file (parameter file) or configure a new one with the nominal parameters of the battery and motor.
8. Set "I max eff" parameter to the 10% of the maximum motor current. In case of the EMRAX 188HV motor, the maximum motor current is 200 A, and so the parameter must be set to 20 A.
9. Store the configuration in the inverter.
10. Go to Diagnostics tab → Manual Read/Write → Set Write ID register to 0x85 → Set Write Value to 4 → Set Read ID register to 0x44.
11. Press the Write button. The user will have 10 seconds to activate the FRG/RUN (enable) signal from the control connector of the inverter once the button is pressed.
12. The motor will turn clockwise from pole to pole until turning 360°.
13. When the motor is still again, press the Read button. The offset value will appear in the Read Value window. This value is automatically copied to the "FB – offset" parameter window.
14. Deactivate the FRG/RUN signal, change the "I max eff" parameter to the wanted value. If CAN bus is used → Bus tab → Set NBT to 4002 for 1 Mbps baud rate → Set the Tx and Rx values to the CAN IDs set in the vehicle's software. Then, save the changes and load the configuration into the inverter.

Even so, some problems may arise if the settings are not done properly:

1. In step 12, the motor turns anticlockwise → phases U and W are inverted.
2. In step 12, the motor does not turn → phases of the motor are incorrectly connected, current limit is set too low for the load of the motor or the Write Value has been incorrectly defined. If this happens, rapidly switch off the HV supply and restart the procedure.
3. In step 12, the motor rotates less than 360° → the number of poles is incorrectly configured.

In figures 93 to 96, some of the steps can be seen. For more information about this procedure or other functionalities, go to *NDrive Manual* or *Bamocar D3 manual*.

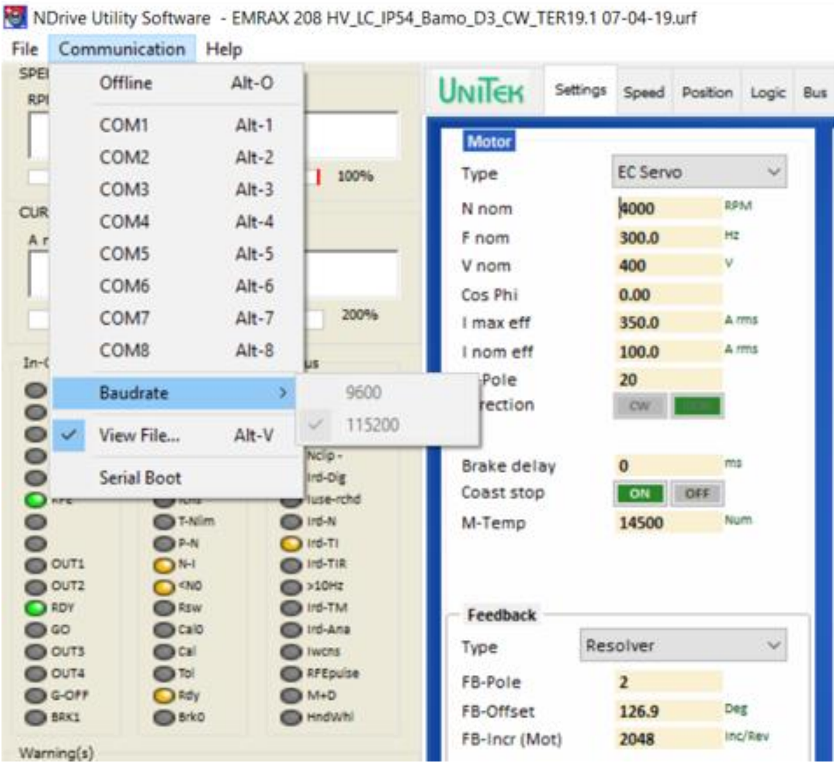


Figure 92: Step 5

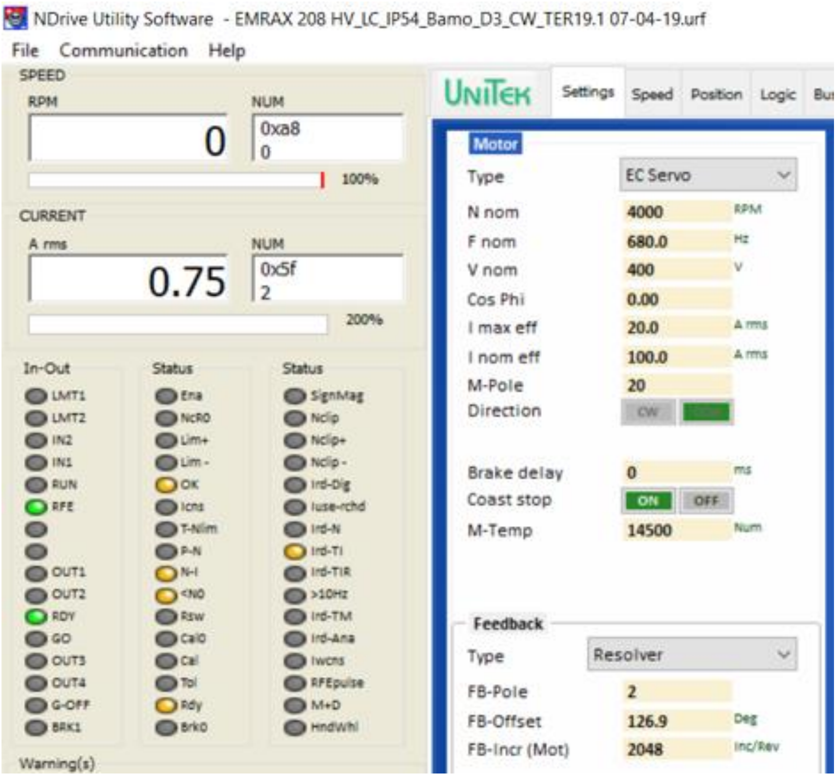


Figure 93: Step 8

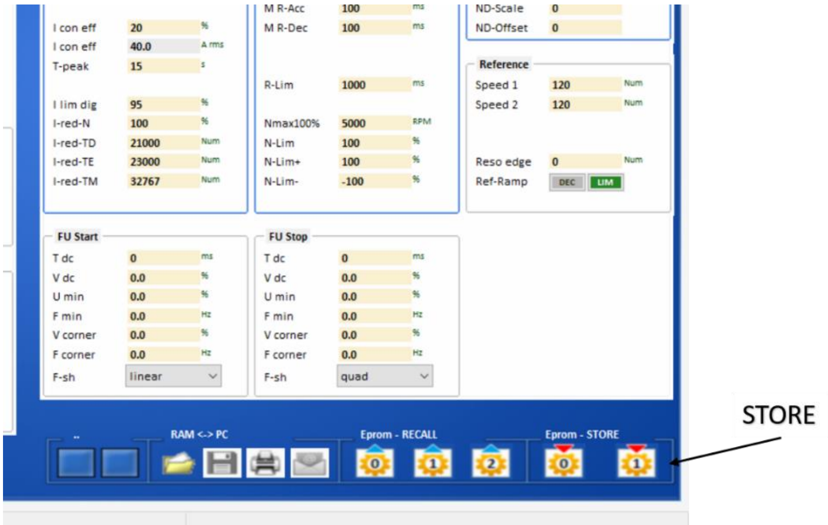


Figure 96: Step 9

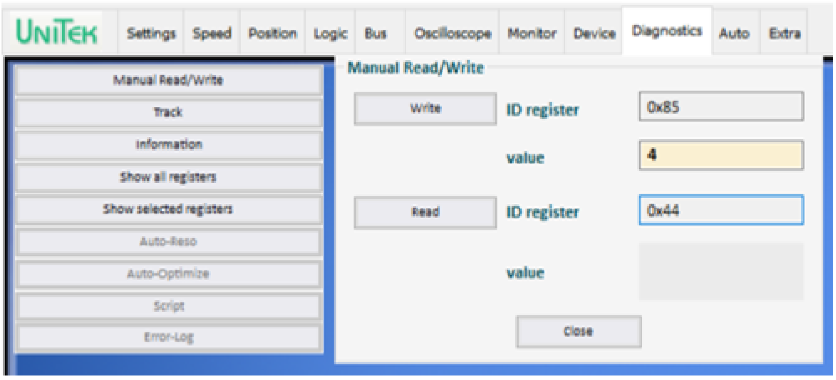


Figure 95: Steps 10 and 11

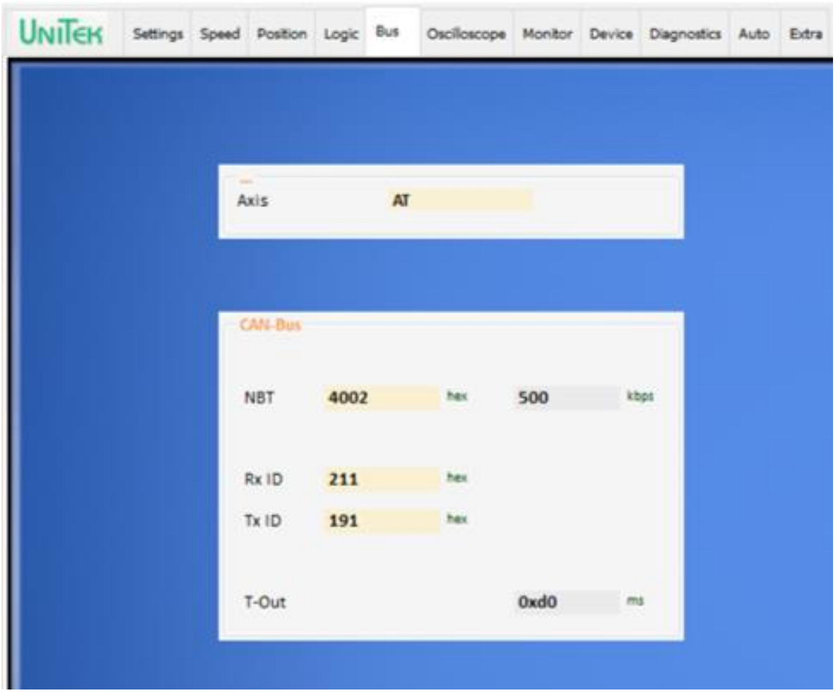


Figure 94: Step 14

Appendix C: CANoe code

This code is developed in the CAPL programming environment for CANoe. More about CAPL can be found on *"Programming with CAPL"*. This function is needed in order to detect a CAN bus timeout from the BMS master module when the accumulator container is connected to the charger, and thus, to the PC.

The BMS master module sends an incremental message through the BMS_Frame ID. Then, the same message is bounced into the BMS_Rx ID. Every cycle of the master module's code, this message will be changing, but if the bus is disconnected, the master module will keep reading the last value that was sent. By comparing the message with a message received 10 ms before, the BMS will notice if there has been a timeout in the bus.

The basis of the code is explained in "*Programming with CAPL"* and "*Design and fabrication of a BMS Master for a Formula Student Car"* by Imanol Etxezarreta.

```
on message BMS_Frame
{
  message BMS_Frame msg3;
  message BMS_Rx msg4;
  msg3.type=rxdata;
  msg3.can=1;
  msg1=this.byte(3);
  msg4.byte(0)=0xFF;
  msg4.byte(1)=msg1;
  msg4.type=txdata;
  msg4.can=1;
  msg4.simulated=0;
 if (rebote == 1) {output(msg4);};
//
//

}
```

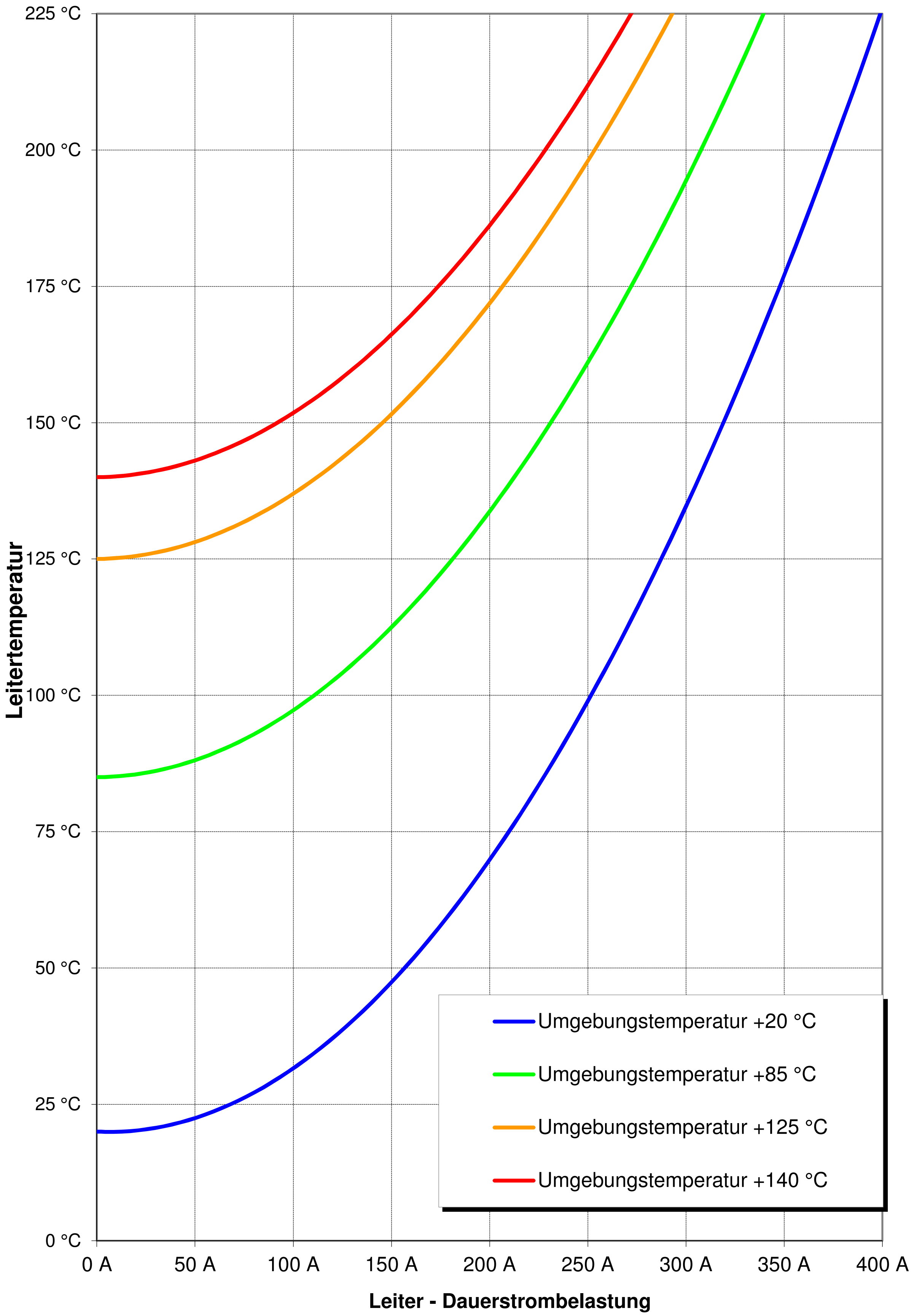
Figure 97: CAPL code from CANoe

Appendix D: Datasheets

In this appendix the following datasheets are provided:

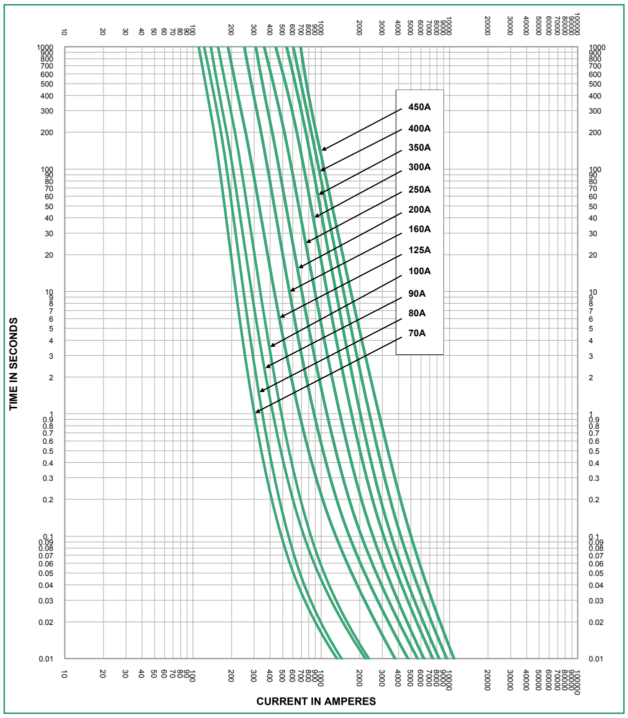
- Temperature graphic of the HV cable
- Melting curve of the selected fuse

Anhang: Strombelastung, Dauerbestromung in Abhängigkeit zur Umgebungstemperatur
Rechnerische Ermittlung gemäß LV112-3 (Entwurf Mai 2009)

