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Power converter design for eMotor test rig

Relatori
Prof. Eric Armando
Dr. Fabio Mandrile

Candidato
Matteo De Bianchi

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Summary

Power electronics has revolutionized the way we transform, control, and distribute electrical energy. Inverters are a fundamental component in this landscape, enabling the efficient conversion of energy from DC to AC. Specifically, inverters accepting higher voltages, such as those at 800V, have sparked increasing interest in the automotive field because operating at 800V rather than the more conventional 400V enables several advantages, including support faster charging speeds and lower current requirements, enhancing energy efficiency and reducing energy losses. In order to ensure the correct operation of the inverter a control board is required. This board is a complex electronic unit that coordinates and regulates numerous processes within the inverter to ensure that the energy conversion occurs efficiently and safely. This thesis deals with the hardware design of a control board for a three phase inverter supplying an eMotor test rig and a DC-side board for managing the high voltage side of the system. The rating of the inverter is 800V and can handle 360 Arms with a typical switching frequency of 20 kHz.

Acknowledgements

Desidero esprimere la mia sincera gratitudine alle persone che hanno reso possibile la realizzazione di questa tesi. Prima di tutto, vorrei ringraziare i miei supervisori, il professor Eric Armando e l'ingegner Fabio Mandrile, per il loro sostegno e i preziosi consigli che hanno contribuito in modo significativo al successo di questo lavoro. Un ringraziamento speciale va anche ai membri della mia famiglia per il loro costante sostegno, incoraggiamento e comprensione durante il mio percorso accademico, in particolare a due persone, a mia Mamma e alla mia fidanzata Elisa. Senza il loro sostegno, non avrei potuto raggiungere questo traguardo.

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Chapter 1

Introduction

Power electronics has revolutionized the way we transform, control, and distribute electrical energy. Inverters are a fundamental component in this landscape, enabling the efficient conversion of energy from DC to AC. Specifically, inverters accepting higher voltages, such as those at 800V, have sparked increasing interest in the automotive field because operating at 800V rather than the more conventional 400V enables several advantages, including support faster charging speeds and lower current requirements, enhancing energy efficiency and reducing energy losses. The inverter used is shown in Fig.1.1. It works at 800V and can handle 360 Arms with a typical switching frequency of 20 kHz

Figure 1.1: Picture of the converter[1].

In order to ensure the correct operation of the inverter a control board is required. This board is a complex electronic unit that coordinates and regulates numerous processes within the inverter to ensure that the energy conversion occurs efficiently and safely. The main functions of an inverter's control board:

1. **Power Control:** The control board manages the power flow of the inverter. It monitors voltage, current, and other variables to regulate the flow of energy from the source to the load. For example, it can manage the torque/speed control of an electric motor, or the energy production of a grid-connected inverter interfacing renewable energy sources
2. **Temperature and Protection Control:** It monitors the temperature of the inverter and its components, activating cooling systems or reducing power if temperature levels exceed safety limits. Additionally, it triggers protective measures to prevent short circuits, overcurrents, or overvoltages that could damage the inverter.
3. **Communication Interface and External Control:** The control board often includes interfaces to communicate with other systems, such as computers or external control devices. This communication enables remote monitoring, operator control, or integration with other system components.
4. **Control and Optimization Algorithms:** It employs algorithms to ensure maximum efficiency in the inverter's operation.

This thesis aims to build a control board for an 800 V inverter and integrate it with the PEIC Lab environment. The overall control scheme is shown in Fig.1.2, which presents compatibility and integration issues:

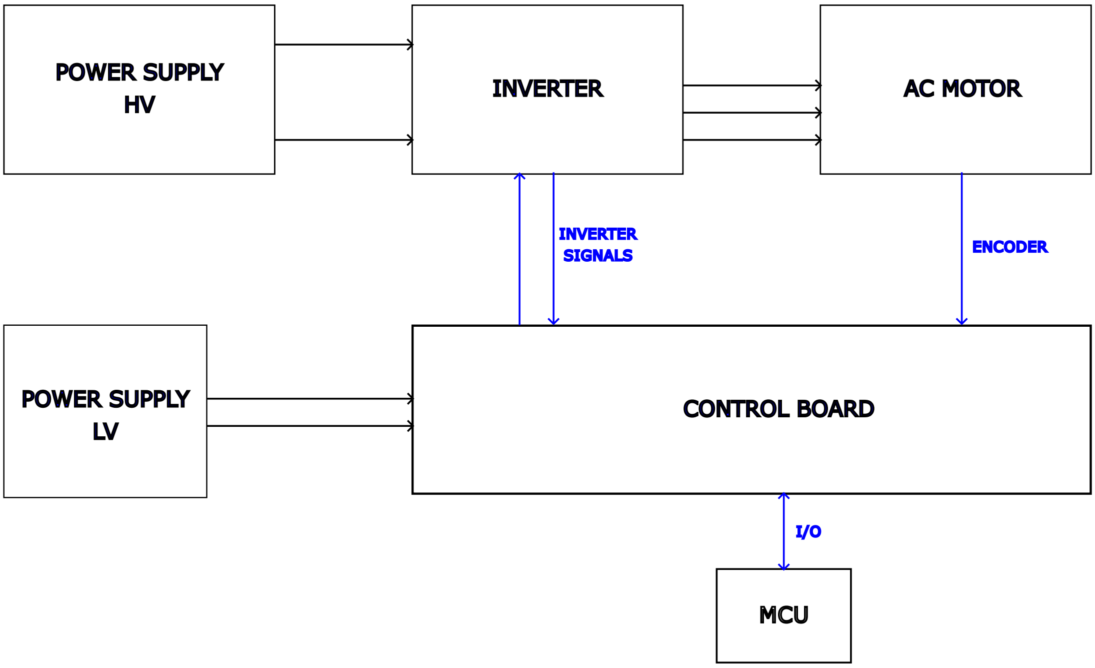

Figure 1.2: Block diagram of the converter.

The current configuration presents only the inverter and its control board with one connector for encoder signals, one for CAN communications and one for external connector used for current-sensing. The DC side of the inverter could be connected to the power supply but there are no filters or circuit breakers. The same considerations for the low voltage control board power supply. The signals between the inverter and the board are the leg signals, VDC and currents measurements, inverter cooling fan actuators and 3 temperature measurements. This configuration is not optimal and the main problems can be reduced to the following points:

1. **Single-ended Encoder:** Single-ended signaling transmits an electrical signal over a single wire, relying on the ground wire to provide a reference point. This approach offers simplicity and cost-effectiveness, but it's susceptible to noise interference due to its reliance on a single reference point.

2. **Filters:** there are no EMI filters and this could lead to voltage and current distortions in the electrical supply, affecting the stability and quality of the power output or the inverter might generate electromagnetic interference that can cause operational issues or malfunctions to the nearby electronic devices or systems.

3. **External connectors:** The current connectors aren't enough for sensors, such as the torquemeter, the flow sensor and the temperature sensors (PT100).

4. **DC side management:** The high-voltage DC side is not managed at all. There is no circuit breaker, no emergency button and and no emergency sequence. Furthermore, the logic managing the startup and shut down is needed. all of these omissions can lead to hazardous situations when the DC-link bank capacitors are charged or are short circuit occurs.

5. **MCU:** The inverter is currently equipped with the control board shown in Fig.1.3, in this setup the microcontroller (MCU) is separated from the board and it is located on a Texas Instruments evaluation board, limiting its versatility in interacting with external components. Moreover in PEIC laboratory STM is the preferred choice.

Figure 1.3: Picture of the existing TI control board[1].

To solve these difficulties a complete re-design control board was done, preserving almost the same dimensions of the original PCB but with different components on it. Firstly the MCU was mounted directly on the board and also there are new connectors and the power supply has been redesigned to supply new sensors such as the torquemeter and the cooling flow sensor. It has been planned an emergency sequence which it can be activated either by the MCU or by the emergency button connected to the board. The lack of safety and control for the DC side are managed with a detached board and an EMI filter before the inverter DC link. On this board there is the logic managing the circuit breaker and various general purpose relays. A complete block scheme of the new setup is shown in Fig.1.4

