

POLITECNICO DI TORINO

Master's Degree in Ingegneria Elettronica



Master's Degree Thesis

Electric and electronic architecture of a FSAE full electric vehicle and design of a BMS for the low voltage system

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Abstract

The thesis project reported in this document, aims to expose a detailed description of the whole electric and electronic system of a competition full electric vehicle, realized by Squadra Corse PoliTO, a student team of Politecnico di Torino.

The description about the vehicle, is divided into two major sections in the base of the electronics treated, high voltage architecture in the first chapter, and low voltage system in the second chapter. This work do not only consider the description, but it also aims to provide an analysis of the whole system, highlighting the main improvements inserted in the season 21, in relation to the previous one, the 19. The analysis can be read in the third chapter of this paper. In brief, the project resumes a work of more than a year in which an almost complete vehicle's electric and electronic architecture has been designed.

The forth chapter of the thesis, describes a proposal of hardware design for a battery management system for the low voltage battery. This board has been designed to be compliant with the rest of the system and includes in the study an active balancing of a Li-ion battery module. The design work includes schematics, PCB layout, and simulations of the circuits introduced in this board. The topic has been elaborated with the assistance of LT Spice for simulation and KiCAD softwares for the electronic design and layout.

In conclusion, this paper aims to enhance the team's knowledge about the vehicle's architecture and inspire about improvements of the design for the battery management systems in the future developments.

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Ai miei relatori Massimo Ruo Roch, Maurizio Martina e Gianluca Botto, che in questi mesi di lavoro, hanno saputo guidarmi, rendendosi disponibili a condividere le loro conoscenze per arricchire me stesso e il lavoro descritto in questo elaborato. Gianluca in particolare, ha da sempre mostrato grande disponibilità e sensibilità invitandomi, nonostante la pandemia, a svolgere il lavoro anche negli uffici della sua azienda, Flag-MS, a cui auguro il meglio per gli anni a venire.

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A Voi oggi presenti,

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“Qualunque cosa tu faccia, falla bene!”
Walt Disney

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Acronyms

AC alternate current.

ADC analog to digital conversion.

AIR accumulator insulation relay.

APPS accelerationpedal position sensor.

AVG average.

BJT bipolar junction transistor.

BMS battery management system.

BSPD brake system plausibility device.

CAN controlled area network.

Cu Copper.

DC direct current.

ESD elctrostatic discharge.

FSM finite state machine.

GND ground.

GPIO general purpose input/output port.

GPS global positioning system.

GPU graphic processing unit.

HMI human-machine interface.

HV High Voltage.

HVD high voltage disconnect.

HW hardware.

HZ High impedance.

ID identifier.

IGBT insulated gate bipolar transistor.

IMD insulation monitoring device.

IMU inertial measurement unit.

IPM internal permanent magnet motors.

LCD liquid crystal display.

LED light emitter diode.

Li-Po polymers of lithium.

LPF low pass filter.

LV Low Voltage.

MCU micro controller unit.

MOSFET metal oxide silica field effect transistor.

MUX multiplexer.

NTC negative temperature coefficient.

OPAMP operational amplifier.

PCB printed circuit board.

PWM pulse width modulation.

RGB red-green-blue led.

rpm revolutions per minute.

RTD ready to drive.

SC21 squadra corse 2021 season.

SOA safe operating area.

SoC state of charge.

SPI serial peripheral interface.

SPST-NO single pole single throw, normally open.

SW software.

SWD serial wire debug.

THT thorough hole technology.

TLB tsal and latch board.

TS tractive system.

TSAL tractive system activation light.

TSMP tractive system measuring point.

TVS Transient Voltage Suppressor diode.

UART universal asynchronous receiver-transmitter.

VCU vehicle control unit.

VRRM maximum repetitive reverse voltage.

Chapter 1

HV system description

1.1 Overview

The High Voltage system must manage a power of 80 kW for more than 30 minutes. The high voltage pack can reach 574 V and a peak current of almost 145 A. This power is transferred through an inverter pack to the 4 wheel motors that can provide a maximum torque of 21 Nm and a maximum velocity of 20 000 rpm. The High Voltage (HV) system of the vehicle can be organized in three parts: the battery pack, in which are stored the modules with cells and the HV battery management system (BMS) with all the necessary electronic components; the inverter pack in which are placed the four legs of the inverter, that must transform the direct current (DC) power in alternate current (AC) and drive the electric motors, each for a wheel. The system can be organized in the following blocks:

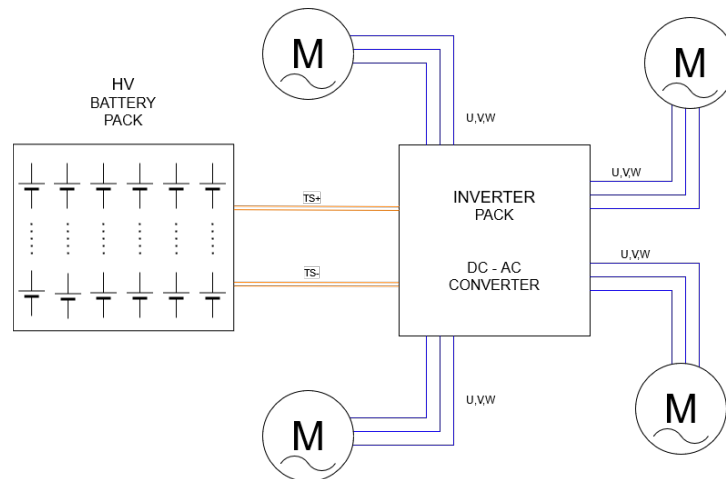


Figure 1.1: Simplified schematic of the HV system

1.2 HV battery pack

The energy of the vehicle is stored in an accumulator pack, it must be capable of containing a sufficient level of energy to complete all competition tests. The pack analyzed provide up to 574.2V with peak currents that can reach peaks of 143A. The cells used are of the type polymer li-ion type cells, arranged in 6 modules of 22s2p each, then connected in series between them, obtaining a final configuration of 132s2p.



Figure 1.2: HV modules with BCM boards

Considering that a cell have a nominal capacity of $7700mAh$ with a maximum voltage of $4.35V$, it means that:

- HV pack nominal capacity:

$$\begin{aligned} C_{TOT} &= C_{cell} \cdot \#parallels = \\ &= 7700mAh \cdot 2 = 15.4Ah \end{aligned}$$

- HV maximum voltage

$$\begin{aligned} V_{max} &= V_{cell} \cdot \#series \cdot \#modules \\ &= 4.35V \cdot 22 \cdot 6 = 574.2V \end{aligned}$$

Cells used are of the Polymer Li-ion type, *Model: SLPBB042126HV* [1] with the following electrical characteristics:

Nominal voltage	3.8 V
Maximum voltage	4.35 V
Minimum voltage	3 V
Continuous discharge current	61.6 A
Peak discharge current	84.7 A
Time for peak discharge current	3 s
Max. discharge temperature	60 °C
Continuous Charge Current	15.4 A
Peak charge current	30.8 A
Time for peak charge current	1 s
Max. charge temperature	60 °C

Table 1.1: Parameters of the HV cells

1.2.1 HV Support Boards

This board aims to obtain an appropriate connection for the cells through busbars mounted on it and to connect cells to the slaves of the battery management system, in order to read voltage and temperature from cells.

To allow the slaves to be connected properly to the battery, two support boards 1.3 are used for each of the six modules:

- SCB, the Slave Chain board
- BCM, the Battery Cell Measurements board

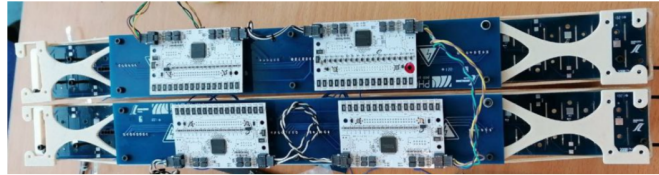


Figure 1.3: Slave chain and support boards

The BCM allows the cell of each module to connect between them in the configuration 22s2p, furthermore the negative temperature coefficient (NTC) terminations are soldered in the board. This board has mounted connectors that must connect voltage and temperature sense signals to the superior slave chain of the BMS HV.

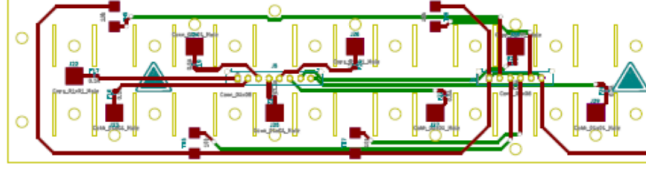


Figure 1.4: PCB layout of the BCM board

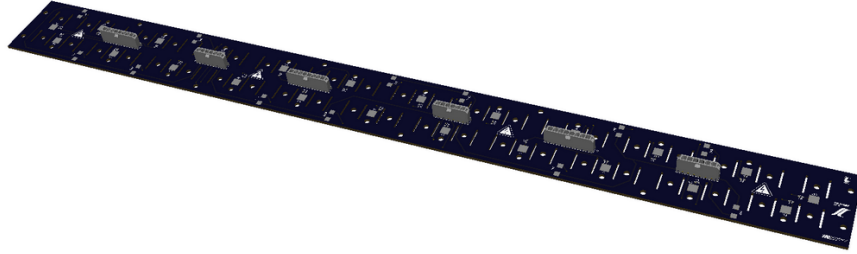


Figure 1.5: 3D CAD of the BCM board

The SCB recovers all signals from the board below and connects them to the two slave monitor devices. The layout of these boards allows mounting the slave daisy chain of the BMS HV. Connectors are present on both sides of the printed circuit board (PCB). Below a picture of the layout of the printed circuit board and the 3D model 1.7.

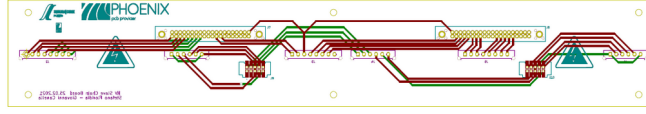


Figure 1.6: Part of PCB layout of the SCB board

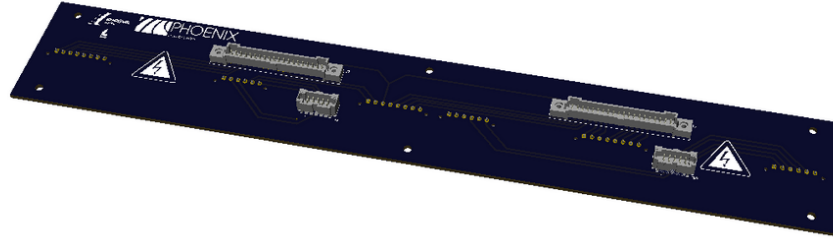


Figure 1.7: 3D CAD of the SCB board

1.2.2 BMS HV

By speaking of an accumulator container composed of polymers of lithium (Li-Po) cells, it is necessary to have a Battery Management System that assures that batteries will always work in a safe operating area, respecting the safe ranges of temperature, voltage, current and state of charge.

The component is organized in the classical master-slave configuration, in which slaves must acquire temperatures and voltages of the cells and execute the balancing, while the master core analyzes data from slaves and manages the situation in real time. To monitor all the cells of the pack, it is needed to have multiple slaves, because each slave mounts the component *BQ76PL455A* [2], that can monitor up to 16 cells. Below the simplified schematic of the device, connected in daisy chain

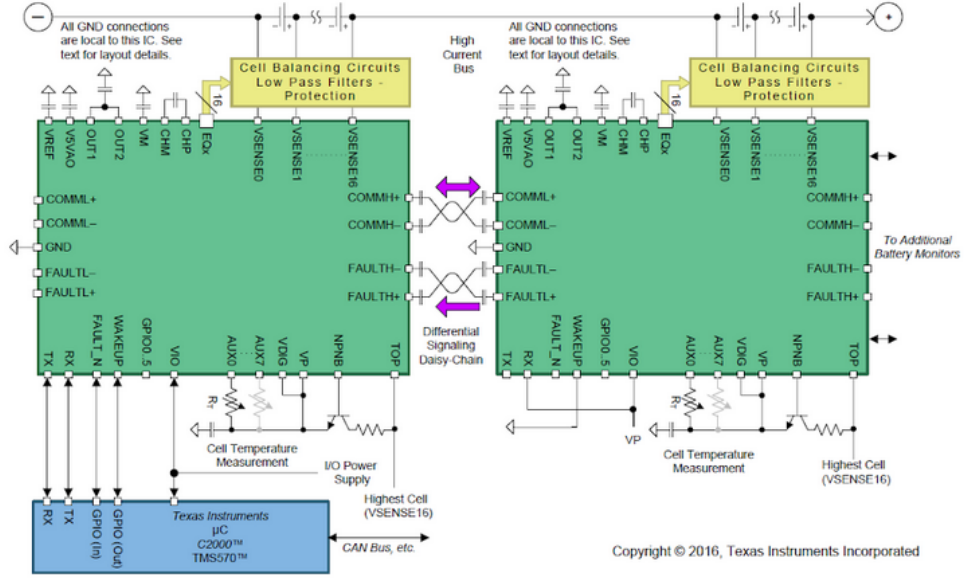


Figure 1.8: Slaves-chain configuration BQ76PL455A, [2]

Considering the configurations of the modules, it is chosen to use 2 slaves for each module, so in total 12 slaves are needed, connected between them in a daisy chain and communicating in UART.

The core provides a series of messages in CAN that give to the rest of the system important information about the state of the HV pack and if some errors are present.

Due to the rules, the core also provides an analog output signal that informs directly if an error occurs in the BMS HV. This BMS error signal is set at High impedance when no error is present, while is set at 0V when at least one error occurs. This signal is used in the TLB system described in the LV system section. In this way it is possible to have a hardwired control system that can set the vehicle in a safe state, with no High Voltage available to the motors.

1.2.3 AIRs

The structure of the HV system must be completed by a safety system that can control the power flow to the capacitors of the inverters. In fact to connect the HV pack to the inverter, typically are present two contactors (AIRs), one for each DC main path, positive and negative pole. This contactors are essentially electrically controlled switches of the form Single Pole Single Throw, Normally Open (SPST-NO). Contactors are driven by the BMS HV Core, which acts only if no errors are

present and if the CAN command of closing contactors is asserted. This is the schematic of the AIRs, as described in the datasheet of the *LEV100H5CNG* [3]:

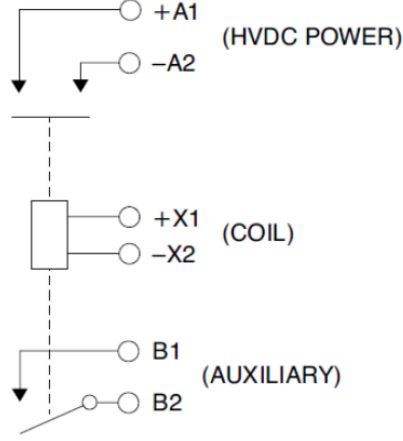


Figure 1.9: Schematic of the AIRs [3]

The Ax terminals are referred to the HV power path, so they must be connected to the Tractive System. The Xx terminals of the contactor are the poles of the coils: when the LV supply is sent to these pins, the relay closes the circuit, creating a short circuit between Ax terminals. The auxiliary switch is mechanically connected to the switch, this is used as a feedback signal to control the effective state of the relay, also in case of failures.

1.2.4 Precharge

Another part of the HV circuit is related to the precharge circuit that must be present in every electrical vehicle with a voltage high like this. The scope of this circuit is to avoid large variations of voltage in the transition of the contactors between the Open circuit state and the short circuit state. In fact, without the precharge, the large variation of the voltage, from 0V to 600V in such a small time, will cause a peak current too large to not damage components like capacitors of the inverter. To clarify, considering that the current in a capacitor can be described in this way:

$$I_{cap} = C * \frac{\delta V}{\delta t}$$

where C is the equivalent capacity of the inverters seen in the DC wires. To limit this current a resistor is needed in series to the current path to limit the current and have a curve of the voltage increasing gradually. To realize this, a third path in parallel to the positive contactor is needed, in which put the precharge circuit that must be composed by a resistor of $1.1k\Omega$ in this case and a precharge relay. Below the schematic:

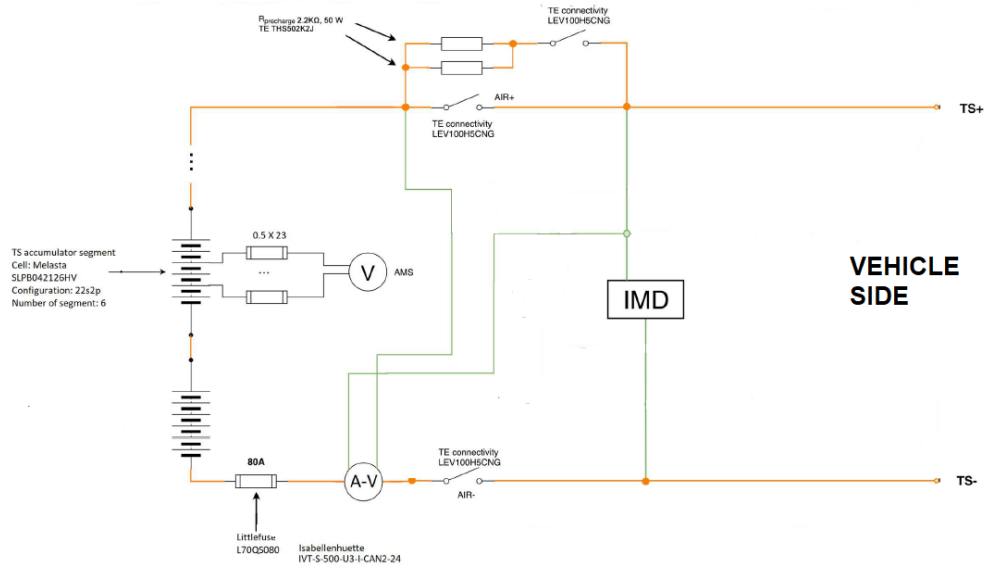


Figure 1.10: Schematic of the HV system between battery and vehicle

The precharge resistor in this system is composed of two resistors in parallel by 50W to better manage the power to be dissipated avoiding components too expensive and to obtain a precharge time not so large. Here a graph in which is represented the precharge curve:

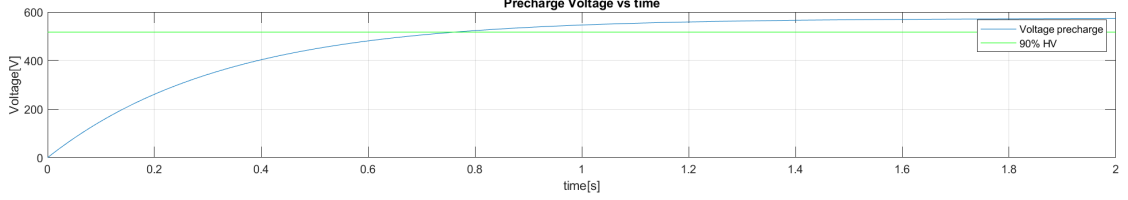


Figure 1.11: Graph of the precharge voltage curve

The exponential curve is obtained by the formula:

$$V_{prech} = V_{max} \cdot (1 - e^{-\frac{t}{\tau}})$$

where the time constant is equal to:

$$\tau = R_{eq} \cdot C_{eq}$$

and the equivalent resistance and capacitance seen is:

$$R_{eq} = \frac{2.2k\Omega}{2} = 1.1k\Omega$$

$$C_{eq} = 300\mu F$$

The equivalent capacity seen in the DC bus is due to the input capacitors of the inverter, which are 5 capacitor of 15uF for each inverter. So having 4 inverters in parallel (from the DC source point of view, all capacitors are in parallel respect the DC path, so it means:

$$C_{eq} = 15\mu F \cdot 5 \cdot 4 = 300\mu F$$

1.2.5 Main fuse

As it is possible to see from the schematic 1.10, a main fuse is used in series with the positive HV DC wire to protect the HV pack from possible short circuits in the load that can damage the cells and all components in the path. The fuse is rated for a working current of 80A that more or less corresponds to the average current requested in a race.

1.2.6 IVT Sensor

Description

Another component that take place in the accumulator container, is the IVT sensor. This device allows to measure:

- HV+ battery side
- HV+ vehicle side
- tractive system (TS) current

This measurements are read by the sensor that put them in the CAN bus, in order to be seen by all other components of the LV system. In particular the voltage measurements and the current needs to the HV BMS to be sure that circuit works correctly. In the figure 1.12 from the data-sheet [4] for this component.

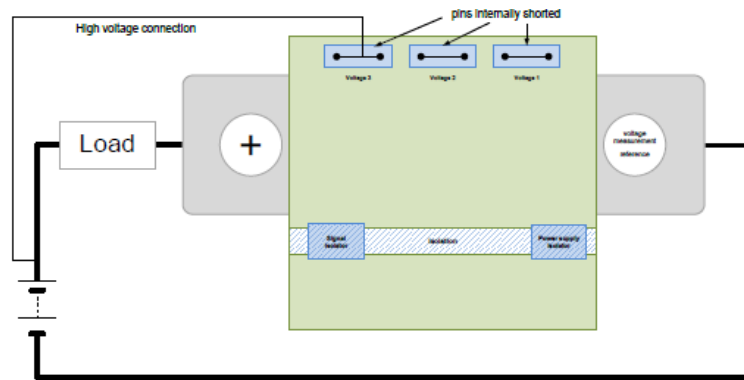


Figure 1.12: Schematic of the IVT sensor, [4]

The IVT sensor must be placed in the TS- path before the AIR- in the battery side, so that the sensor can refers all voltage measurements to this point.

CAN messages

Regarding the CAN messages of the node IVT sensor, it sends the following information:

- *IVT_Msg_Result_I*, ID: 0x521, return the value of the instantaneous measured current in the TS path
- *IVT_Msg_Result_U1*, ID: 0x522, return the value of the instantaneous measured voltage in the TS+ vehicle side
- *IVT_Msg_Result_U2*, ID: 0x523, return the value of the instantaneous measured voltage in the TS+ battery side
- *IVT_Msg_Result_W*, ID: 0x526, return the value of the instantaneous measured power, referring to the current I and the voltage U1
- *IVT_Msg_Result_Wh*, ID: 0x528, return the value of the measured energy, referring to the current I and the voltage U1

1.2.7 IMD

The insulation monitoring device (IMD), is a commercial boards, in particular is a *Bender IR55-3204*. This device must monitor the resistance between TS (+/-) and LV-, and send the IMD Error if the resistor is lower than $500\Omega/V$, as explained in the FSAE rules. This means that IMD Error occurs when the resistance is less than:

$$R_{insulation} = 500\Omega/V \cdot 574.2V = 287.1k\Omega$$

The IMD error is sent to the HV BMS and to the tsal and latch board (TLB) Master board to be latched by the system and open the shutdown circuit if the error occurs.

1.3 Inverter Pack

1.3.1 Inverter Theory

The basic principle of an inverter is to convert a DC voltage source into AC to drive a motor.

To allow this, a particular component much used in the power electronics, known as insulated gate bipolar transistor (IGBT) can be used. This is the most used component in power electronics, it acts like a voltage controlled switch: by applying a certain quantity of voltage between terminals G and E, it results in having a short circuit between terminals C and E.

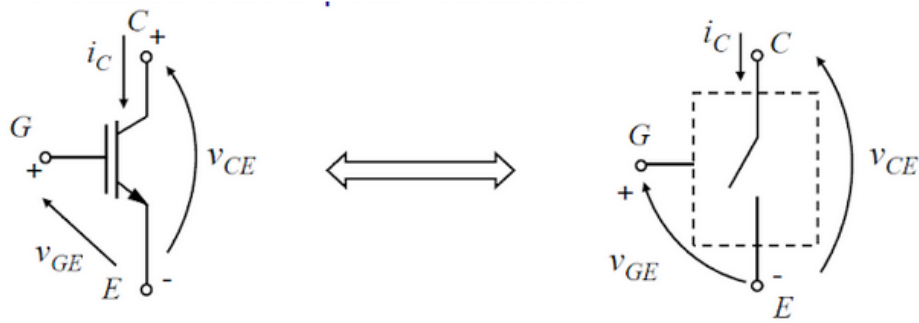


Figure 1.13: Schematic of a IGBT switch

This device can be described as a combination of a PNP bipolar junction transistor (BJT) and a NPN metal oxide silica field effect transistor (MOSFET):

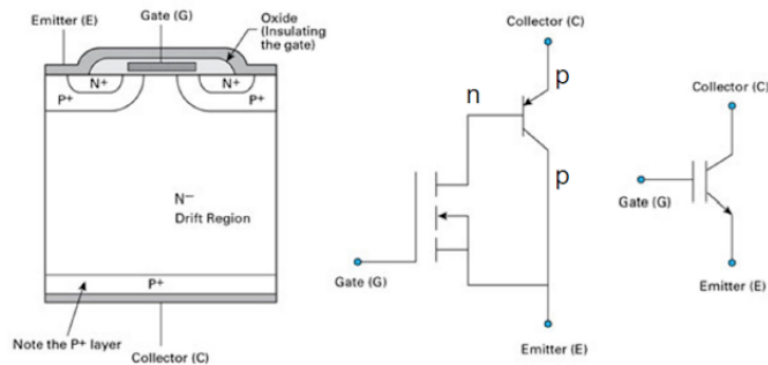


Figure 1.14: Technology of an IGBT switch

When the mosfet is turned on, it opens the base of the bipolar transistor that then goes into saturation, so the switch is in closed circuit.

The characteristic curve of the output voltage and current is similar to the curve of a mosfet, with the difference that the curve is shifted by a threshold voltage $V_{ce_{th}}$. The IGBT state depends on the V_{ge} :

- OFF, if

$$V_{ge} < V_{ge_{th}} \quad \& \quad V_{ce} < V_{ce_{br}}$$

where “br” stays for breakdown voltage of the bipolar transistor

- ON, if

$$V_{ge} > V_{ge_{th}} + \frac{i_c}{G_m}$$

where G_m [S] is the transconductance

Typically the $V_{ge_{th}}$ threshold voltage is about [2 : 4]V

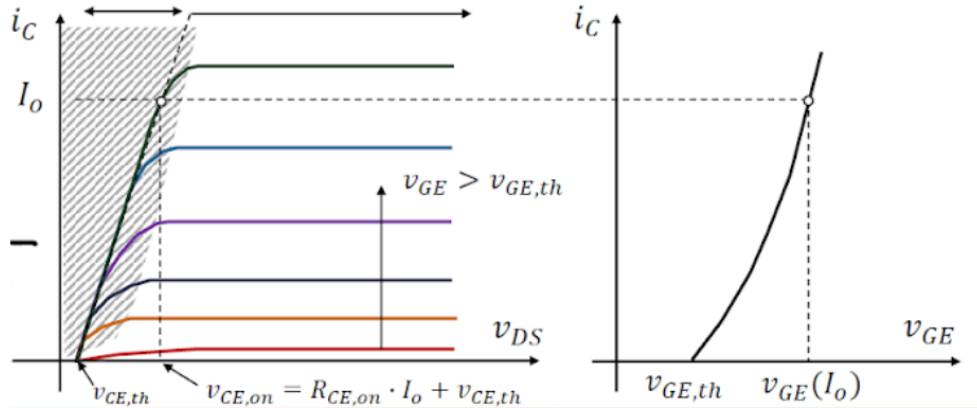


Figure 1.15: Electrical characteristics of the IGBT

The IGBT is suitable for high voltage applications (more than 600V) and switching frequencies of 5-50 kHz, so can be used for this scope with 600V and 10 KhZ of switching frequency.

At high voltage ($> 600V$), the ON state resistance of an IGBT is lower with respect to the ON state resistance of a mosfet. This means less conduction losses.

By the way, the IGBT presents a slower commutation with respect to power mosfets due to the bipolar transistor that has a switching time of the microseconds order. To create an inverter leg, a bidirectional switching cell must be used. To allow this, for a single phase full bridge inverter is used this configuration:

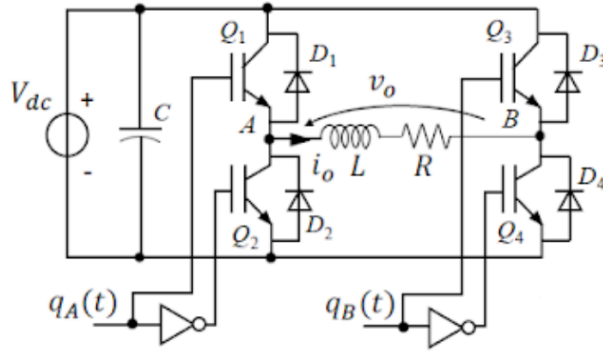


Figure 1.16: Schematic of full bridge single phase inverter

So four IGBT, with a diode in parallel to the emitter-collector terminals, are needed to have a bidirectional switching cell.

The gate of each IGBT is properly commanded by a generation circuit that set the value of q_A and q_B using the pulse width modulation (PWM) technique. Below the typical schematic of an unipolar switching command circuit for single phase full bridge inverter:

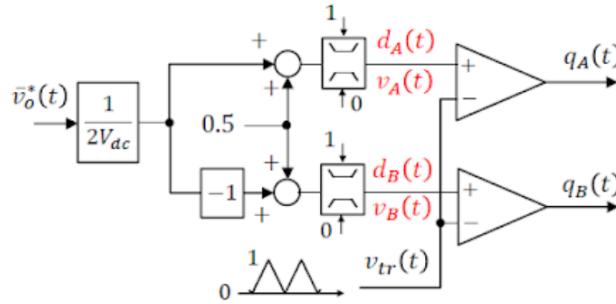


Figure 1.17: Schematic of a unipolar switching command circuit

So by starting from the desired output voltage V_o^* , that presents a range $[-V_{dc}; V_{dc}]$, the value is normalized by $0.5/V_{dc}$. Then an offset of 0.5 is added to the signal, that corresponds to the average of the unitary range, in order to obtain a range of $[0; 1]$. To be sure a saturation block is added and then a threshold amplifier is used to set the quantized values of q_A and q_B . The threshold voltage of the amplifier is obtained by a triangular wave generator.

The output voltage pulses are of values: $0, -V_{dc}, V_{dc}$. So the peak-to-peak voltage variation is $2 * V_{dc}$ presents lower current ripple ($1/4$) with respect to a bipolar modulation for the same L of the load. Therefore, odd voltage harmonics at switching frequency are eliminated: the first harmonics will only be in the side-bands around the double of the switching frequency.