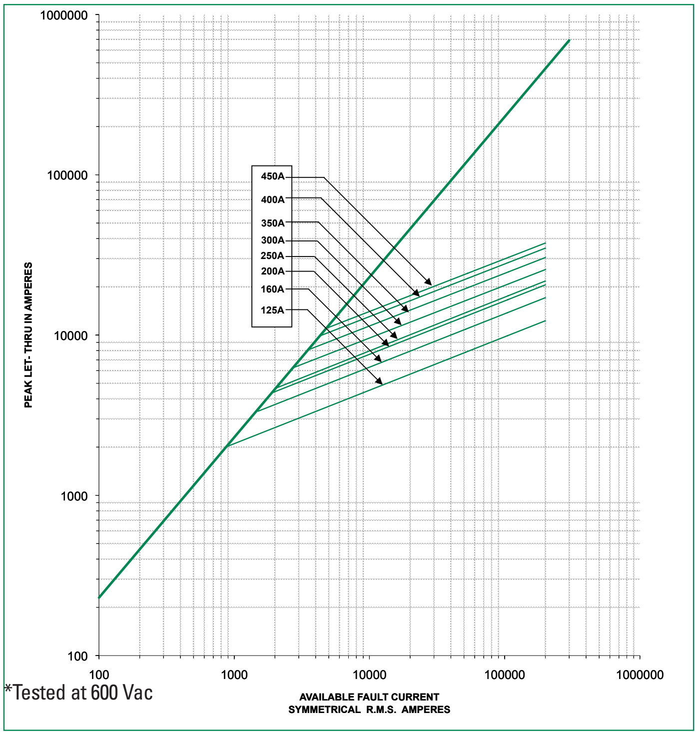


SPFJ SERIES DC FUSE

Time Current Curve



Peak Let-Thru Curve (125-450 A)



*Tested at 600 Vac

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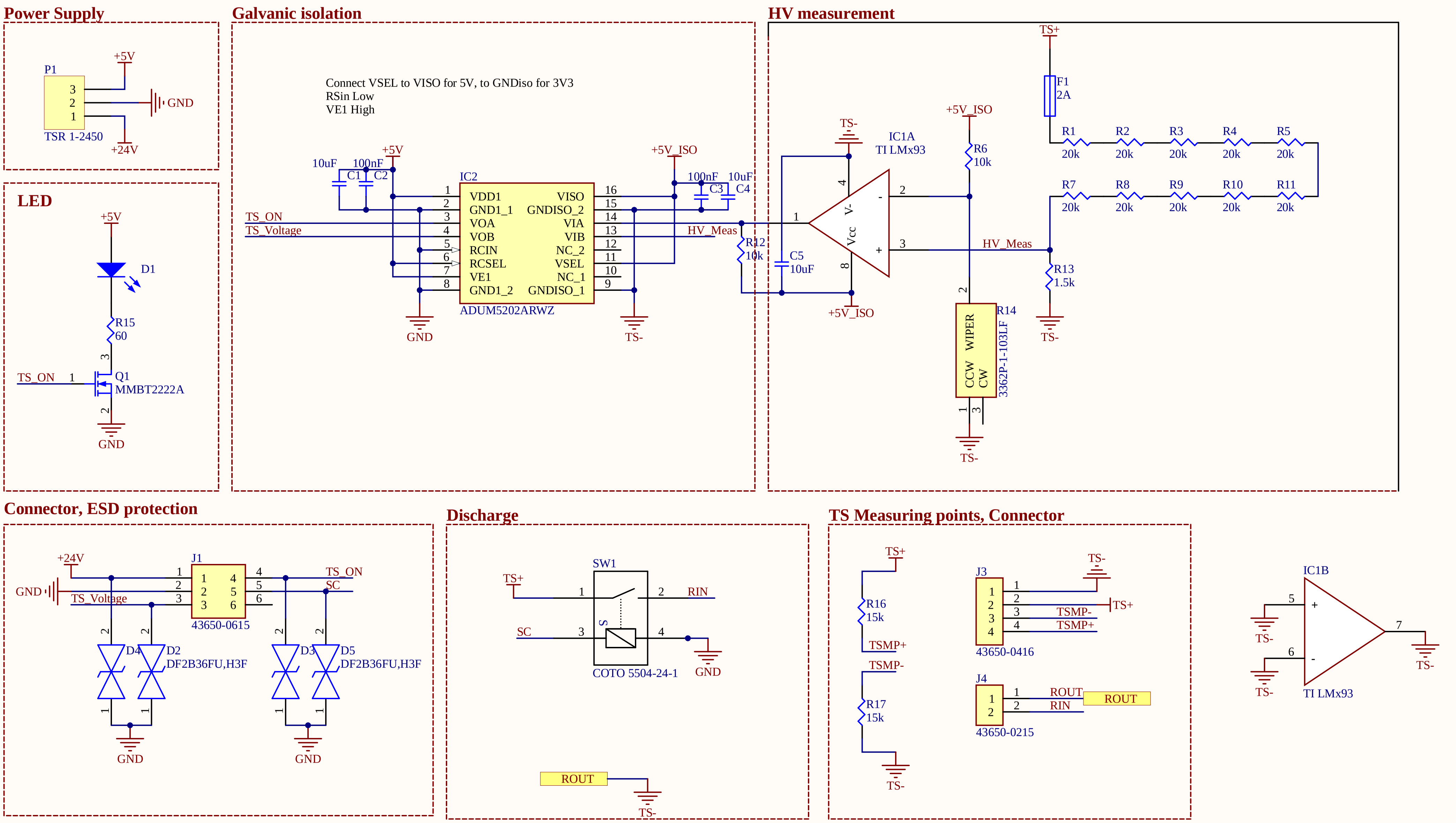
Appendix E: PCB schematics and masks

In this appendix the following PCB schematics and masks are provided:

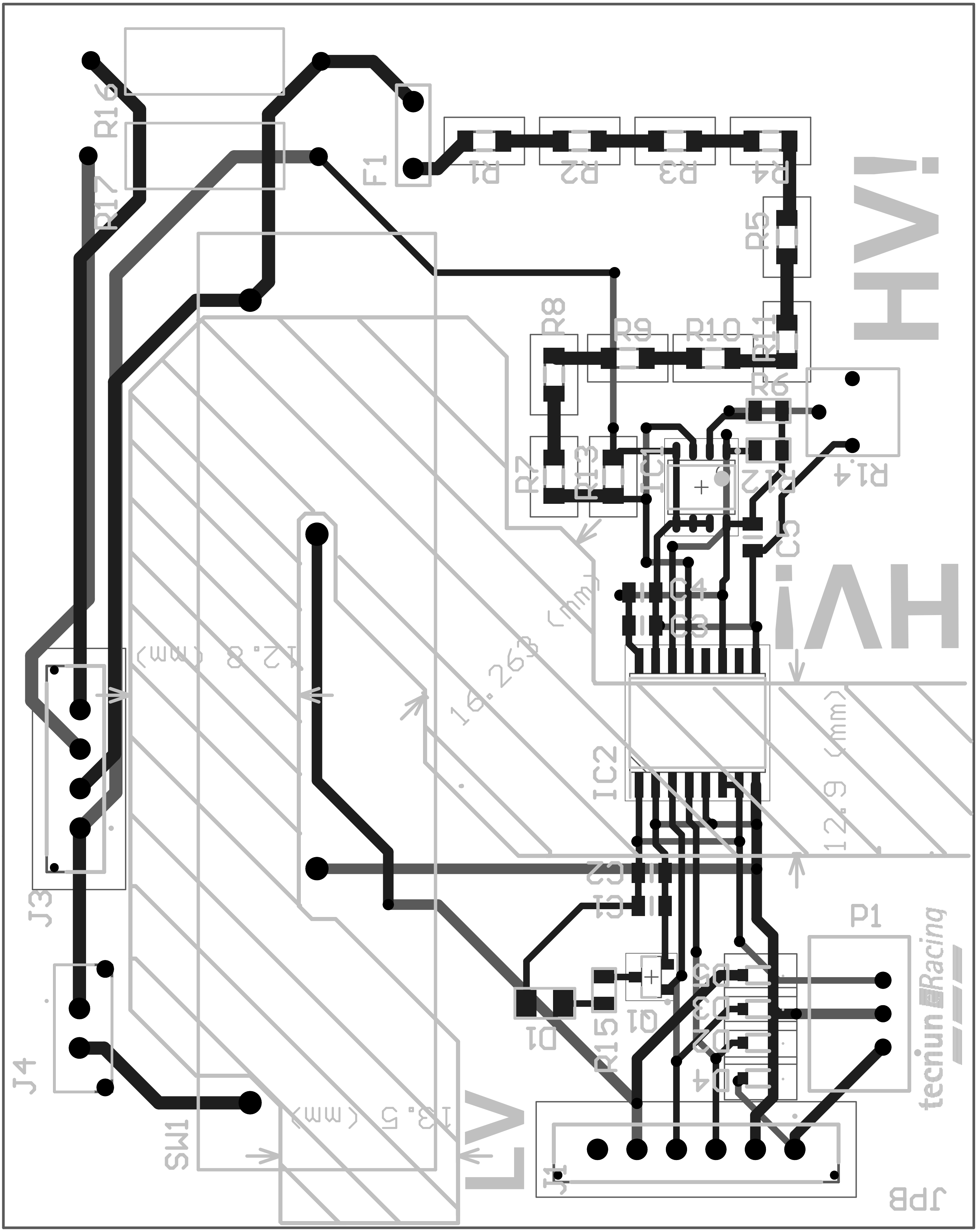
- Discharge PCB
- Voltage Indicator PCB
- BMS master module PCB
- BMS slave module PCB

Discharge PCB



Title **Discharge**			Jon Perez
Size: A4	Number: 1	Revision: 1	
Date: 18/06/2020	Time: 16:52:24	Sheet 1 of 1	

tecnun eRacing



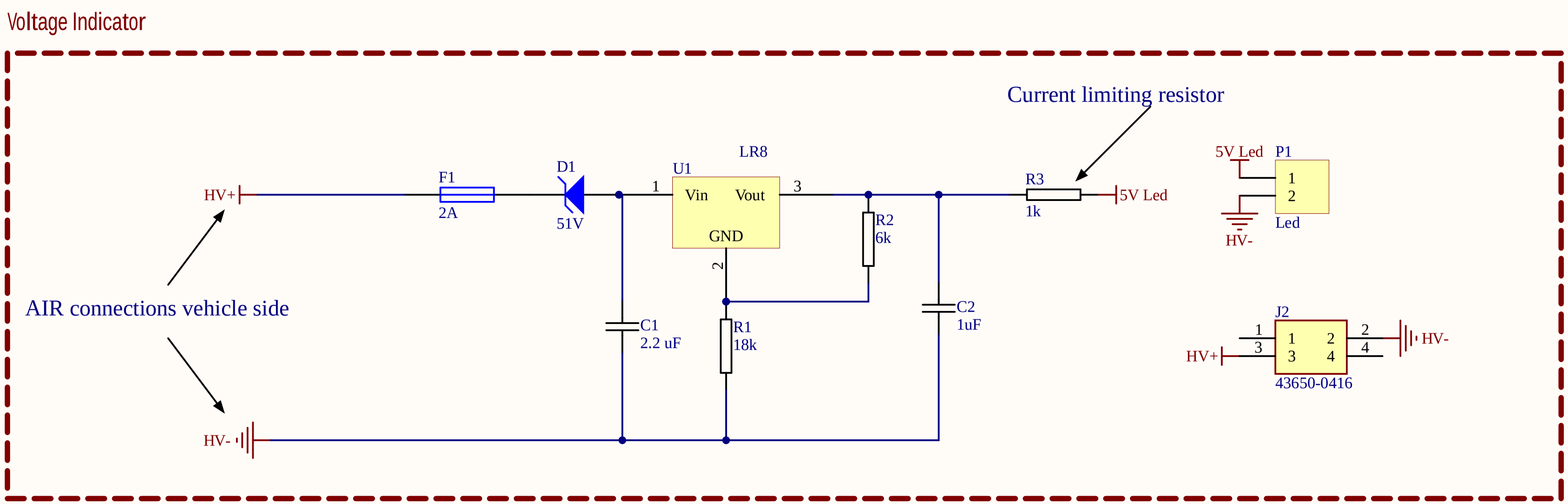
HV!
LV
IC1
IC2
J1
J3
J4
SW1
P1
F1
D1
Q1
tecnun Racing
JPB

Voltage Indicator PCB

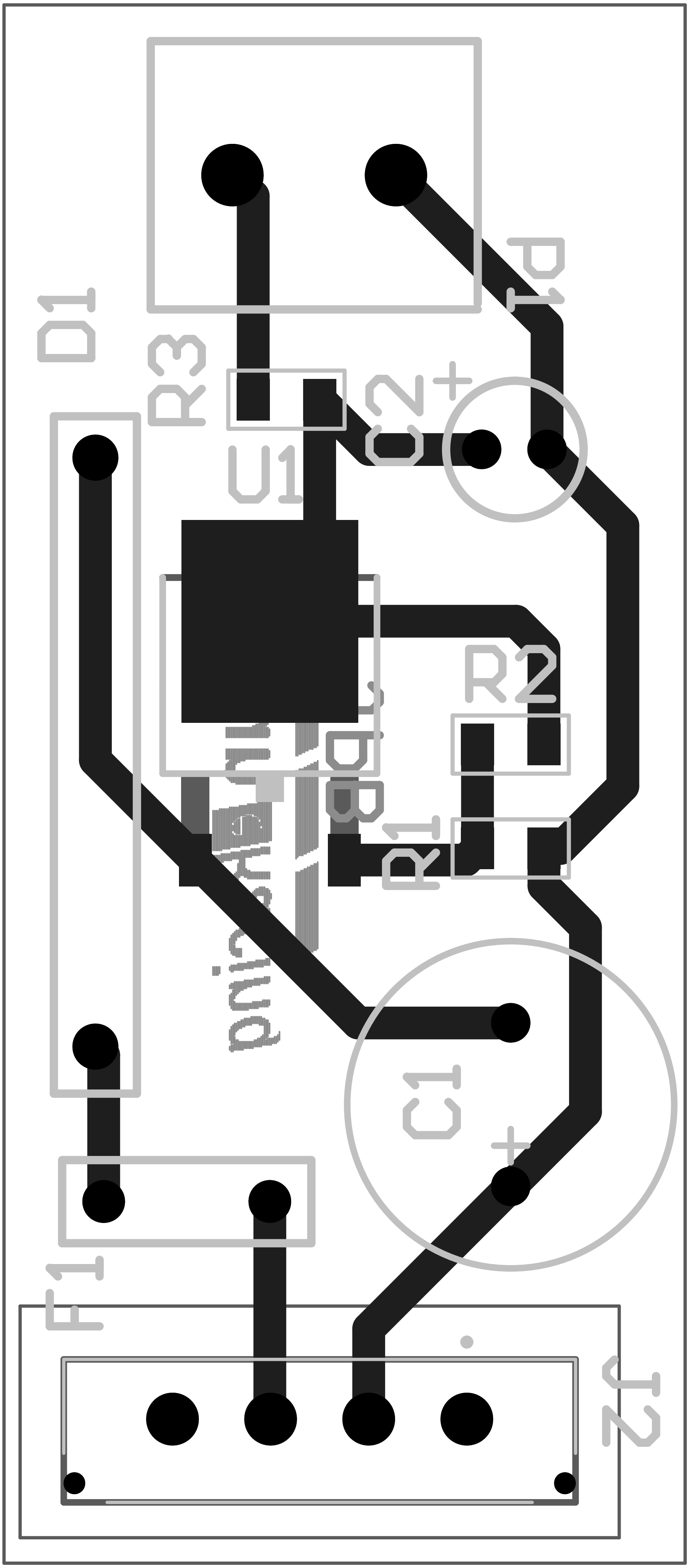
For a voltage of 55V, 4V will break through the 51V Zener diode and the output of the LR8 linear regulator will be about 2V. The indicator used needs 2V to start lighting up, so when the voltage is about 55V it will start lighting up, so when the voltage is 60V, 9 volts will break through the diode and the output will be 5V, so the indicator will be lighted.

Resistors and capacitors are requested in the linear regulators datasheet.