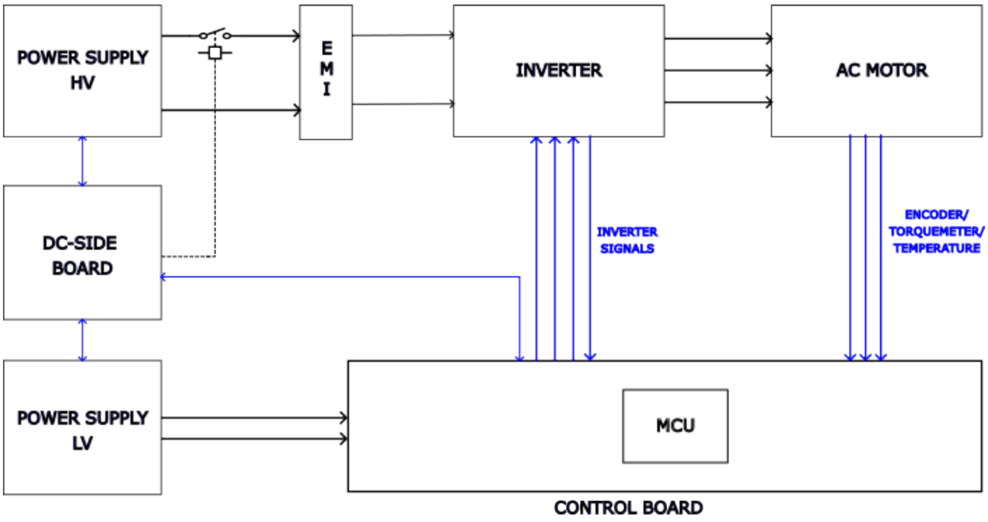

Figure 1.4: Block diagram of the new system.

Chapter 2

DC Side Board

The DC side control board, is an electronic circuit board that regulates and manages the power flow on the DC side of the inverter. It's been used particularly to control the startup and shut down of the inverter and for the auxiliaries supply such as cooling fans and relays. Figure 2.1 depicts the configuration of the board's constituent blocks, all of those then are linked to the DC-side connector, the interface between this board and the control board.

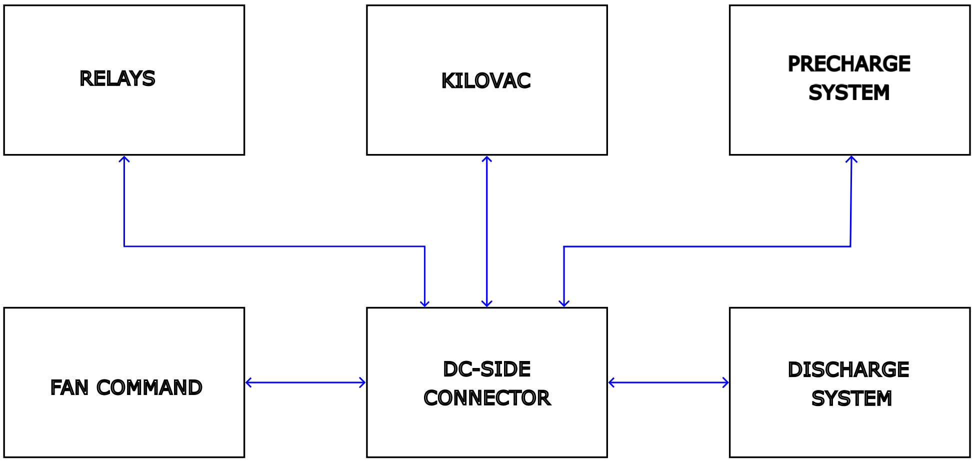

Figure 2.1: Block diagram of the DC link management board.

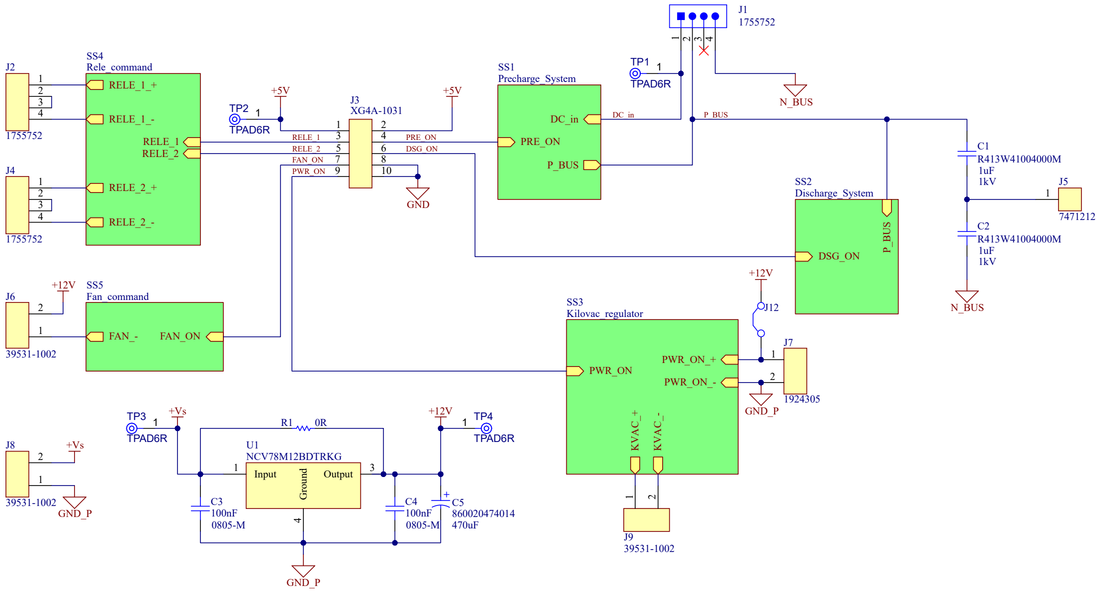

Figure 2.2: DC-SIDE Altium schematic.