For an inverter that must pilot a motor, the configuration is the following:

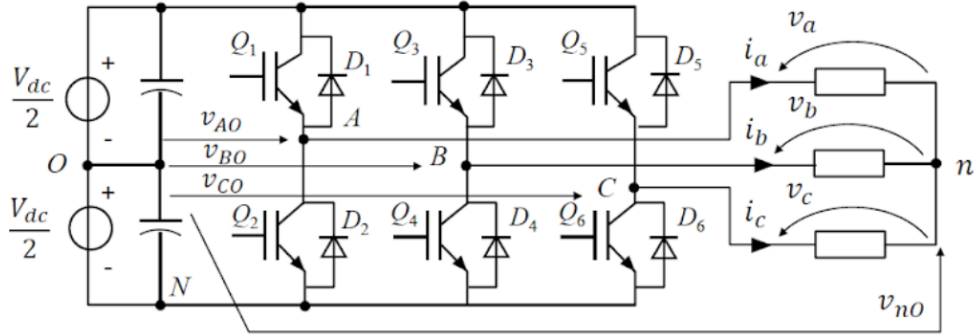


Figure 1.18: Schematic of a unipolar switching command circuit

It is possible to distinguish the 3 inverter legs, each for one of the three phases for the electric motor to pilot. So in total for each AC motor a six pack IGBT module is needed.

1.3.2 Description

The *AMK More Drive* [5] inverter pack is composed of 4 inverters, one for each motor. The inverter pack is organized in 2 parts, left and right side that can be considered independent from the hardware point of view. For each side it is possible to distinguish:

- 1 supply board
- 1 control board
- 2 power board, one for each AC motor

The supply board distributes the Low voltage supply to all electronics components of the inverter pack and reads the temperature from an internal thermocouple of the motors.

The board provides LV supply to the system and can communicate by CAN all important parameters about the HV state. In particular it provides the current of each of the three phases of the inverter leg.

The control board instead, manages the IGBT switching of the inverter leg, implementing the vehicle control system commands received by CAN from the Vehicle Control Unit through its MCU optimized for motor drive.

While the power board is the place in which IGBT are placed with current sensors for all phases and a thermocouple to monitor the temperature of the power module. Below a schematic of the signals for one side of the inverter (only for two motors). It is possible to connect to the inverter system by CAN line or Ethernet to properly configure the main parameters of the motor control system.

In the system it is important to control the temperature of each component when the system is working. To properly monitor it, in this architecture is present a thermocouple in each IGBTs pack and internal to each motor.

The technology of the pack is an IGBT4 - LoPo kind, that means Low Power switching losses. This particular structure minimizes power losses with the trench + field stop structure.

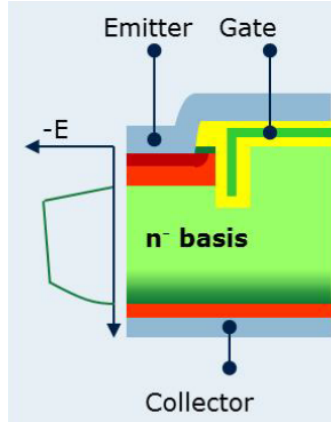


Figure 1.19: IGBT4 - T4 technology process [6]

The switching command circuit for a 3-phases inverter of this kind can be schematized in the following way:

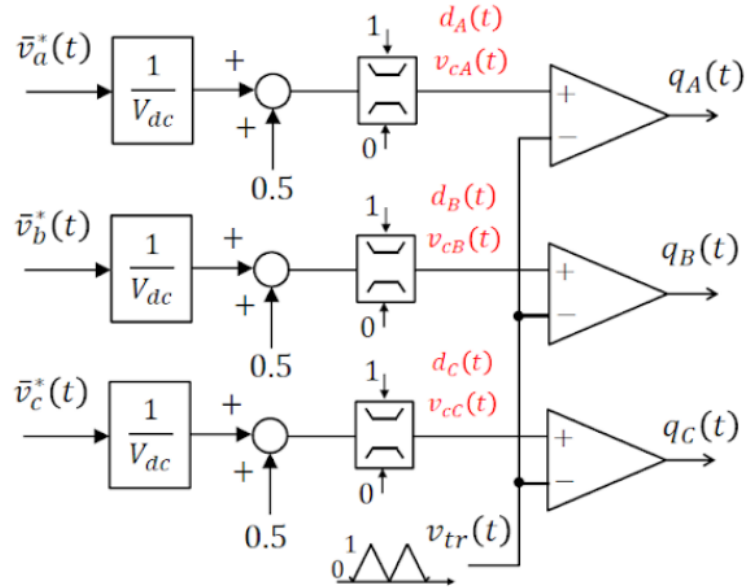


Figure 1.20: Schematic of a unipolar three phase switching command circuit[7]

This time requires three quantized components q_A, q_B, q_C that can be obtained starting by the 3 output voltages of the load V_A, V_B, V_C .

At the input of the threshold amplifier the voltage follows the equation:

$$V_{C_x} = \frac{V_x^*}{V_{dc}} + 0.5 = d_x$$

V_{C_x} signal corresponds to the duty cycle wave of the pulse width modulation.

So by the data-sheet here the schematic of the inverter used to pilot the motorS in the vehicle described:

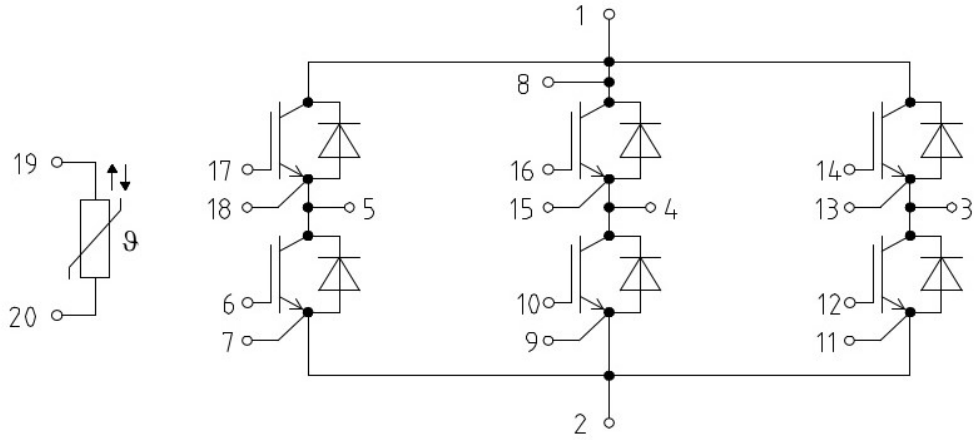


Figure 1.21: Schematic of the six pack inverter used in the vehicle[5]

In this packaging are included a thermocouple to monitor temperature of IGBT and both IGBT and diodes.

The figure below instead, take a picture of the power module that also contain the six pack IGBT of the analyzed vehicle:

In the power module it is possible to see the DC input at the right side, and the three AC outputs on the left side. On the right image instead, it is possible to observe in red the five capacitors by $15\mu\text{F}$ and in blue the 3 current sensors for the 3 phases.

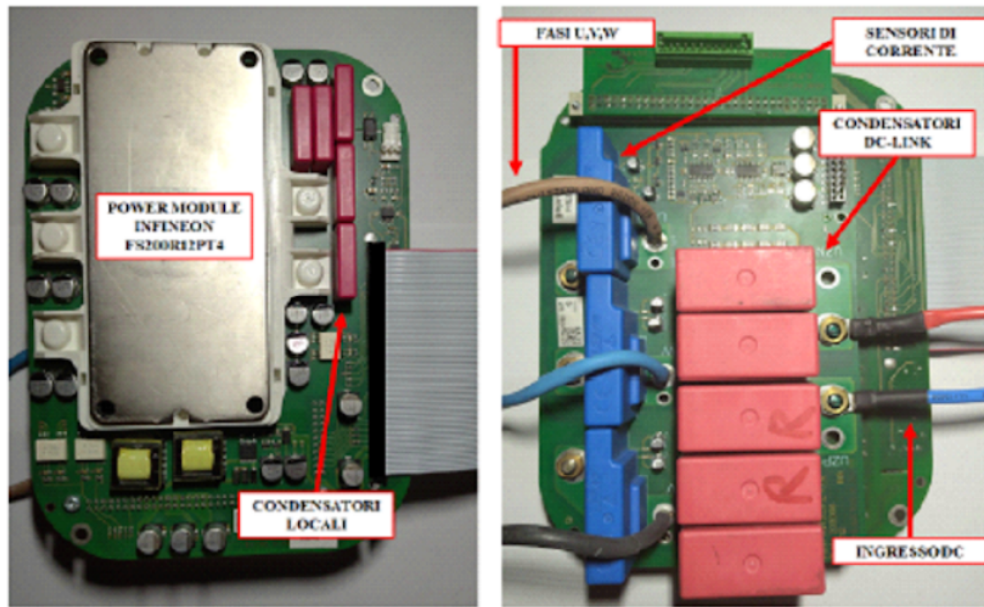


Figure 1.22: Power module, front and back side

Then in the following figure 1.23 it is possible to see the inverter pack in its covering packaging to insert it in the vehicle:

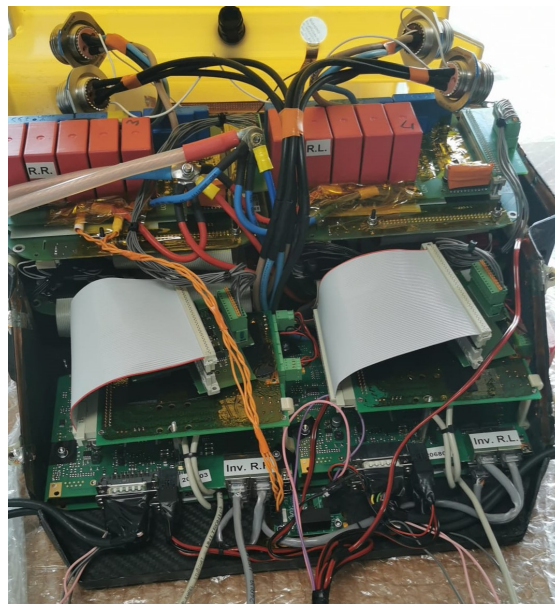


Figure 1.23: Inverter pack of the vehicle

1.4 Electrical motors

1.4.1 eMotor theory

The electric power of the vehicle is transformed into mechanical power by four AC motors, one for each wheel. The motor are internal permanent magnet motors (IPM) eMotors of the model *DD5-14-10-POW*.

An IPM motor is an electric synchronous three phase motor, it means that its speed is:

$$\omega = 2 * \pi * \frac{f}{p}$$

where p is the number of pole pairs in the stator.

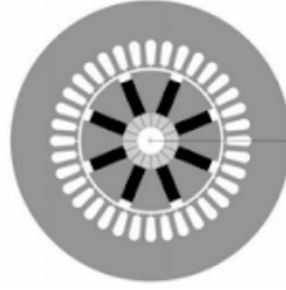


Figure 1.24: IPM motor schematic [7]

Differently from other types of synchronous motors, IPM presents permanent magnets into the rotor, organized in a way to obtain an anisotropic rotor from the point of view of the rotation axis of the motor.

In this way it is possible to distinguish the following forces:

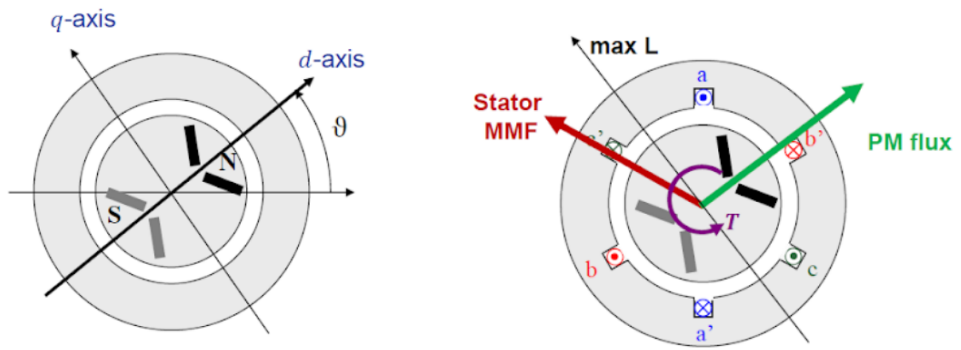


Figure 1.25: IPM motor forces [7]

The resultant torque is maximized thanks to the contribution of 2 forces, the torque generated by the magnetic flux and the one by the reluctance:

$$T = T_{pm} + T_{rel}$$

In fact, in this kind of motor, the magnetic flux is different from 0, and the inductance in the q frame is higher with respect to the d frame.

$$\lambda_m \neq 0$$

$$L_q > L_d$$

For an IPM motor the main torque is generated by the permanent magnets:

$$T_{pm} \gg T_{rel}$$

Then below are explained the principal characteristic of the motor [5] used for this vehicle:

Description	
Kind of motor	IPM
Cooling	liquid
Mounting	IMB5
Protection	IP65
Insulating class	F
Performance	
Nominal Torque	9.8 Nm
Max Torque 21	Nm
Nominal Power	12.3 kW
Nominal velocity	12000 rpm
Max velocity	20000 rpm
Electrical data	
nominal voltage	350 V
nominal current	41 Arms
max current	105 Arms
pole pairs	5
winding resistance	0.135 ohm

Table 1.2: Parameters of the eMotors

In the following figure is represented a section of the internal winding of the motor. It is possible to see the 10 poles permanent magnets that are internal to the stator, and the winding wire in the rotor, in which the three phases current flows.



Figure 1.26: IPM motor internal section

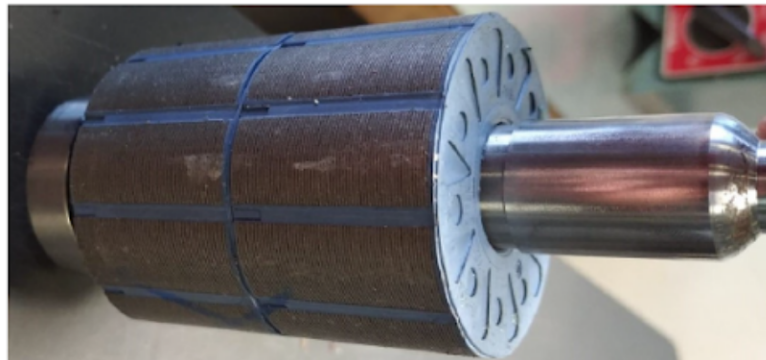


Figure 1.27: View of the rotor of the eMotors

1.5 Derivation Box

1.5.1 Discharge

Obviously, when the HV power must be turned off, the equivalent input capacitor of 300uF must be discharged from the 600V to 0V to return to a safe state. To not damage the components, like the precharge, it needs a discharge circuit. This circuit consists of a board self-developed that must connect a resistor of discharge when the vehicle is turned off. Next the scheme of the discharge: As it is possible to

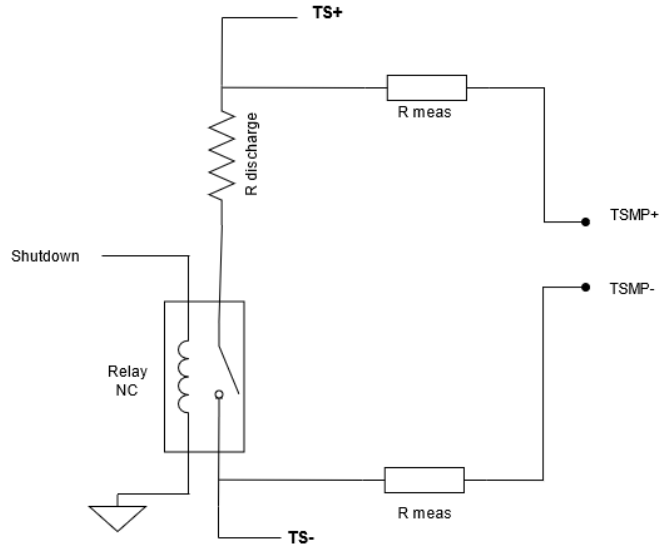


Figure 1.28: Schematic of the discharge

see, the switch used is a Normally closed relay, that guarantees galvanic insulation from the HV circuit and connects the resistor to the 2 poles of the HV.

In the circuit are also inserted 2 resistors for the Tractive System Measuring Points. This resistor is introduced for safety, to limit the current in the case the 2 measuring points are touched. In the case of a short circuit between TSMP+ and TSMP-, the equivalent resistor will be 2 times the Rmeas. The value chosen is of 15k Ohm for this resistors, in order to have at the maximum a current of:

$$I_{measp} = \frac{V_{max}}{2 * R_{meas}} = 20mA$$

The resistance is chosen in order to have a not so high discharge current. For this vehicle a 3.9Kohm resistor with a power of 100W is chosen. Then the discharge current and power are:

$$I_{disch} = \frac{V_{max}}{R_{disch}} = \frac{574.2}{3900} = 148mA$$

$$P_{disch} = \frac{V_{max}^2}{R_{disch}} = \frac{574.2^2}{3900} = 84W$$

Then the values are compatible with the resistor chosen.

The discharge voltage curve can be described in the following graph:

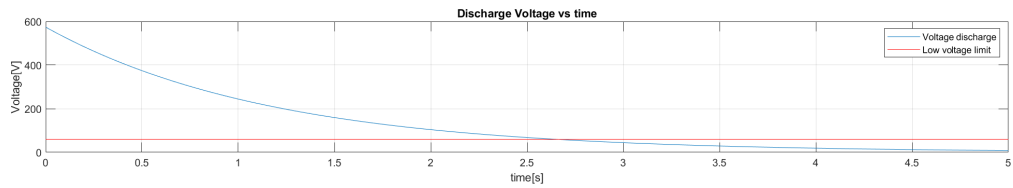


Figure 1.29: Graph of the discharge curve

By rules, the voltage is considered active until it will not be lower than 60V (red line). So the discharge time for the system is 2.6 seconds. It respects the rules that want a maximum discharge time of 5 seconds.

So the final discharge board is the following:



Figure 1.30: View of the discharge board

It is possible to see the discharge resistor in orange, the two measuring point resistors in brown and the discharge relay in black.

1.5.2 Other components

Description

The derivation box in the vehicle is also the place of other components:

- VI board
- Energy Meter
- Hall effect current sensor

The task of the VI board is to take measurements in real time of the voltage and current in the DC bus, between HV pack and inverter and send it in the LV CAN bus to be available to the rest of the system. The Vehicle Control Unit uses this measurements as input to properly regulate the vehicle control system. Voltage measurements are taken by wires connected in parallel to the DC bus, while the current is measured by an Hall effect current sensor that sends the measurements to this board.

Hall effect current sensor

The Hall effect current sensor [8] presents the following output characteristics:

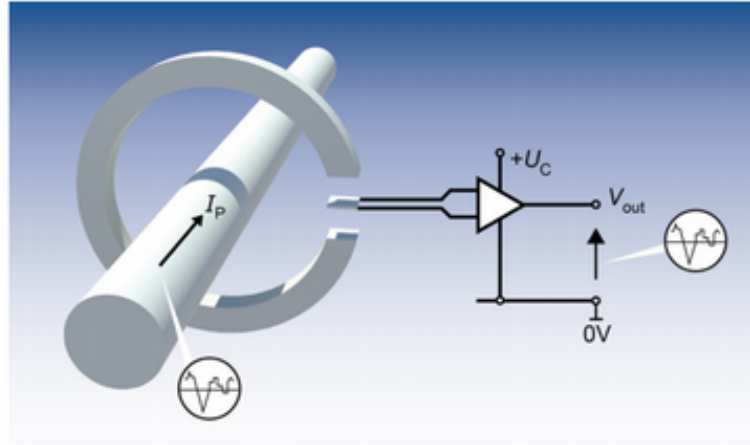


Figure 1.31: General scheme of the hall effect current sensor [8]

The output of the sensor is a ratio metric dc voltage that allows to obtain the TS current through the formula:

$$I_{TS} = (\frac{5V}{U_c} \cdot V_{out} V_O) \cdot \frac{1}{G}$$

with:

- $G = 6.67 \text{ mV/A}$ that is the gain of the sensor
- $U_c = 5V$ and corresponds to the supply of the sensor provided by the VI board
- $V_O = 2.5V$ is the reference voltage, that corresponds to the output voltage value when the current in bus is 0A

The last component present in the derivation box of the vehicle is the Energy Meter, a data-logger provided by officials that must control both the DC bus and the CAN bus. This device must monitor the vehicle during the event competitions. At the competition, officials can connect to the energy meter through an exclusive Ethernet line.

Chapter 2

LV system description

2.1 Overview

The Low Voltage system of the vehicle is organized in different types of board, commercial and custom, each with a specific role in the architecture. Most of them communicate in a controlled area network (CAN) network to exchange important information through the system. Many other devices are part of the LV system: light emitter diode (LED) and buttons in the cockpit, fans and pumps of the cooling systems, different kind of analog sensors distributed in the vehicle. A general scheme of the LV architecture is explained in the fig. 2.1.

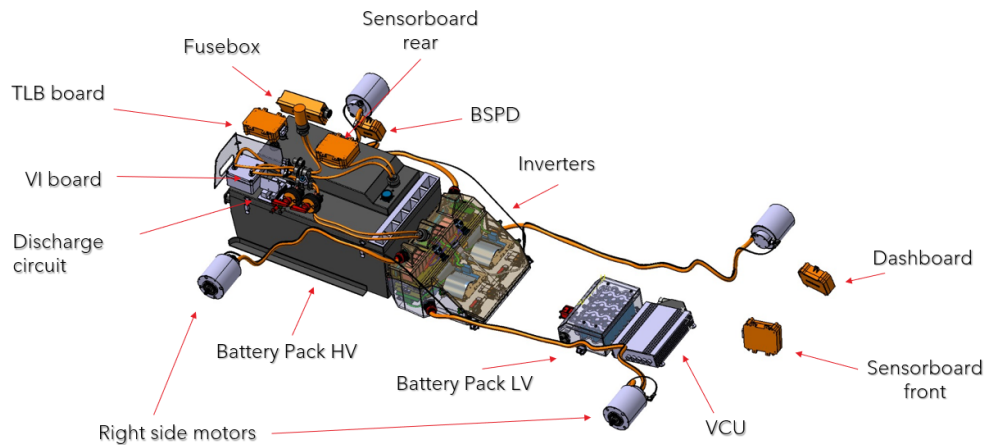


Figure 2.1: Global architecture on 3D CAD

2.2 CAN

The architecture is organised in 6 CAN lines in order to transmit properly all data, according to the devices placed in the vehicle. The CAN protocol is the CAN 2.0 at 1 Mbit/s of speed.

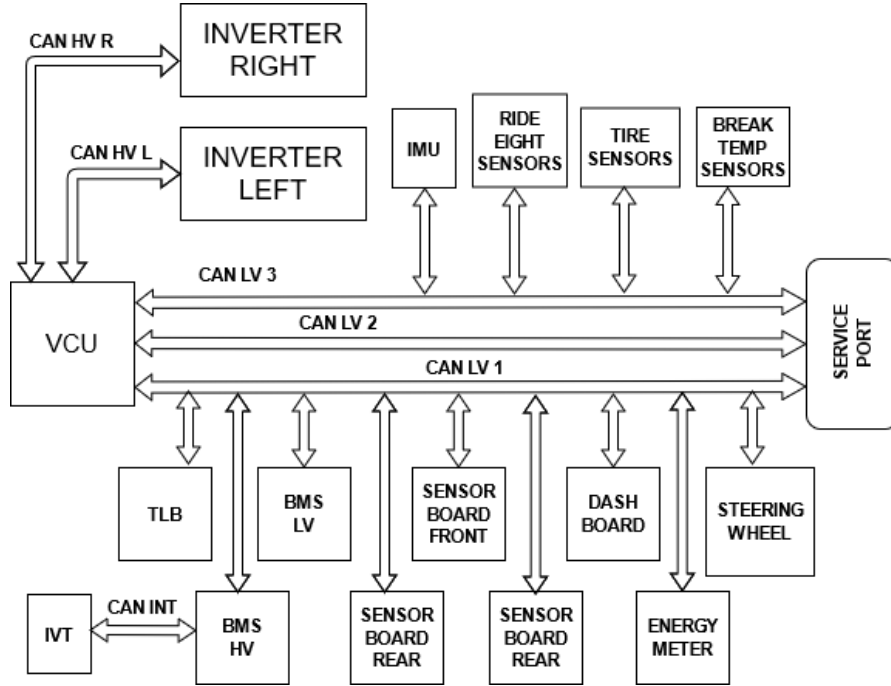


Figure 2.2: CAN communication system in the vehicle

The vehicle control unit (VCU) is the managing unit of the control system of the vehicle, so all CAN lines must converge in this box to allow the VCU to receive data from the whole system and send all needed commands.

As it is possible to note, there are two can lines that are exclusively used for the communication between the VCU and each side of the inverter: left and right, CAN HV Left and CAN HV Right. While the remaining CAN lines are CAN LV 1 and CAN LV 2. In the CAN LV 1, all the LV custom boards of the systems are connected, this allows to have available a large quantity of data to the whole system. In this line are also connected the HV BMS and the competition data logger: the Energy Meter.

The CAN LV 3 is a line dedicated to optional sensor that can be inserted in the system during tests of the vehicle, it results useful to add new device in the system, without overcrowd the other bus lines. The CAN LV 2 line is used to transmit important signal that VCU can provide within all the signals that receive from the CAN HV lines.

However this line can be also used to connect an external data logger and logs all interested signals from VCU.

The notation of the signals that takes part of the CAN messages follows the Intel notation, except the messages referred to the nodes HV BMS and VI Board that follow the Motorola notation.

2.3 LV battery

The LV Battery is a module composed by Li-ion cells of the model *Molicel - INR1700-P42A* [9]. The characteristic of this cells is resumed below tab 2.1: The

Nominal Capacity	4200 mAh
Nominal Cell Voltage	3.6V
Maximum Cell Voltage	4.2V
Minimum Cell Voltage	2.5V
Standard Charge Current	4.2A
Standard Charge Time	1.5hr
Typical Impedance	16 mΩ (DC 10A/1s)
Max Temperature	60 °C

Table 2.1: Electrical characteristics of the LV cells, Molicel P42A

configuration chosen in the SC21 season is a 7s5p. This means that the LV pack has got the following characteristics:

- $C_{TOT} = C_{cell} \cdot \#parallels = 4200mAh \cdot 5 = 21Ah$
- $V_{pack} = V_{cell} \cdot \#series = 4.2V \cdot 7 = 29.4V$

The LV pack is designed to supply power to the whole LV system that by previous measurements needs the quantity of current shown below tab 2.2. LV current requested at 27.6V (open circuit voltage):

This means that:

Radiator fans	12A
Pumps	10A
HV fans	5A
LV fan	33mA
Inverter boards	5A
Rest of the boards	5.7A

Table 2.2: Consumption of the LV system

- the maximum requested LV current is about 38A
- the maximum requested power by LV system is about $P_{LV} = I \cdot V = 37.7A \cdot 27.6V = 1040.5W$

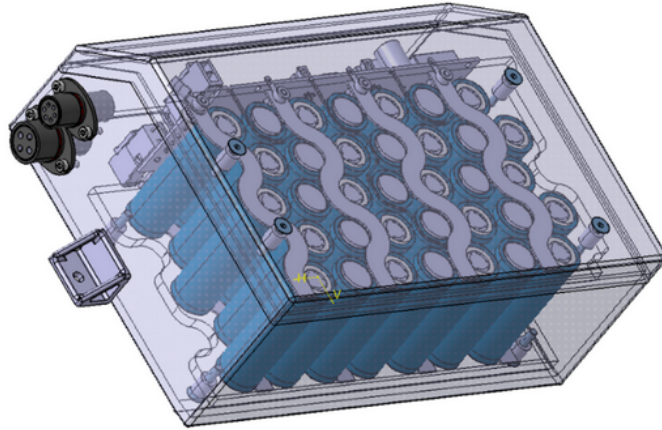


Figure 2.3: 3D CAD of the LV pack with the designed container

2.4 Commercial Boards

2.4.1 Description

Referring to the commercial boards present in the vehicle, beyond the HV BMS, the VI Board and the Energy Meter already described in the derivation box section 1.5 of the HV system chapter 1, below the list of all commercial boards:

- VCU, the dSpace MicroAutoBox II is the vehicle control unit, it executes the vehicle control system written in Matlab code.
- BMS HV, a system of a core and twelve slave in daisy chain, internal to the accumulator container, that is the responsible of monitoring the HV cells. See section 1.2.2.
- Inverter Control Boards, internal to the inverter pack, each for one of the four motors, implement the IGBT switching and monitors the activity of the motors. See section 1.3.
- Modem Wireless, used for telemetry. It works as bridge between remote users and the VCU. It also allows the pilot to initialize a VoIP communication with the box during the race.
- VI board, for real time voltage and current measurements of the TS DC bus.
- IMU, SBG system component, that provides global positioning system (GPS) position for telemetry.

- IMD, that monitors the insulation between TS+ and LV-, more details in the section 1.2.7.



Figure 2.4: Some of the commercial boards in the vehicle. IMU in red, VCU in white and IMD in green

2.4.2 CAN messages

VCU

The VCU is a central node that must communicate with many components to allow the car to reach the Ready to Drive condition, to request to close the contactors of the HV pack, to enable torque for the electrical motors.

- *DSPACE_ACK_RTD*, [TX], ID: 0x40, with contains only one signal:
 - *ACK*, this signal is used in the FSM of the RTD and can have the values 0x0, 0x1, 0x2 or 0x3 if the vehicle is respectively in the status IDLE, CNT_EN_ACK, RTD_ACK or RESET.
- *DSPACE_DASH_TIMER*, [TX], ID: 0x43, used to count how many times a RTD button is pushed. The signal are:
 - *CMD_COUNT0*, that can assume value RESET (0x46) or READ (0xFF) if the value pressed first time is read or not.
 - *CMD_COUNT1*, that can assume value RESET (0x46) or READ (0xFF) if the value pressed second time is read or not.
- *BMS_00_CMD*, [TX], ID: 0x110, it is described in the BMS HV can messages section.
- *AMK_SetPoints_XX*, [TX], used to send the set-point of torque and velocity to the inverters. It is described in the Inverters can messages section.