The power dissipated by the regulator is (403.2V-51V) * 20 mA (LED) = 7.044W
The maximum power dissipation of the regulator is 480V * 20 mA = 9.6W

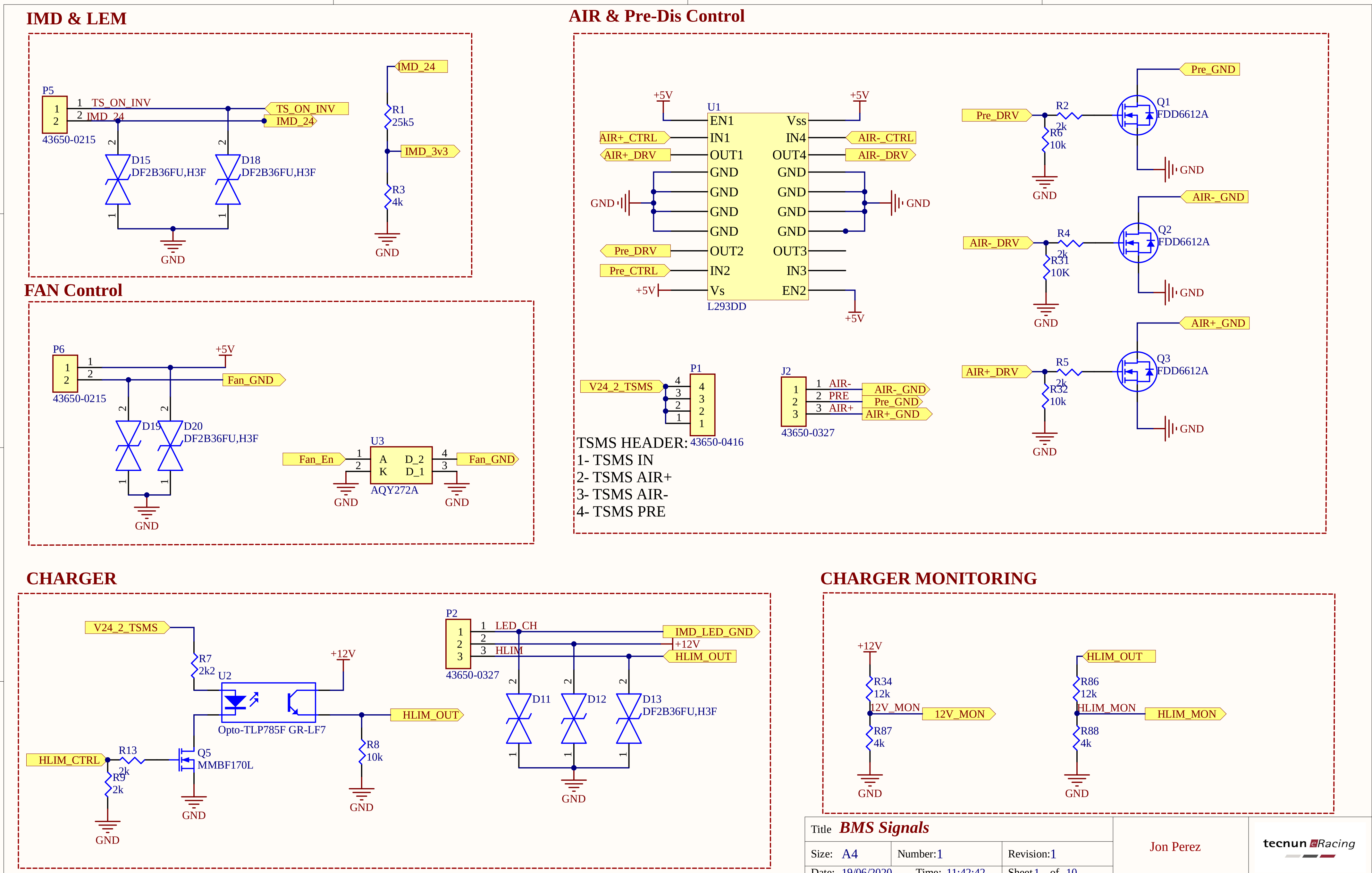


Title	Voltage Indicator		Jon Perez	tecnun eRacing
Size: A4	Number: 1	Revision: 1		
Date: 19/06/2020	Time: 11:53:10	Sheet 1 of 1		



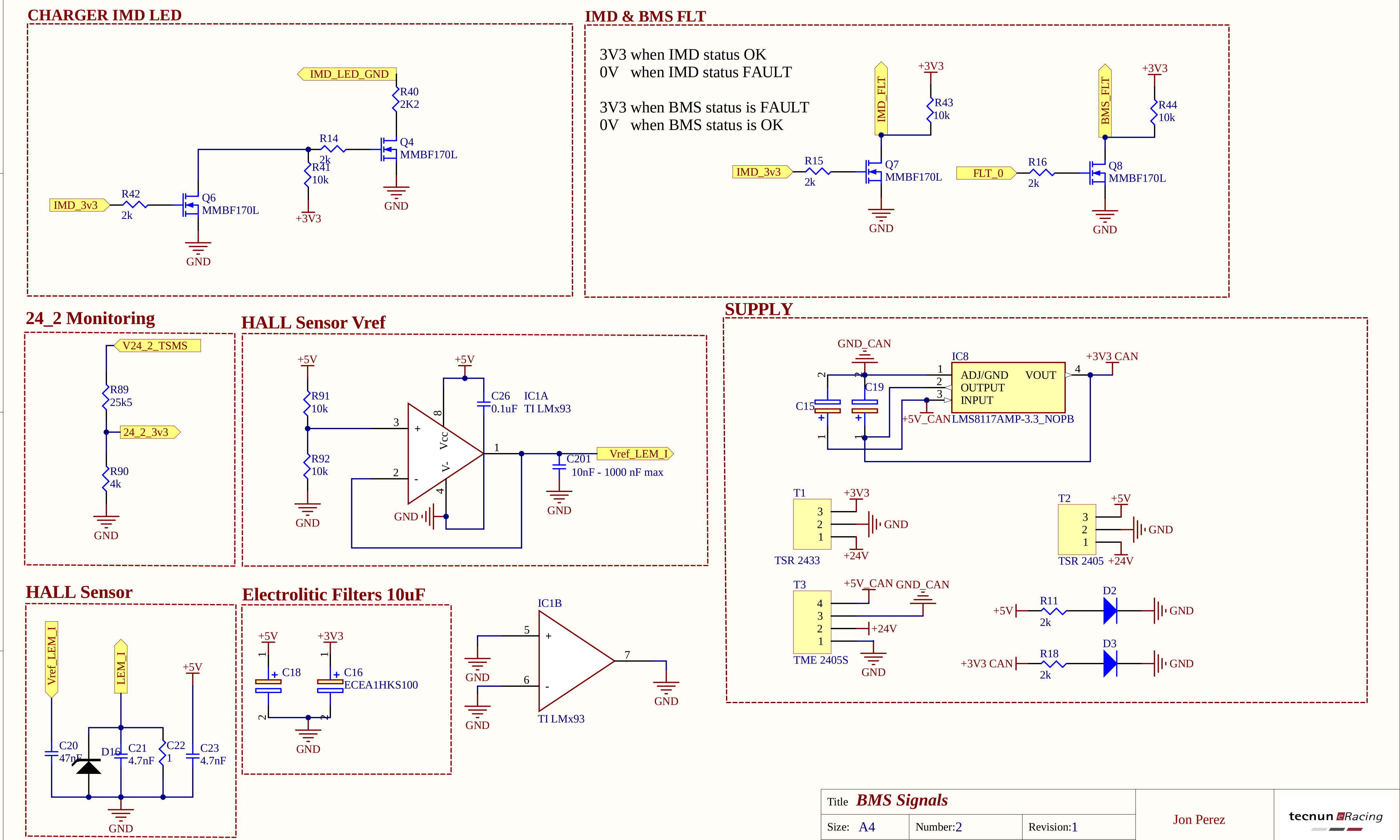
P1
D1
R3
C2
U1
R2
R1
C1
F1
J2

BMS master module PCB

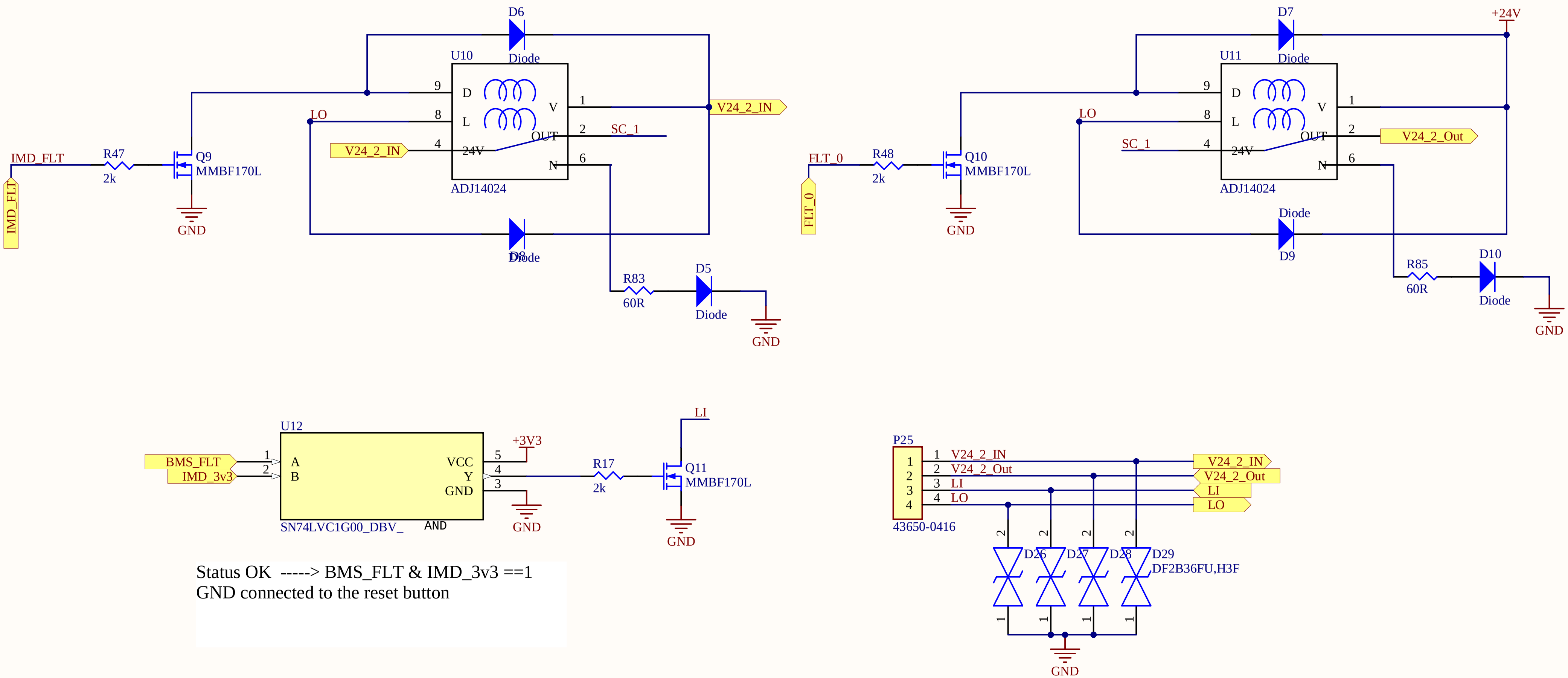


Title ***BMS Signals***			Jon Perez
Size: A4	Number: 1	Revision: 1	
Date: 19/06/2020	Time: 11:42:42	Sheet 1 of 10	

tecnun eRacing

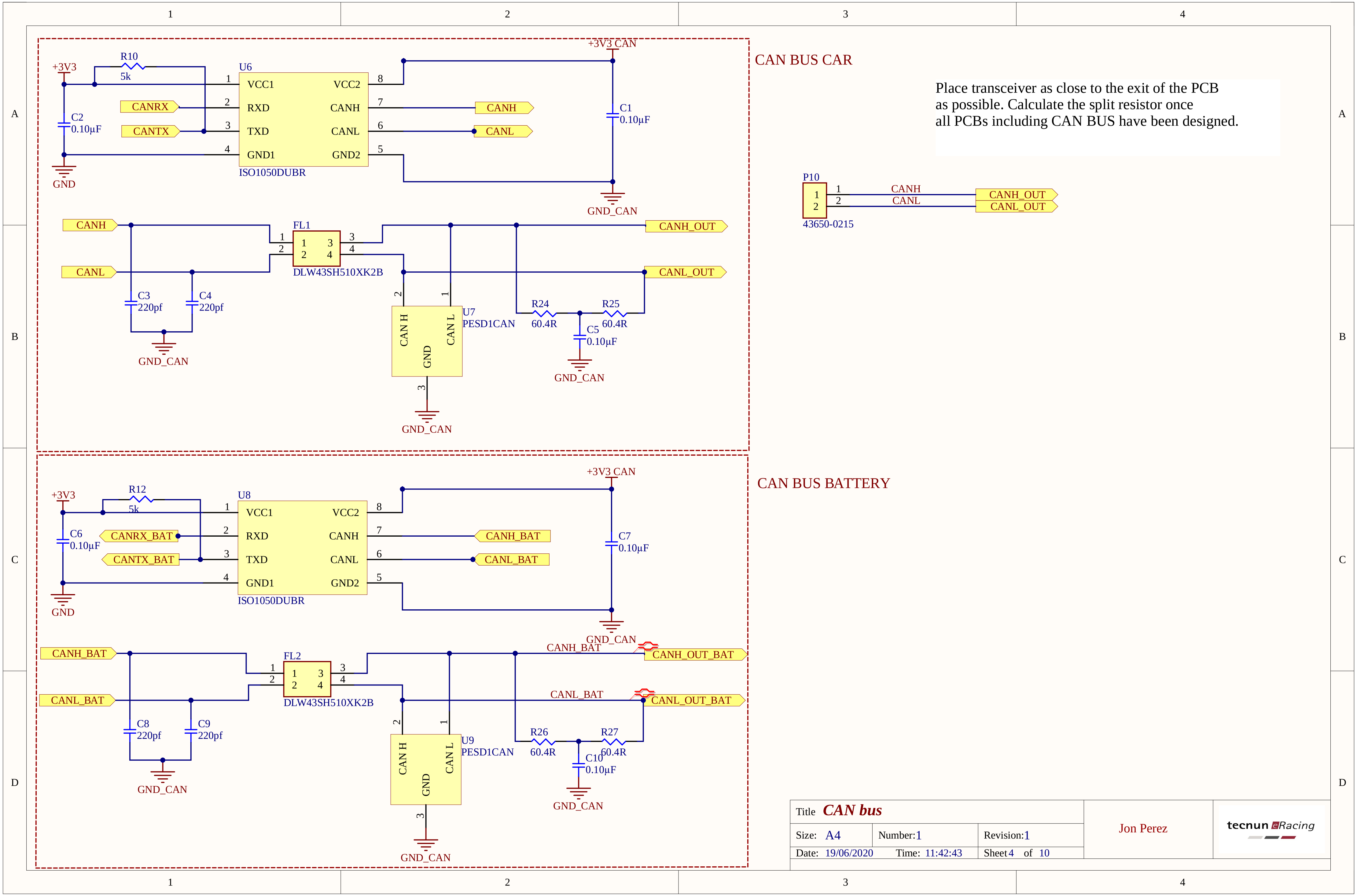


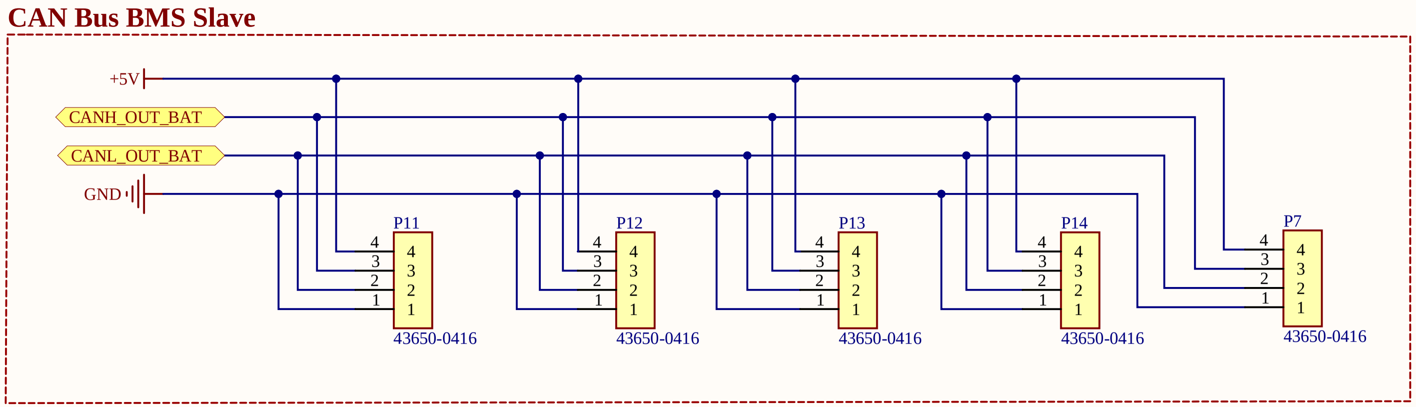
Title	BMS Signals		Jon Perez	tecnun Racing
Size: A4	Number:2	Revision:1		
Date: 19/06/2020	Time: 11:42:42	Sheet 2 of 10		



Title **Shutdown Circuit**			Jon Perez
Size: A4	Number: 1	Revision: 1	
Date: 19/06/2020	Time: 11:42:43	Sheet 3 of 10	