Fig. 2.2 shows the internal schematic. 5V supply comes from the control board through the XG4 connector where also the MCU signals (PWR-ON, DSG-ON, ecc) are provided. There is also another supply specific for the DC-side board coming from connector J5. Since this board can be used for different applications with different voltages but all the components run at 12V is necessary to place a voltage regulator like U1 to have more flexibility. If the supply +Vs is already 12V U1 can be bypassed by a 0R.

2.1 Kilovac regulator

Kilovac LEV200 is a series of high-voltage relayS from TE Connectivity. They are designed for use in a variety of applications, including power generation, power transmission, and industrial automation. In this application, it is used the LEV200 A4NAA illustrated in Fig. **??**.

Figure 2.3: Picture of the LEV200A4NAA[2].

Here are some of the key features of the Kilovac LEV200 A4NAA [2]:

- High voltage ratings: available with voltage ratings up to 900VDC.
- High current ratings: available with current ratings up to 500A.
- Wide operating temperature range: The LEV200 can operate in temperatures from -40°C to +85°C.
- Compliance with various safety standards: The LEV200 series is compliant with various safety standards, including IEC 61800-5-1 and IEC 60947-5-1

The Kilovac regulator system (Fig.2.4) has been made to better control the voltage across the coil, which helps reduce the power consumption of the device.

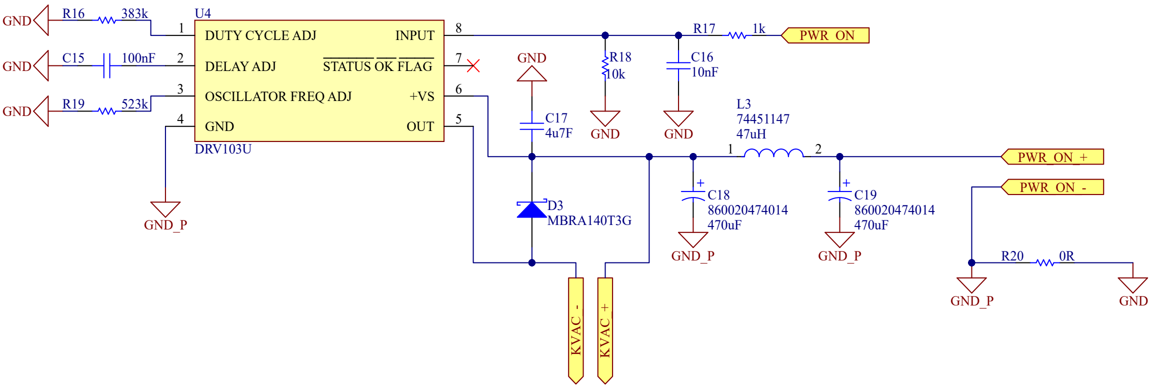

Figure 2.4: Kilovac regulator scheme.

In the scheme there are different components, the core is the DRV103U and then there is a CLC filter (C18, C19, L3) for the 12V supply, another filter (C16) for the MCU signal PWR-ON, other tuning resistance and capacitance (R16, R19, C15) and a schottky diode (D3). The DRV103U is a low-side DMOS power switch employing a pulse-width modulated (PWM) output. PWM operation conserves power and reduces heat rise, resulting in higher reliability and in addition, adjustable PWM allows fine control of the power delivered to the load [3].

2.1.1 Operating principles

During the startup phase, PWR-ON signal is sent by the MCU and the DRV103U is enabled. The driver enables the coil of the Kilovac at nominal voltage and after a defined time it starts modulating.

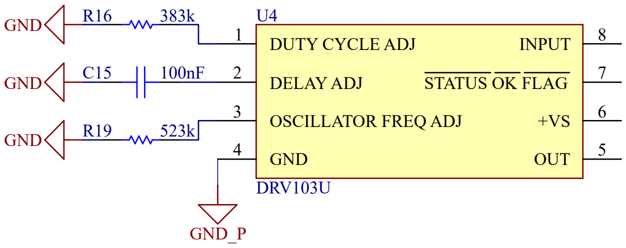

Figure 2.5: DRV103U tuning pins.