BMS HV

Regarding the CAN messages of the node BMS HV, there are the following messages:

- *BMS_00_CMD*, [RX], ID: 0x110, used by the VCU to send commands to the BMS. It is composed by the signals:
 - *BMS_bBlncEn*, when set at 1 allows to start the passive balancing of the HV pack
 - *BMS_bCtorEn*, when set at 1 allows to closing the contactors to make available the HV power for the inverters.
 - *BMS_bChrgDis*, when set at 1 stop the charging and disable the charger.
 - *BMS_bAllVTEn*, when set at 1 enable the measuring of voltages and temperatures from the slaves.
 - *BMS_bDschrEn*, when set at 1 allows the DC bus to be discharged

- *BMS_cntCmd*, counter that increases whatever this message is sent
- *BMS_crc8Cmd*, cyclic redundancy check that is compliant to the SAE J1850 CRC8 (poly: 0x1D, initial value: 0xFF, final XOR: 0xFF) calculated on previous message bytes.
- *BMS_01_CellV*, [TX], ID: 0x111, that informs about the voltage of the HV cells, is composed by the signals:
 - *BMS_VCellHi*, reports the highest cell voltage
 - *BMS_VCellLo*, reports the lowest cell voltage
 - *BMS_VCellAvg*, reports the average cell voltage
 - *BMS_VCellHiId*, reports the ID of the cell with the highest voltage
 - *BMS_VCellLoId*, reports the ID of the cell with the lowest voltage
- *BMS_02_CellT*, [TX], ID: 0x112, that reports the temperature of the HV cells, is composed by the signals:
 - *BMS_TCellHi*, reports the highest cell temperature
 - *BMS_TCellLo*, reports the lowest cell temperature
 - *BMS_TCellAvg*, reports the average cell temperature
 - *BMS_TCellHiId*, reports the ID of the cell with the highest temperature
 - *BMS_TCellLoId*, reports the ID of the cell with the lowest temperature
- *BMS_05_Sys01*, [TX], ID: 0x115, that tells about the status of many functionalities, explained in the following signals:
 - *BMS_eSysSts*, reports the status of the system that can be OFF, IDLE, MONITORING, DRIVING, CHARGING, SHUTDOWN (respectively from 0 to 5)
 - *BMS_eInvSts*, informs about the status of the inverters
 - *BMS_eChgSts*, informs about the status of the charger
 - *BMS_eCtorSts*, informs about the status of the contactors
 - *BMS_eDevSts*, informs about the status of the slaves chain
 - *BMS_eImdSts*, informs about the status of the IMD device
 - *BMS_TBrd*, displays the ambient temperature
 - *BMS_RImdSns*, displays the insulation resistance measured from IMD
- *BMS_06_Diag*, [TX], ID: 0x116, that tells about the status of many functionalities, explained in the following signals:

- *BMS_bFaultCellOT*, informs when Over Temperature error occurs, it goes to 1 when the temperature of cells exceed the 60°C
- *BMS_bFaultCellOV*, informs when Over Voltage error occurs, it goes to 1 when the voltage of cells exceed the 4.35V
- *BMS_bFaultCellUV*, informs when under Voltage error occurs, it goes to 1 if the voltage decrease under the 3V
- *BMS_bFaultPresent*, informs about the general error status of the HV BMS, it goes to 1 if any error occurs
- *BMS_bCANCmd*, informs when a CAN communication error is detected, it goes to 1 if an error occurs

Inverters

The four inverters are divided in 2 groups (for each side). Each couple has got an exclusive CAN line that connect inverters to the Vehicle Control Unit. In this CAN connection are sent the following messages, as described in the datasheet [5]:

- *AMK_Actual_Values_1_XX*. The XX value change in base of the inverter taken into account: the ID are 0x283, 0x284, 0x287, 0x288 for respectively RR, FR, RL, FL inverter. In which frame message the inverter sends the signals listed below:
 - *AMK_SystemReady*, that informs about the status of the inverter, it goes to 1 if the inverter is ready to work without any warning or error
 - *AMK_Error*, goes to 1 if any error occurs in the inverter
 - *AMK_DcOn*, informs if the Tractive system power is available in the inverter side, it goes to 1 when asserted
 - *AMK_InverterOn*, goes to 1 when the low voltage supply of the inverter arrive in all boards.
 - *AMK_Derating*, goes to 1 when the derating function is activated
 - *AMK_ActualVelocity*, informs about the actual velocity of the motor
 - *AMK_TorqueCurrent*, informs about the actual torque of the motor
 - *AMK_MagnetizingCurrent*, informs about the measured magnetizing current in the motor
- *AMK_Actual_Values_2_XX*. The XX value change in base of the inverter taken into account: the ID are 0x285, 0x286, 0x289, 0x290 for respectively RR, FR, RL, FL inverter. In which frame message the inverter sends the signals listed below:

- *AMK_TempMotor*, return the temperature value sent by the thermocouple of the motor
- *AMK_TempInverter*, return the temperature value sent by the thermocouple of the inverter
- *AMK_ErrorInfo*, informs about possible detected temperature errors
- *AMK_IGBT_Temp*, return the temperature value sent by the thermocouple in the IGBT switches.
- *AMK_SetPoints_XX*, message sent by the VCU, to commands the inverters. The XX value change in base of the inverter taken into account: the ID are 0x184, 0x185, 0x188, 0x189 for respectively RR, FR, RL, FL inverter. This frame is composed by the signals below:
 - *AMK_InverterOn*, requests to turn on the inverter leg
 - *AMK_Enable*, requests to enable the inverter to provide power to motors
 - *AMK_ErrorReset*, requests a clear of all errors presents
 - *AMK_DcOn*, requests to enable the Tractive System power in input of the inverters
 - *AMK_TargetVelocity*, used to set the target velocity, the maximum is about 20.000 RPM
 - *AMK_TorqueLimitPositiv*, used to set the maximum positive Torque to provide at the motor, this value is set by the VCU control, in order to not overcome the 80kW allowable.
 - *AMK_TorqueLimitNegativ*, used to set the minimum negative Torque to provide at the motor.

VI board

The VI Board inform the system about the real time measured current and voltage of the TS. The message sent by this board is the following:

- *IVCAN_msg*, [TX], ID: 0x686, it return the real time values of current and voltage of the TS. It is composed by the signals listed below:
 - *IDC_A*, that informs about the measured current value, read by the Hall effect current sensor
 - *VDC_V*, that informs about the measured voltage value, read between TS+ and TS- in the vehicle side.

2.5 Custom electronics

In the vehicle the electronic architecture is distributed into many boards, each with a particular task. This strategy allows to limits the number of wires in the vehicle and to reduce the complexity by subdividing the whole circuit in subsystems. This approach corresponds to that used today in automotive with the electronics complexity that increase more and more.

It is required custom electronics for many tasks:

- LV supply distribution
- Battery management for the low voltage battery
- Acquisition of analog signals, like sensors or critical measurements
- data transmission between subsystems
- rules compliance of hardwired only circuits TSAL, error latching, brake system plausibility device (BSPD)
- Cockpit management and human-machine interface (HMI)
- Cooling management

2.5.1 LV distribution unit

The distribution of the LV supply that comes from the LV battery pack must be distributed in the rest of the LV system. The subdivision is performed by the Fuse-box board, in fig. 2.5.

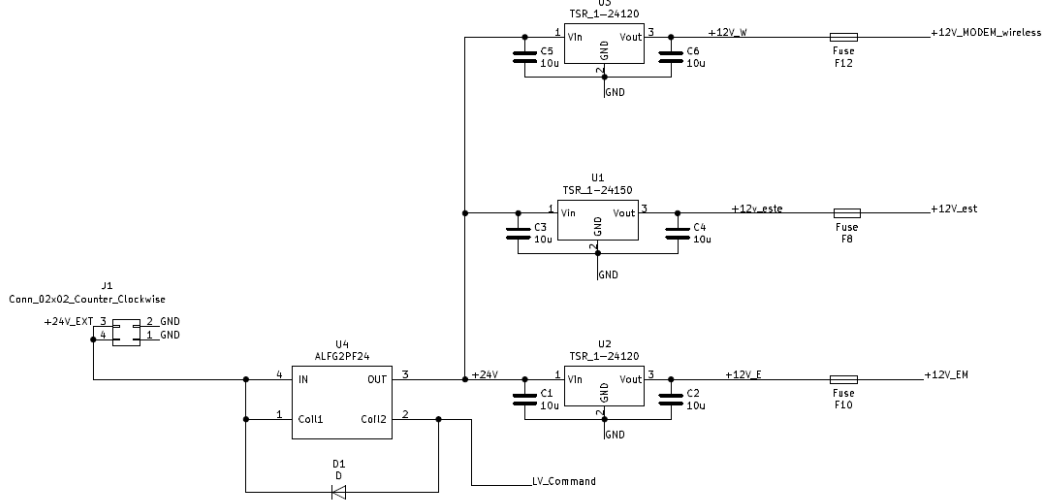


Figure 2.5: Schematic of the fuse-box board of the SC21 vehicle

The fuse-box is composed by a Global LV Relay that is controlled by a remote analog signal, *BMS_LV_cmd* coming from the BMS LV. In the system are needed the following supply voltage:

- 24V for HV and radiator fans, pumps, VCU, BMS HV, TSAL, Inverter and custom boards.
- 12v for modem, VI board and the competition data-logger.

The voltage from the battery, after the relay is dropped to 12V using a DC-DC converter *TSR-24120*.

Therefore custom boards have got an internal DC-DC used to convert locally the 24V to 5V and 3.3V. This distributed solution is preferred due to the distance between boards in the vehicle that is not negligible. Naturally each wire is protected with a fuse sized in an appropriate way, depending on the current that must flow through it.

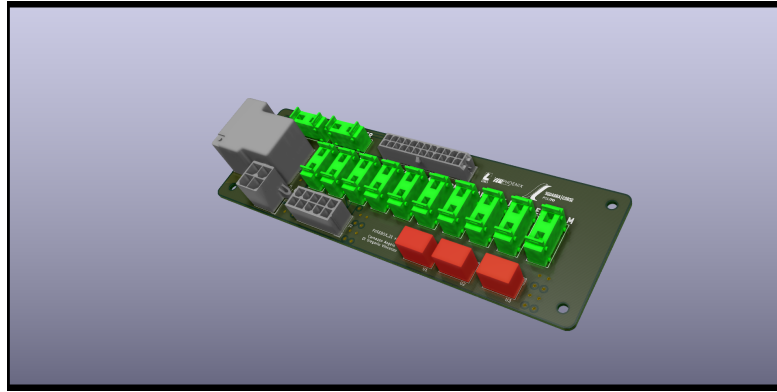


Figure 2.6: 3D CAD of the fuse-box board

2.5.2 Sensors

Description

The acquisition of the signals from sensors distributed in the vehicle is mainly implemented thanks to two boards realized with the same design, the Sensorboards Front and Rear. As suggested by the name, to properly manage a large number of sensors, the twin boards are placed in front and rear side of the vehicle.

In the vehicle are present a large number of sensor to acquire:

- steering wheel angle
- acceleration request by the driver
- amount of pressure in the braking circuit
- compression of the brake pedal
- NTC thermistors for cooling monitoring
- Potentiometer to measure extension of the suspension system

The distribution of sensor in the vehicle is organized as written in the table 2.3. The PCB of the boards are perfectly equal, this allows a less expensive production and give the possibility to add other sensor in the system if necessary by using the unused input of the Rear Sensorboard.

The steering wheel angle is measured thanks to a magnetic rotary encoder sensor, represented in the figure 2.7.

type of sensor	Front	Rear
steering	1	0
throttle	1 (x2)	0
brake pressure	1	1
strain gauge brake	1	0
NTC	4	4
damper	2	2

Table 2.3: Distribution of the sensor in the vehicle

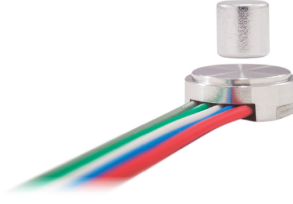


Figure 2.7: Pics of the magnetic rotary encoder, base and magnet [10]

The sensor is composed of a magnet that must be fixed in the steering axis and the base that transforms the variation of the induced magnetic field in a DC output voltage that may vary linearly in the range $[0,5]V$ and can measures an angle range of $[0^\circ, 360^\circ]$. In the figure 2.8 is represented the output characteristic. As repre-

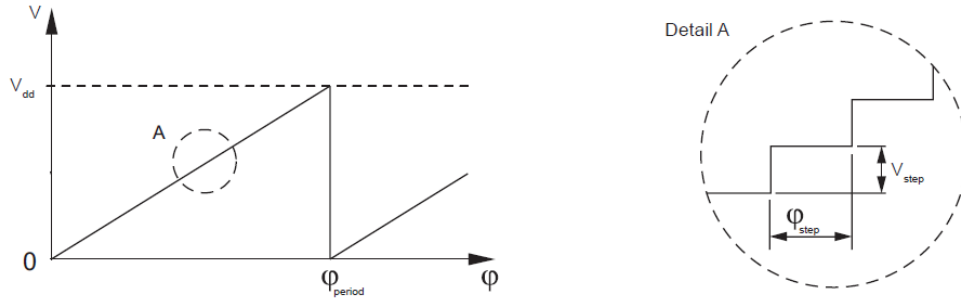


Figure 2.8: Output-Input characteristic of the sensor [10]

sented, the characteristic is a saw tooth, that if focused, can be modeled as a scale of step of length equal to the angle resolution ϕ_{step} and high an amount of voltage V_{step} .

$$\phi_{step} = \frac{\phi_{period}}{N_{step}} = \frac{360^\circ}{1024} = 0.35^\circ$$

$$V_{step} = \frac{V_{dd}}{N_{step}} = \frac{5V}{1024} = 4.88mV$$

The throttle sensor, due to rule recommendations, must be redundant and must be supplied by different boards for increase the safety. So in the vehicle are used a redundant current sensor of the kind: Hall effect rotary sensor AR-019-07 2.10, that can measure an angle till 30° with an output range of [0.5, 4.5]V.



Figure 2.9: Pics of the throttle sensor [10]

The characteristic Output-Input of the two throttle signals is linear as it is possible to see in figure 2.10 and inverted between them, ever for rule issues.

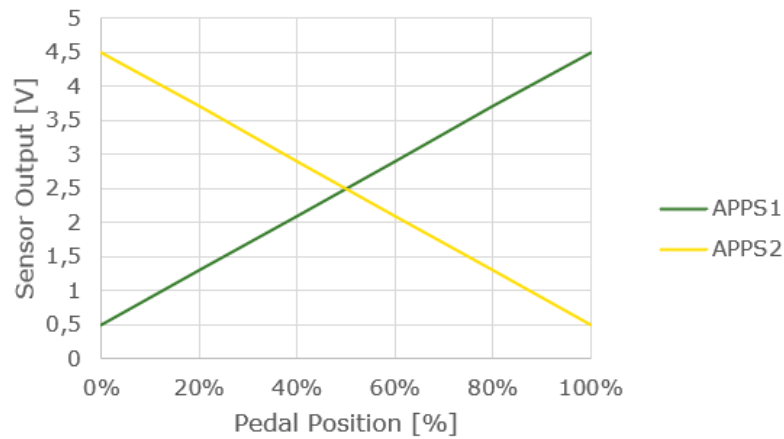


Figure 2.10: Graph of the cross output of the throttle sensor

The voltage outputs of the throttle sensor are sent by the Sensorboard Front to the VCU that assigns a percentage of acceleration from 0 to 100%. The relation is explained in the table 2.4. An important issue to consider is that the pedal position valid is that the value of the two cross signals, one time one of their is inverted, must no be different of more than 10%.

The hydraulic braking implant is measured thanks to two brake pressure sensors Aviorace SP100-M102.11 [11] inserted in the hydraulic system, one on the front

Position	APPS 1	APPS 2
0%	0,5	4,5
20%	1,3	3,7
40%	2,1	2,9
60%	2,9	2,1
80%	3,7	1,3
100%	4,5	0,5

Table 2.4: Relation between pedal position and output of the throttle sensor

part and another on the rear one. The sensor can measures a range of $[0,100]$ Bar traduced in a linear output range of $[0.5, 4.5]$ V. This sensor is used as input in the



Figure 2.11: Picture of the brake pressure sensors

BSPD board to calculate the amount of braking and for the ready to drive (RTD) procedure.

The strain gauge sensor used to measure the compression of the brake pedal, gives important information for the regenerative braking system of the vehicle that must recharge the pack when the vehicle is braking.

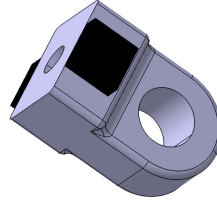


Figure 2.12: Picture of the strain gauge sensor[11]

The strain gauge can measures till 1250N of force and due to the fact that the sensor is internally amplified with a specific IC, gives in output a linear voltage in a range $[0, 5]$ V.

Thermistors are needed to monitor the cooling system. Then eight NTC sensors are insert in the vehicle, in particular in the cooling jacket of the motors and for the radiators on the rear. NTC thermistors typically present the following characteristics:

- High sensitivity, from $-3 \text{ } \%/^{\circ}\text{C}$ to $-10 \text{ } \%/^{\circ}\text{C}$
- High resistivity
- Low time constant
- Measurement range : $[-100 ; +300]^{\circ}\text{C}$
- Strongly non-linear transduction function

The model used is *Vishay NTCAIMME3C90373* [12], figure 2.13.

The output characteristic of the NTC, as in the figure 2.14, is logarithmic. A commonly used input/output characteristic for NTC thermistors is the β value expression:

$$R_T = A \cdot e^{\frac{\beta}{T}}$$

The coefficient is estimated by two known temperatures T1 and T2 that corresponds to two resistance values R1 and R2:

$$\beta = \frac{T_1 \cdot T_2}{T_2 - T_1} \cdot \ln \frac{R_T}{R_0}$$



Figure 2.13: Pic of the NTC sensors [12]

in which $R_T = 1066\Omega$ is the resistance at maximum temperature of the range, $R_0 = 10k\Omega$ is the resistance at the minimum temperature. Then the β for the range of interest $[T_1 = 25^\circ C, T_2 = 85^\circ C]$, is equal to 3284. The β parameter can be

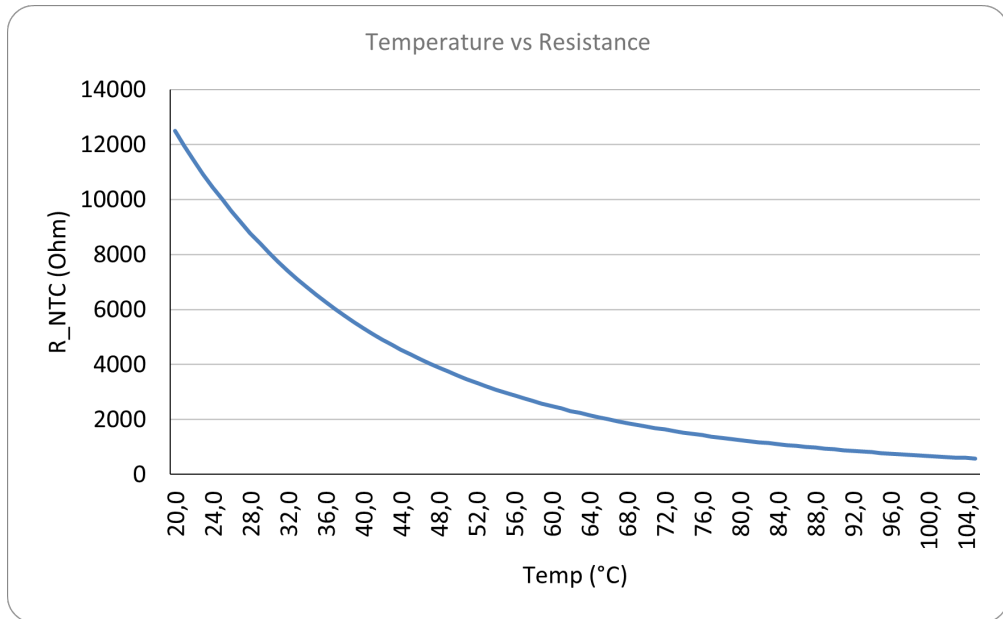


Figure 2.14: Graph of the NTC characteristics

used for the calibration function of the NTC:

$$T = \frac{1}{\frac{1}{T_1} + \frac{1}{\beta} \cdot \ln \frac{R_T}{R_0}}$$

The linear potentiometer are used in proximity to the dampers of the vehicle, then

in the vehicle are present four potentiometer of the type: *DIA9,5-75* [13].

The potentiometer from the electronic point of view, is a variable resistive partition.



Figure 2.15: Picture of the potentiometer [13]

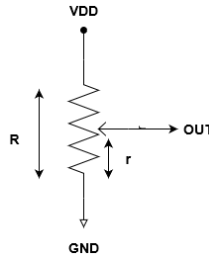


Figure 2.16: Schematic of the potentiometer

The value of the output is equal to:

$$V_{out} = \frac{V_{dd}}{R} \cdot r$$

where the R is the total value of the potentiometer that is $10k\Omega$ and r is the partition selected by the extension of the dampers.

Analog acquisitions

The acquisition of the signals from sensors is carried out by the two sensorboards. The general schematic of acquisition circuit is explained in the figure 2.17.

As it is possible to see, the acquisition circuit is composed, starting by the input signal, of Zener diodes *SM05T1G* used as electrostatic discharge (ESD) protection. Therefore, a couple of fast switching diodes *BAV99* used to saturate the value that comes from sensor in the case it will have a value greater than 5V or lower than 0V. This diodes will protect the analog input of the μ controller from over voltages. Then is present a partition that scales the signal by a factor 0.594, this is due to

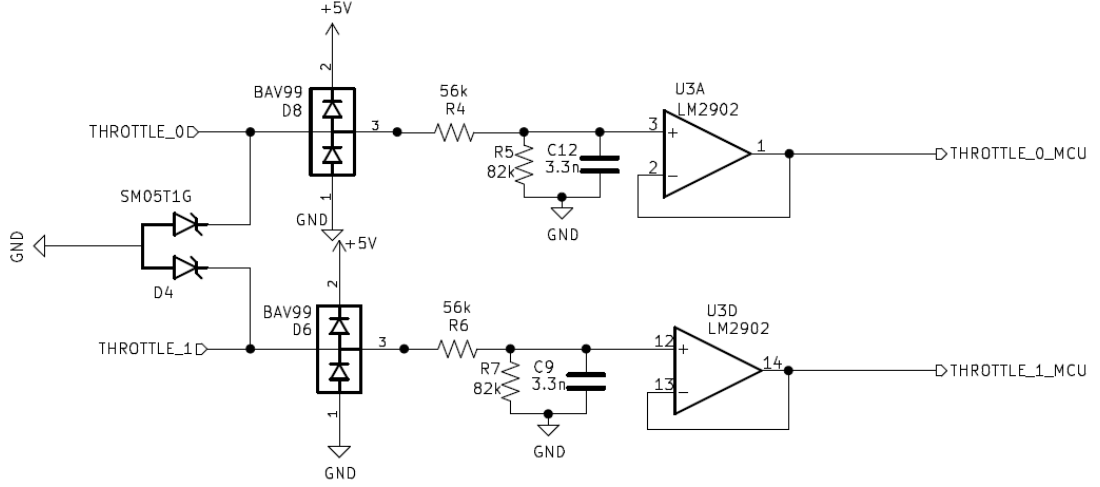


Figure 2.17: Schematic of the conditioning circuit for sensor acquisitions

the fact that analog inputs of the μ controller can read in a range $[0, 3]V$ but the signals can have a range of $[0, 5]V$.

$$p = \frac{3V}{5V} = 0.6 = \frac{82k\Omega}{82k\Omega + 56k\Omega}$$

To the partition is also added a capacitor to create a low pass filter that can filter the noise over the band of the sensor that transmit a DC voltage signal.

$$f_{cut} = \frac{1}{2 \cdot \pi \cdot \tau}$$

The cut-off frequency of the LPF can be calculated by find the equivalent time constant:

$$\tau = R_{eq} \cdot C$$

In this case $R_{eq} = 31.82k\Omega$ is equal to the parallel between the resistors, and the capacitor is $C = 3.3nF$. This means that the cut-off frequency is equal to $f_{cut} = 1.52kHz$. After the filter, is inserted a voltage follower to decouple the impedance. This scheme is suitable for the main parts of sensors connected to the sensorboard: Throttle, brake pressure, steering and strain gauge. This scheme is also used for the potentiometers, with the only difference that the partition is made after the voltage follower to not falsify the output of the sensor.

NTC thermistors are sensed with a conditioning circuit composed by a pull up resistor of $10k\Omega$ connected to the $3.3V$ supply, similarly as written in the design of

the BMS LV, see section 4. Thanks to this schematic, the output characteristic that can be read by μ controller is represented in figure 2.18.

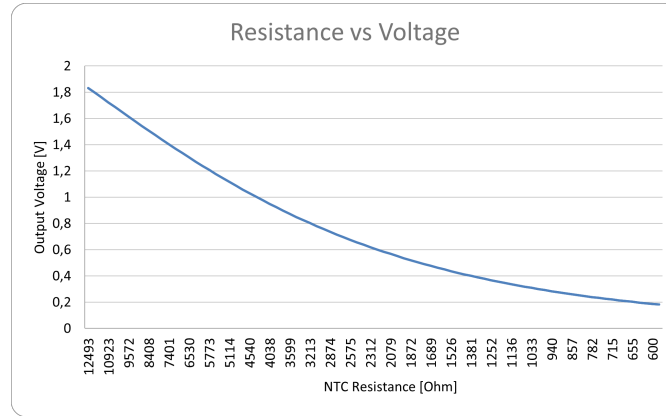


Figure 2.18: Graph of the output characteristic of the NTC acquisition circuit

CAN messages

The values from sensors are acquired, converted in digital and sent by the Sensorboards Front and Rear to the CAN BUS LV. The Sensorboard Front sent the following message:

- *SENSORBOARD_FRONT_1*, ID: 0x10, messages that contains the values from throttle, steering and brake sensors.
 - *THROTTLE0*, variable that returns the angle of the acceleration pedal expressed in voltage. The analog to digital conversion (ADC) till the value contained in the CAN message is the following:

$$\begin{aligned} V_{sensor} &= [0.5; 4.5]V \\ p &= 0.6 \\ V_{cond} &= p \cdot V_{sensor} = [0.3; 2.7]V \end{aligned}$$

Considering that each ADC channel uses a resolution of 12bit, the quantized value corresponds to:

$$\begin{aligned} Nb &= 12bit \\ V_{dd} &= 3.3V \\ V_q &= \frac{V_{dd}}{2^{Nb}-1} = 0.000806V \end{aligned}$$

This means that the conversion from the output voltage value to the digital read "D" in the messages is:

$$V_{sensor} = D \cdot \frac{V_q}{p} \quad f = \frac{V_q}{p} = 0.00137$$

In order to better manage the value in the SW code of the μC , it is useful to shift right the factor, to always have a value smaller than 1. In this way:

$$\begin{aligned} f &= 0.000137 \\ D_{max} &= f \cdot (2^{12} - 1) = 0.561 \end{aligned}$$

Due to this calculation, the range of possible values will become:

$$[0.5; 4.5]V \rightarrow [372; 3350]bits$$

- *THROTTLE1*, variable that returns the angle of the acceleration pedal expressed in voltage, with inverted range respect to the THROTTLE0 but the same analog to digital conversion.

- *STEERING*, it returns the value of the steering rotary sensor, that is subject to the same conversion of the throttle:

$$[0; 5]V \rightarrow [0; 3722]bits$$

- *BRAKE*, variable that informs about the pressure in the braking hydraulic system. As for the steering and throttle the voltage value is converted in the same way and it can assume a range of value:

$$[0.5; 4.5]V \rightarrow [372; 3350]bits$$

- *SENSORBOARD_FRONT_2*, ID: 0x11, that contains the values from the potentiometers and the strain gauge in the brake pedal. it is divided in:

- *POT FL*, variable that describes the extensions of the damper positioned in the front left side of the vehicle. The ADC conversion till the value contained in the CAN message is the following:

$$V_{sensor} = [0; 3.3]V$$

$$p = 0.9 \quad V_{cond} = p \cdot V_{sensor} = [0; 2.97]V$$

Considering that each ADC channel uses a resolution of 12bit, the quantized value corresponds to:

$$Nb = 12bit$$

$$V_{dd} = 3.3V$$

$$V_q = \frac{V_{dd}}{2^{Nb}-1} = 0.000806V$$

This means that the conversion from the output voltage value to the digital read "D" in the messages is:

$$V_{sensor} = D \cdot \frac{V_q}{p} \quad f = \frac{V_q}{p} = 0.0000896$$

In order to better manage the value in the SW code of the μC , it is useful to shift right the factor, to always have a value smaller than 1. In this way:

$$f = 0.00000896$$

$$D_{max} = f \cdot (2^{12} - 1) = 0.367$$

Due to this calculation, the range of possible values will become:

$$[0; 3.3]V \rightarrow [0; 3683]bits$$

- *POT FR*, variable that describes the extensions of the damper positioned in the front right side of the vehicle. The conversion from analog to the digital value is the same respect to the conversion for the POT FL.
- *STRAIN GAUGE*, this value informs about the extensions of the brake pedal. the conversion is executed in the same way of the THROTTLE, the final range are:

$$[0; 5]V \rightarrow [0; 3722]bits$$

- *SENSORBOARD_FRONT_NTC*, ID: 0x12, this message contains all signals referred to the NTC placed in the vehicle to monitor the temperature in different part of the cooling system. This signals are:

- *NTC MOTOR RL*, the voltage value contained by this signal is obtained by a partition with pull-up resistor of 10K and a Supply voltage of 3.3V. This means that:

$$Rt = [1.066; 10]k$$

$$V_{NTC} = V_{dd} \cdot \frac{Rt}{R_{pull} + Rt} = [0.317; 1.65]V$$

The complete graph with the relation between resistance and voltage is reported in the fig 2.18. Due to this calculation, the range of possible values will become:

$$[0; 1.65]V$$

That range is converted in celsius degrees until to be inserted into the CAN signal, so that the range will become:

$$[0; 1.65]V \rightarrow [25; 105]^{\circ}C$$

- *NTC MOTOR RR*, the voltage value of the thermistor placed in the rear right motor contained by this signal is obtained by a partition with pull-up resistor of 10K and a Supply voltage of 3.3V. The conversion is performed in the same way respect to the other NTC.
- *NTC MOTOR FL*, the voltage value of the thermistor placed in the rear right motor contained by this signal is obtained by a partition with pull-up resistor of 10K and a Supply voltage of 3.3V. The conversion is performed in the same way respect to the other NTC.
- *NTC MOTOR FR*, the voltage value of the thermistor placed in the rear right motor contained by this signal is obtained by a partition with pull-up resistor of 10K and a Supply voltage of 3.3V. The conversion is performed in the same way respect to the other NTC.