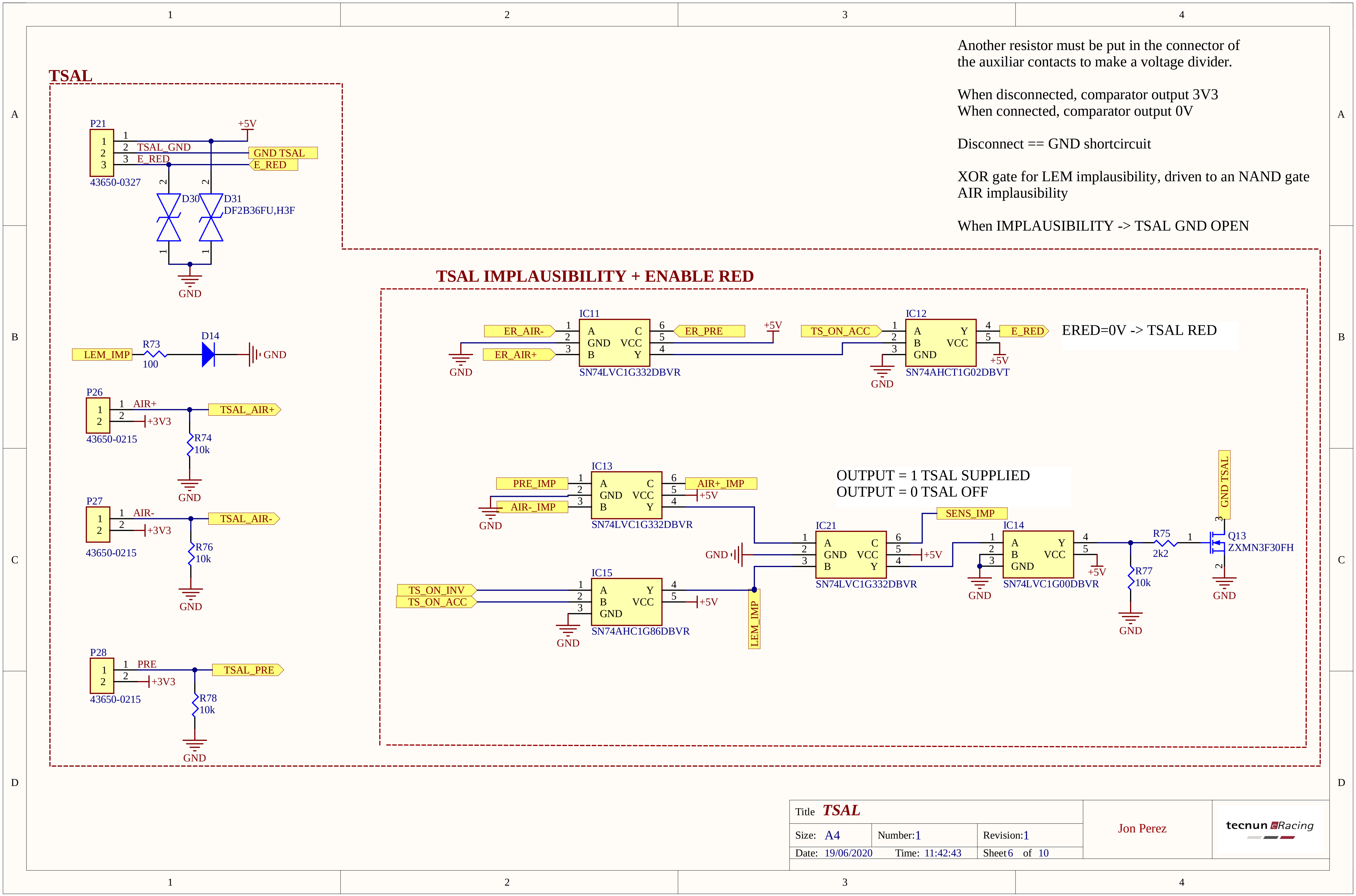
tecnun Racing


CAN BUS CAR
+3V3
R10
5k
U6
VCC1
RXD
TXD
GND1
VCC2
CANH
CANL
GND2
ISO1050DUBR
CANRX
CANTX
C2
0.10µF
GND
+3V3 CAN
C1
0.10µF
GND_CAN
CANH
CANL
FL1
DLW43SH510XK2B
C3
220pf
C4
220pf
U7
PESD1CAN
CAN H
CAN L
GND
R24
60.4R
R25
60.4R
C5
0.10µF
CANH_OUT
CANL_OUT
Place transceiver as close to the exit of the PCB
as possible. Calculate the split resistor once
all PCBs including CAN BUS have been designed.
P10
43650-0215
CAN BUS BATTERY
R12
5k
U8
CANRX_BAT
CANTX_BAT
C6
0.10µF
C7
0.10µF
CANH_BAT
CANL_BAT
FL2
C8
220pf
C9
220pf
U9
R26
60.4R
R27
60.4R
C10
0.10µF
CANH_OUT_BAT
CANL_OUT_BAT
Title CAN bus
Size: A4
Number:1
Revision:1
Date: 19/06/2020
Time: 11:42:43
Sheet 4 of 10
Jon Perez
tecnun eRacing

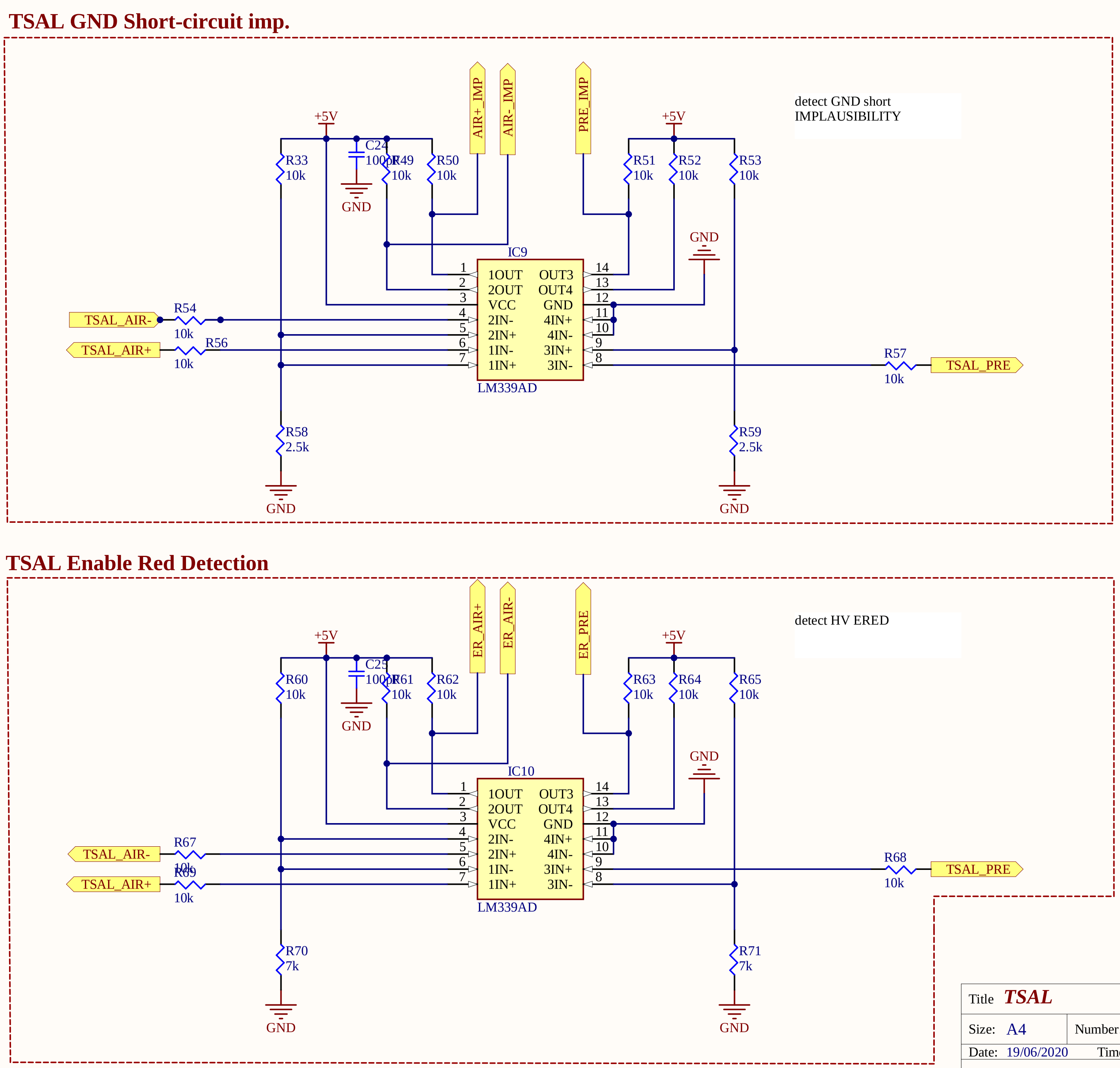


Title **CAN bus**		
Size: A4	Number: 2	Revision: 1
Date: 19/06/2020	Time: 11:42:43	Sheet 5 of 10

Jon Perez

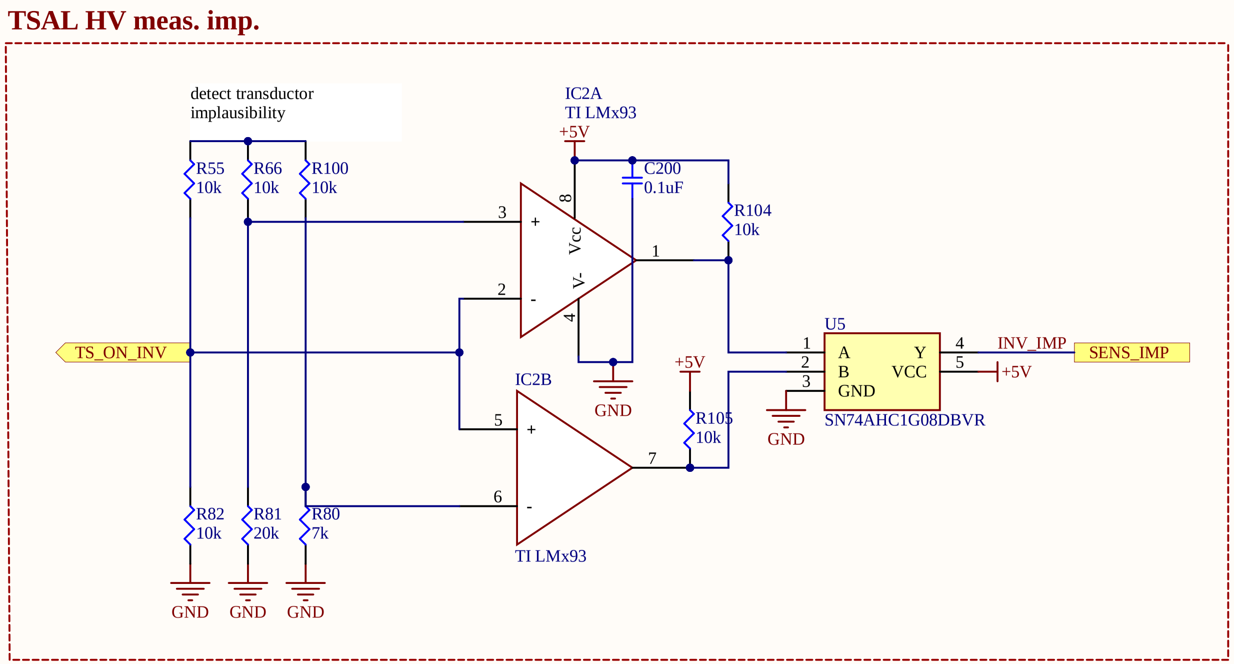


Another resistor must be put in the connector of
the auxiliar contacts to make a voltage divider.
When disconnected, comparator output 3V3
When connected, comparator output 0V
Disconnect == GND shortcircuit
XOR gate for LEM implausibility, driven to an NAND gate
AIR implausibility
When IMPLAUSIBILITY -> TSAL GND OPEN
TSAL
TSAL IMPLAUSIBILITY + ENABLE RED
ERED=0V -> TSAL RED
OUTPUT = 1 TSAL SUPPLIED
OUTPUT = 0 TSAL OFF
P21
43650-0327
TSAL_GND
E_RED
GND TSAL
D30
D31
DF2B36FU,H3F
LEM_IMP
R73
100
D14
P26
AIR+
TSAL_AIR+
R74
10k
P27
AIR-
TSAL_AIR-
R76
10k
P28
PRE
TSAL_PRE
R78
10k
43650-0215
IC11
SN74LVC1G332DBVR
ER_AIR-
ER_AIR+
ER_PRE
IC12
SN74AHCT1G02DBVT
TS_ON_ACC
E_RED
IC13
SN74LVC1G332DBVR
PRE_IMP
AIR-_IMP
AIR+_IMP
IC15
SN74AHC1G86DBVR
TS_ON_INV
TS_ON_ACC
IC21
SN74LVC1G332DBVR
SENS_IMP
IC14
SN74LVC1G00DBVR
R75
2k2
R77
10k
Q13
ZXMN3F30FH
GND TSAL
Title TSAL
Size: A4
Number:1
Revision:1
Date: 19/06/2020
Time: 11:42:43
Sheet 6 of 10
Jon Perez
tecnun eRacing

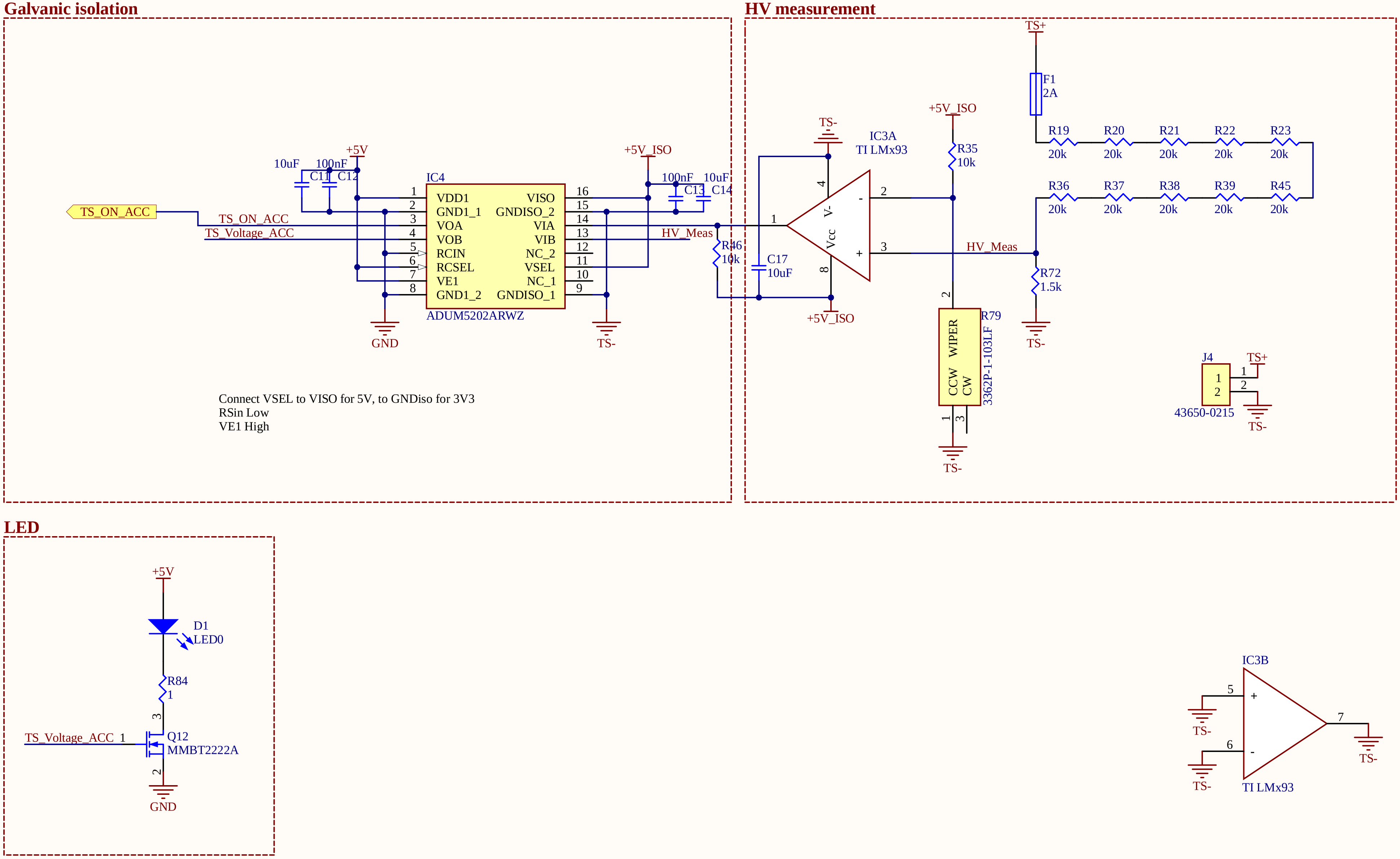


Title **TSAL**			Jon Perez
Size: A4	Number:2	Revision:1	
Date: 19/06/2020	Time: 11:42:44	Sheet 7 of 10	

tecnun eRacing



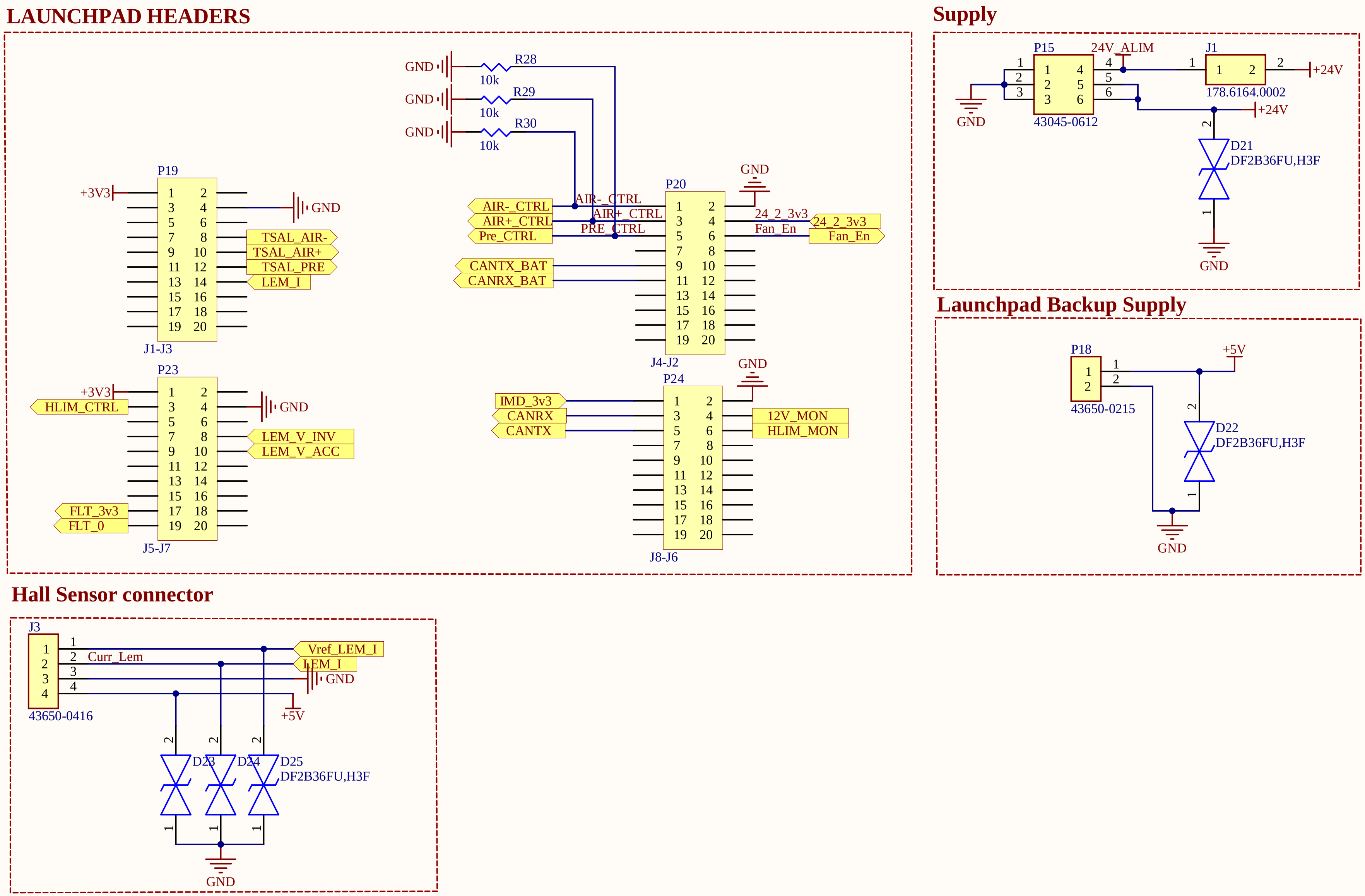
Title TSAL			Jon Perez
Size: A4	Number:3	Revision:1	
Date: 19/06/2020	Time: 11:42:44	Sheet 8 of 10	