2.5.3 TLB subsystem

Description

The TLB subsystem must satisfy many rules issues. The system represented in figure 2.19, must control the Tractive system Activation Light (TSAL) that inform all people in proximity to the vehicle, if in the car are present more than 60V (the light will flashing in red color) or less than 60V but more than 0V (the color will be green fixed). The system is composed by 3 boards:

- TLB Board, master placed in the rear side of the vehicle
- TLB Inverter, slave in the inverter pack
- TLB Battery, slave in the accumulator pack

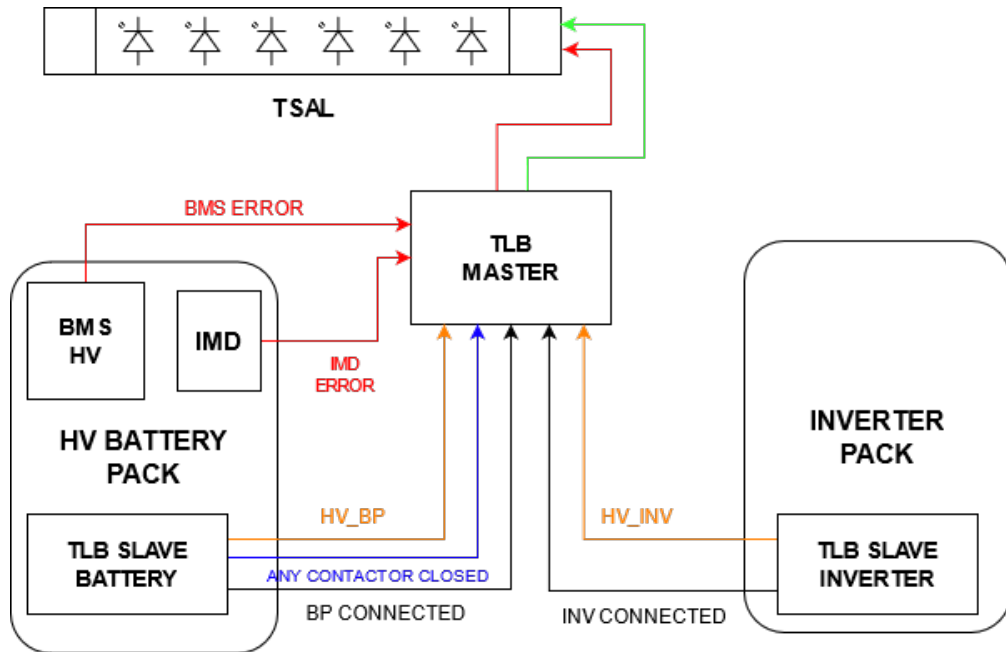


Figure 2.19: General scheme of the TLB system

The TLB master board to control if in the vehicle are present more than 60V must measure the TS DC voltage into the accumulator container and into the inverter pack. This task is performed by the two slave boards and must be executed using only hardwired logic by rules. The circuit used to read the TS voltage is that represented in the figure 2.20. Therefore in the TLB slave battery, a specific control

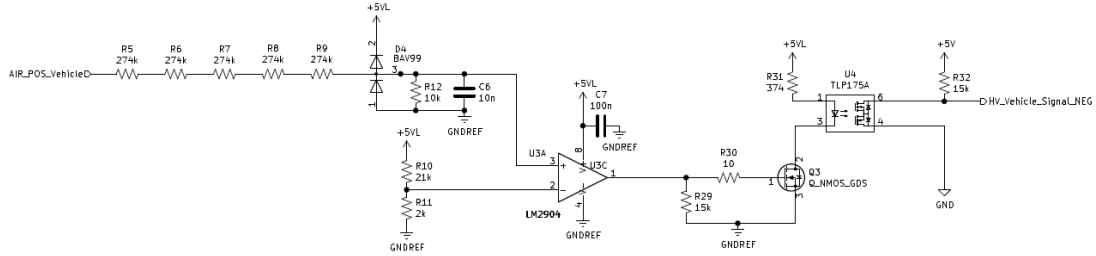


Figure 2.20: Schematic of the HV reading for tlb system

of the real state of the contactors must be read. To accomplish this necessity, the contactors' feedback status is read in accordance with a OR logic:

IF at least 1 of the AIRs or the precharge relay is closed
THEN any_contactor_closed signal is asserted

Another feature of the TLB slave battery is to report by a visible red voltage indicator in the pack, if TS DC voltage is available after contactors. This task is performed with the following hardwired circuit 2.21.

Led will turn ON only if in the vehicle side will be present more than 60V.

The TLB master board, to decide the colour of the TSAL light, receive by slaves the following signal:

- any_contactor_closed, already described
- HV_in_BP, asserted if more than 60V in the accumulator container
- HV_in_Inverter, asserted if more than 60V in the inverter pack.
- BP_connected, asserted when the accumulator container is connected to the system
- Inverted_connected, asserted when the inverter is connected to the system

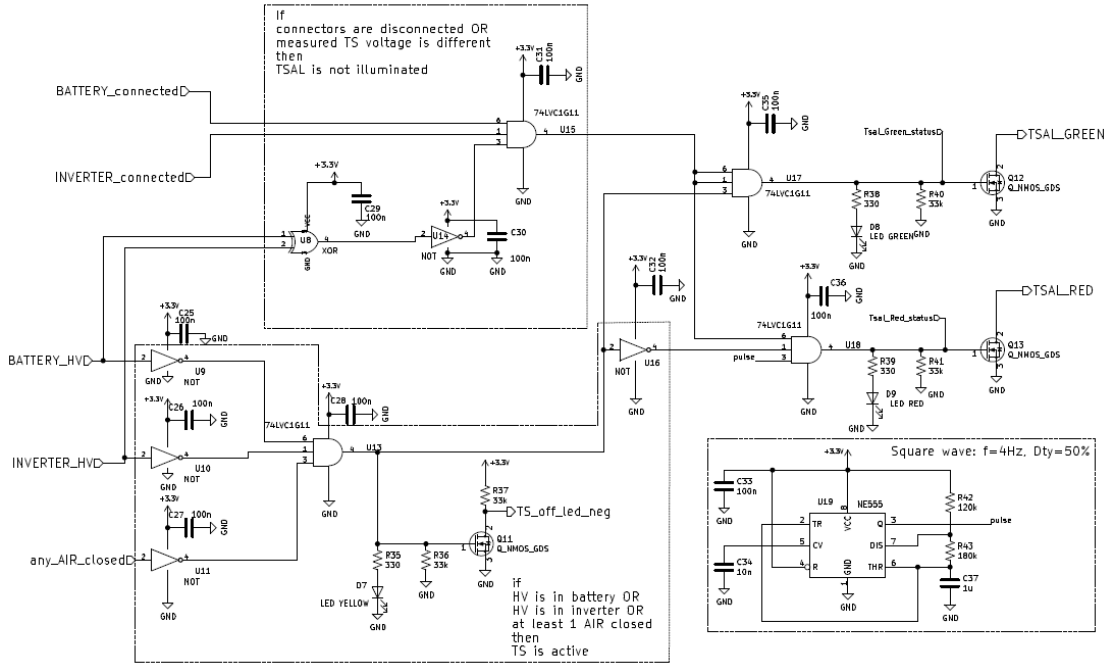


Figure 2.22: Schematic of the tsal driving circuit

- BMS error, when any error is present in the HV BMS, this signal is at 0V, otherwise is in HZ.
- IMD error, when any error is reported, this signal is at 0V, otherwise it is set to +24V.

This two errors are latched by the TLB board that must activate the shutdown circuit procedure, described in the section 2.5.9. In the schematic 2.23 it is possible to see also the Reset of the latches, that can be performed by a push button placed in the side of the chassis.

The last task of the TLB master is to read IMD, BMS and BSPD errors and make them available in CAN LV1, in order to be read by the Dashboard that will turn the cockpit leds indicator. This task can be realized by sent this error in input to a μ -controller that will sent the information in CAN.

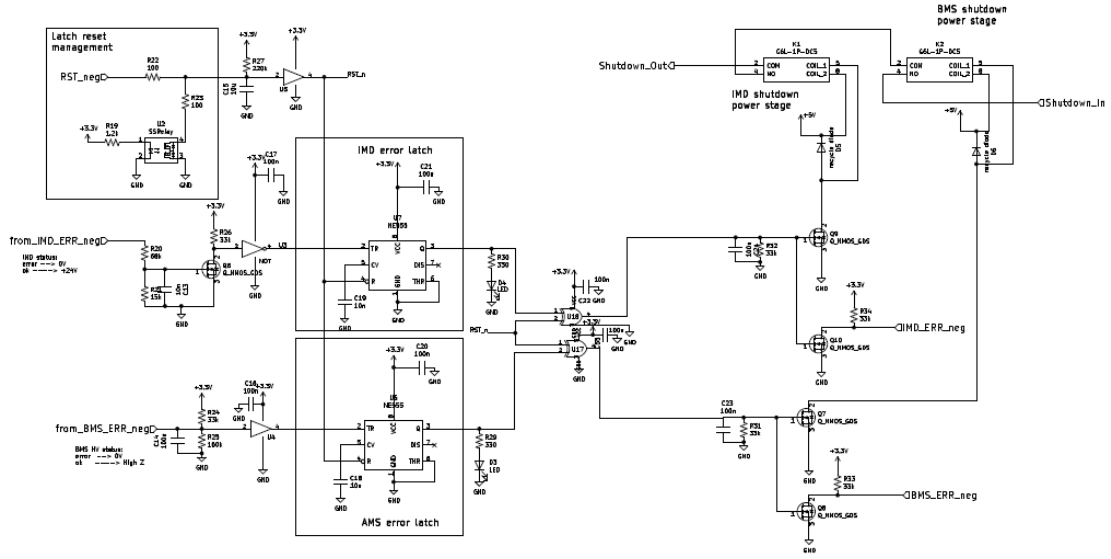


Figure 2.23: Schematic of BMS and IMD errors latching

CAN messages

About the TLB Master CAN node, it sends important messages used to decide to turn ON/OFF some LEDs on the cockpit, used to advertise the pilot about some error states of the vehicle. The message from this boards are the following:

- *TLB_ERROR*, [TX], ID: 0x20, in which are included information about the errors from HV pack and BSPD. This message is received by the dashborad that then will turn the cockpit leds with a logic coherent with this message. Signals are the following:
 - *TS_OFF*, it goes to 1 if less than 60V are present in the vehicle, otherwise is 0
 - *BMS_ERR*, it goes to 1 if a fault from the HV BMS is latched by the TLB, otherwise is 0.
 - *IMD_ERR*, it goes to 1 if a fault from the IMD is latched by the TLB, otherwise is 0.
 - *BSPD_ERR*, it goes to 1 if a plausibility error is detected from an analog signal coming from BSPD to the TLB, otherwise is 0.

- *TLB_BRAKELIGHT*, [RX], ID: 0x22, the TLB read this message from SENSORBOARD FRONT to driver the break-light led strip on the rear side of the vehicle, that must turn on one time the brake pedal is pressed. The only one signal present in this message is:
 - *BRAKE_LIGHT*, that goes to 1 when the brake pedal is pressed, otherwise is 0.

2.5.4 BSPD

The Brake System Plausibility board, is a device requested by rules. It must open the shutdown circuit when at the same time hard braking occurs and a power $\geq 5kW$ is provided to motors for more than 500ms.

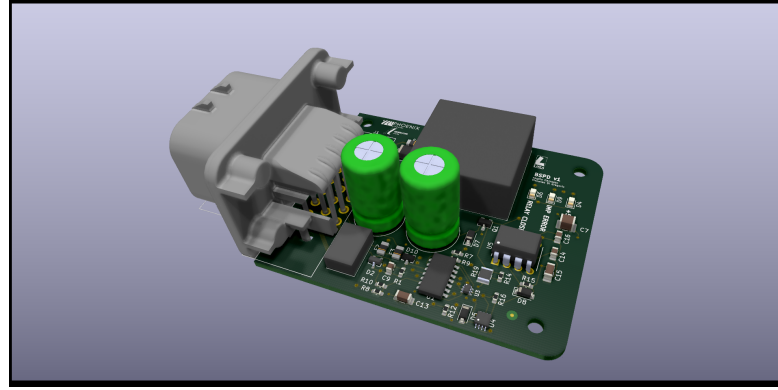


Figure 2.24: View of the BSPD board

Hard braking is measured thanks to brake pressure sensors that must detect when the pressure of the hydraulic system is $\geq 30bar$.

The schematic used to read this two quantities is represented in the figure 2.25.

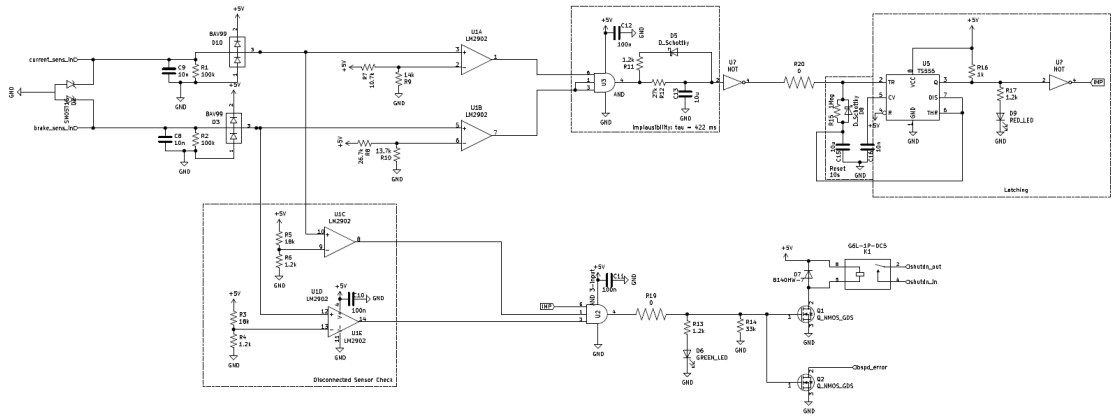


Figure 2.25: Schematic of the BSPD circuit

As represented in the figure above, to sense are used threshold amplifiers, with a threshold value calculated as explained below:

- 5kW, at worst case [574V] corresponds to a current

$$I_{pow} = \frac{Pow_{th}}{V_{max}} = \frac{5kW}{574V} = 8.71A$$

The sensitivity of the current sensor is $S = 40mV/A$ and offset is $V_o = 2.5V$, then

$$V_{th_pow} = I_{pow} \cdot S + V_o = 2.848V$$

- 30bar, the sensitivity of the brake sensor 2.11 is $S = 0.04v/bar$ amd sensor offset is $V_o = 0.5V$, then

$$V_{th_break} = Pr_{th} \cdot S + V_o = 30bar \cdot 0.04V/bar + 0.5V = 1.7V$$

The 500ms implausibility time, is set by an RC circuit that increase the voltage on the capacitor with a delay of 422ms to be safe. The error is than latched by a 555 timer, that keep the error for 10 seconds as said in rules.

Another condition to be monitored is to control if both the sensors are connected in the vehicle: the second part of the circuit execute this control and if the voltage offset of the sensors is no long seen, the shutdown circuit triggers.

2.5.5 Cockpit

Description

The cockpit panel is managed by the dashboard, figure 2.27. This board must control the following components present in the cockpit, figure 2.26, to help the driver with useful feedback about the state of the vehicle:

- IMD error led
- BMS error led
- TS OFF led
- RTD led
- RTD button
- Buzzer



Figure 2.26: View of the cockpit

The IMD and BMS LEDs must indicate if some errors from IMD and BMS are present in the vehicle. The dashboard can acquire this information thanks to a CAN signal sent by the TLB master board that latches this two errors that comes from the battery pack.

TS OFF led inform about the level of voltage active in the vehicle, if led is ON means that more than 60V can be present on the vehicle. This signal ever comes from TLB and is transmitted through CAN bus to the dash board. Buzzer, RTD led and button are parts of the Ready To Drive procedure, explained in the RTD section 2.5.6.

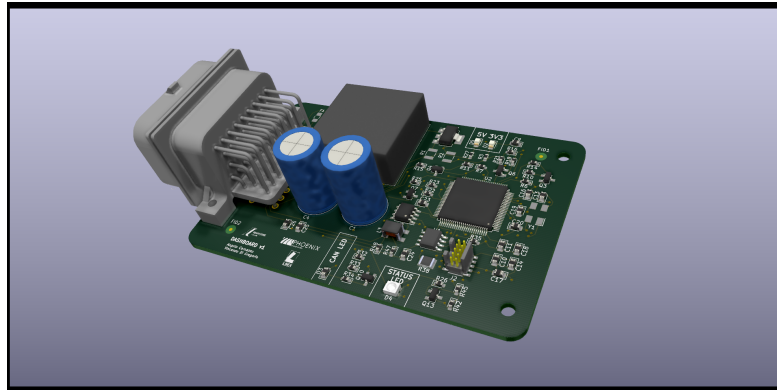


Figure 2.27: 3D view of the Dashboard

CAN messages

The can message that is related to the cockpit is the following:

- *TLB_ERROR*, [RX], ID: 0x20, already described in the TLB section, used to decide the status of the cockpit leds.

2.5.6 RTD

Description

The Ready to Drive procedure is requested by rules and is based on a finite state machine in which VCU and Dashboard exchange a series of acknowledge messages with the finally state that allows the closing of AIRs and makes available the power from battery pack to motors. The FSM is the following in figure 2.28:

The meaning of each state is explained below:

- IDLE, attending till the RTD button is pushed
- CTOR EN, Dashboard send to VCU the request to enable contactors
- WAIT CTOR EN ACK, Dash attends the acknowledge message from VCU
- RTD EN, Dash received the acknowledge, now attends that the driver pushes the RTD button and the brake pedal at the same time
- WAIT RTD EN ACK, Dash attends the acknowledge of the VCU to enter in RTD
- RTD, the vehicle is in RTD, Dash activate the RTD led and the buzzer, that emits a sound to inform about the RTD state of the vehicle, the TSAL will blink red at 4 Hz
- STOP, buzzer stops the sound after 2 seconds

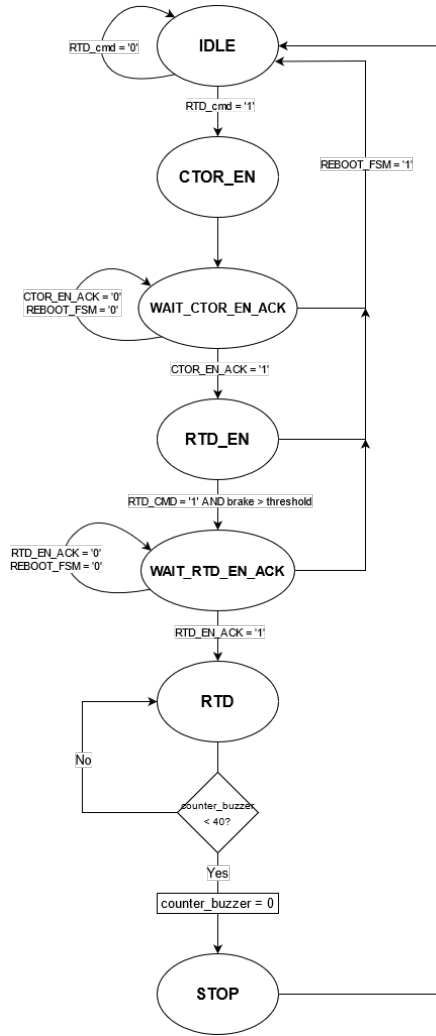


Figure 2.28: FSM of the RTD procedure

CAN messages

The messages described in this sections are related to the communication between VCU and Dashboard to perform the FSM for the Ready to Drive procedure. Beyond the messages already described in the VCU CAN message section, other messages involved and sent by the Dash ECU are:

- *CMD_RTD*, [TX], ID: 0x42, message that contains only one signal with the same name: *CMD_RTD* that must go to 1 when the RTD button is pressed by the driver, otherwise is 0. When is at 1 it starts the FSM procedure for the Ready to Drive.

- *ACK_RTD*, [TX], ID: 0x40, message used to communicate the acknowledgement of the data sent from VCU to the Dashboard. In particular this messages is composed by the following signals:
 - CTOR EN ACK, it indicates the acknowledge of the closing contactors starting procedure. It goes to 1 when the signal is asserted, otherwise is 0.
 - RTD EN ACK, it indicates the acknowledge of the RTD enabled. It goes to 1 when the signal is asserted, otherwise is 0.
 - REBOOT FSM, signal used to reboot the FSM if some fault state or communication error occurs. It will be 1 to indicate the reset state, otherwise will be at 0.

2.5.7 Cooling management

Description

The cooling system is needed to maintain components that dissipate a large amount of power into a safe temperature range. In particular in the vehicle are used three fans to decrease high temperature on the HV battery pack, figure 2.29, two for heat dissipation of the liquid coolant into radiators 2.30, that passes through motors' jacket and coldplates placed on inverter power modules. The liquid coolant can flow through the circuit thanks to two pumps. Both fans and pumps are controlled by dashboard. This devices can assume different states:

- OFF, sleeping mode. The device is not supplied
- ON, device works at full power
- AUTO, device's power is managed by a PWM signal from the Dashboard that regulate the functionality in a range 0-100%.

This PWM can be applied to the fans and can be decided directly by the pilot rotary switches located in the steering wheel front panel or from an automatic control system that takes into account the temperature of the HV battery pack (for HV fans) available in CAN thanks to the HV BMS or the temperature of NTC sensors into the liquid cooling system thanks to the Sensorboards. In this way the cells can work at the optimal temperature range, about 40 degree, and motors will not go in derating. On the other way there will be an optimization of the power consumption of the LV battery that will increase his duration.



Figure 2.29: Picture of the HV battery fans [14]



Figure 2.30: Picture of radiator fans [15]

In the table 2.5 a description of the main characteristics of fans used in the HV battery pack, and in the radiators.

Characteristic	HV fans	Rad fans
Air flow [m^3/h]	570	222
Nominal Voltage [V]	24	24
Sound level [dB]	78	69
Power input [W]	120	40.8
Nominal speed [rpm]	11000	14900

Table 2.5: Main characteristic of the fans used in the vehicle [14] [15]

CAN messages

About the CAN messages sent by the Steering Wheel Control Unit, that transforms the analog value written by the rotary encoders in the steering into a digital value, and it assigns a percentage from 0 to 100% to send at the Dash. This percentage indicate the power provided by the FAN, respectively from "MIN" to "MAX". The percentage is referred to the percentage of duty cycle of the command wave that must pilot the fans. Clearly, considering that the fan goes at maximum when the wave is keep at 0V, a 100% of PWM command corresponds to a 0% of Duty cycle and vice versa.

The CAN message used is the following:

- PWM, [RX], ID: 41, it must drive the fans of the radiators and also that of the battery pack. The control is performed through this two signals:
 - PWM RAD FAN, this signal can assume a value from 0 to 100 that corresponds at the grade of velocity of the radiator fans.
 - PWM BP FAN, this signal can assume a value from 0 to 100 that corresponds at the grade of velocity of the fans in the HV battery pack.

2.5.8 Human Machine Interface

Description

The steering wheel boards is composed of a quite different design respect the other boards. This is due to the small ambient in which the board is placed, that forced a new design for the power supply. As indicated in the fig. 2.31, the DC-DC used is a V7805-2000, with less protections respect the solution for the rest of the custom boards.

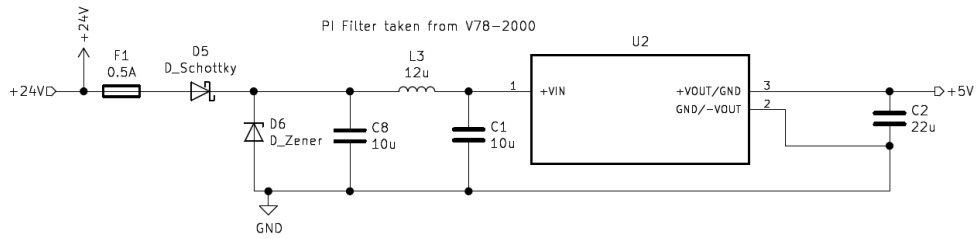


Figure 2.31: Schematic of the supply circuit for the steering wheel board

This boards must manage the buttons and rotary switches on the steering, see fig. 2.32, and send information read on CAN bus to the commercial display *pixxiLCD-25P4* graphic processing unit (GPU) [16] that will drive the liquid crystal display (LCD) display to show the information, see fig. 2.33.

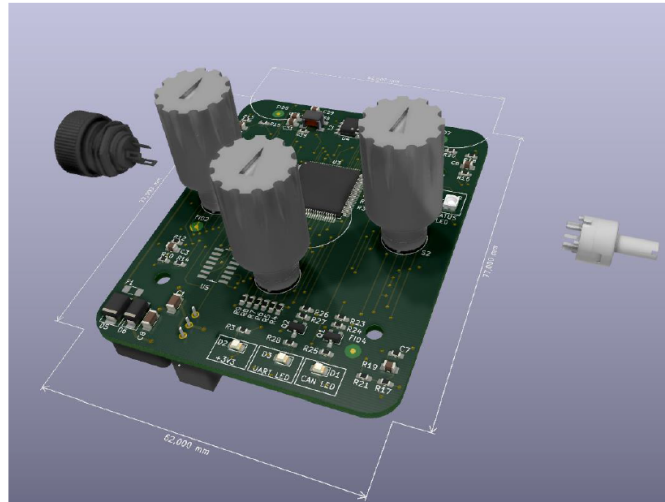


Figure 2.32: 3D CAD of the steering wheel board

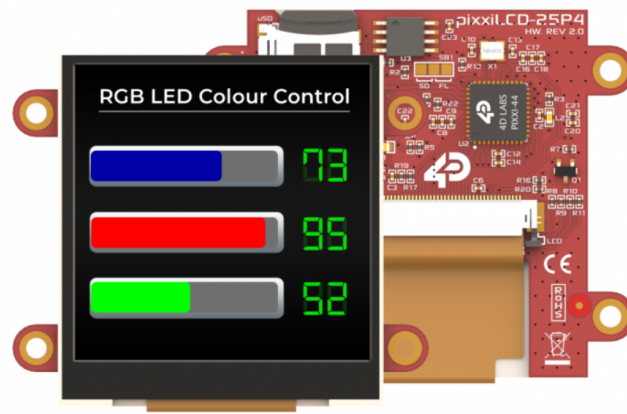


Figure 2.33: 3 of the supply circuit for the steering wheel board [16]

The communication between the STM32 micro-controller and the GPU, is performed through universal asynchronous receiver-transmitter (UART) protocol. The choice of an external GPU for driving the LCD display, allows a smarter and modern graphics. Information to send to the display are:

- Lap time
- Power and Torque
- BSPD error status
- Temperatures of the battery pack
- SoC

The circuit to read buttons are realized using HW de-bouncing protections as showed in the figure 2.34. The LPF filter is used to filter the mechanical fluctuation caused by humans pushing of the buttons.

Buttons are used for:

- push to talk, trigger when the driver is speaking, useful for communication errors.
- marker button, to trigger the current state, and signals the event in the log recording.
- emergency button, to allows the driver to indicate potential dangerous events.
- OK button, to send the acknowledgment in case of mistakes in vocal communication.

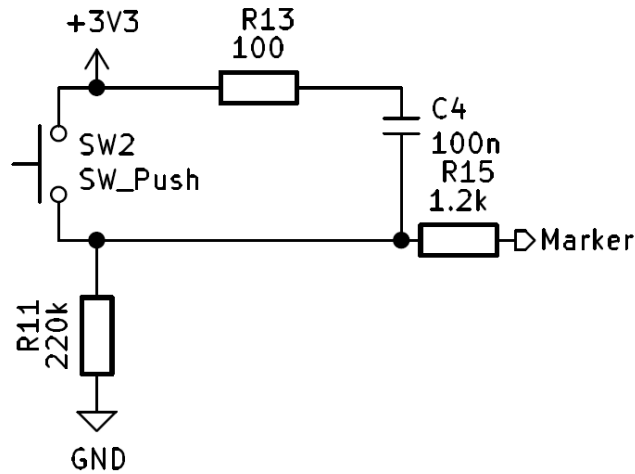


Figure 2.34: Schematic of the de-bouncing circuit for the buttons

The potentiometer is used to set the level of the luminosity of the display. The rotary switches are potentiometers from the electronic point of view. It is read by using a voltage follower to decoupling the impedance between output and input, as designed for the analog sensors in the Sensor board circuit. This switches are used to allow the driver to manually control the level of cooling and to move to different mode of the vehicle, if needed.

CAN messages

About the CAN messages used for the HMI system, the frames described below gives info about the status of the buttons and rotary switches in the steering wheel. The frames are:

- *BUTTONS*, [TX], ID: 0x100, in which are described the status of each button present in the steering. The signals included in the message are:
 - ERR, is used to indicate the status of the error button, it goes to 1 when asserted, otherwise is 0.
 - OK, is used to indicate the status of the ok button, it goes to 1 when asserted, otherwise is 0.
 - PUSHTALK, is used to indicate the status of the pushtalk button, it goes to 1 when asserted, otherwise is 0.
 - MARKER, is used to indicate the status of the marker button, it goes to 1 when asserted, otherwise is 0.

- *ROTARY*, [TX], ID: 0x101, in which are indicated the status of the rotaries in the steering. Signals included in this frame are:
 - C SL, indicate the status of the center left switch. It can have a value from 0 to 6 to indicate one of the 7 possible positions. It is used to set the grade of velocity for the radiator fans.
 - C SR, indicate the status of the center right switch. It can have a value from 0 to 6 to indicate one of the 7 possible positions. It is used to set the grade of velocity for the battery pack fans.
 - C SM, indicate the status of the center middle switch. It can have a value from 0 to 6 to indicate one of the 7 possible positions.
 - C LEFT, indicate the status of the left rotary potentiometer. It can have a value from 0 to 100. It is used to set the intensity of the screen brightness from 0 to the 100%.
 - C RIGHT, indicate the status of the left rotary potentiometer. It can have a value from 0 to 100. It is reserved for future implementations.

2.5.9 Shutdown circuit

The shutdown circuit, is essentially the supply line for the AIRs that are Normally Open contactors. When the shutdown line is interrupted, the AIRs turn in open circuit the TS path between battery and the vehicle. The line is composed by numerous switches, as it is possible to see in the figure 2.35, that must interrupt the line if any error occurs. The position and the number of switches is dictated by FSAE Rules.

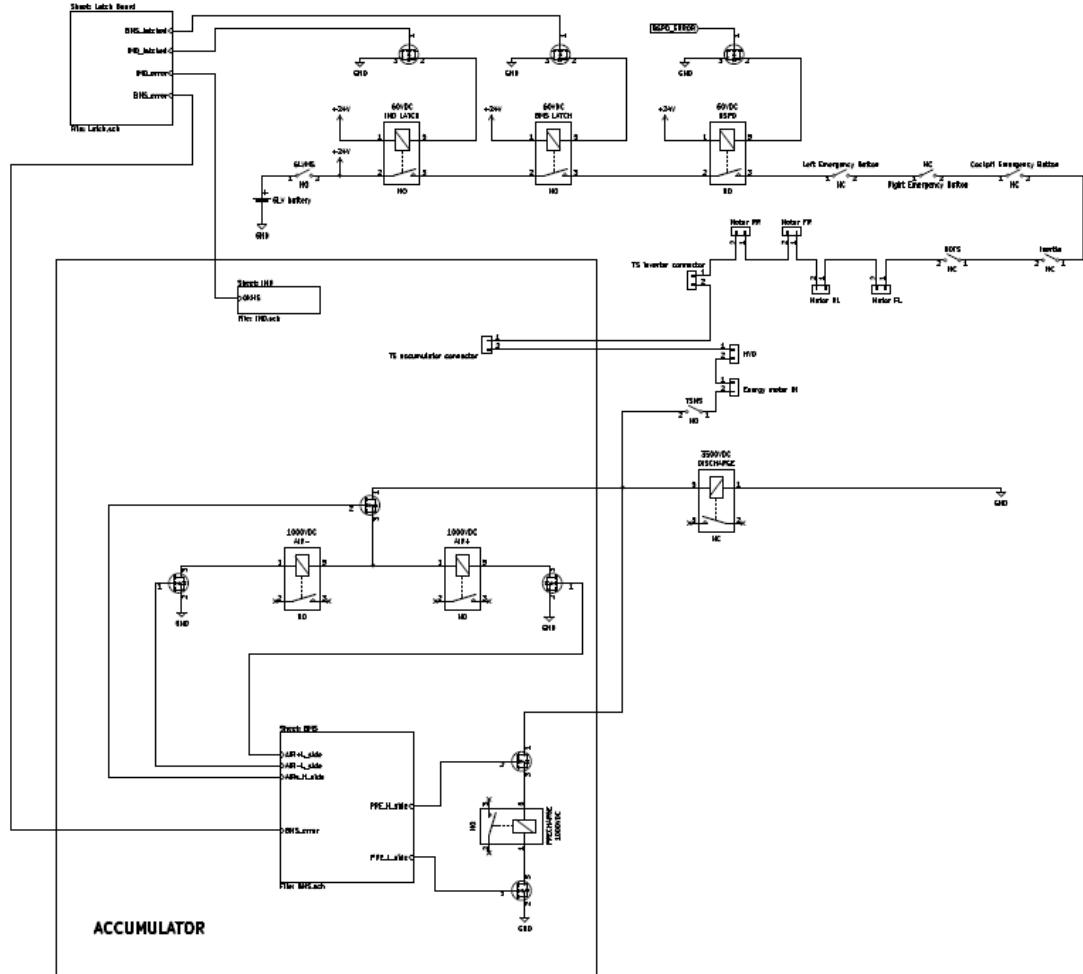


Figure 2.35: Schematic of the shutdown circuit

As represented in the figure, there are different kind of switches, someone are electrically driven relays, other are mechanically driven like the mushroom emergency stop buttons and the Master Switches. At the end of the shutdown circuit is also present the supply for a Normally Closed relay, used for the discharge procedure, that must

connect the discharge resistor between TS+ and TS- one time the shutdown line is interrupted.

The different conditions that can trigger the shutdown, are that in the list below:

- BMS HV error
- IMD error
- BSPD error
- Master Switches, GLV and TS
- Emergency Stop Buttons, that are placed, for safety reason on the side of the main hoop (two), on the cockpit and below the brake pedal (if broken it triggers the shutdown)
- HV connector interlocks, the shutdown must pass into all TS connector and must go in open circuit if anyone is disconnected.
- high voltage disconnect (HVD), security connector that disconnect both: the shutdown circuit and directly the TS path.

However by rules issue, the shutdown must pass through all connections to the wheel motors, in order to disconnect the circuit if any wheel break away, before that TS wires could remain free floating.

Chapter 3

Analysis of the architecture

3.1 SC19 issues

The SC21 vehicle described in this project thesis descending from the previous vehicle realized, the SC19. The SC19 vehicle has been analyzed to correct any electrical problems encountered and other improvements have been inserted in the electrical and electronic system of the SC21 vehicle. The previous vehicle's issues are related to the parts in the following list:

- Power supply of the custom boards
- Sensors' analog conditioning circuit
- Protection on the wires
- BSPD auto-reset
- HV detection in the contactors side
- Voltage indicator circuit
- HV and radiator fans PWM control
- Fusebox PCB layout
- Steering Wheel
- BMS Low voltage

3.1.1 Power supply

The circuit proposed in the SC19 vehicle is that represented in the fig. 3.1. The components used are chip and simple, but are not suitable when there are large variations on the input signal in an automotive environment.

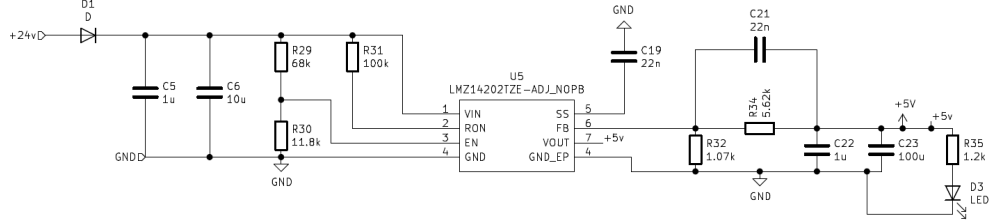


Figure 3.1: Schematic of the power supply in the custom boards of the SC19 vehicle

Therefore, the Buck converter was not properly protected in the input from overvoltage and overcurrent. This protection has been inserted in the SC21 configuration. However an input PI filter is inserted to reduce variations on the input signal that can affect the supply unit.

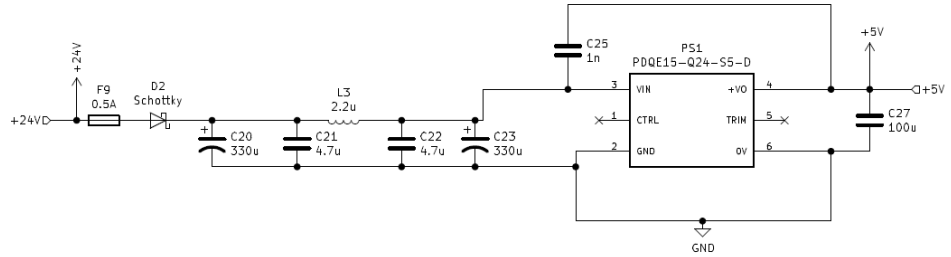


Figure 3.2: Schematic of the power supply in the custom boards of the new SC21 vehicle

The new configuration in figure 3.2, is composed of a Buck switching DC-DC converter suitable for automotive, a *PDQE15-Q24-S5-D*. This solution allows to obtain a more robust and reliable solution respect the previous one. The negative feature of this solution is related to the area occupied, in fact this is a more bulky solution. The inductance of the PI filter must be great enough to filter as possible variations, but not so much in order to maintain an appropriate occupation of the board. So for the PI filter, a second order filter the value chosen are:

$$C = 330 + 4.7 + 4.7 + 330 = 669.4\mu F$$

$$L = 2.2\mu F$$

$$f_{cut} = \frac{1}{\pi\sqrt{LC}} = 8.29kHz$$

Capacitors C20 and C23 chosen are of electrolytic type to allows to insert a larger value of capacitance.

3.1.2 Conditioning circuit for sensors

The conditioning circuit for sensor in sc19 was realized by using the same circuit in the figure 3.3.

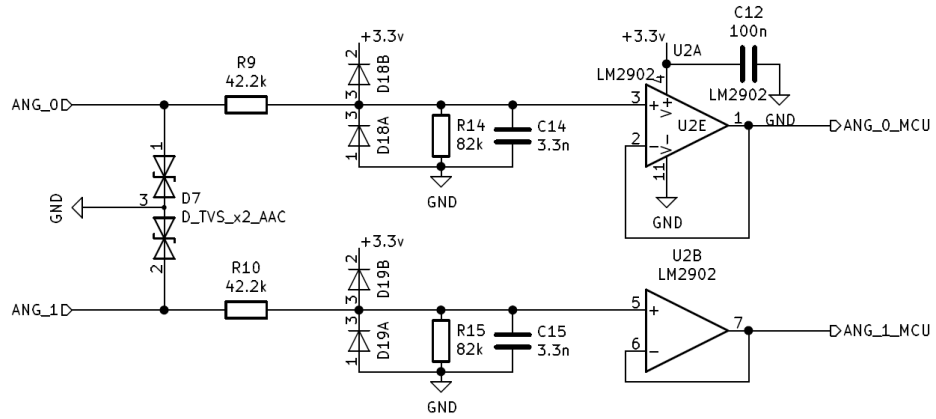


Figure 3.3: Schematic of the conditioning circuit for sensors in the SC19 vehicle

An improvement related to this circuit is made on the measurement range in the input. In fact, to obtain a better resolution in the measurement is convenient to increase the input range of the voltage follower by supplying its at 5V:

- Last configuration: $Amp19_{max} = 3.3V - 1.5 = 1.8V$
- New partition factor: $Amp21_{max} = 5V - 1.5 = 3.5V$

With an input partition factor of 0.6 the range of all sensors is $[0, 3V]$, this means that all values greater than 1.8V were not visible. This modification is designed in the SC21 vehicle as it is possible to see in the figure 3.4. Another problem is related to the Transient Voltage Suppressor diode (TVS) placed in the analog inputs that come from sensors, the components' characteristics were not suited for this application, they are substituted with TVS with the right characteristics.

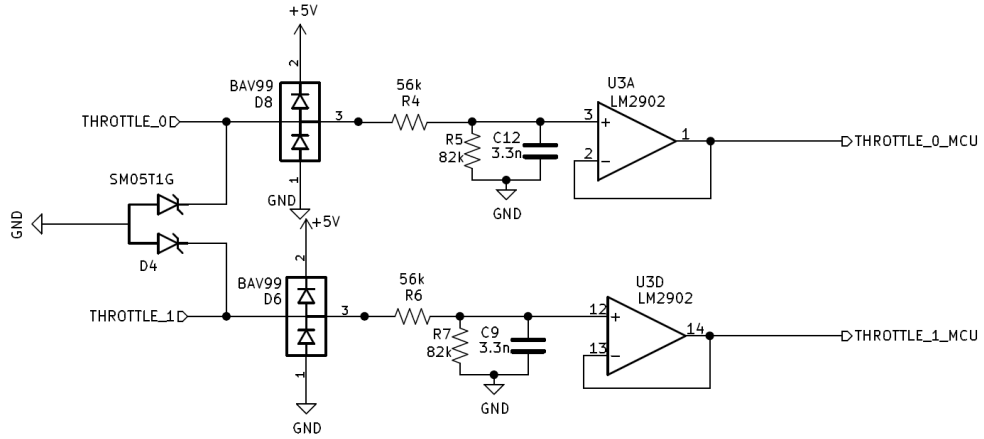


Figure 3.4: Schematic of the conditioning circuit for sensors in the SC21 vehicle

Speaking about the potentiometers, the conditioning circuit proposed cannot work: in fact, the potentiometers represents essentially a variable resistor partition. To read correctly its output value must be used a voltage follower to decouple the impedance. This change was applied in the SC21 configuration with the scheme in the figure 3.5.

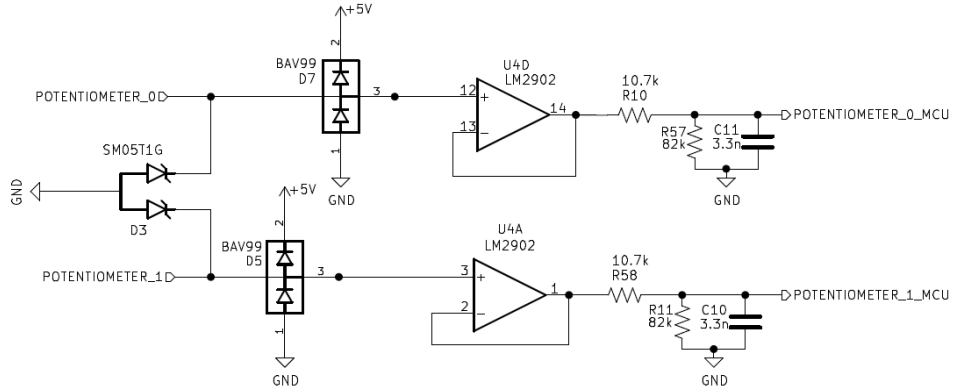
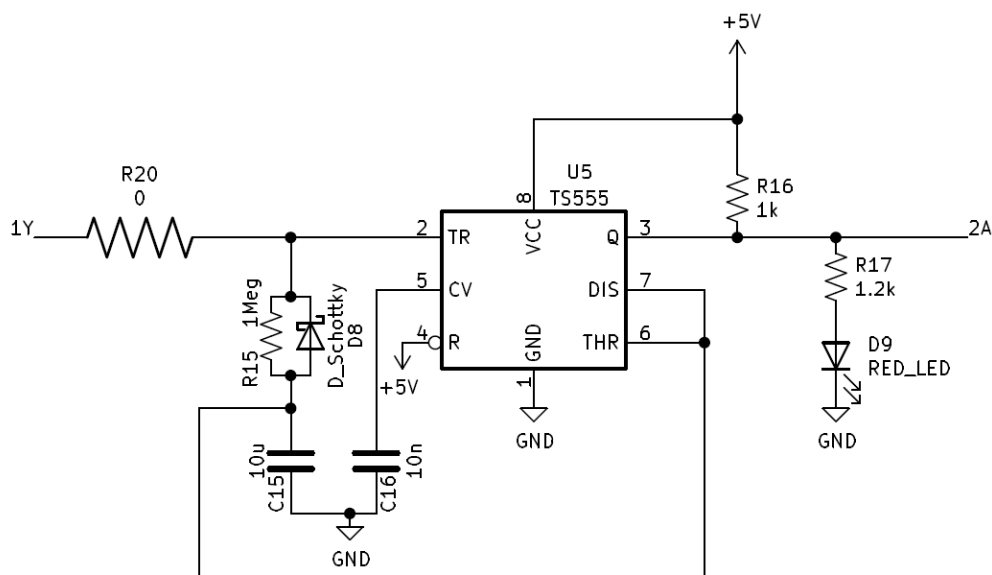


Figure 3.5: Schematic of the conditioning circuit for damper's sensors in the SC21 vehicle



- $C = 10\mu F$
- $\tau = R \cdot C = 10s$

The time to reset the circuit should be approximately equal to $1 \cdot \tau$. The Schottky diode is used to allow the transient only after the BSPD error is turned ON, so only for the charging state of the branch, the discharge bypass the resistor by use the path of the diode.

3.1.5 HV detection

The HV detection circuit is a circuit that must detects if the HV can be present in the vehicle side of the system, then after the AIRs. To be sure of this condition, as FSAE rules tells, a circuit must control if at least one of the AIR is effectively closed. In the SC19, to control the real state of AIRs, a crossed voltage measurements was effectuated, as explained in the scheme below 3.7:

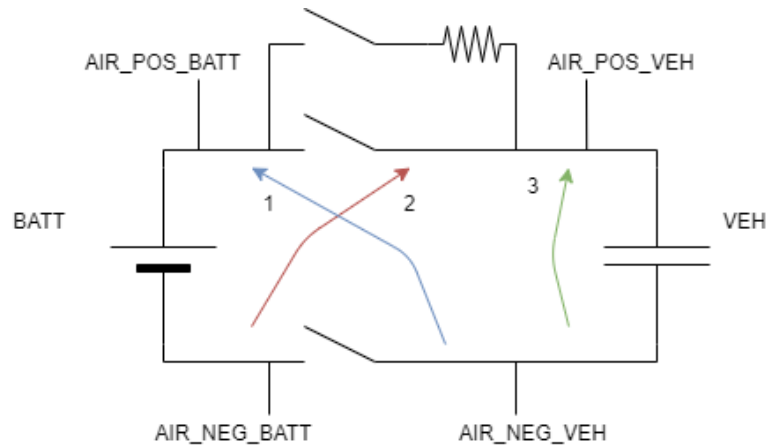


Figure 3.7: Scheme of the cross voltage reading for the HV detection in the SC19 vehicle

This method valid in theory, in the reality does not work. This was due to the large variations of the voltage of the battery pack, that can't guarantee a stable voltage signal, due to the variation of the load. So this circuit can be considered valid in static conditions, but did not works at dynamic conditions. Another problem related to this schematic is the difference of the voltage reference in the 3 measurements: this difference affected the correctness of the measurements when the negative AIR is open, generating a false detection. A new way has been chosen, by using an auxiliary feedback circuit provided by the AIRs, visible in the figure 3.8.

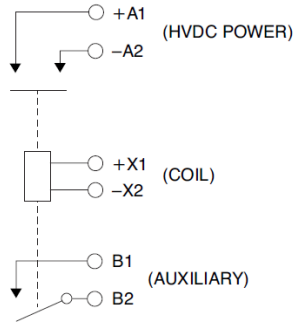


Figure 3.8: Scheme of AIRs with the feedback wires used for the HV detection in the SC21 vehicle

The feedback circuit give the possibility to assure the effective state of the relay, because it is mechanically connected to the switch. So when relay is closed, the two terminals of the feedback circuit are in short circuit, when relay is open, the circuit is disconnected. This signal is sent to the TLB Slave battery that sense the status of all the three relays: positive, negative and precharge and with a logic OR between this three feedback, return the status of *ANY_AIR_CLOSED* to the TLB Master board.

3.1.6 FAN control

The Fans control has been improved by adding a third mode, beyond ON and OFF states, the AUTO mode as in fig. 3.9. In this mode, the fans are regulated by a Pulse Width Modulation signal that takes as feedback the temperature of cells for the HV fans and the temperature of the cooling system for the motors. In this way is possible to maintain the devices in an optimal operating range, guaranteeing better performance and less power consumption of the Low Voltage battery. In this way, data about the power consumption of LV system will help to choose a right design of future LV packs. The PWM control of the fans can also be controlled by the driver, through the rotary switches placed in the steering wheel, if necessary by conditions. This functionality can represent a good solution by considering a future electronic system regulated by a DC-DC that takes energy directly by the HV pack, in that case the consumption is more important.

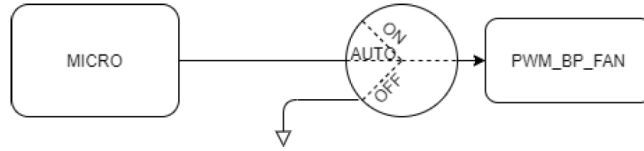


Figure 3.9: Principle scheme of the control for Fans in the SC21 vehicle

The ON mode is represented by a pin in HZ (High Impedance) state, the OFF is connected to the LV GND and the AUTO pin is connected to the micro at the PWM output driver. The driver port is designed as in fig. 3.10, it consists of a mosfet in inverting configuration.

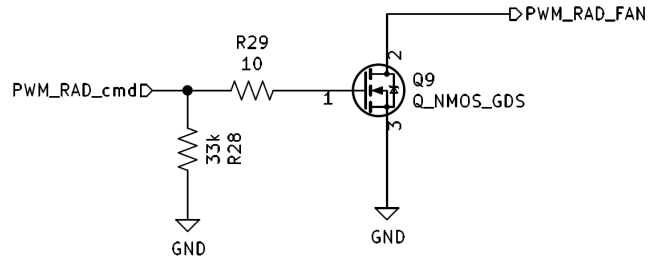


Figure 3.10: Schematic of the driver for the fans in the SC21 vehicle

3.1.7 Fuse-box layout

The Fuse-box produced in the SC19 suffered the overheating caused by the large amount of current requested to the LV battery by the loads in the vehicle. Pumps, fans and inverter boards, can even request a current of 35 A when all is turned on. This caused a temperature of the PCB of the fuse-box that can reach 100° degrees in few minutes. To reduce the overheating, that can damage the electronics devices, the layout of the PCB was changed by increasing the width of the connection between components. When possible, as for the GND and +24V wires, a zone was created that covers the entire surface of the board. A particular of the final layout is represented in the figures 3.11 and 3.12 below, respectively front and rear of the fuse-box board.

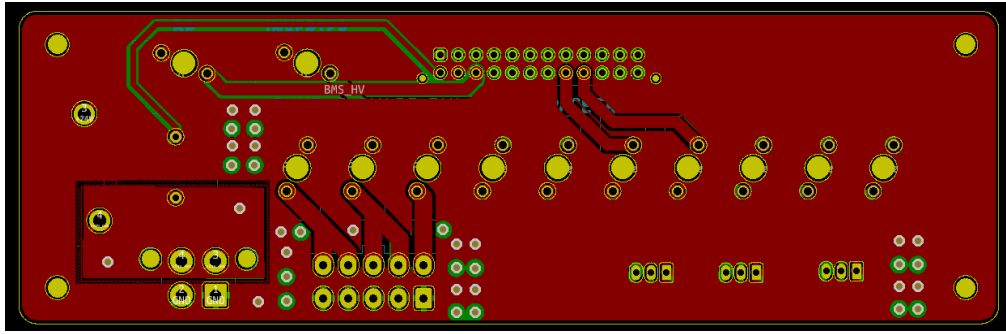


Figure 3.11: PCB front layout of the fuse-box board in the SC21 vehicle

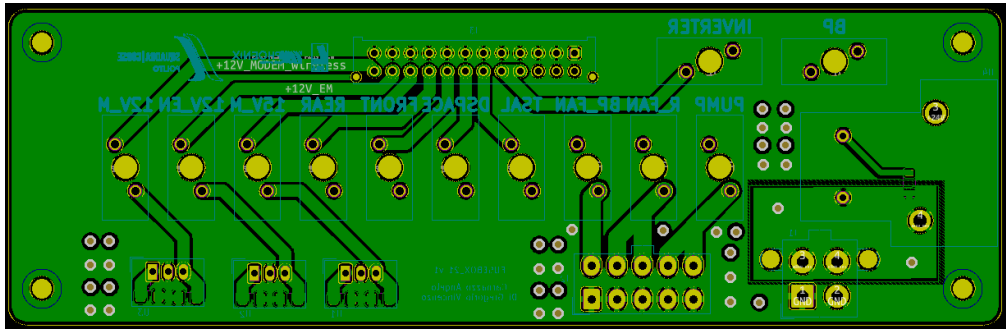


Figure 3.12: PCB rear layout of the fuse-box board in the SC21 vehicle

3.1.8 Steering wheel

The steering wheel board in the SC19 vehicle never properly worked. The problems are related to the display configuration that was swapped, causing the burn of the LCD display (supply pins inverted), and to a bad configuration of the rotary switches that did not allow to read correctly the switches' position. In particular, with the configuration of the SC19, represented in the figure 3.13, the change of impedance viewed by the micro-controller side always was almost the same.

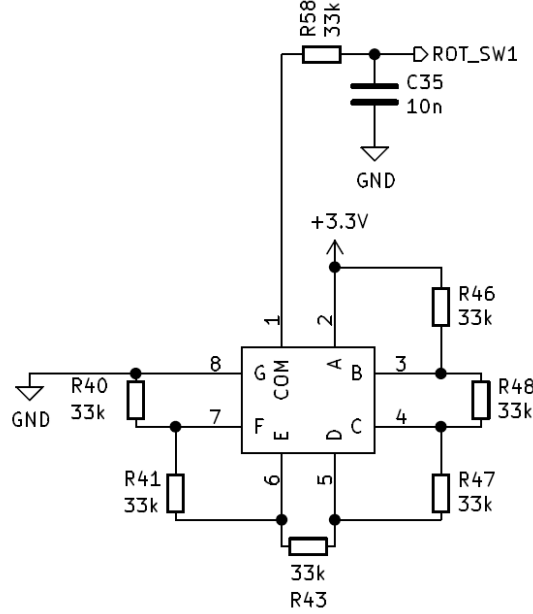


Figure 3.13: Schematic of the rotary switches in the SC19's steering wheel

The new configuration, in the fig. 3.14 used for the rotary switches is a simple voltage partition composed by six resistor of 200 ohm, that divide the 3.3V voltage provided by the DC-DC of the steering wheel.

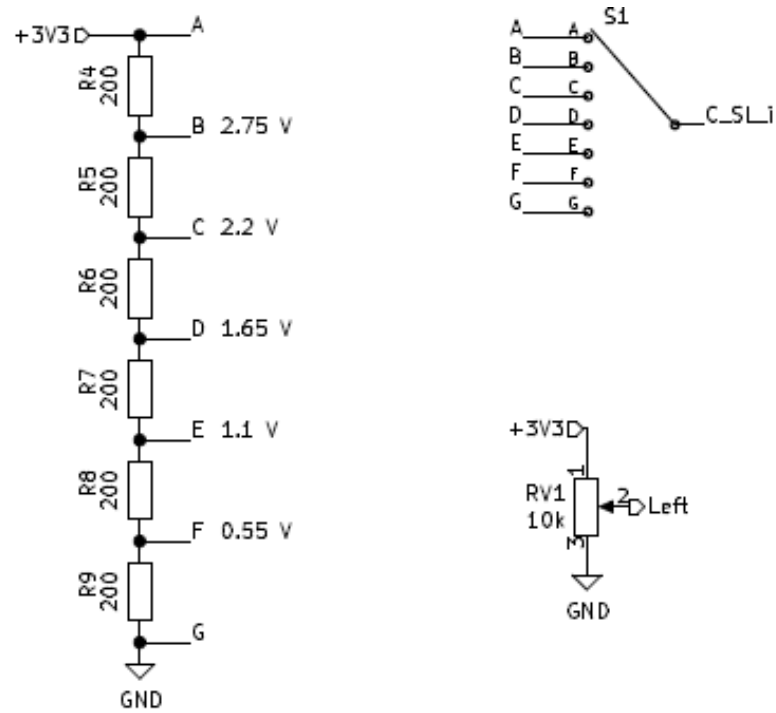


Figure 3.14: Schematic of the rotary switches in the SC21's steering wheel

After the partition generated by the rotary switches, a voltage follower, in fig. 3.15, is used to decouple the impedance between output and input.

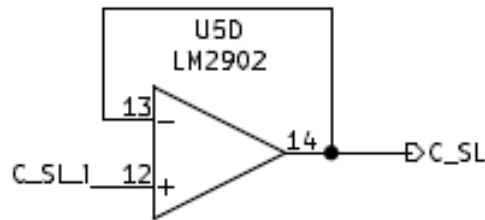


Figure 3.15: Schematic of the voltage follower used for rotary switches in the SC21 vehicle

Another important choice respect the last season is the managing of the display, no more committed to the micro-controller of the STM32 configured by the team: in fact, to allow a more complex and modern display layout, was chosen a display

with an integrated GPU, that can communicate in UART with the STM32 micro of the steering wheel board. In this way the new display, a *pixxiLCD-25P4*, can be configured by the help of a specific software, reducing the complexity of programming the graphics. Further information about Steering wheel board are described in the related section of the chapter 2.

New feature has been added to help the driver. In particular, a larger number of push buttons are available to trigger the following actions:

- Marker, useful signal for time tracking and analysis
- Push to talk, to start radio communication or signaling an ongoing communication
- ERR, to report a generic error
- OK, to signal the correct reception of the message

3.1.9 BMS for Low Voltage

The BMS for the low voltage system of the SC19 suffers about problems in communication between master and slave micros, because the protocol of Wake-up the slave was not correct as described in the datasheet of the *bq76pl455a-q1*. Other problems encountered in this board are related to the power supply and on the transceiver, as already described in the section of this components above. Another problem was about the current sensor for measuring the LV current path: the previous current sensor used was a *CAS6NP*, with a measurement range of $\pm 20A$ max. To properly measure the current requested by the LV system, it needs a *CAS15NP*, a $\pm 50A$ of range. A proposal of BMS for Low Voltage system is explained in the section 4, adding new features like active balancing, beyond the resolution of the problems listed above.

Chapter 4

Battery Management System for LV

4.1 Target

The main target of this board is to monitor the activity of the LV Battery Pack of the vehicle, assuring that the batteries will remain in the Safe Operating Area (SOA), through the main parameters of the cells: Voltage, Current and Temperature. Another feature of this board is to calculate the SoC of the pack in order to better evaluate the remaining life of the battery.

The board is also capable of recovering the situation when the cells of the pack become unbalanced, thanks to an appropriate active balancing circuit.

4.2 Specifications

To properly design the Battery Management System, it is needed to define the characteristics of the LV pack and the consumption of the system.

The configuration of the LV pack, that is a 7s5p, is resumed in the paragraph 2. The battery cells are of the type *Molicel - INR1700-P42A* [9] and their characteristics are summarized in the tab 2.1.

The requested current for each LV subsystem, at the measured open circuit voltage of 27.6V that indicates the State of Charge of the battery, is that indicated in the tabular 2.2.