Title *HV Measurement*		
Size: A4	Number:1	Revision:1
Date: 19/06/2020	Time: 11:42:44	Sheet9 of 10

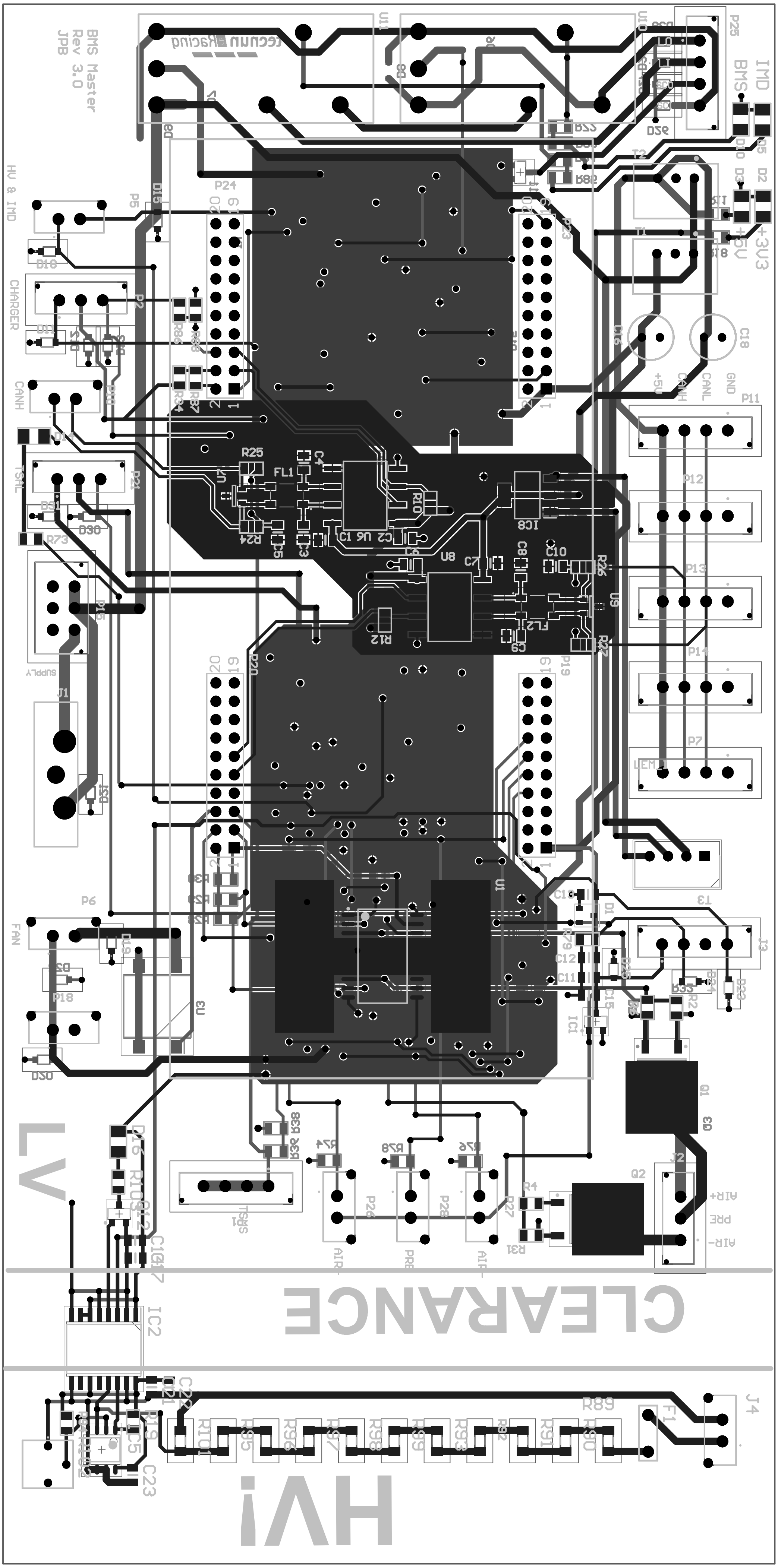
Jon Perez

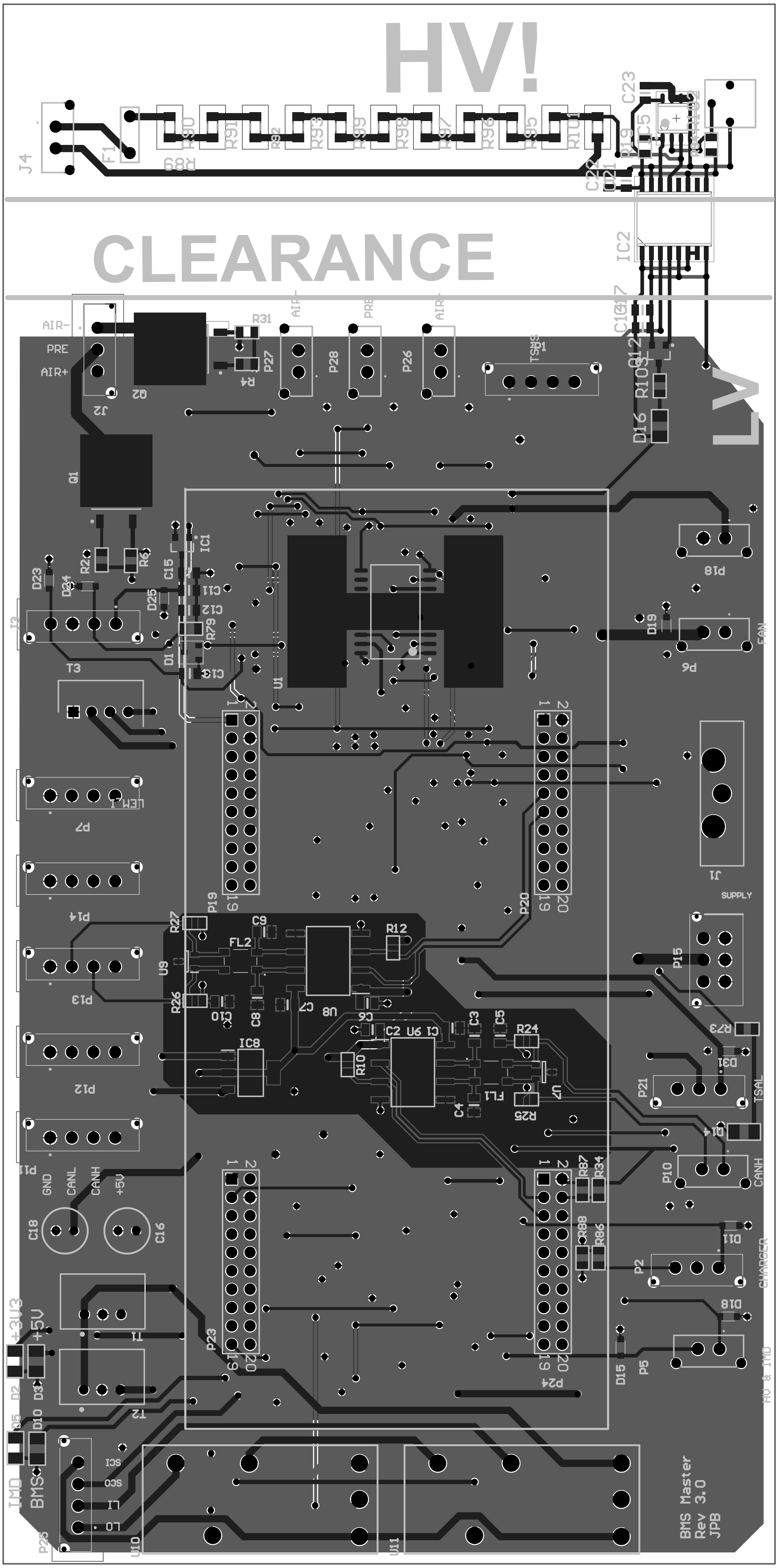
tecnun eRacing



Title **Headers**			Jon Perez
Size: A4	Number:1	Revision:1	
Date: 19/06/2020	Time: 11:42:44	Sheet 10 of 10	