The specification for the Battery Management System for the Low Voltage can be described in the following list:

- Flexibility, the Hardware must be chosen in order to support different configurations with few modifications. In this way, the BMS will be useful in the case that the LV pack might have a nominal voltage of 12V, in the future developments. This means that the configurations to support are 4s and 7s.
- Real time measurements. The system should be capable to measure the cell voltage of each series (from 4 to 7), the temperature of at least the 30% of the cells and the LV main path current, that can be in the both direction: negative in case of recharging the LV pack.
- Safety, the system should monitoring the LV pack in order to guarantee that the battery will remain the Safe Operating Area (SOA). This means that the battery cells must functioning into a determined range of the voltage and temperature. It is possible to distinguish four different threshold parameters to not overcome:
 - OV, Over Voltage that could damage the battery pack. OV threshold is equal to 4.2V for this cells
 - UV, Under Voltage that could permanently damage the LV pack, that will not more be rechargeable. For this cells the UV is at 3.2V
 - OT, Over Temperature. If the Li-ions cells overcome the 60 °C, a chemical reaction could occurs causing in the worst case the burning of the pack.
 - UT, Under Temperature. If the pack drop down a certain temperature, the internal chemical components can be permanently damaged. However the condition in which the vehicle will be used, will never reach temperatures lower than -10 °C.
- Over Current (OC) protections: between an external automotive fuse (as in FSAE rules)

- Active balancing
- Managing the current flowing to the rest of the system
- CAN communication, to provide information on the LV supply and inform when errors occurs
- LV fan control

4.3 General Scheme

The architecture of the board can be divided into the three blocks, explained in the figure 4.1. The Master Control Unit chosen, a *STM32F303VET6* μ controller,

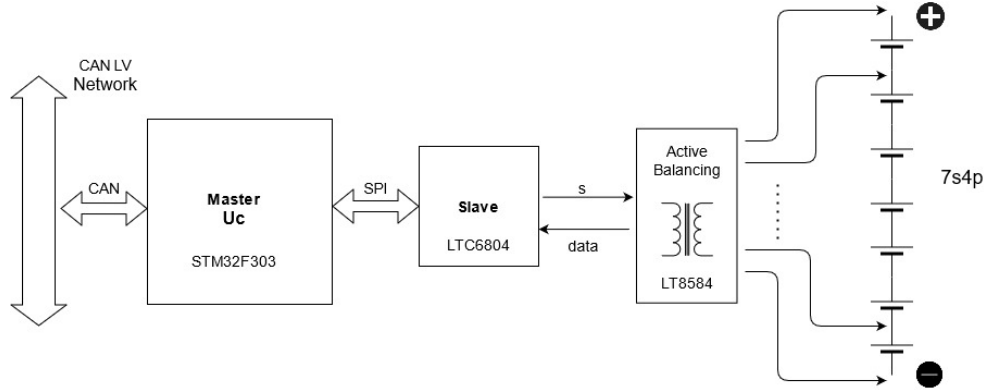


Figure 4.1: General schematic of the BMS LV

is responsible for the analysis of the data received from the Slave LTC6804 using a SPI protocol of communication. The Master directly acquires the whole LV current measured by an Hall effect current sensor and makes all relevant data available in the CAN Network of the vehicle. However, the Master uC manages the LV supply to all the rest of the vehicle through the control of a relay that allows the LV current to flow to the loads. In this way, if there is any error about the LV pack, the BMS LV can open the LV path and the vehicle can go to a safe state.

4.4 Power Supply

4.4.1 Design

This block aims to convert the nominal 24V LV supply, into 5V to supply power for the *LTC6804* and the current sensor, and to 3.3V for the μ C. For the conversion from 24V to 5V is used a DC-DC step down converter, a *LTM8021*. This converter can provide an efficiency about the 80%. Protections are introduced in the input port of the converter, from high currents through a fuse, from reverse polarity, thanks to a Schottky diode, chosen because it has a lower voltage drop respect a classic diode, both in series with the signal. Protections from over-voltages thanks to a TVS diode in parallel with the signal. For a good stability of the input signal, it is better to introduce a Pi filter that presents a cut-off frequency of 8 kHz. To reach this low pass filter (LPF) of second order, 2 capacitors of 330 μ F and an

inductor of $2.2\mu\text{H}$ are chosen. Due to the large capacity it is convenient to use electrolytic capacitors. The inductor is a bulky component, so it is important to not choose a too large inductance, the quantity chosen is sufficient. The schematic is available in the figure 4.2. As suggested in the datasheet of the component, a capacitor is added at the output of the switching regulator this time the capacity is lower, then it is possible to use a ceramic type.

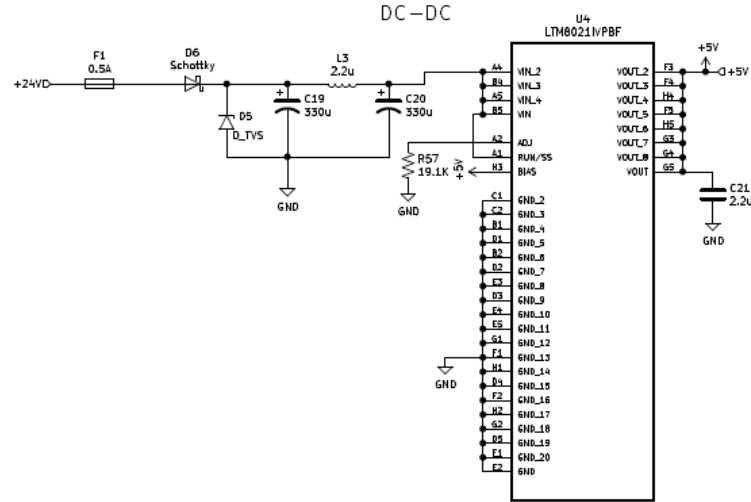


Figure 4.2: Schematic of the power supply

This switching converter DC-DC allows to step-down the voltage with an high percentage of efficiency, however the output will present a considerable ripple, it was put in series a linear voltage regulator, a *LM1117*, to reach the 3V3 supply for the μC and to have a lower level of ripple. The schematic for this component is in the figure 4.3.

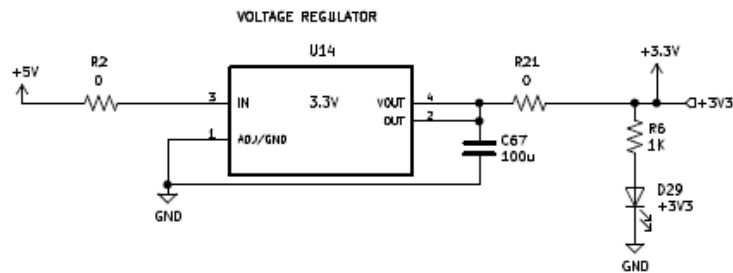


Figure 4.3: Schematic of the linear voltage regulator

The 0Ω resistors are used to isolate the circuit in the case of testing issues. The linear regulator needs a high ceramic capacitor in the output, to increase the stability, so $C24$ was added. In order to see if the supply is available in the board, a blue led is inserted within a series resistor to limit the current that can flow in the diode, otherwise it could easily burn.

$$i_d = \frac{V_{dd} - V_{drop}}{R_{lim}}$$

$$V_{dd} = 3.3V$$

$$V_{drop} = 1.5V$$

$$i_d = 1.8mA$$

$$R_{lim} = 1k\Omega$$

4.4.2 Simulations

The simulations of the power supply scheme has been performed in LT Spice to note the behavior on the transient state with a stable voltage and then using variable voltage (a sine) to evaluate the attenuation of the input second order filter. The simulated circuit is reported in the figure 4.4.

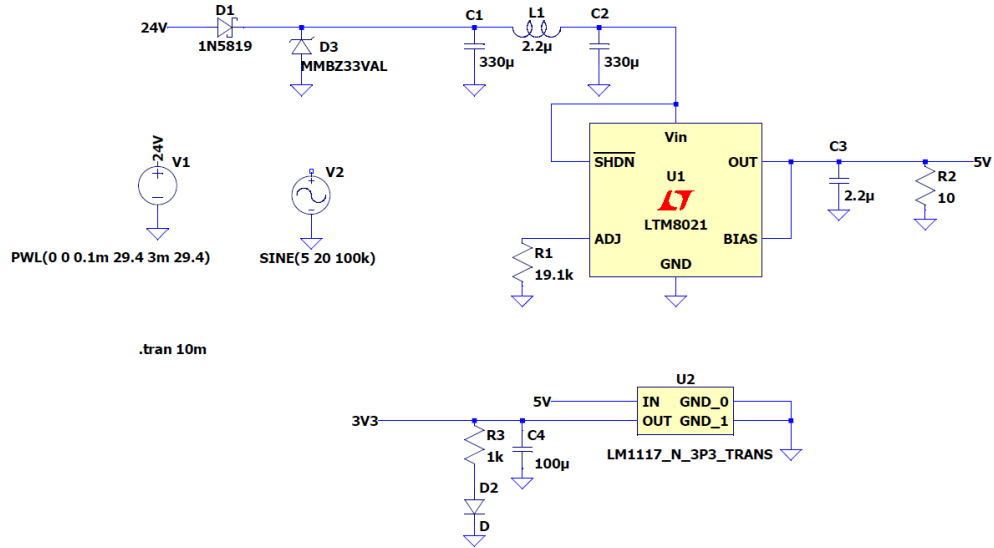


Figure 4.4: Schematic of the simulation circuit on LT Spice

The behavior of this circuit in transient analysis is reported in the graph 4.5, in which is possible to distinguish the different voltages obtained (3.3V and 5V), by starting from the input voltage provided by the LV battery pack.

Another simulation performed is made by sending an input sine waveform at 100KHz, in order to see the response of the circuit in case of unstable fluctuations of the input voltage. It is possible to note in the figure 4.6 that the circuit seems to be strong enough to this variations, giving however a stable output voltage at 5V and 3.3V.

In this last figure 4.6, the voltages on the node 1 and node 2 are referred respectively the measured voltage before and after the PI filter before the DC-DC converter. It is possible to note how the TVS Diode cut off the wave over 33V and how the fluctuations are strongly reduced by the PI-filter, because the sine wave at 100KHz the frequency point is over 1 decade respect the cut-off frequency of the filter.

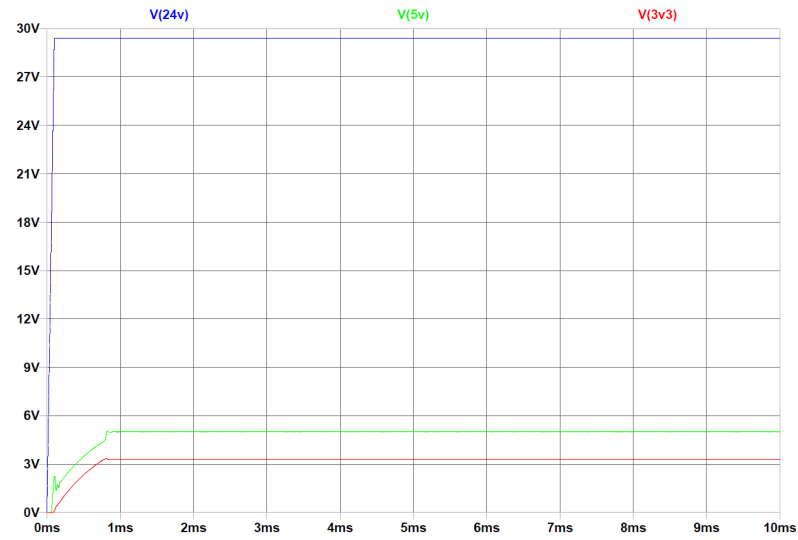


Figure 4.5: Transient nominal analysis of the output voltage for the supply circuit

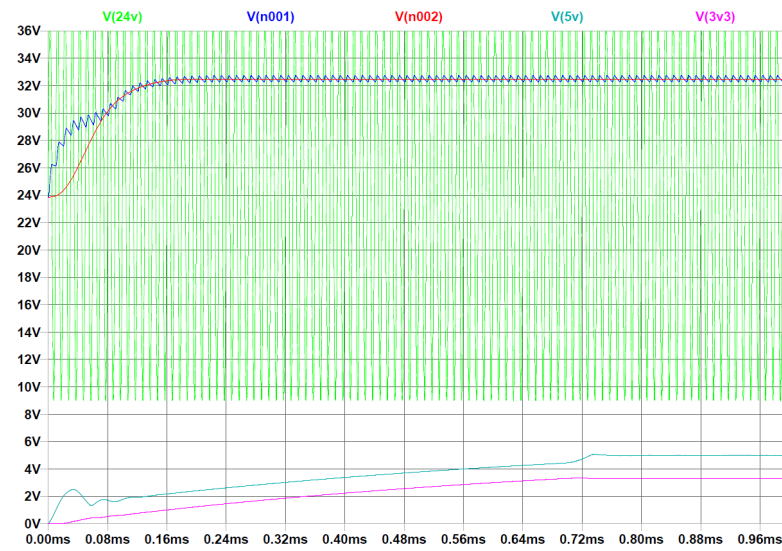


Figure 4.6: Transient sine wave analysis of the output voltage for the supply circuit

The RSTN pin is configured in order to have a correct reset timing with an RC circuit that limits the charge of the capacitor. This pin is used within SWCLK and SWDIO for flashing the micro by the serial wire debug (SWD) protocol.

The partition connected to the BOOT0 pin manages the boot mode, in this case it is mostly needed to boot the flash memory, so the $R56$ should not be mounted. If needed the resistor can be mounted to flash also other parts of the memory.

VDDA is the supply for all the analog internal components of the μC like the operational amplifiers and the DACs, while VREF+ is the positive reference for the operational amplifier (OPAMP). Instead VBAT/VDD represent the supply for all other internal components and for the external clock.

4.5.2 Oscillator

The micro controller unit (MCU) clock is externally generated by a quartz oscillator Y1, used to work at higher frequencies, precisely at 8 MHz. It is a very precise device but it is mandatory to use a correct conditioning circuit to work correctly. Quartz oscillator, in the scheme 4.8 is the *ABM3B-8MHz-10-D-1-G-T*.

Load capacitors $C11$ and $C10$ chosen as described in the datasheet of the quartz.

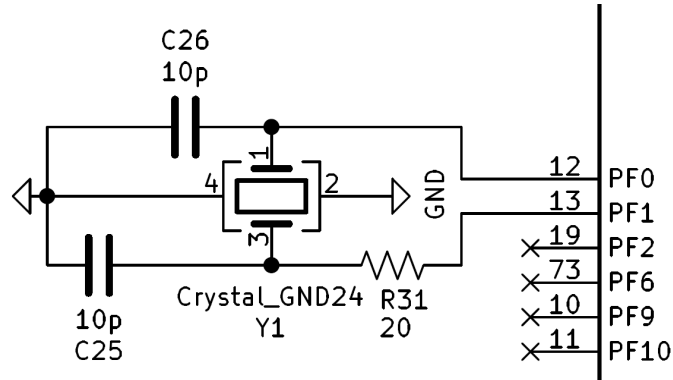


Figure 4.8: Schematic of a quartz oscillator external circuit

The resistance $R10$ chosen is of 20 Ω , respecting the indication limit of 200 Ω of the component's datasheet.

4.6 Decoupling filters

4.6.1 Design

For decoupling the supply in the master μC , a LC filter between VDDA and Vref was chosen, as suggested in the datasheet of the *STM32*. A ferrite *L1* is used within two different capacitors of 1 μF and 100 nF for each pin, to have a LPF of second order. Below, figure 4.9 the schematic of the filter. The other decoupling

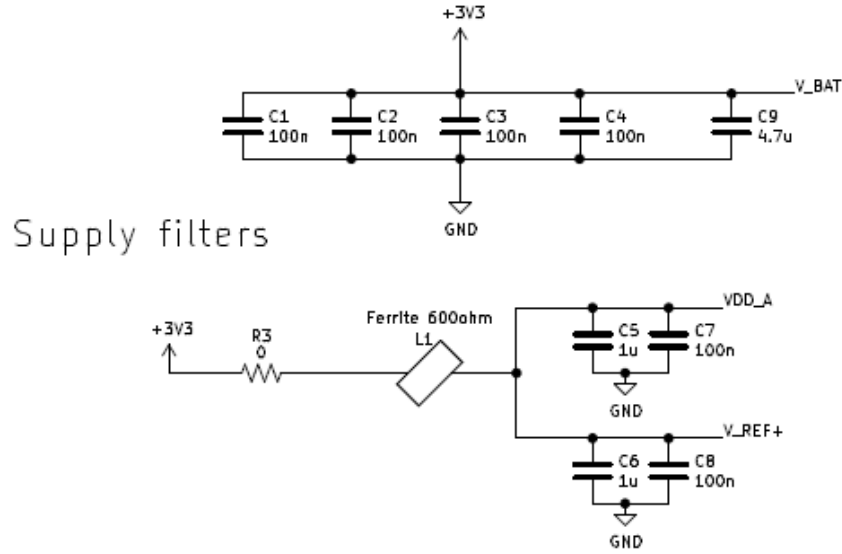


Figure 4.9: Schematic of the supply decoupling filter

capacitors for VBAT and VDD are placed near all pins of the μC .

4.6.2 Simulations

The filters used to decouple the 3.3V supply, has been chosen according to the advice of the datasheet of the μC . The circuit simulated is reported in the figure 4.10. The analysis simulated is clearly in the frequency domain, in order to analyze

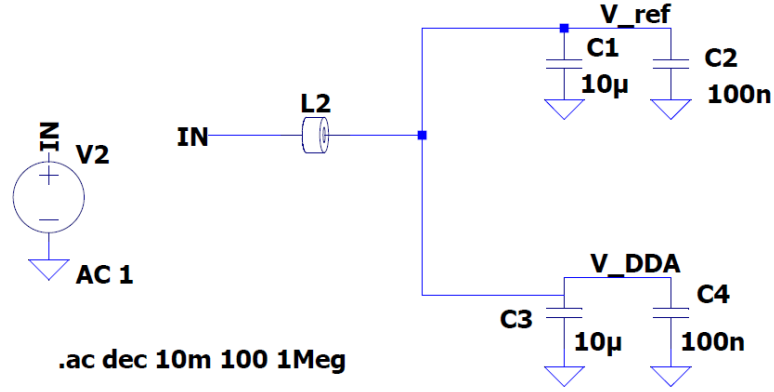


Figure 4.10: Schematic of the circuit simulated on LT Spice

the spectre of the circuit at different frequencies. The LPF is that represented in the image 4.11, with a cut-off frequency about 100KHz.

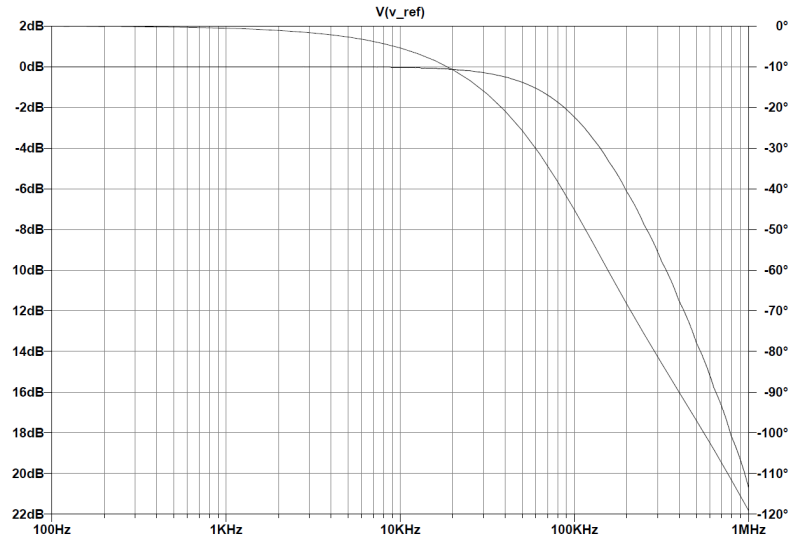


Figure 4.11: Schematic of the circuit simulated on LT Spice

4.7 SPI

SPI is a synchronous, full duplex master-slave based interface. The data from the master or the slave is synchronized on the rising or falling clock edge. Both master and slave can transmit data at the same time. The SPI interface can be either 3-wire or 4-wire. This board is configured to use the 4-wire SPI interface. For this SPI, as represented in the figure 4.12 communication are needed:

- MOSI, used to send data from master to slave
- MISO, used to send data from slave to master
- SS, used for wake up the slave
- SCLK, clock sent by master to slave for synchronizing the communication

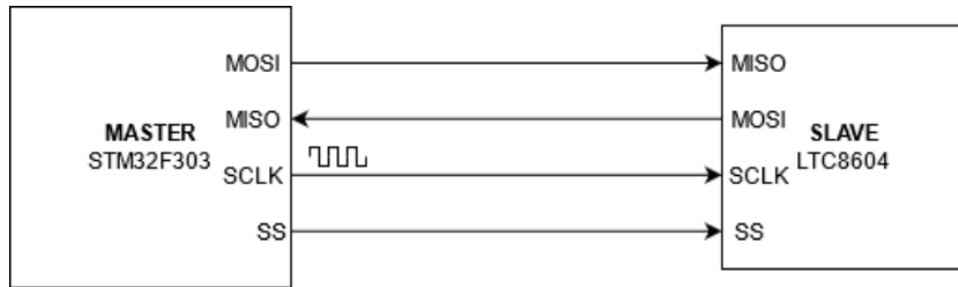


Figure 4.12: Scheme of the 4-wire SPI protocol

4.8 CAN Transceiver

4.8.1 Design

To connect the μC to the bus, a CAN transceiver is need: a *SN65HVD234* integrated circuit is used, with the schematic as in the figure 4.13:

Each CAN network must have at the start and at the end side of the network a

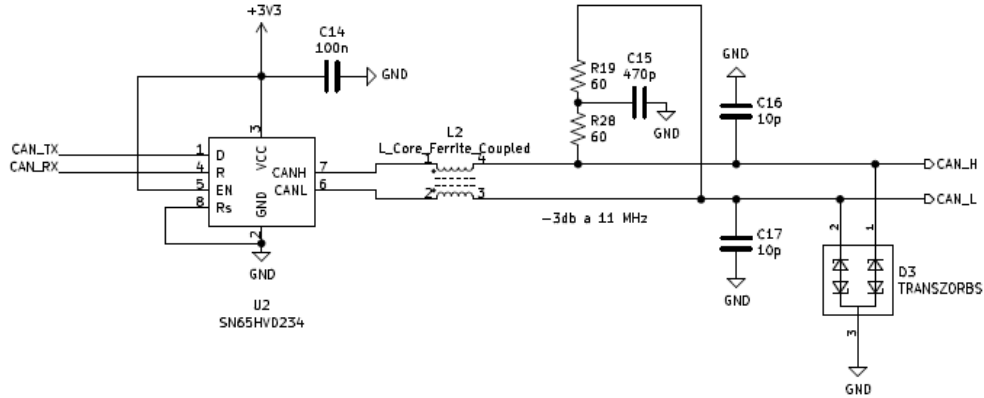


Figure 4.13: Schematic of the transceiver CAN

resistor of 120Ω , as the standard CAN imposes. The CAN of the vehicle must work at 1 Mbit/s, at this speed the line can be considered a transmission line so it is needed to obtain a matched line and attenuate possible reactive waves, thanks to this resistors. Then to terminate the CAN bus, two resistances of 60Ω ($R19$, $R28$) are placed in series between CANH and CANL, otherwise it will be a frame error. A capacitor of 470 pF $C15$ is placed between the 2 resistances to obtain a LPF for the differential line and to attenuate frequencies over the baud rate.

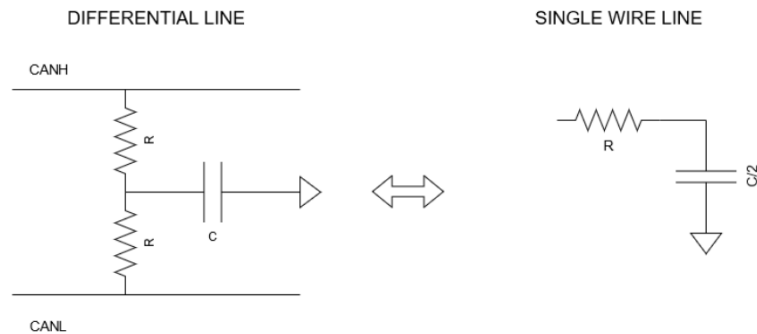


Figure 4.14: Scheme of a LPF for single wire and differential line

$$f_{cut} = \frac{1}{\frac{2 \cdot \pi \cdot R \cdot C}{2}}$$

The cut-off frequency is now set to about 11 MHz, one decade over the baud rate, enough to avoid possible attenuations of the transmission. The Common mode coupled ferrite component $L2$ is used to attenuate the common mode noise over 10 MHz with the auxilium of the two capacitors of 10 pF in each wire of the CAN line.

Finally to protect the transceiver from possible over-voltages from external sources (for example due to mistakes in the cabling), it is a common choice to introduce TVS diodes $D3$ as protection. They must be placed as near as possible the connector of the board. A decoupling capacitor of 100 nF $C14$ is placed on the supply input pin of the transceiver.

4.8.2 Simulations

The simulations are executed to note the behavior of the filters inserted in the transceiver. The schematic used to simulate this circuit is represented in the figure 4.15.

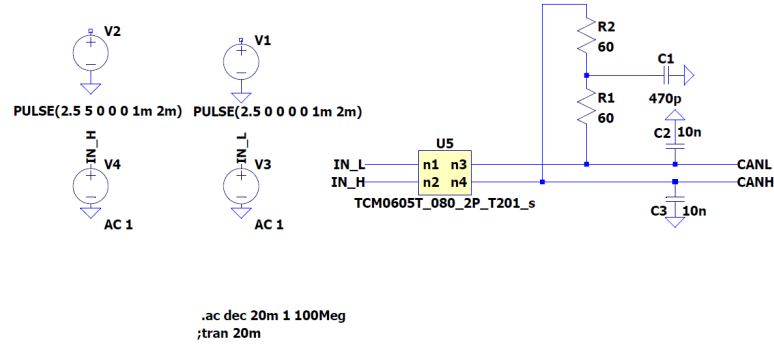


Figure 4.15: Schematic of the simulation circuit of the transceiver filter

The transient simulation, reported in the figure 4.16, explain the output voltage of the CAN wires, CAN H and CAN L the goes from the transceiver to the CAN bus lines. The frequency domain analysis, in the figure 4.17, confirms that the band of the low pass filter is about 10 MHz as designed, and will not disturb the communication at 1 MHz.

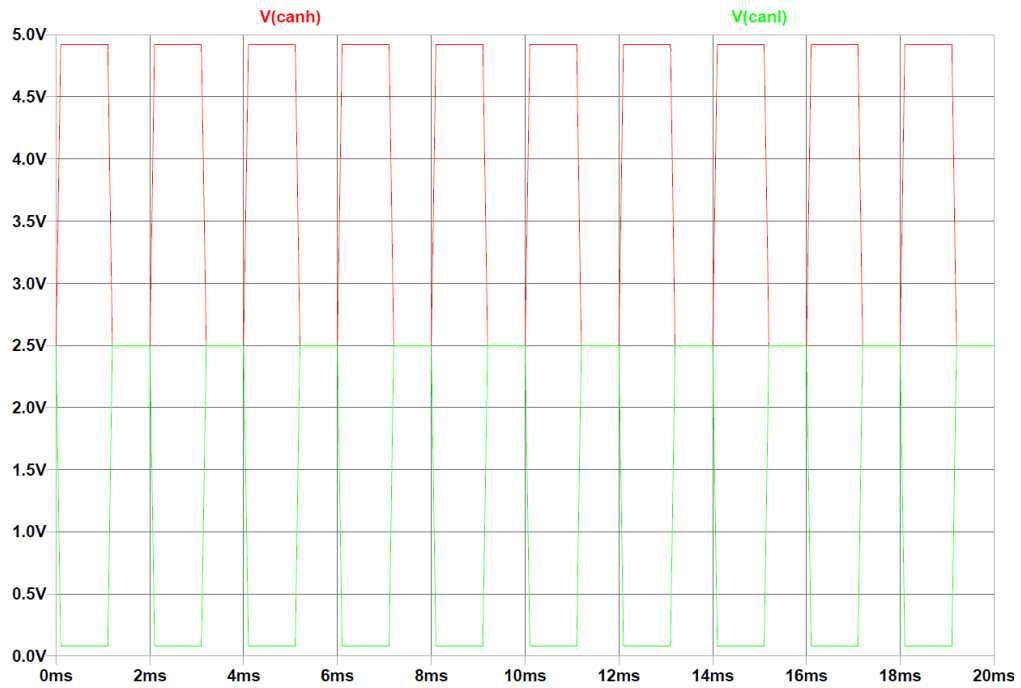


Figure 4.16: Graph of the output voltage of the CAN lines after the filter

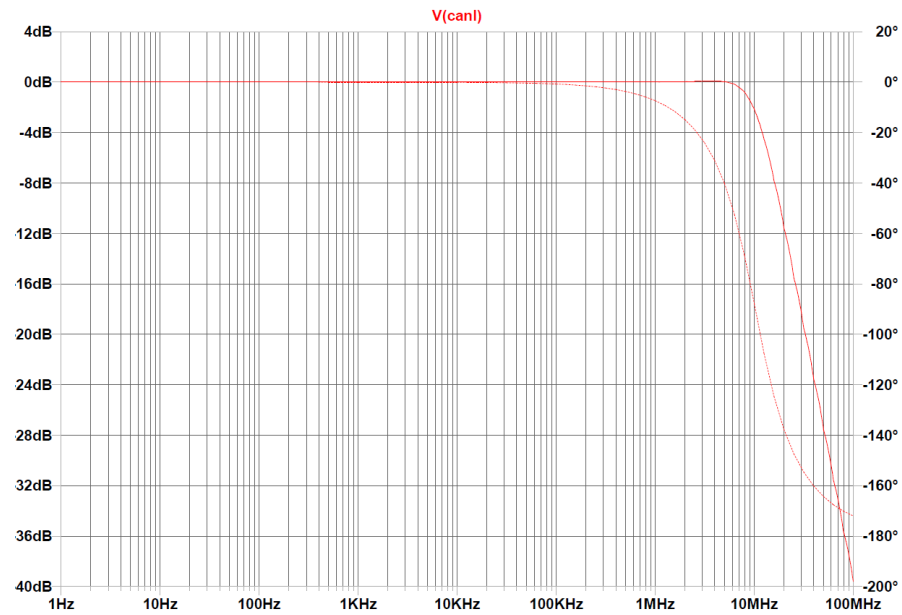


Figure 4.17: Bode diagram of the frequency domain behavior of the transceiver filter

4.9 Current Sensor

4.9.1 Design

The current sensor used to measure the total LV current of the pack, is a Flux-Gate sensor, a *CAS25NP* [17]. Below in figure 4.18 is represented the schematic:

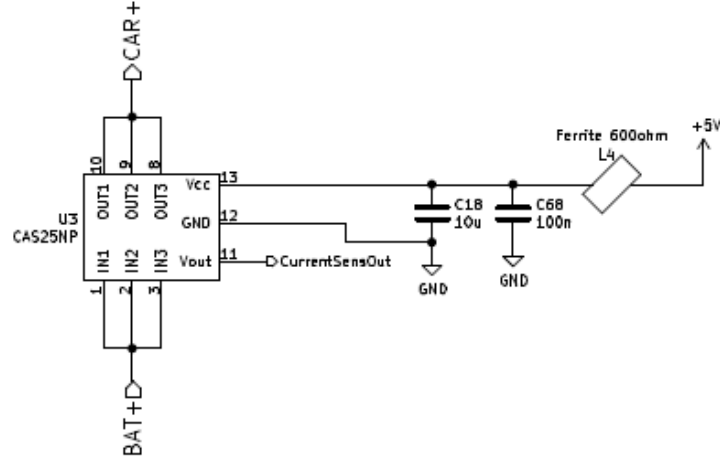


Figure 4.18: Scheme of the current sensor for LV

The component is a through hole technology (THT) device, placed in series with the LV path. The supply pin is filtered using a second order LP filter, in order to reduce noise and to allow a more accurate reading of the current measured.