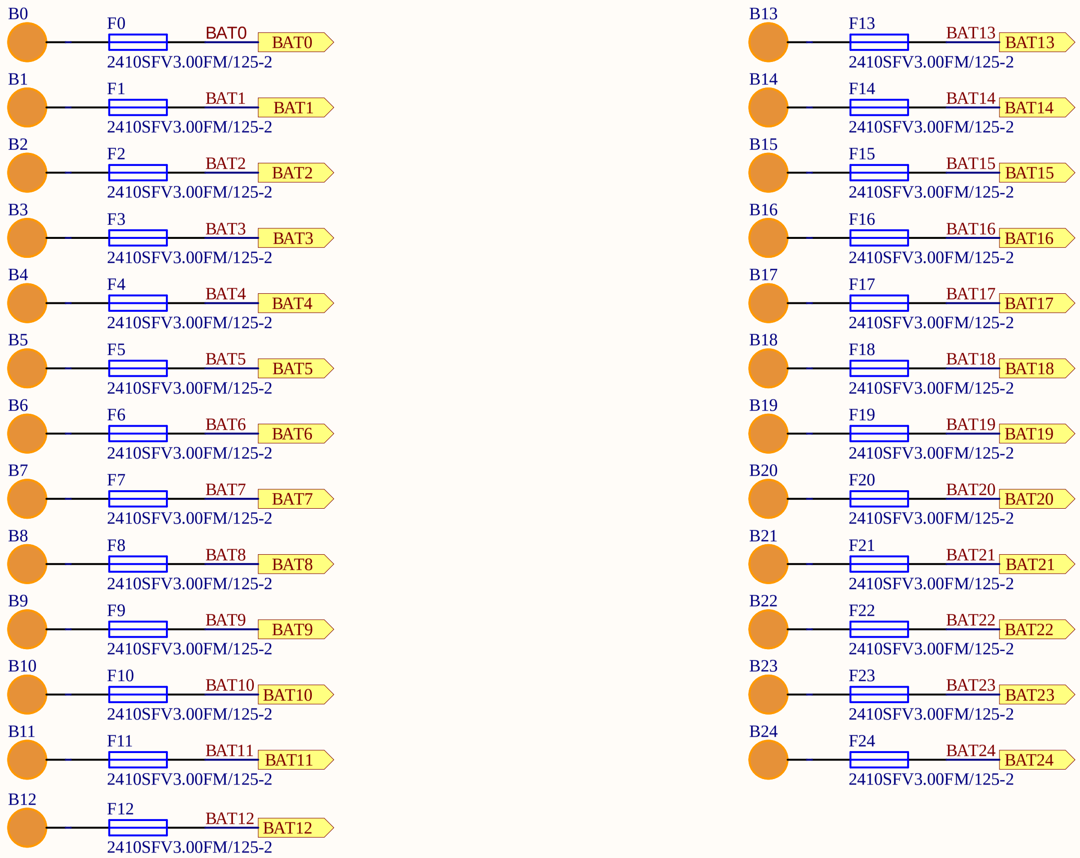
tecnun eRacing



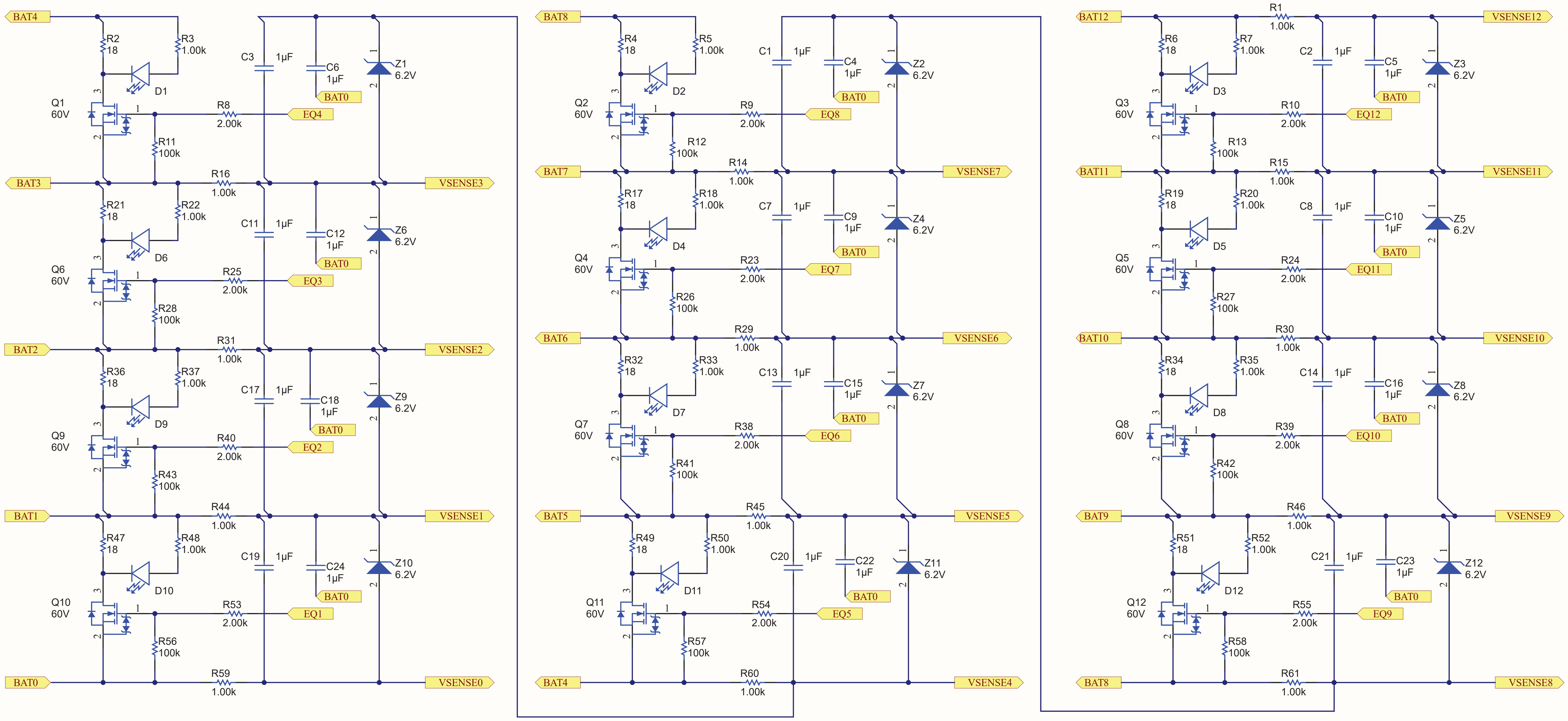


HV!
CLEARANCE
LV
BMS Master
Rev 3.0
JPB

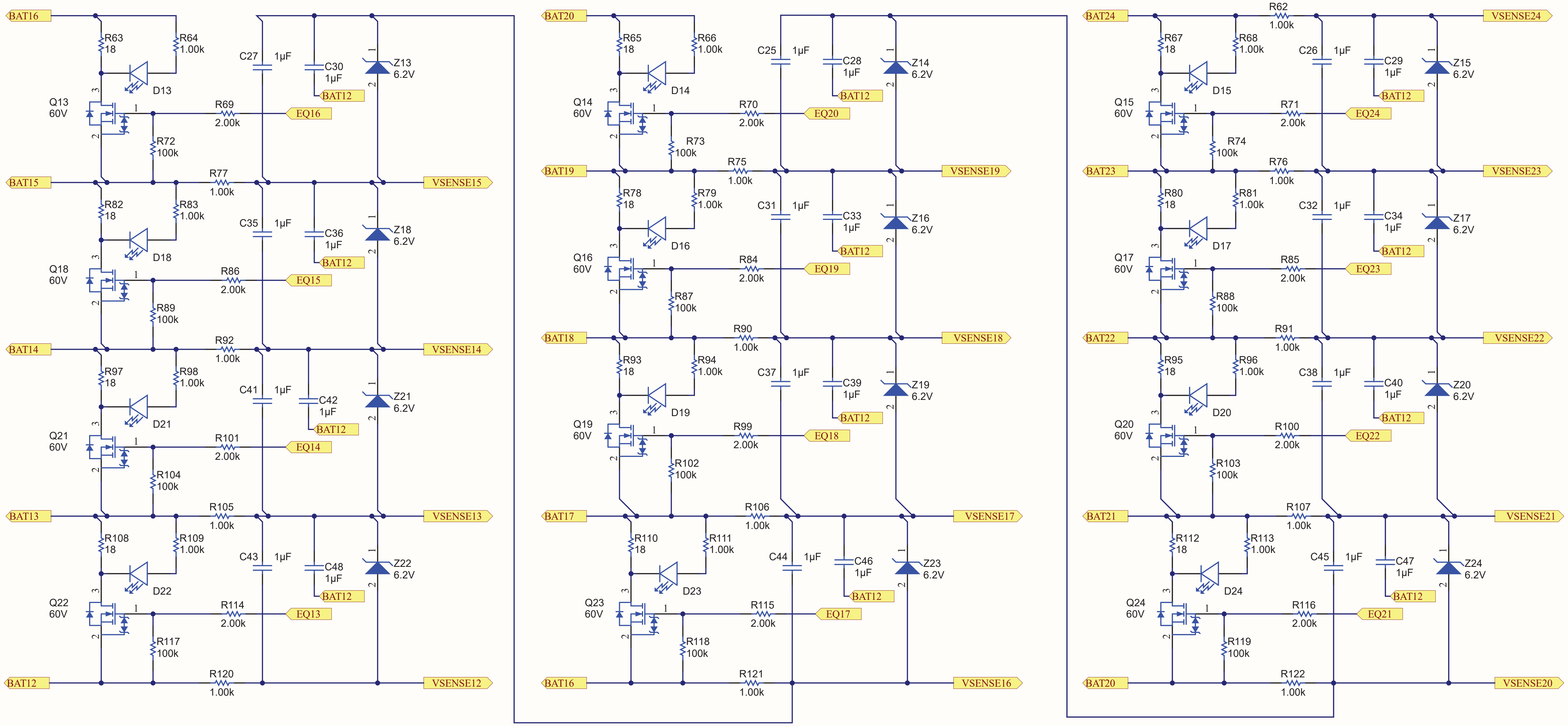
BMS slave module PCB



Title **Cell Connections**			Jon Perez	tecnun eRacing
Size: A4	Number: 1	Revision: 1		
Date: 19/06/2020	Time: 11:49:02	Sheet 1 of 8		

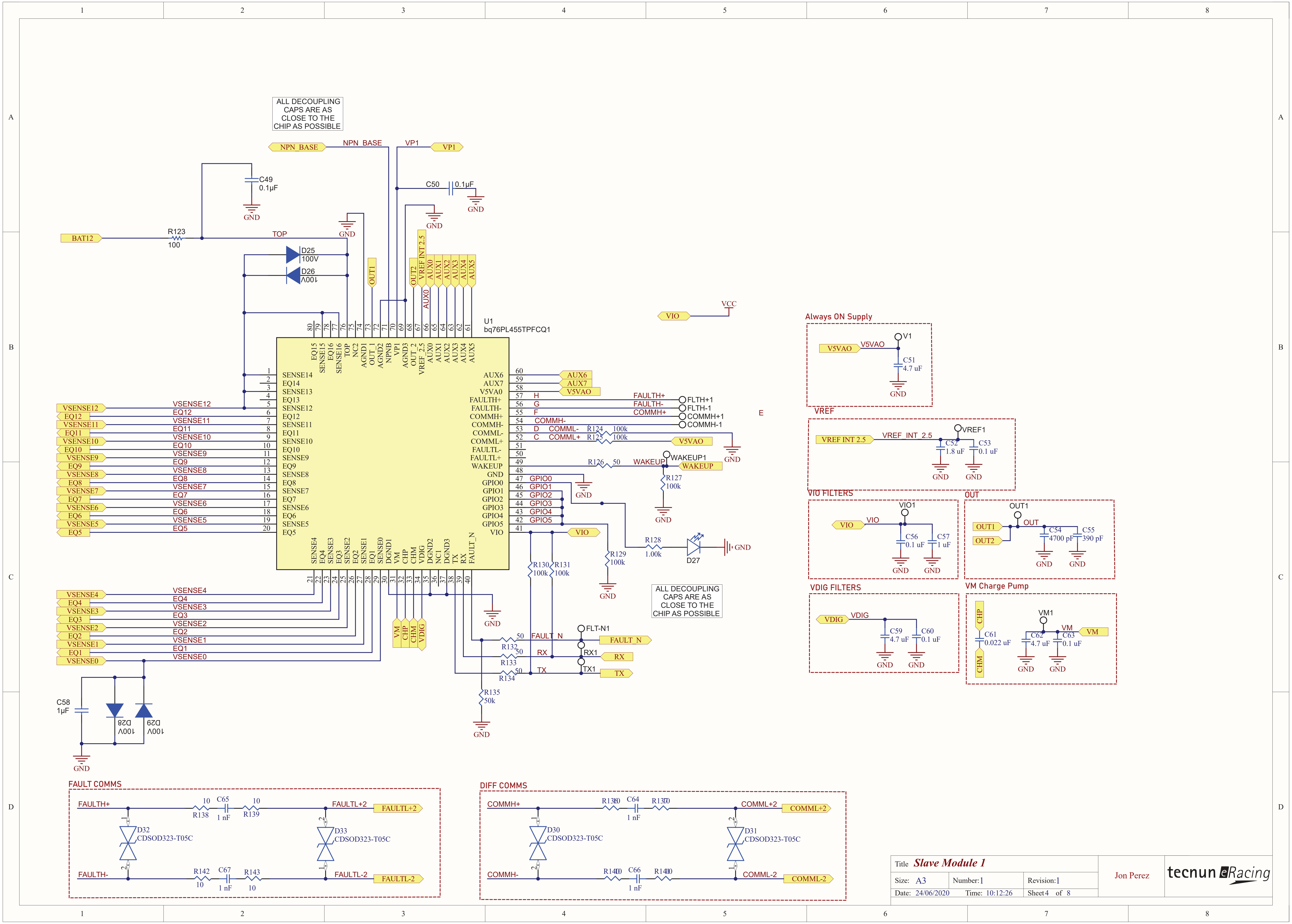


Title *Bat. Connections*			Jon Perez
Size: A3	Number: 1	Revision: 1	tecnun eRacing
Date: 24/06/2020	Time: 10:12:23	Sheet 2 of 8	

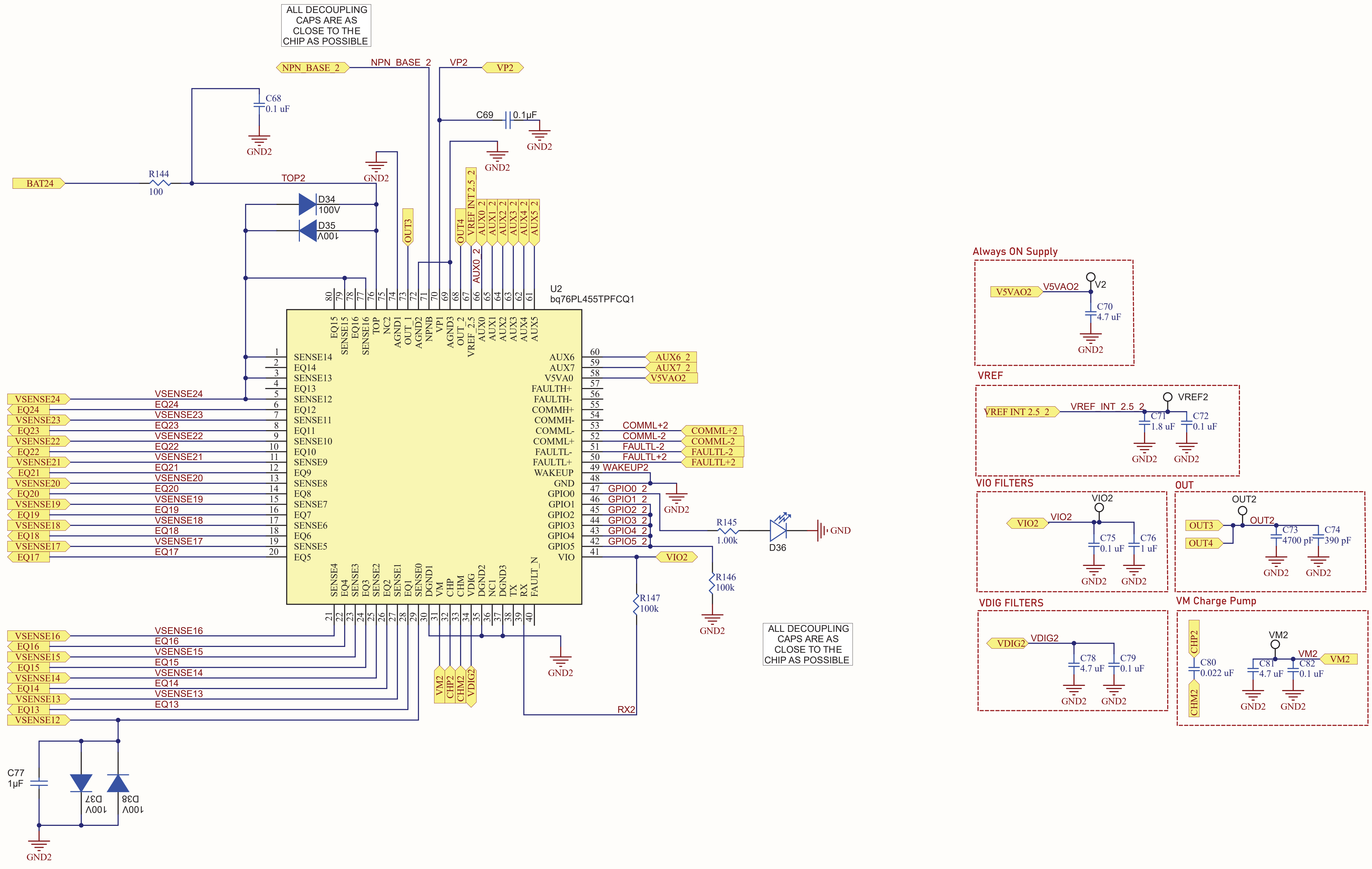


Title **Bat. Connections**			Jon Perez
Size: A3	Number:2	Revision:1	
Date: 24/06/2020	Time: 10:12:20	Sheet3 of 8	

tecnun eRacing



ALL DECOUPLING CAPS ARE AS CLOSE TO THE CHIP AS POSSIBLE
NPN_BASE
VP1
C49 0.1µF
C50 0.1µF
GND
BAT12
R123 100
TOP
D25 100V
D26 100V
OUT1
OUT2
VREF INT 2.5
AUX0
AUX1
AUX2
AUX3
AUX4
AUX5
U1
bq76PL455TPFCQ1
SENSE14
EQ14
SENSE13
EQ13
SENSE12
EQ12
SENSE11
EQ11
SENSE10
EQ10
SENSE9
EQ9
SENSE8
EQ8
SENSE7
EQ7
SENSE6
EQ6
SENSE5
EQ5
EQ15
SENSE15
EQ16
SENSE16
NC2
AGND1
OUT_1
AGND2
NPNB
AGND3
OUT_2
VREF_2.5
AUX6
AUX7
V5VAO
FAULTH+
FAULTH-
COMMH+
COMMH-
COMML-
COMML+
FAULTL-
FAULTL+
WAKEUP
GPIO0
GPIO1
GPIO2
GPIO3
GPIO4
GPIO5
VIO
SENSE4
EQ4
SENSE3
EQ3
SENSE2
EQ2
SENSE1
EQ1
SENSE0
DGND1
VM
CHP
CHM
VDIG
DGND2
NC1
DGND3
TX
RX
FAULT_N
VSENSE12
VSENSE11
VSENSE10
VSENSE9
VSENSE8
VSENSE7
VSENSE6
VSENSE5
VSENSE4
VSENSE3
VSENSE2
VSENSE1
VSENSE0
FLTH+1
FLTH-1
COMMH+1
COMMH-1
R124 100k
R125 100k
R126 50
WAKEUP1
R127 100k
VCC
R128 1.00k
D27
R129 100k
R130 100k
R131 100k
FLT-N1
RX1
TX1
R132 50
R133 50
R134 50
R135 50k
C58 1µF
D28 100V
D29 100V
Always ON Supply
V1
C51 4.7 uF
VREF
VREF1
VREF_INT_2.5
C52 1.8 uF
C53 0.1 uF
VIO FILTERS
VIO1
C56 0.1 uF
C57 1 uF
OUT
OUT1
C54 4700 pF
C55 390 pF
VDIG FILTERS
C59 4.7 uF
C60 0.1 uF
VM Charge Pump
VM1
C61 0.022 uF
C62 4.7 uF
C63 0.1 uF
FAULT COMMS
R138 10
C65 1 nF
R139 10
FAULTL+2
D32 CDSOD323-T05C
D33 CDSOD323-T05C
R142 10
C67 1 nF
R143 10
FAULTL-2
DIFF COMMS
R136 10
C64 1 nF
R137 10
COMML+2
D30 CDSOD323-T05C
D31 CDSOD323-T05C
R140 10
C66 1 nF
R141 10
COMML-2
Title Slave Module 1
Size: A3
Number: 1
Revision: 1
Date: 24/06/2020
Time: 10:12:26
Sheet 4 of 8
Jon Perez
tecnun eRacing



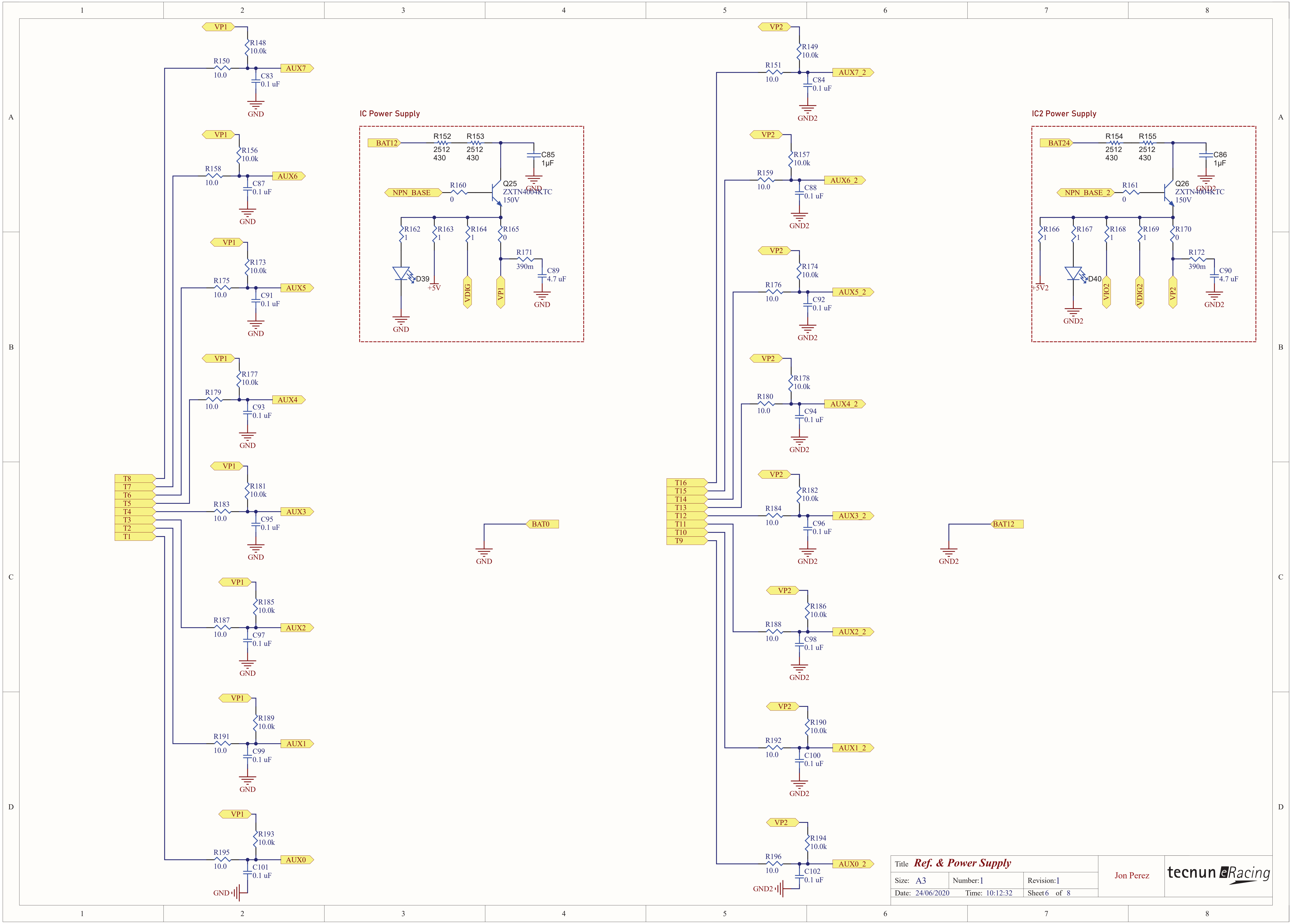
Title *Slave Module 2*

Jon Perez

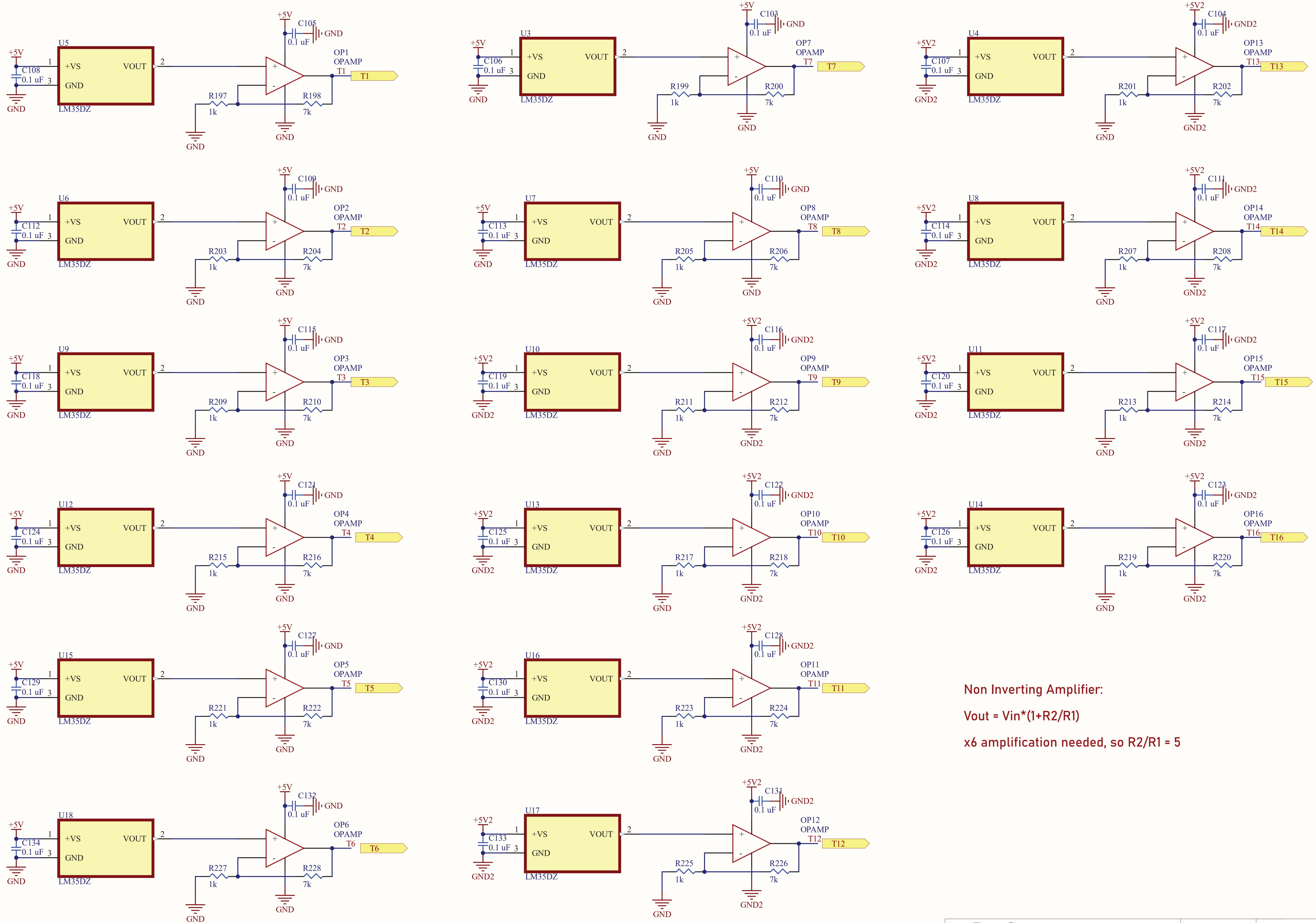
tecnun eRacing

Size: A3 | Number: 1 | Revision: 1

Date: 24/06/2020 | Time: 10:12:29 | Sheet 5 of 8



IC Power Supply
BAT12
R152 2512 430
R153 2512 430
C85 1µF
GND
NPN_BASE
R160 0
Q25 ZXTN4004KTC 150V
R162 1
R163 1
R164 1
R165 0
R171 390m
C89 4.7 uF
D39
+5V
VDIG
VP1
IC2 Power Supply
BAT24
R154 2512 430
R155 2512 430
C86 1µF
GND2
NPN_BASE_2
R161 0
Q26 ZXTN4004KTC 150V
R166 1
R167 1
R168 1
R169 1
R170 0
R172 390m
C90 4.7 uF
D40
+5V2
VIO2
VDIG2
VP2
T8 T7 T6 T5 T4 T3 T2 T1
T16 T15 T14 T13 T12 T11 T10 T9
R148 10.0k R150 10.0 C83 0.1 uF AUX7
R156 10.0k R158 10.0 C87 0.1 uF AUX6
R173 10.0k R175 10.0 C91 0.1 uF AUX5
R177 10.0k R179 10.0 C93 0.1 uF AUX4
R181 10.0k R183 10.0 C95 0.1 uF AUX3
R185 10.0k R187 10.0 C97 0.1 uF AUX2
R189 10.0k R191 10.0 C99 0.1 uF AUX1
R193 10.0k R195 10.0 C101 0.1 uF AUX0
R149 10.0k R151 10.0 C84 0.1 uF AUX7_2
R157 10.0k R159 10.0 C88 0.1 uF AUX6_2
R174 10.0k R176 10.0 C92 0.1 uF AUX5_2
R178 10.0k R180 10.0 C94 0.1 uF AUX4_2
R182 10.0k R184 10.0 C96 0.1 uF AUX3_2
R186 10.0k R188 10.0 C98 0.1 uF AUX2_2
R190 10.0k R192 10.0 C100 0.1 uF AUX1_2
R194 10.0k R196 10.0 C102 0.1 uF AUX0_2
BAT0
BAT12
Title Ref. & Power Supply
Size: A3
Number: 1
Revision: 1
Date: 24/06/2020
Time: 10:12:32
Sheet 6 of 8
Jon Perez
tecnun eRacing

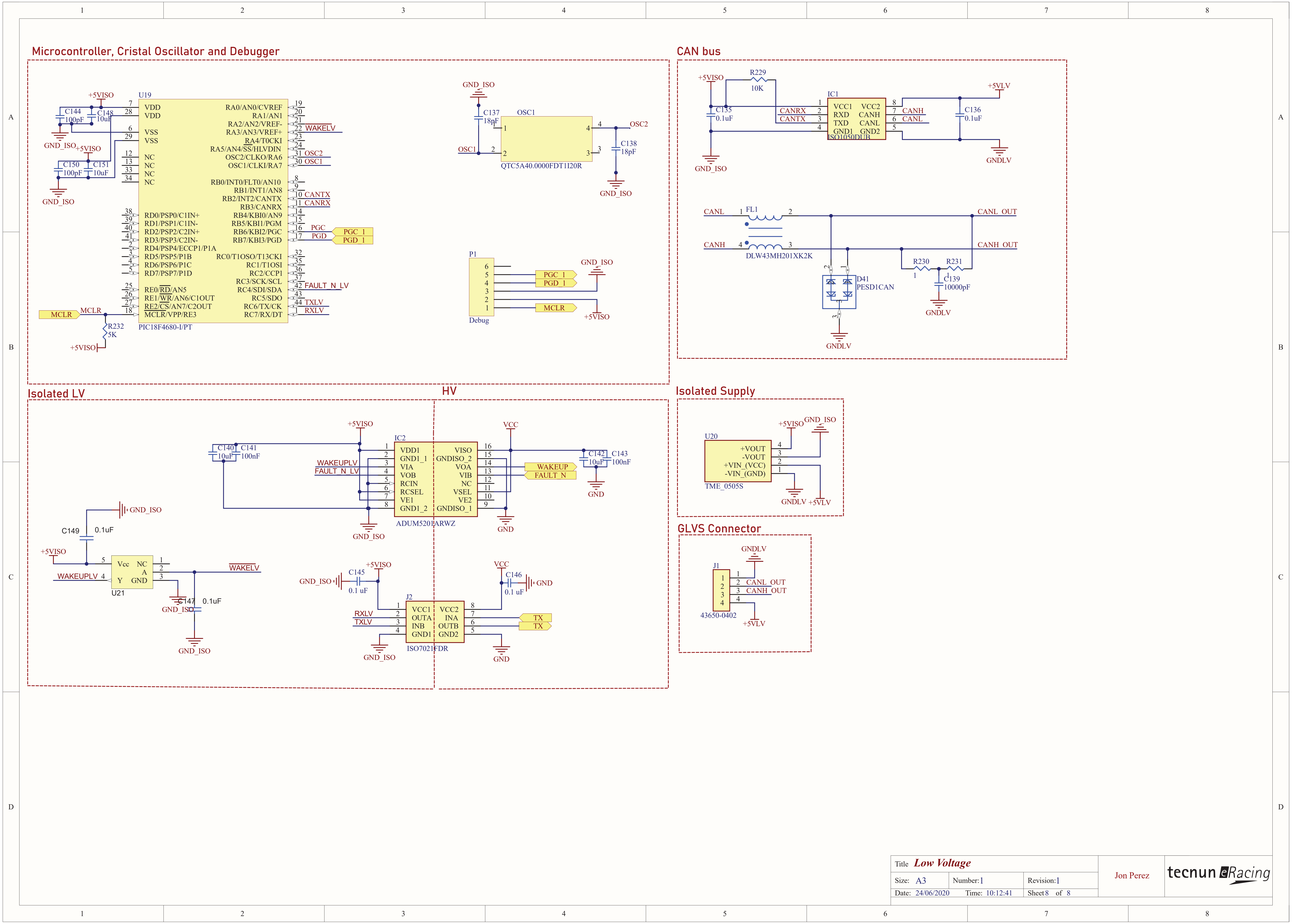


Non Inverting Amplifier:

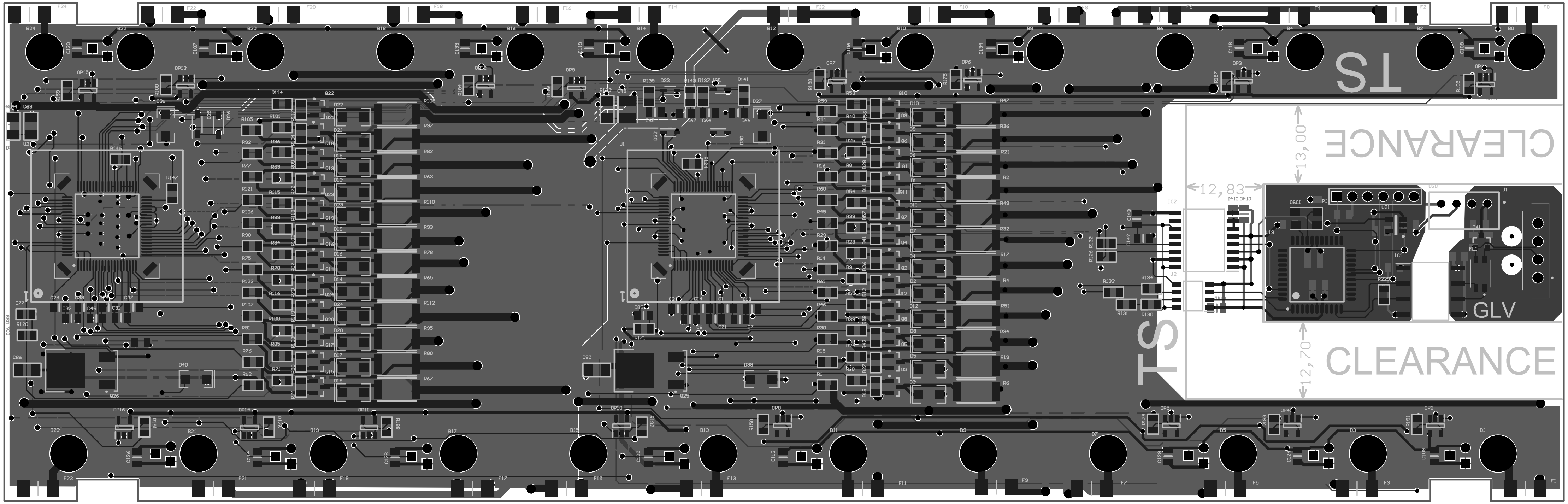
Vout = Vin*(1+R2/R1)

x6 amplification needed, so R2/R1 = 5

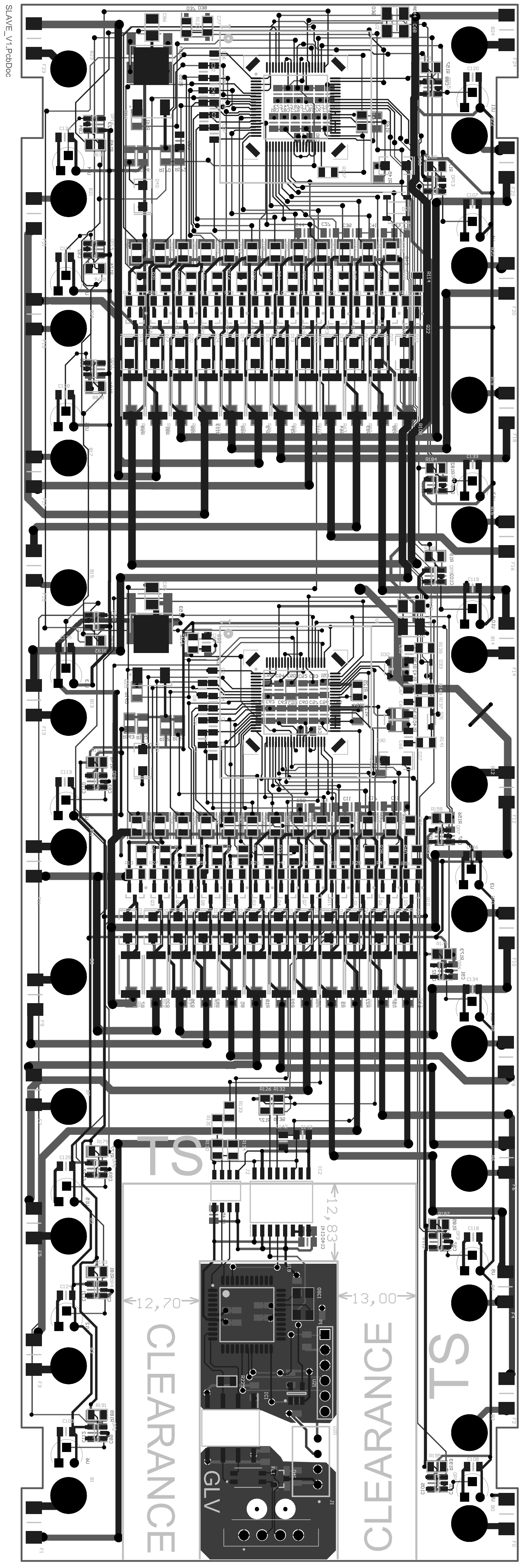
Title *Temp. Sensors*			Jon Perez
Size: A3	Number: 1	Revision: 1	tecnun eRacing
Date: 24/06/2020	Time: 10:12:36	Sheet 7 of 8	



Microcontroller, Cristal Oscillator and Debugger
CAN bus
Isolated LV
HV
Isolated Supply
GLVS Connector
U19
PIC18F4680-I/PT
OSC1
QTC5A40.0000FDT1120R
P1
Debug
IC1
ISO1050DUB
FL1
DLW43MH201XK2K
D41
PESD1CAN
IC2
ADUM5201ARWZ
U21
J2
ISO7021FDR
U20
TME_0505S
J1
43650-0402
Title Low Voltage
Size: A3
Number: 1
Revision: 1
Date: 24/06/2020
Time: 10:12:41
Sheet 8 of 8
Jon Perez
tecnun eRacing