The output of the sensor, that is available in the V_{out} pin of the sensor, follows this graph 4.20.

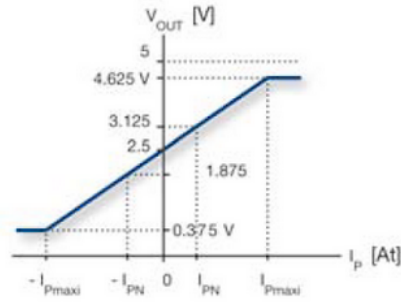


Figure 4.19: Graph of the output characteristic of the current sensor [17]

To be read correctly, as represented in the figure 4.20 without damaging the analog input pin of the Master μC , the range is partitioned in order to scale by factor $\times 0.66$. Then the range goes from 0.375 - 4.625 to 0.248 - 3.053. The capacitor $C13$ in parallel to the signal is used to have a LPF and attenuate noise out the band.

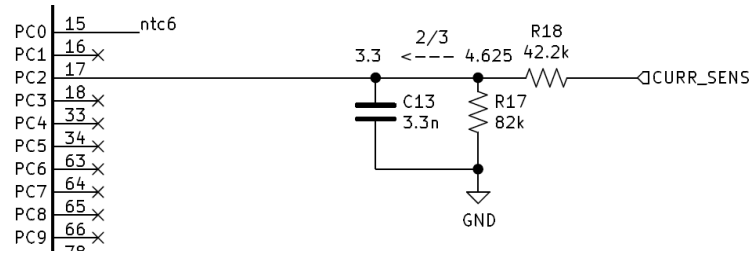


Figure 4.20: Schematic of the connection between μC and current sensor output

4.9.2 Simulations

The simulations performed on the current sensor supply filter are performed using the following circuit in the figure 4.21.

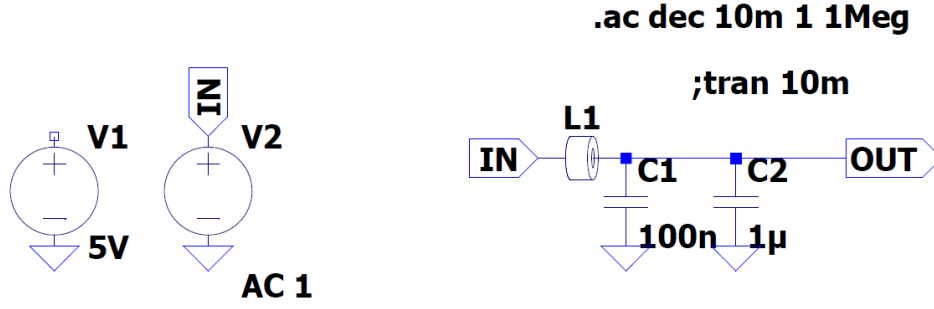


Figure 4.21: Simulation circuit of the filter used for the supply voltage of the current sensor

The frequency domain analysis, in the figure 4.22 explains the band of the low pass filter that will attenuate variations with frequency higher that 100 KHz.

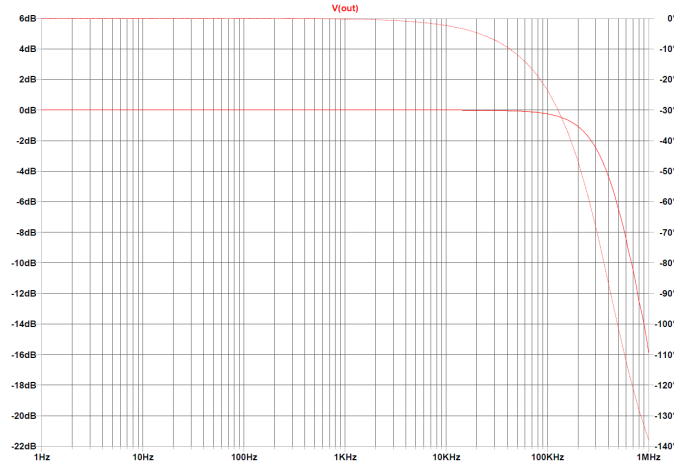


Figure 4.22: Bode diagram of the filter for the supply voltage of the current sensor

4.10 Drivers

The output ports, as shown in the figure 4.23 are protected by using a mosfet in the inverting stage as driver. The 330 k Ω and 330 Ω resistors are used to make the configuration more stable to attenuate from the parasitic effects of the mosfet. In this case the driver must open/close the relay that distributes the LV supply to the rest of the vehicle. The mosfet is connected to the lower side of the relay's coil in the fuse-box, and when output pin goes to 1, the mosfet becomes a short circuit allowing the coil to conduct and to close the switch in series with the LV path.

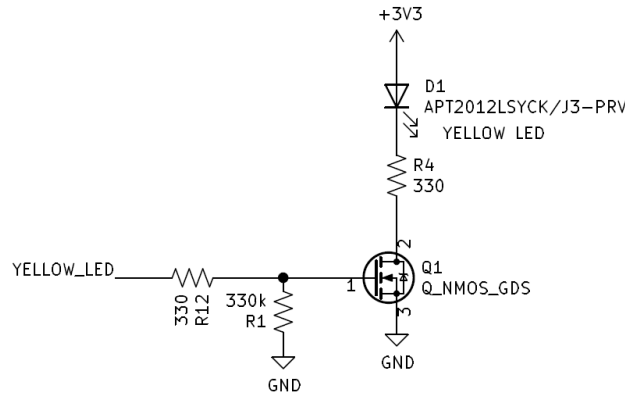


Figure 4.23: Schematic of a driver for a LED

As can be viewed above, these resistors in the gate have been used for all kinds of drivers. In the board, there are 3 different led, one to indicate the SPI communication between Master and Slave, a second to indicate the CAN messages that Master transmits in the vehicle network, and a third red-green-blue led (RGB) to indicate the status of the board. The resistor $R4$ in series with the diode is used to limit the current that can flow in the diode, avoiding a dangerous burning of the led.

$$R4 = \frac{vdd - V_{drop}}{I_d}$$

$$I_{min} < I_d < I_{max}$$

So I_d wanted is 5mA.

These LEDs could be useful in the testing step of the development process. Another digital output port is used to command the Fan in Pulse Width Modulation (PWM) and follows the same schematic as the previous drivers in the gate of the mosfet. The FAN to properly work must have, beyond the supply pins, the control pin set in High impedance (HZ) to work at maximum speed and a 0 logic

to arrest the speed. So this can be easy to solve by using a mosfet in open drain configuration, as shown in the figure 4.24:

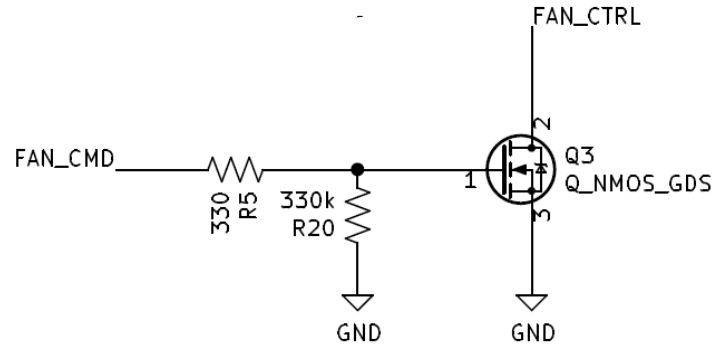


Figure 4.24: Schematic of a driver for the FAN

4.11 Slave monitoring device

4.11.1 Device

The Slave is an *LTC6804* is a multicell battery stack monitor that measures up to 12 series connected battery cells with a total measurement error of less than 1.2 mV. The cell measurement range of 0V to 5V makes the *LTC6804* suitable for this application. It is used within the *LT8584* components, in order to read important parameters of each cell that can be then transmitted to the Master through the SPI communication.

4.11.2 Voltages monitoring

As it is possible to see in the figure 4.25, pins Sx are used to enable the balancing, while the Cx pins are analog input pins, used to read different values provided by the *LT8584*.

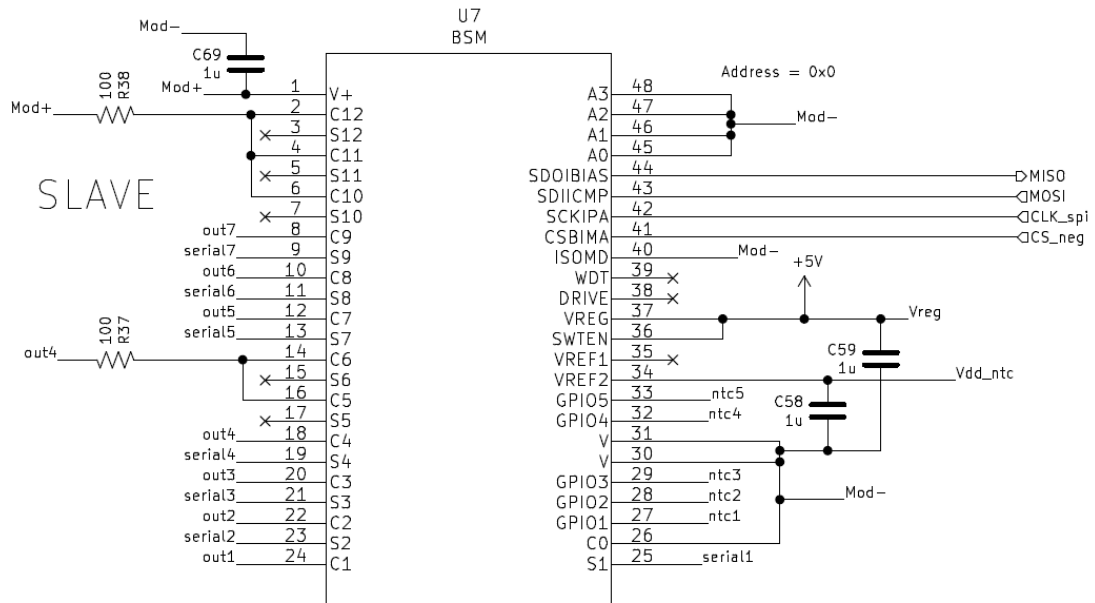


Figure 4.25: Schematic of the *LTC6804* slave monitoring device

Cx pins are part of a system of 2 ADC, as shown in figure 4.26 each with a multiplexer (MUX) of 6 inputs, so the stack must be divided into 2 groups, this is visible thanks to a 100 Ω resistor, set in the top of each group of cells. The group

with lower potential is composed by 4 cells, while the other group by the remaining 3 cells.

The point MOD+ is connected to the higher voltage value of the battery stack,

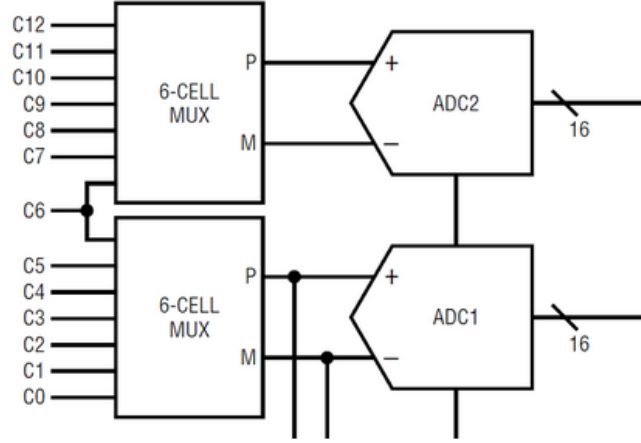


Figure 4.26: Scheme of the ADC system in the slave [18]

that in this case can be at the full charge, 29.4V, while MOD- is the lower potential, that corresponds to the negative pole of the first cell of the stack, at 0V. This level of potential is also used for the GND of the board. Pins Ax are used to set the address of the slave, in the case there will be multiple slaves in the same system. In this case only one slave is needed, so the address can be set to 0x0000.

4.11.3 Temperature monitoring

There also are GPIO pins that can be used as analog input pins, then in this project are used to measure the temperature of the cells, thanks to the Murata NTCs connected in the configuration shown below 4.27:

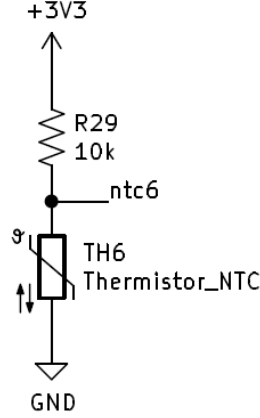


Figure 4.27: Schematic of a conditioning circuit for NTC sensors

This is the most common solution to read NTCs, using a pull up resistor, in this case of 10 $k\Omega$, and then recovered by the equation:

$$T = \frac{1}{\frac{1}{T_0} + \frac{1}{\beta} \cdot \ln\left(\frac{R_T}{R_0}\right)}$$

The whole uncertainty can be calculated by taking into account the following parameter in the table 4.1.

Parameter	Value
T_0	333 °K
β	3380
R_T	3024
R_0	10 $k\Omega$
$\Delta\beta$	0.01 β
ΔR_T	0.01 R_T

Table 4.1: Parameters of the NTC used for the temperature monitoring

$$\frac{\delta T}{\delta \beta} = \frac{T_0 \cdot \ln\left(\frac{R_T}{R_0}\right)}{(T_0 \cdot \ln\left(\frac{R_T}{R_0}\right) + \beta)^2} = -0.0116$$

$$\frac{\delta T}{\delta R_T} = -\frac{\beta T_0^2}{R_T \cdot (\beta + T_0 \cdot \ln \frac{R_T}{R_0})^2} = -0.0108$$

$$\Delta T_{60^\circ} = \left| \frac{\delta T}{\delta \beta} \right| \Delta \beta + \left| \frac{\delta T}{\delta R_T} \right| \Delta R_T = 0.71^\circ C$$

So the uncertainty on the the temperature measurement is at the maximum 0.71 °C Also was added in parallel to the supply for the NTC circuit and for the supply pin of the slave, a decoupling capacitor of 1uF.

NB: due to the fact that NTC to be measured are 6 and there are only 5 GPIOs available, one of the thermostors was linked to an analog input pin of the Master STM32.

4.11.4 Active Balancing

The LV Battery is in the configuration 7s5p, it can be useful to balance cells in order to increment the life of the battery in discharge [19]. This is due to the fact that the charge/discharge of each cell can be influenced by some parameters like temperature, humidity, current, voltage and position in the stack. If a cell presents a different quantity of charge, this must be corrected to allow the battery pack to work at full potential.

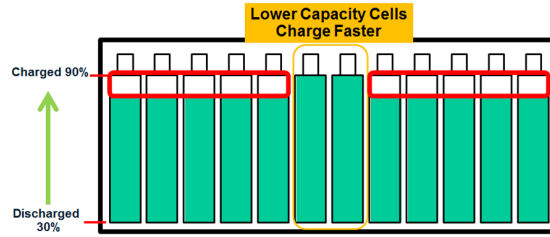


Figure 4.28: Case lower capacity of the stack during charging [19]

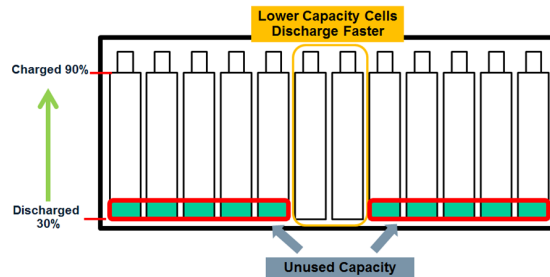


Figure 4.29: Case lower capacity of the stack during discharging [19]

It is possible to divide balancing methods into 2 categories: passive and active solutions. Passive balancing results in all battery cells having a similar SoC by simply dissipating excess charge in a bleed resistor as shown in 4.30;

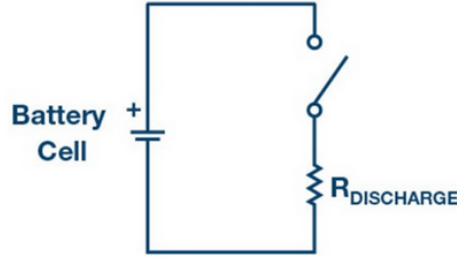


Figure 4.30: Passive balancing, discharging method explanation [20]

It does not, however, extend system run time. Furthermore the energy dissipated in the resistor will become heating and can affect the circuit. Below in the figure 4.31 an example of a typical passive balancing circuit, using the same slave chosen for this project:

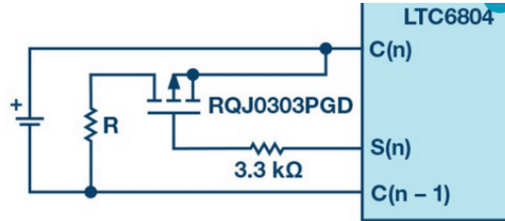


Figure 4.31: Schematic example of a passive balancing circuit with same components used [20]

Active cell balancing instead, is a more complex balancing technique that redistributes charge between battery cells during the charge and discharge cycles, thereby increasing system run time by increasing the total usable charge in the battery stack, decreasing charge time compared with passive balancing, and decreasing heat generated while balancing.

The balancing is applied by discharging the cell more charged with respect the other and the energy is redistributed in all the stack. Every time that the balancing is applied to a cell, the final effect is to recharge all the cells in the series, except the selected one.

The series of the battery stack is seven, so seven *LT8584* must communicate directly with the slave *LTC6804*. The slave will extract cell parameters to be sent to the master by using a particular serial communication with two wires for each *LT8584*, that corresponds to Cx and Sx pins. This components are connected as the schematic below in figure 4.32.

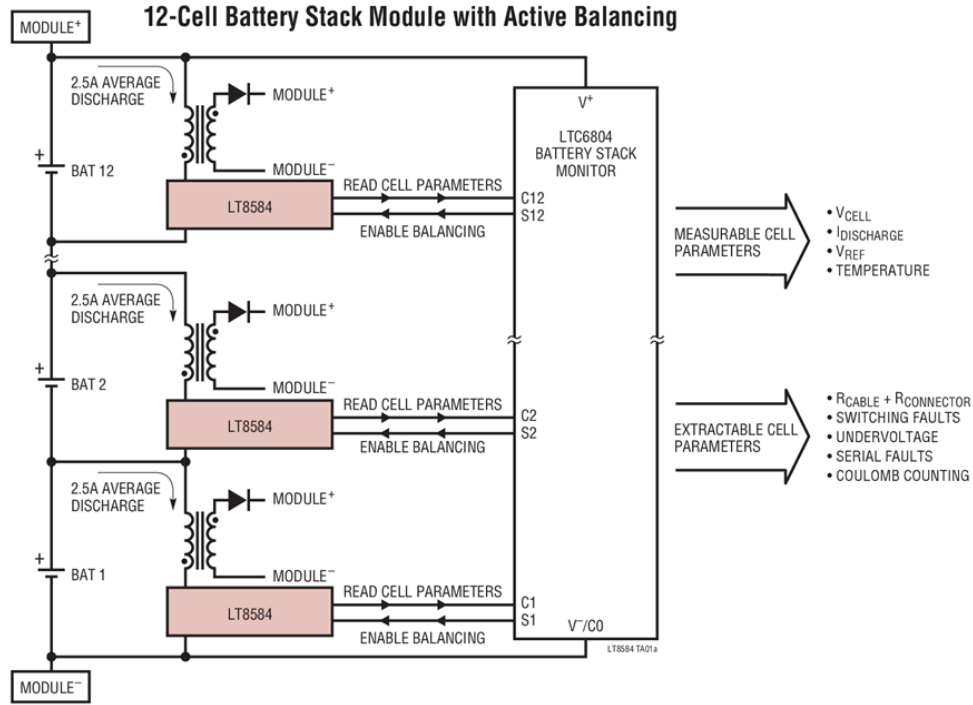


Figure 4.32: Scheme of the connection circuit between *LT8584* balancer and the *LTC6804* slave [19]

In particular, the active balancing proposed needs of a circuit mostly composed of 3 devices, with an appropriate circuitry:

- *LTC6804*, to select the cell to be discharged
- *LT8584* that execute the discharge only for the selected cell
- *NA6252-ALD*, transformers that must transfer the energy from the single cell, to the battery stack

Below the schematic 4.33 implemented for this components: the resistor *R39* of $100k\omega$ is used to set a timer used for the communication with the *LTC6804*, while

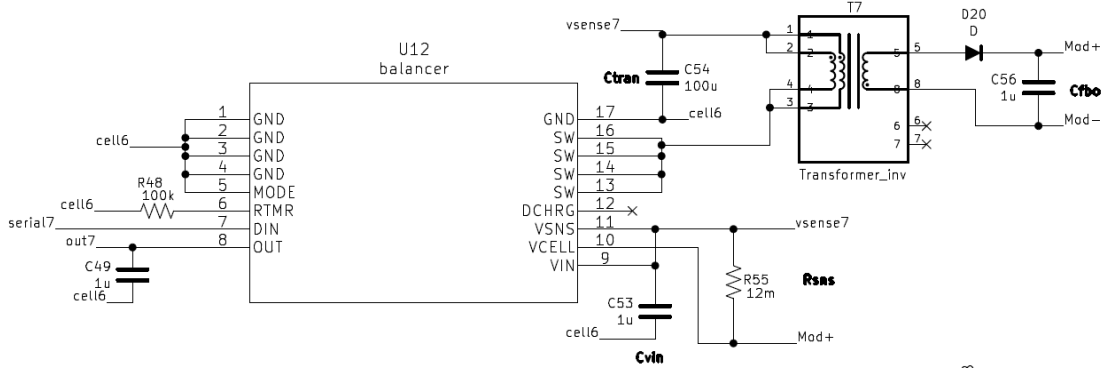


Figure 4.33: Schematic of the external circuit for the LT8584 balancer

the resistor $R55$ of $12m\Omega$ is needed to measure the discharge current during the balancing. The components $C49$, $C53$, $C54$ and $C56$ are used as bypass capacitors, each of them is sized in order to be at least $X5R$. It means that the capacitor in the range -55°C (X) to $+85^{\circ}\text{C}$ (5) could have a maximum variation of the capacity of 15%. This is suggested in the data-sheet of the LT8584, to be sure that the device works correctly.

Speaking of the transformer, it must transfer the energy required during the discharge of the cell, so the behavior must be inverting as shown in the figure 4.34. The secondary coils have opposite signs with respect to the two primary coils.

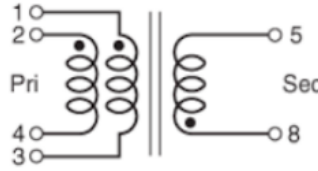


Figure 4.34: Scheme of the transformer NA6252-ALD [21]

In order to charge the stack, the current must flow in the direction of the positive pole.

For the chosen transformer, the turn ratio between primary and secondary coils is 11:15. The diode D15 in the secondary coils path, is used to avoid that energy return back. The output diode is selected based on the maximum repetitive reverse voltage (VRRM) and the average forward current, $I_F(\text{AVG})$ that can tolerate. VRRM must be greater than $V_{\text{module}} + N \cdot V_{\text{in}}$ with N that is the turn ratio.

$$V_{\text{module}} = 29.4V$$

$$V_{\text{in}} = 4.2V$$

Therefore, the LT8584's internal circuitry triggers at 50V, so to be sure to have appropriate OVP, the diode must have $VRRM > V_{module} + N \cdot (50V + V_{in})$. So $VRRM > 89V$. The output diode's forward current $I(AVG)$ should exceed $\frac{I_{peak}}{2N}$, the average short-circuit current. The average diode current is also a function of the output voltage.

$$I_F(avg) = \frac{0.5 \cdot I_{pk} \cdot V_{in}}{V_{module} + N \cdot V_{in}}$$

The *LT8584* in this configuration works in serial mode: this mode allows it to extract more parameters from the cell. In particular is now possible to read:

- Vcell, cell voltage
- Vsns, voltage used to measure the discharge current through the equation:

$$I_{disch} = \frac{V_{cell} - V_{sns}}{R_{sns}}$$

- Vtemp, a voltage proportional to the internal IC temperature to monitor the overheating

The serial mode works in the following way, as described in the graphs 4.36.

When we are in the shutdown mode, the voltage in the output pin of *LT8584* (connected to Cx) will be equal to the voltage of Vin, at the activation of the serial mode, there will be a handshaking window that will last a time that depends on the Rsns chosen. For this purpose, the Rsns is a resistor of 100 kΩ, so the time window will be of 16.3 ms. After this time, in the output pin will be available the selected parameters.

To choose the parameter to be read, it is possible to send a certain number of pulses through the Sx output that is connected to the Din input of the *LT8584*. In particular, the Din signal of the *LT8584* is sent to a counter that selects a certain input of the internal analog MUX and so it is possible to choose the parameters in the output pin. The structure is clearly explained in the scheme 4.35.

The protocol for the choice of the wanted parameters to be extracted, is resumed in the following table 4.36.

The pulse count is referred to the number of pulse that the Slave *LTC6804* will sent to the *LT8584* through the Sx pins. An example of the protocol is reported in the figure 4.37. The average discharge of the cell is about 2.5A. This means that considering that a cell has a capacity of 4753 mAh and due to the configuration 7s5p, the total capacity of the LV pack is then quintupled: so it is about 23.7 Ah. Assuming a charge displacement of the 5% of the pack capacitance, that is 1188 mAh, to rebalance the pack is needed a time about 28 minutes:

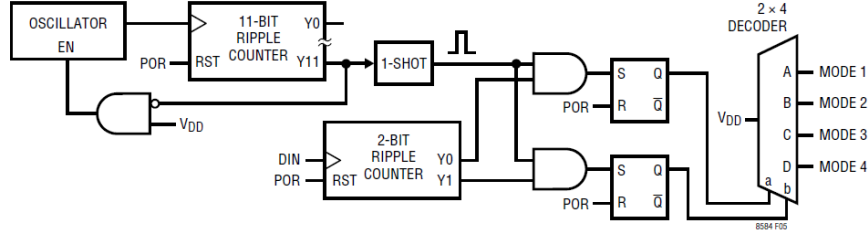


Figure 4.35: Serial communication architecture of the *LT8584* [22]

PULSE COUNT	MODE	DISCHARGER STATE	MUX OUTPUT	HANDSHAKE VOLTAGE ($V_{VIN} - V_{OUT}$)
Part Disabled	0	Disabled	V_{CELL}	N/A
0	Fault	Disabled	V_{FAULT}	1.4
1	1	Enabled	V_{CELL}	0.2
2	2	Enabled	V_{SNS}	0.4
3	3	Enabled	V_{TEMP}	0.6
4	4	Disabled	V_{TEMP}	0.8
≥ 5	Fault	Disabled	V_{FAULT}	1.4

Figure 4.36: Serial mode states [18]

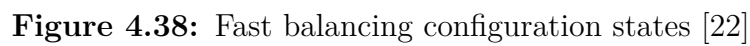
$$time = \frac{Q_{displacement}}{I_{discharge}} \cdot 1h$$

$$time = \frac{1.188Ah}{2.5A} \cdot 60min = 28.5min$$

The time needed to balance the cell is quite long.

To decrease this time, a possibility is to increase the average discharge current of the balancing circuit, but it needs more complex solutions or other components. A possibility, not used in this design, is to use 2 *LT8584* in parallel to discharge up to 5A. Below a possible schematic in fig. 4.38.

In that case the time will be one half, then about 15 minutes. But this means that we will need the double of the *LT8584* and the transformers required, so this would result in a more complex balancing circuit. For this reasons this scenario was discarded.



4.11.5 Simulations

The circuit used to perform the simulation of the active balancing circuit is composed of an IC of the *LT8584*, a transformer and all related capacitor, diodes and resistances, inserted to complete the subcircuit. This circuit is reported in the figure 4.39.

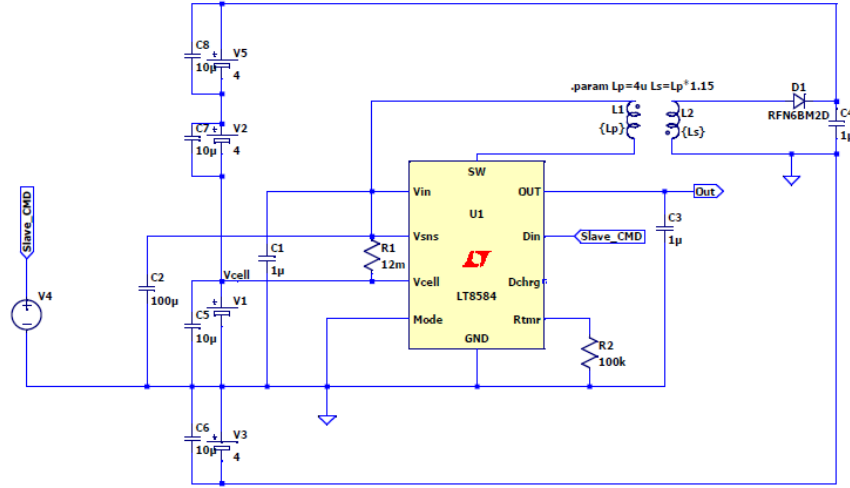


Figure 4.39: Schematic of the balancing circuit simulated on LT Spice

A first analysis is made to control the normal functionality of the balancing circuit, available in the figure 4.40, which means that when the Slave *LTC6804* request data at the *LT8584* through the Din port, the *LT8584* should respond through the port OUT that is directly connected to the *LTC6804* "C" input port, to read data. The behavior is simulated by trying to read the Vsns voltage, a value that allows to read the discharge current that flows through the 12 mΩ resistor and arrive to the transformer that will transfer the energy to the battery stack.