SLAVE_V1.PcbDoc



SLAVE_V1.PcbDoc
TS
CLEARANCE
GLV
12,70
13,00
12,83

Appendix F: Slave module code

In this appendix, the code developed for the testing of the slave module software is shown.

```
#include "Prueba_va_2.h"
#include "Prueba_va_2_private.h"

/* Block signals (default storage) */
B_Prueba_va_2_T Prueba_va_2_B;

/* Block states (default storage) */
DW_Prueba_va_2_T Prueba_va_2_DW;

/* Real-time model */
RT_MODEL_Prueba_va_2_T Prueba_va_2_M_;
RT_MODEL_Prueba_va_2_T *const Prueba_va_2_M = &Prueba_va_2_M_;
int var =0;
int buffLen=4;
int State;
int i;
int errFlg = NOERROR;
unsigned int recbuff[16];
void  Configuration (int cnt);
void  SendConfiguration (int cnt);
void SampleSend(int cnt);


void Prueba_va_2_step(void)
{
  /*********** UART data *****************/
  {
    for (i = 0; i < 17; i++)
      recbuff[i] = 1;
    /* Receiving data */
    errFlg = scic_rcv(recbuff,buffLen, LONGLOOP, 1);
    memcpy( &Prueba_va_2_B.SCIReceive[0], recbuff, 14);
  }

  /********* Send CAN Msg *************/
  {
          {

           Prueba_va_2_B.CANPack.ID = 0U;
           Prueba_va_2_B.CANPack.Length = 8U;
           Prueba_va_2_B.CANPack.Extended = 0U;
           Prueba_va_2_B.CANPack.Remote = 0;
           Prueba_va_2_B.CANPack.Data[0] = Prueba_va_2_B.SCIReceive[0];
           Prueba_va_2_B.CANPack.Data[1] = Prueba_va_2_B.SCIReceive[1];
           Prueba_va_2_B.CANPack.Data[2] = Prueba_va_2_B.SCIReceive[3];
           Prueba_va_2_B.CANPack.Data[3] = Prueba_va_2_B.SCIReceive[2];
           Prueba_va_2_B.CANPack.Data[4] = Prueba_va_2_B.SCIReceive[5];
           Prueba_va_2_B.CANPack.Data[5] = Prueba_va_2_B.SCIReceive[4];
           Prueba_va_2_B.CANPack.Data[6] = Prueba_va_2_B.SCIReceive[7];
           Prueba_va_2_B.CANPack.Data[7] = Prueba_va_2_B.SCIReceive[6];
```

```
                }

                {
                  tCANMsgObject sTXCANMessage;
                  sTXCANMessage.ui32MsgLen = Prueba_va_2_B.CANPack.Length;// size
of message
                  sTXCANMessage.pucMsgData              =              (unsigned
char*)Prueba_va_2_B.CANPack.Data;
                  sTXCANMessage.ui32MsgID    =    Prueba_va_2_B.CANPack.ID;//    CAN
message ID - use 1
                  sTXCANMessage.ui32MsgIDMask = 0;   // no mask needed for TX
                  sTXCANMessage.ui32Flags = MSG_OBJ_NO_FLAGS;
                  CANMessageSet(CANB_BASE, 2, &sTXCANMessage, MSG_OBJ_TYPE_TX);
                }

                {
                    Prueba_va_2_B.CANPack.ID = 1U;
                    Prueba_va_2_B.CANPack.Length = 8U;
                    Prueba_va_2_B.CANPack.Extended = 0U;
                    Prueba_va_2_B.CANPack.Remote = 0;
                    Prueba_va_2_B.CANPack.Data[0] = Prueba_va_2_B.SCIReceive[9];
                    Prueba_va_2_B.CANPack.Data[1] = Prueba_va_2_B.SCIReceive[8];
                    Prueba_va_2_B.CANPack.Data[2] = Prueba_va_2_B.SCIReceive[11];
                    Prueba_va_2_B.CANPack.Data[3] = Prueba_va_2_B.SCIReceive[10];
                    Prueba_va_2_B.CANPack.Data[4] = Prueba_va_2_B.SCIReceive[13];
                    Prueba_va_2_B.CANPack.Data[5] = Prueba_va_2_B.SCIReceive[12];
                    Prueba_va_2_B.CANPack.Data[6] = Prueba_va_2_B.SCIReceive[14];
                    Prueba_va_2_B.CANPack.Data[7] = var;
                }

                {
                  tCANMsgObject sTXCANMessage;
                  sTXCANMessage.ui32MsgLen = Prueba_va_2_B.CANPack.Length;// size
of message
                  sTXCANMessage.pucMsgData              =              (unsigned
char*)Prueba_va_2_B.CANPack.Data;
                  sTXCANMessage.ui32MsgID    =    Prueba_va_2_B.CANPack.ID;//    CAN
message ID - use 1
                  sTXCANMessage.ui32MsgIDMask = 0;   // no mask needed for TX
                  sTXCANMessage.ui32Flags = MSG_OBJ_NO_FLAGS;
                  CANMessageSet(CANB_BASE, 3, &sTXCANMessage, MSG_OBJ_TYPE_TX);
                }

        }

        /********************** Calculate Block Diagram ************************/
        {

            /*
             * State 1 : Wake Up
             * State 2 : Configuration
             * State 3 : Respond
             * State 4 : SendConfiguration
             * State 5 : Sample&Send
             *
             */
```

```
        if (State==1)           // Wake-Up
        {
          GPIO_WritePin(0,1);
          DELAY_US(50);
          State=2;

        }else if (State==2)    //Configuration
        {
          Configuration (var);

        }else if (State==3){   //Respond

            State=2;
            if (Prueba_va_2_B.CANPack.Data[0]==0 && var==4)
            {
                var=5;
                buffLen=16;
                State=4;
            }

        }else if (State==4){   //SendConfiguration

            SendConfiguration (var);

        }else if (State==5){   //Sample&Send

            SampleSend(var);
        }

        for(i=0;i<10000;i++){}
    }
  }

  /* Model initialize function */
  void Prueba_va_2_initialize(void)
  {
    /* Registration code */

    /* initialize error status */
    rtmSetErrorStatus(Prueba_va_2_M, (NULL));

    /* block I/O */
    (void) memset(((void *) &Prueba_va_2_B), 0,
                  sizeof(B_Prueba_va_2_T));

    {
      Prueba_va_2_B.CANPack = CAN_DATATYPE_GROUND;
    }

    /* states (dwork) */
    (void) memset((void *)&Prueba_va_2_DW, 0,
                  sizeof(DW_Prueba_va_2_T));

    /* Start for S-Function (c28xsci_rx): '<Root>/SCI Receive' */
```

```
    {
        GPIO_SetupPinMux(0,GPIO_MUX_CPU1,1);
        GPIO_SetupPinOptions(0,1,GPIO_PULLUP);

    }

    /* Initialize Prueba_va_2_B.SCIReceive[0] */
    {
      Prueba_va_2_B.SCIReceive[0] = (uint8_T)2.0;
      Prueba_va_2_B.SCIReceive[1] = (uint8_T)2.0;
      Prueba_va_2_B.SCIReceive[2] = (uint8_T)2.0;
      Prueba_va_2_B.SCIReceive[3] = (uint8_T)2.0;
      Prueba_va_2_B.SCIReceive[4] = (uint8_T)2.0;
      Prueba_va_2_B.SCIReceive[5] = (uint8_T)2.0;
    }

    /* Start for S-Function (c280xcanxmt): '<Root>/eCAN Transmit' */
    {
        State=1;
    }
  }

  /* Model terminate function */
  void Prueba_va_2_terminate(void)
  {
    /* (no terminate code required) */
  }

  /************** Functions *********************/

  void  Configuration (int cnt)
  {
      if (var==0)                                   //Set Baud Rate
           {
               var=1;
               Prueba_va_2_P.baud_Value[0]=0xF2;
               Prueba_va_2_P.baud_Value[1]=0x10;
               Prueba_va_2_P.baud_Value[2]=0x10;
               Prueba_va_2_P.baud_Value[3]=0xE0;
               Prueba_va_2_P.baud_Value[4]=0x3F;
               Prueba_va_2_P.baud_Value[5]=0x35;
               var=1;
               scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
           }else if (var==1)                        // Autoadress1
           {
               Prueba_va_2_P_2.adres_Value[0]=0xF1;
               Prueba_va_2_P_2.adres_Value[1]=0x0E;
               Prueba_va_2_P_2.adres_Value[2]=0x10;
               Prueba_va_2_P_2.adres_Value[3]=0x54;
               Prueba_va_2_P_2.adres_Value[4]=0x5F;
               scic_xmit(&Prueba_va_2_P_2.adres_Value[0], 5, 1);
               var=2;
           }else if (var==2)                        //Autoadress2
           {
               Prueba_va_2_P_2.adres_Value[0]=0xF1;
               Prueba_va_2_P_2.adres_Value[1]=0x0C;
```

```
                Prueba_va_2_P_2.adrres_Value[2]=0x08;
                Prueba_va_2_P_2.adrres_Value[3]=0x55;
                Prueba_va_2_P_2.adrres_Value[4]=0x35;
                scic_xmit(&Prueba_va_2_P_2.adrres_Value[0], 5, 1);
                var=3;
            }else if (var==3)                          //SetAdressIC
            {
                var=4;
                Prueba_va_2_P_2.adrres_Value[0]=0xF1;
                Prueba_va_2_P_2.adrres_Value[1]=0x0A;
                Prueba_va_2_P_2.adrres_Value[2]=0x00;
                Prueba_va_2_P_2.adrres_Value[3]=0x57;
                Prueba_va_2_P_2.adrres_Value[4]=0x53;
                scic_xmit(&Prueba_va_2_P_2.adrres_Value[0], 5, 1);
            }else if (var==4)                              //Disable High Side
Receiver
            {
                Prueba_va_2_P.baud_Value[0]=0x81;
                Prueba_va_2_P.baud_Value[1]=0x00;
                Prueba_va_2_P.baud_Value[2]=0x0A;
                Prueba_va_2_P.baud_Value[3]=0x00;
                Prueba_va_2_P.baud_Value[4]=0x2E;
                Prueba_va_2_P.baud_Value[5]=0x9C;
                scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
            }

    }
    void  SendConfiguration (int cnt)
    {
        if (var==5)                                          //Disable Low Side
Transmitter
        {
            var=6;
            Prueba_va_2_P.baud_Value[0]=0x92;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x10;
            Prueba_va_2_P.baud_Value[3]=0x10;
            Prueba_va_2_P.baud_Value[4]=0x20;
            Prueba_va_2_P.baud_Value[5]=0xB4;
            Prueba_va_2_P.baud_Value[6]=0x00;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 7, 1);

        }else if (var==6){                              //Clear Fault IC
            var=7;
            Prueba_va_2_P.baud_Value[0]=0x92;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x10;
            Prueba_va_2_P.baud_Value[3]=0x10;
            Prueba_va_2_P.baud_Value[4]=0xC0;
            Prueba_va_2_P.baud_Value[5]=0xB5;
            Prueba_va_2_P.baud_Value[6]=0x88;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 7, 1);

        }else if (var==7){                               //Clear Fault IC
            var=8;
            Prueba_va_2_P.baud_Value[0]=0x92;
```

```
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x52;
            Prueba_va_2_P.baud_Value[3]=0xFF;
            Prueba_va_2_P.baud_Value[4]=0xC0;
            Prueba_va_2_P.baud_Value[5]=0x59;
            Prueba_va_2_P.baud_Value[6]=0xAC;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 7, 1);
        }else if (var==8){                                   //Initial Sampling
delay
            var=9;
            Prueba_va_2_P.baud_Value[0]=0x91;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x3D;
            Prueba_va_2_P.baud_Value[3]=0x00;
            Prueba_va_2_P.baud_Value[4]=0x3C;
            Prueba_va_2_P.baud_Value[5]=0x6C;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
        } else if (var==9){                                 //Sample period
            var=10;
            Prueba_va_2_P.baud_Value[0]=0x91;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x3E;
            Prueba_va_2_P.baud_Value[3]=0xBC;
            Prueba_va_2_P.baud_Value[4]=0x3D;
            Prueba_va_2_P.baud_Value[5]=0x2D;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
        }else if (var==10){                                     // Oversampling
rate
          var=11;
          Prueba_va_2_P.baud_Value[0]=0x91;
          Prueba_va_2_P.baud_Value[1]=0x00;
          Prueba_va_2_P.baud_Value[2]=0x07;
          Prueba_va_2_P.baud_Value[3]=0x00;
          Prueba_va_2_P.baud_Value[4]=0x2E;
          Prueba_va_2_P.baud_Value[5]=0xCC;
          scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);

        }else if (var==11)                                    //Clear and Check
Faults 1
        {
            Prueba_va_2_P.baud_Value[0]=0x91;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x51;
            Prueba_va_2_P.baud_Value[3]=0x38;
            Prueba_va_2_P.baud_Value[4]=0x10;
            Prueba_va_2_P.baud_Value[5]=0xBE;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);

            var=12;
        }else if (var==12)                                    //Clear and Check
Faults 2
        {
            Prueba_va_2_P.baud_Value[0]=0x92;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x52;
            Prueba_va_2_P.baud_Value[3]=0xFF;
```

```
            Prueba_va_2_P.baud_Value[4]=0xC0;
            Prueba_va_2_P.baud_Value[5]=0x59;
            Prueba_va_2_P.baud_Value[6]=0xAC;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 7, 1);
            var=13;
        }else if (var==13)                                        //Clear and Check
Faults 3
        {
            Prueba_va_2_P.baud_Value[0]=0x81;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x51;
            Prueba_va_2_P.baud_Value[3]=0x00;
            Prueba_va_2_P.baud_Value[4]=0x15;
            Prueba_va_2_P.baud_Value[5]=0xAC;
            var=14;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
        }else if (var==14)                                           //Select num
cells 1
        {
        Prueba_va_2_P.baud_Value[0]=0x91;
        Prueba_va_2_P.baud_Value[1]=0x00;
        Prueba_va_2_P.baud_Value[2]=0x0D;
        Prueba_va_2_P.baud_Value[3]=0x07;
        Prueba_va_2_P.baud_Value[4]=0x69;
        Prueba_va_2_P.baud_Value[5]=0xAE;
        var=15;
        scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);
        } else if (var==15)                                          //Select num
cells 2
        {
            var=0x17;
            Prueba_va_2_P.baud_Value[0]=0x94;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x03;
            Prueba_va_2_P.baud_Value[3]=0x00;
            Prueba_va_2_P.baud_Value[4]=0x7F;
            Prueba_va_2_P.baud_Value[5]=0x00;
            Prueba_va_2_P.baud_Value[6]=0x00;
            Prueba_va_2_P.baud_Value[7]=0xA0;
            Prueba_va_2_P.baud_Value[8]=0x11;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 9, 1);

            int i=0;
            for(i=0;i<10000;i++){}

            Prueba_va_2_P.baud_Value[0]=0xF1;
            Prueba_va_2_P.baud_Value[1]=0x02;
            Prueba_va_2_P.baud_Value[2]=0x00;
            Prueba_va_2_P.baud_Value[3]=0x50;
            Prueba_va_2_P.baud_Value[4]=0x93;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 5, 1);

            for(i=0;i<10000;i++){}

            Prueba_va_2_P.baud_Value[0]=0x81;
            Prueba_va_2_P.baud_Value[1]=0x00;
```

```
            Prueba_va_2_P.baud_Value[2]=0x02;
            Prueba_va_2_P.baud_Value[3]=0x20;
            Prueba_va_2_P.baud_Value[4]=0x28;
            Prueba_va_2_P.baud_Value[5]=0x84;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);



        }else if (var==0x17){
            var=0x16;
            State=5;
                                                //Balance Config.
            Prueba_va_2_P.baud_Value[0]=0x91;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x13;
            Prueba_va_2_P.baud_Value[3]=0x98;
            Prueba_va_2_P.baud_Value[4]=0x20;
            Prueba_va_2_P.baud_Value[5]=0x66;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);

            int i=0;
            for(i=0;i<10000;i++){}
                                                //Balance enable
            Prueba_va_2_P.baud_Value[0]=0x92;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x14;
            Prueba_va_2_P.baud_Value[3]=0x00;
            Prueba_va_2_P.baud_Value[4]=0x00;//0x3F ON
            Prueba_va_2_P.baud_Value[5]=0xB9;
            Prueba_va_2_P.baud_Value[6]=0xC9;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 7, 1);

            for(i=0;i<10000;i++){}
                                                //Open          Wire
Detection test
            Prueba_va_2_P.baud_Value[0]=0x91;
            Prueba_va_2_P.baud_Value[1]=0x00;
            Prueba_va_2_P.baud_Value[2]=0x1E;
            Prueba_va_2_P.baud_Value[3]=0x10;
            Prueba_va_2_P.baud_Value[4]=0x37;
            Prueba_va_2_P.baud_Value[5]=0xD8;
            scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);




        }

    }
    void SampleSend(int cnt)
    {
                                            //Sample and send
        Prueba_va_2_P.baud_Value[0]=0xF1;
        Prueba_va_2_P.baud_Value[1]=0x02;
        Prueba_va_2_P.baud_Value[2]=0x00;
        Prueba_va_2_P.baud_Value[3]=0x50;
```

```
    Prueba_va_2_P.baud_Value[4]=0x93;
    scic_xmit(&Prueba_va_2_P.baud_Value[0], 5, 1);

    for(i=0;i<10000;i++){}

    Prueba_va_2_P.baud_Value[0]=0x81;
    Prueba_va_2_P.baud_Value[1]=0x00;
    Prueba_va_2_P.baud_Value[2]=0x02;
    Prueba_va_2_P.baud_Value[3]=0x20;
    Prueba_va_2_P.baud_Value[4]=0x28;
    Prueba_va_2_P.baud_Value[5]=0x84;
    scic_xmit(&Prueba_va_2_P.baud_Value[0], 6, 1);

}

/*
```