As it is possible to see, when two negative edges are read by the *LT8584*, the device enter in the Mode 2, it means that the voltage on the OUT port will provide the Vsns voltage after the decode window. In this case the device gives a Vout=2.8V. The Vsns value is amplified of 20 times in order to be better readable. To recover the value of the discharge current:

$$I_{discharge} = \frac{V_{cell} - V_{sns}}{20 \cdot R_{sns}} = 5A$$

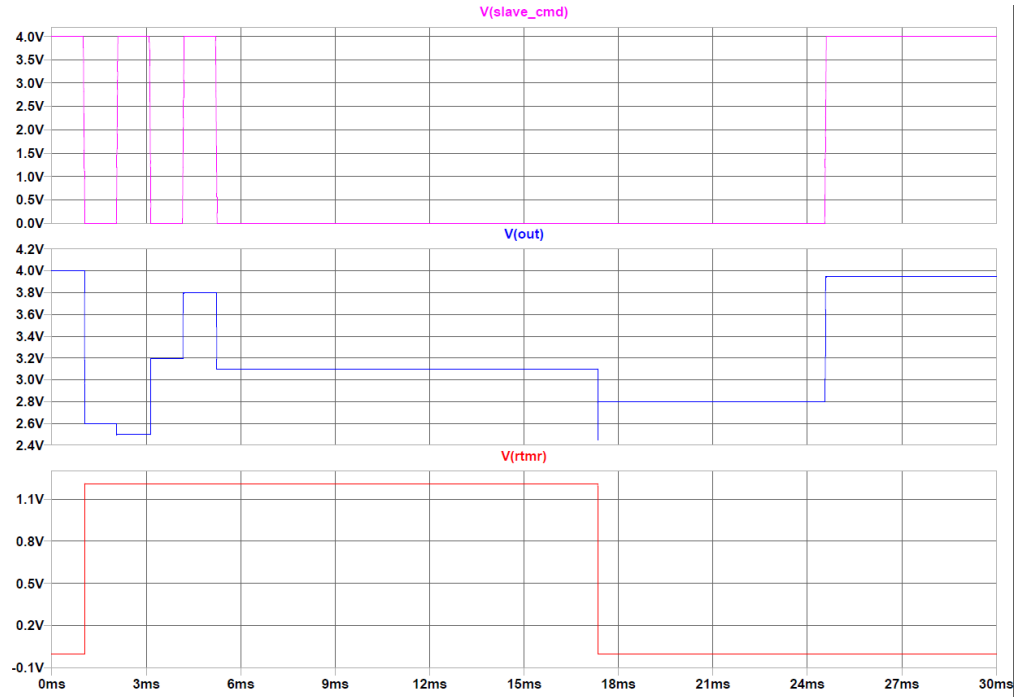


Figure 4.40: Graphs of the waveform given by the procedure to read the V_{sns} voltage value of a cell

The current value corresponds to that showed in the graph 4.41, in which is reported the discharging of the cell. It is possible to note a pulse current with a peak about the 5A, that flows to the transformer's primary winding and then to the diode that guides the current to the battery stack. The discharge starts, one time that the decode window stops and last until the Din pin is reported to Vin voltage that indicate the Shutdown state for the *LT8584* device.

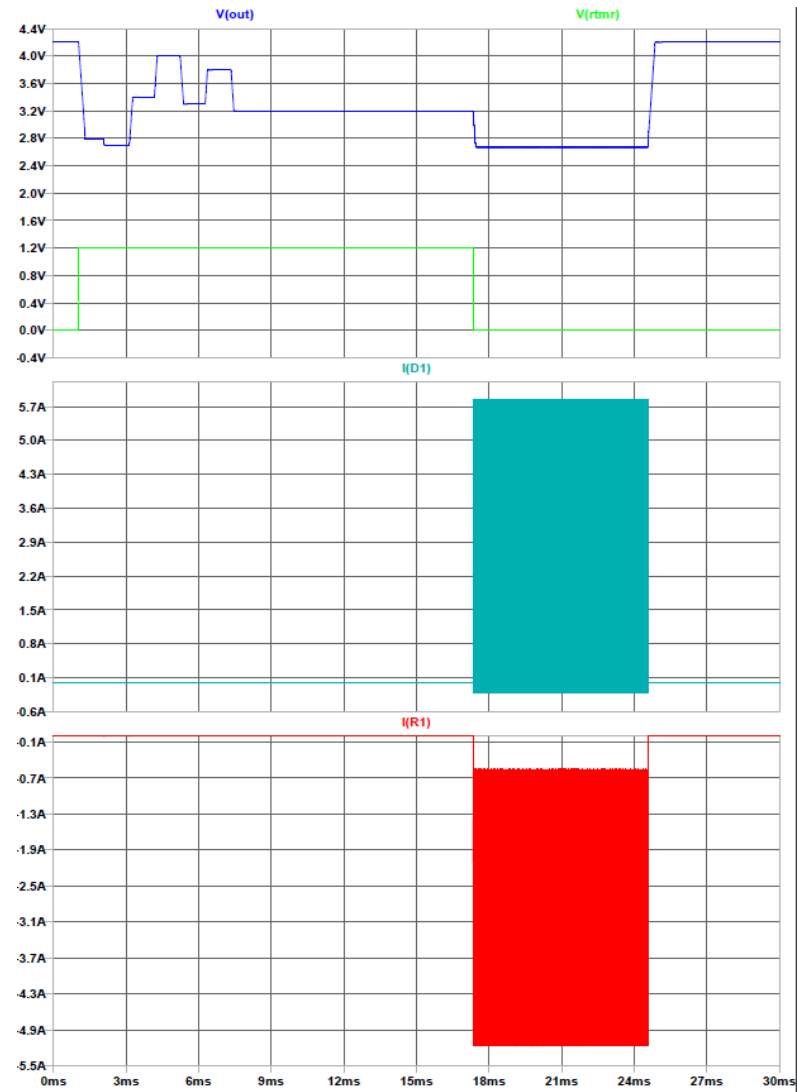


Figure 4.41: Graph of the waveforms that starts when the discharge of a cell is enabled

The discharge current is composed of a series of pulses with a peak that can reach 6A and a nominal value that is about 2.5A. To note in details this shapes, it is possible to see the figure 4.42, in which are indicated the wave forms of the discharge current and the voltage in the SW port. The behavior of the waveforms is correct and corresponds to what is indicated in the datasheet of the device.

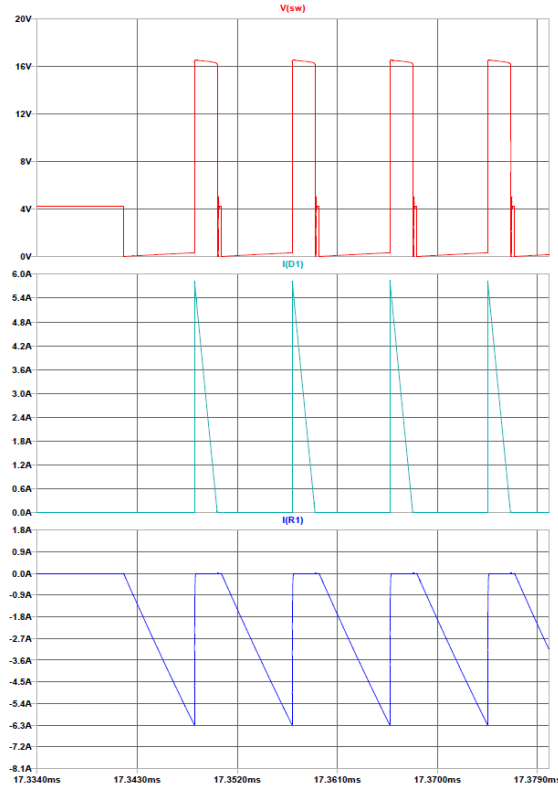


Figure 4.42: Graph of the waveforms in details during the discharging of a cell

Other analysis has been performed in order to consider fault situations that can affect the reliability of the system. For example, in the figure 4.43, is reported the status in which an error of communication occurs.

In particular, in this case, the wake up signal sent from the *LTC6804* to the *LT8584* device hasn't enough edges, so in this case the value of the voltage in the OUT port, after the decode window, is equal to the fault voltage:

$$V_{FAULT} = V_{in} - 1.4V = 2.6V$$

Another fault communication can happen if the number of edges is more than 4, as in the figure 4.44, in this case the voltage value of the OUT pin is always the FAULT voltage value.

A last FAULT situation is reported when the cell suffers for example, an under voltage condition, in this case the device sent the OUT value to the voltage fault value, and remain in that state until a Shutdown is reclaimed by the *LTC6804*. The condition is reported in the figure 4.45.

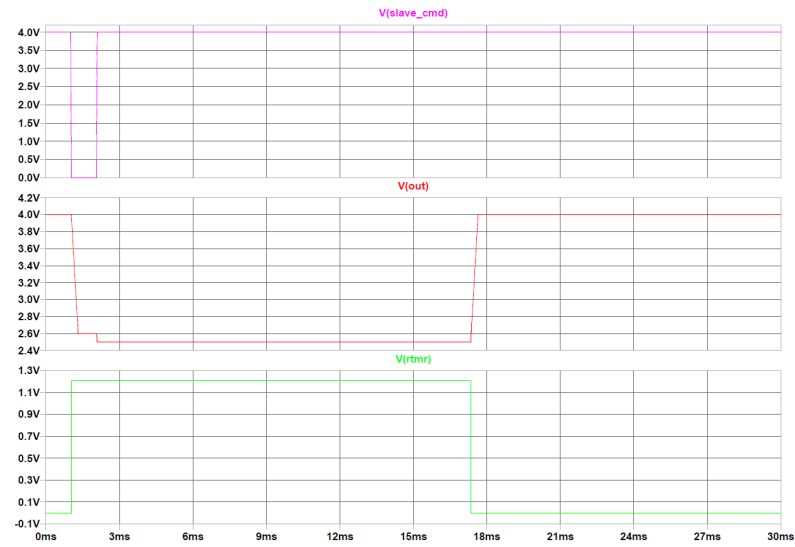


Figure 4.43: Graph of the fault situation in communication with not enough edges

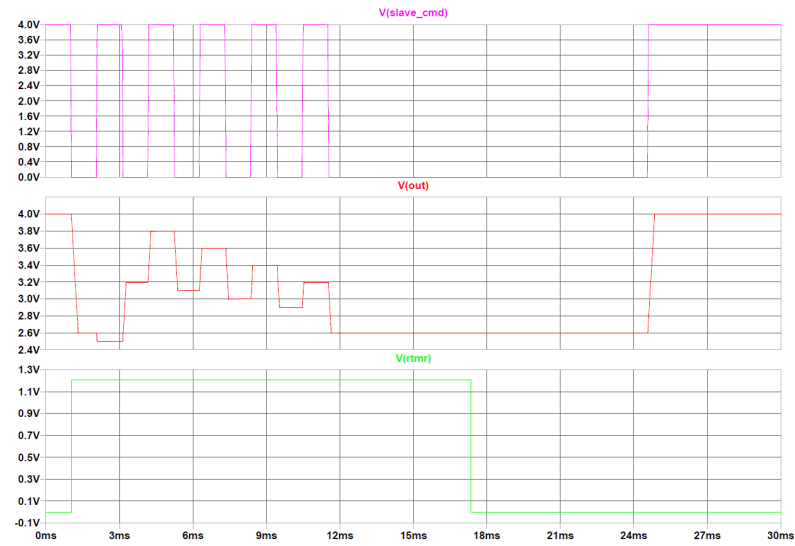


Figure 4.44: Graph of the fault situation in communication with too many edges

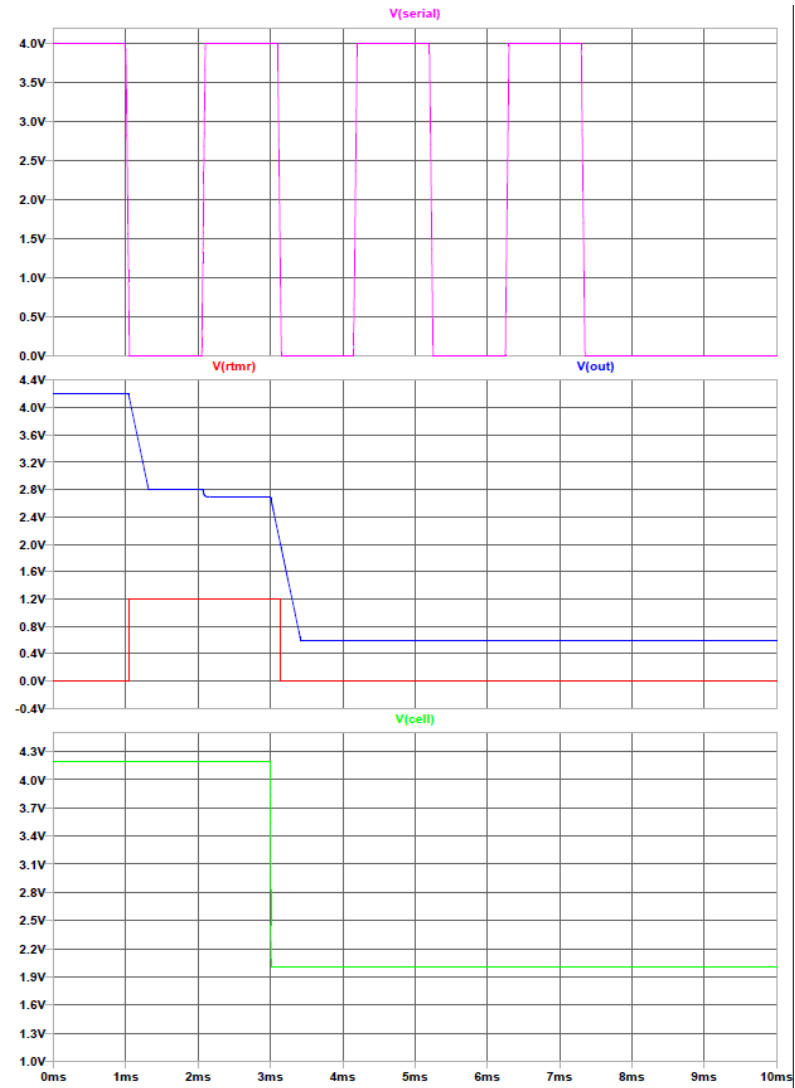


Figure 4.45: Graph of the fault situation in case of a cell in UV

4.12 PCB layout

The PCB of this board is structured into four Copper (Cu) layers, in order to be capable to complete all connections designed into the schematic. The front and back layers, respectively in red and green, are used mostly for the signals, while the internal upper Cu layer is used as ground plane, that in this way will give two main advantages: the easiness of connection for all the pins short circuited to ground, because all are routed directly through a hole in the board to the ground plane; the large area of copper also conducts the large return currents from many components without significant voltage drops, ensuring that the ground connection of all the components should be at the same reference potential. The internal downer layer is used to help to link thermistors contacts that are placed all around the board and all other signals distributed in the busiest areas.

The edges of the board has been decided by the structure of the LV supply, in fact this board should be placed above the LV battery pack. In the upper side of the LV pack, all the voltages connections of the cells' series are available to be connected to the board thanks to some Tin's square areas. At the same way the connection wires of the NTCs will reach the board, being soldered into smaller Tin square areas. The particular is visible in the picture 4.46.

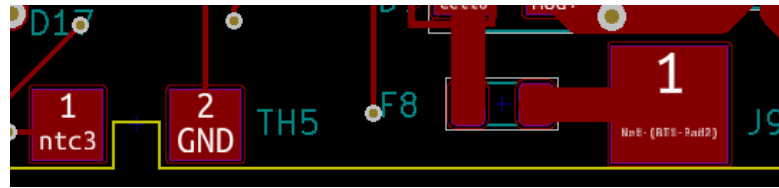


Figure 4.46: View of the layout for soldering point to connect to the thermistors on the left and cells terminals on the right

About the layout settings, the PCB has been designed, respecting the following characteristics:

- 4 layers
- components mounted in the both sides of the board
- thickness of the printed circuit at 1.6 mm
- track thickness set at 0.25mm, 0.4mm and 1.5mm, based on the current that could pass on the path. A larger track will dissipate better the increasing of temperature due to the current

The PCB layout has been designed by subdividing the board into three zones:

1. Power supply
2. MCU
3. Balancing

The first zone is composed of all components needed to manage the supply of the whole board and it will provide as output 5V and 3.3V as supply voltages. In the picture 4.47 a detail of the layout of this zone:

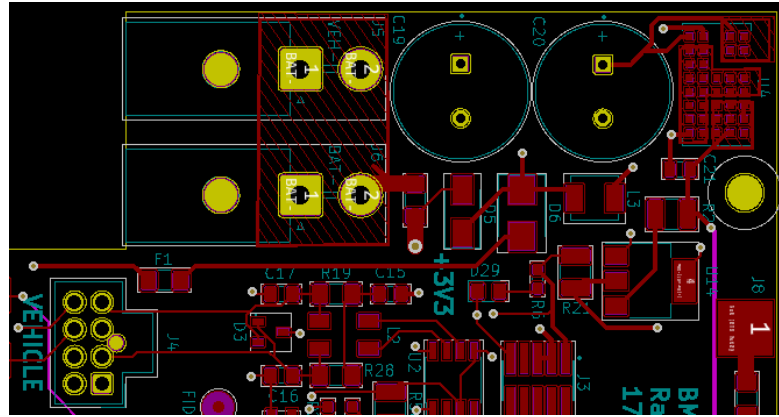


Figure 4.47: Layout of the supply circuit zone

The connection path, that starts from the Molex connector in which the nominal 24V arrives from the LV master switch, go through all needed components before to supply all devices.

The second zone is occupied by most of the components related to the MCU circuit, and are placed indicatively on the left center of the board, to easily allow to link all wires.

The second zone is related to all circuits near the MCU, included the slave device. This area represents the core of the system, in which most of the connections should arrive. A figure of the zone is available in the figure 4.48.

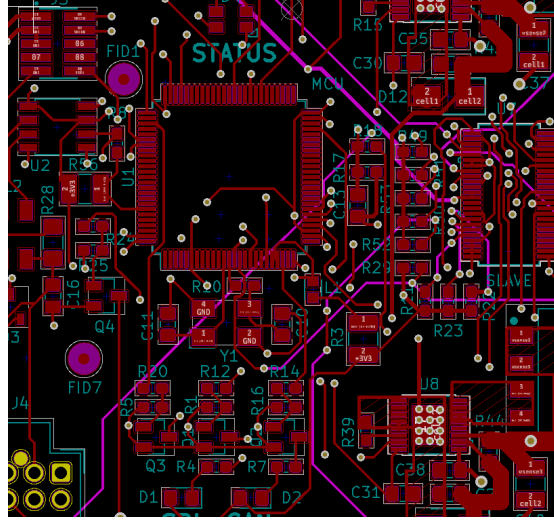


Figure 4.48: Layout of the MCU zone, in the left side the master and in the right one, the slave device

It is possible to note the large number of components and connections passing on this area. To ensure that the connections could be completed, a possible rule to follow could be to draw all horizontal lines using the back layers and all the vertical lines using the front Cu layer: in this way, a best number of back doors can be used.

The third zone is the place of the balancing circuit, that occupied an area of more than a half of the surface of the board, due to the bulky component of the circuit, like the transformers and for the larger lines introduced to better dissipate the current that will pass through them. A picture of this zone can be found in this figure 4.49.

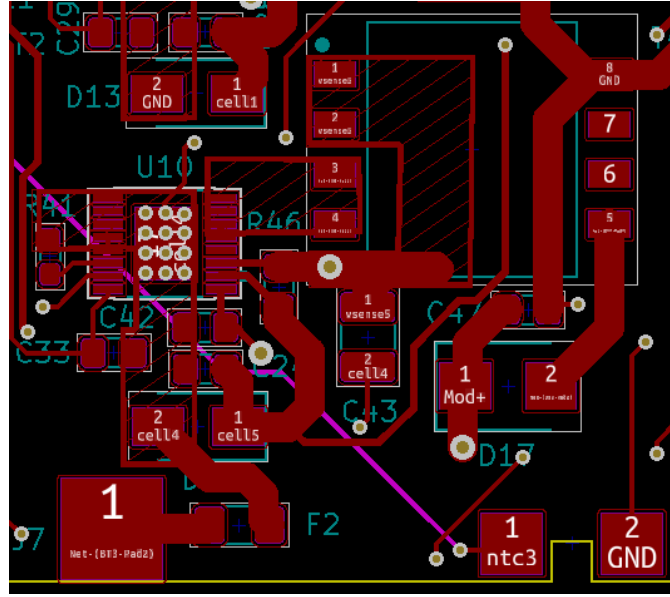


Figure 4.49: Layout of the balancing circuit for a cell, with the LT8584 in the left and the transformer in the right

For each transformer, the recommended layout from the datasheet of the component has been utilized. This layout requires the design of zones entirely covered of Cu in order to better dissipate the temperature increasing. To support this planning, some vias are included in the design, because this holes will help to dissipate heating.

Then, the final appearance of the PCB layout is represented in the figure 4.50 with a view of the front and figure 4.51 for the back side.

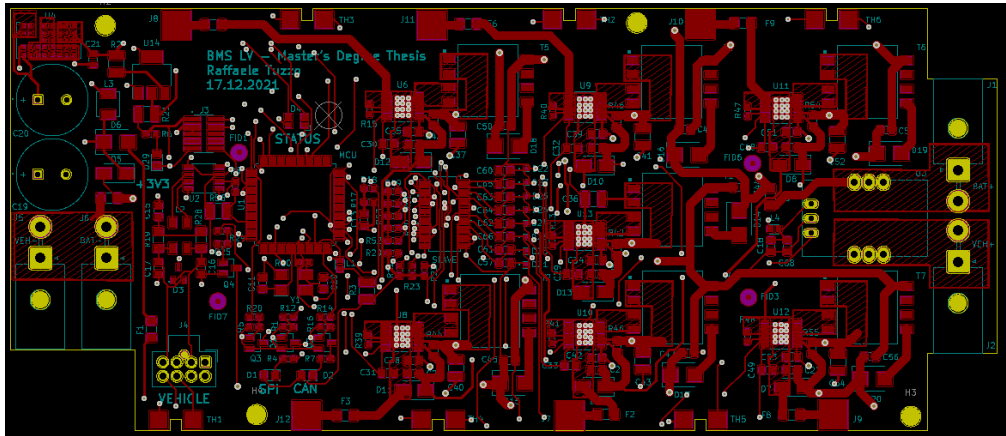


Figure 4.50: View of the PCB's front side for the BMS Low Voltage

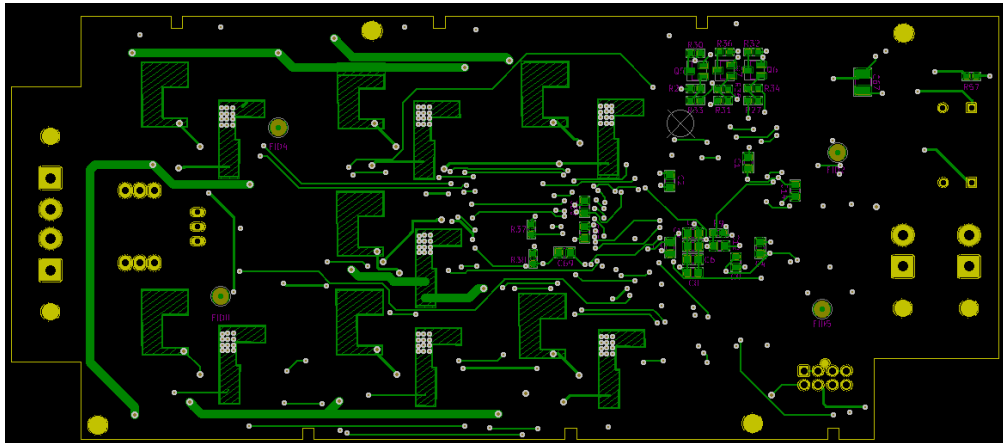


Figure 4.51: View of the PCB's rear side for the BMS Low Voltage

4.13 CAD 3D

In this last section, some images of the 3D cad of the BMS LV project are inserted. In particular, the picture 4.55 represent a transverse view of the board, while the picture 4.52, 4.53 and 4.54 contains respectively the front, back and lateral right view. Each component has been accurately reported in the CAD, including the connectors, in this way a check of the encumbrances in the board could be done.

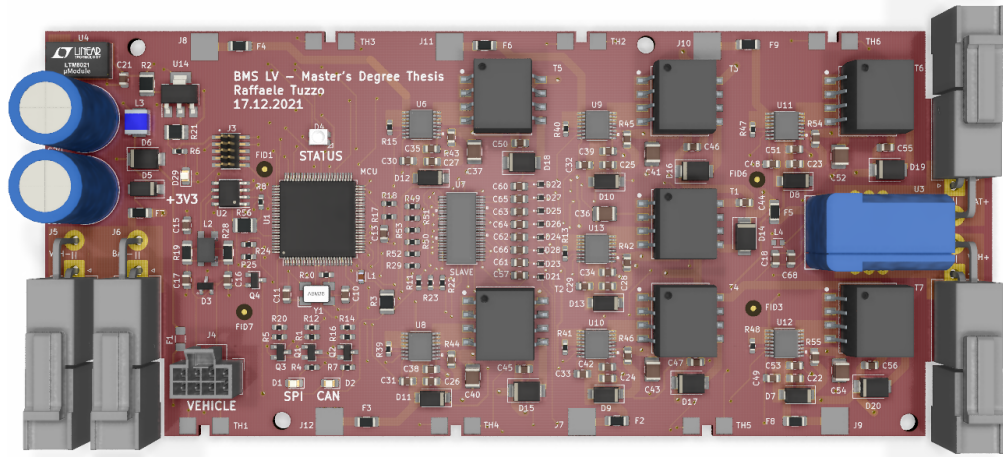


Figure 4.52: View of the BMS LV board from above

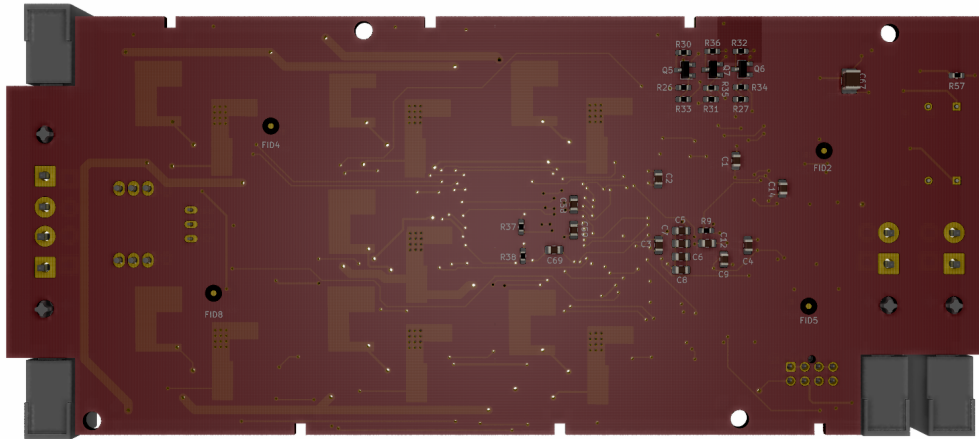


Figure 4.53: View of the BMS LV board from below



Figure 4.54: View of the BMS LV board from the lateral side

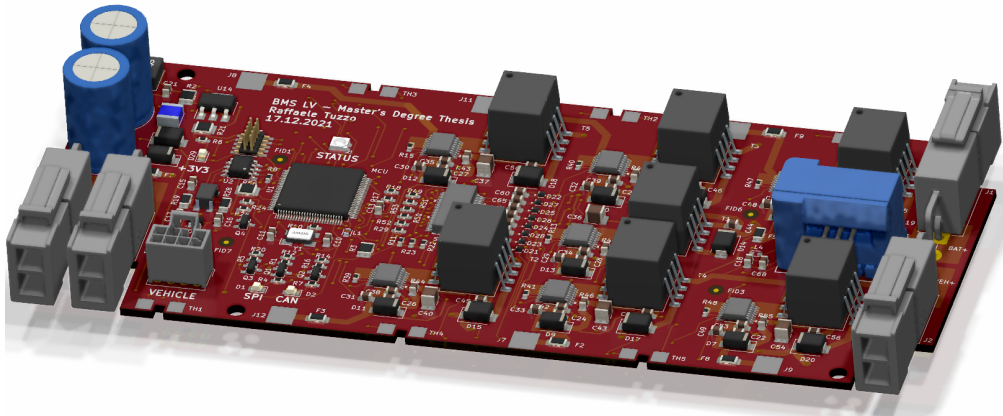


Figure 4.55: View of the BMS LV board from the trasnversal side

Chapter 5

Conclusions

This project provided a detailed analysis of a full electric vehicle for FSAE competition. The arguments discussed, described the whole electric and electronic system of the vehicle, looking to provide a details point of view of each component, but at the same time offering a system point of view of the various areas in the vehicle. Therefore, a solution about the issues encountered in the analysis of the vehicle is given in this paper, helping the future designs of this kind of vehicle.

This work resumed a dedication of almost two years in the design and realization of this vehicle, in collaboration with the members of the Squadra Corse PoliTO team. Moreover, an improved battery management system was fully designed and simulated, with an active balancing system, in order to bring this technology for future developments, not only for the low voltage system but also for the high voltage accumulator.

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