Pin 1 is responsible for the duty cycle adjustment. In this application the nominal voltage is 12V but from laboratory test, the minimum voltage required for the coil to keep the contact closed is around 3V. So the calculation for the duty cycles are:

$$D = \frac{V_{OUT}}{V_{in}} = \frac{3}{12} = 0.25 \tag{2.1}$$

where D is the duty-cycle, V_{out} is the output required voltage (3V) and V_{in} is the nominal input voltage (12V). Since the the coil resistance of the contactor is (R_{coil}) 11Ω the power consumption can be lowered from:

$$P_1 = \frac{V_{OUT1}^2}{R_{coil}} = \frac{12^2}{11} \cong 13W \tag{2.2}$$

To:

$$P_2 = \frac{V_{OUT2}^2}{R_{coil}} = \frac{3^2}{11} \cong 0.8W \tag{2.3}$$

Duty cycle is easily programmable by connecting a resistor R_{pwm} between the Duty Cycle Adjust pin (pin 1) and ground.

Table 2.1: Duty Cycle R_{PWM} (Nearest 1% Values) [3].

(%)	5kHz	25kHz	100kHz
5	374k	75k	16.9k
10	402k	80.6k	19.1k
20	475k	95.3k	22.6k
30	549k	110k	26.1k
40	619k	124k	29.4k
50	681k	137k	33.2k
60	750k	150k	37.4k
70	825k	165k	40.2k
80	887k	182k	44.2k
90	953k	196k	47.5k
95	1M	200k	49.9k

From the datasheet the resistance table 2.1 does not give the values at 25% at 10kHz so to select the right value a linear interpolation is required. The final result is approximately 383 kΩ Pin 2 sets the duration of the initial 100% duty cycle before the output goes into PWM mode. According to the laboratory test on the Kilovac, it was observed that the minimum time required for the coil to engage the switch is around 100 ms so based on the table 2.2 given by the manufacturer it's been chosen a capacitor of 100 nF.

User	**Value**
INITIAL CONSTANT OUTPUT DURATION	CD
1μs	Pin 2 Tied to +5V
18μs	Pin 2 Open
110μs	100 pF
1.1ms	1 nF
11ms	10 nF
110ms	100 nF
1.1s	1 µF
11s	10 µF

Table 2.2: Manufacturer delay time vs CD capacitance [3].

Lastly pin 3 sets the PWM oscillator frequency. It's been chosen a 523kΩ to have a 10kHz PWM accordingly to table 2.3

OSCILLATOR FREQUENCY	R_{FREQ}
100kHz	47.5 kΩ
50kHz	100 kΩ
25kHz	205 kΩ
10kHz	523 kΩ
5kHz	1.07 MΩ
500Hz	11.3 MΩ

Table 2.3: Values of OSCILLATOR FREQUENCY and RFREQ [3].

2.2 Precharge system

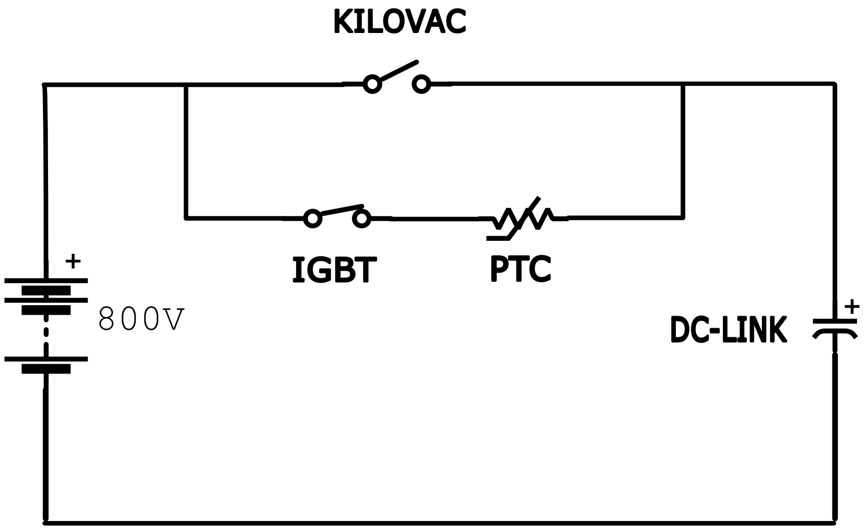

Figure 2.6: simplified precharge system.

A precharge system is often used in DC link circuits to safely and gradually load the DC link capacitors before connecting them to the power source. This is important for several reasons including reducing inrush current because when capacitors are initially connected to a power source, they act like a short circuit until they are charged. This can result in a strong inrush current that can damage components.

2.2.1 Operating principle

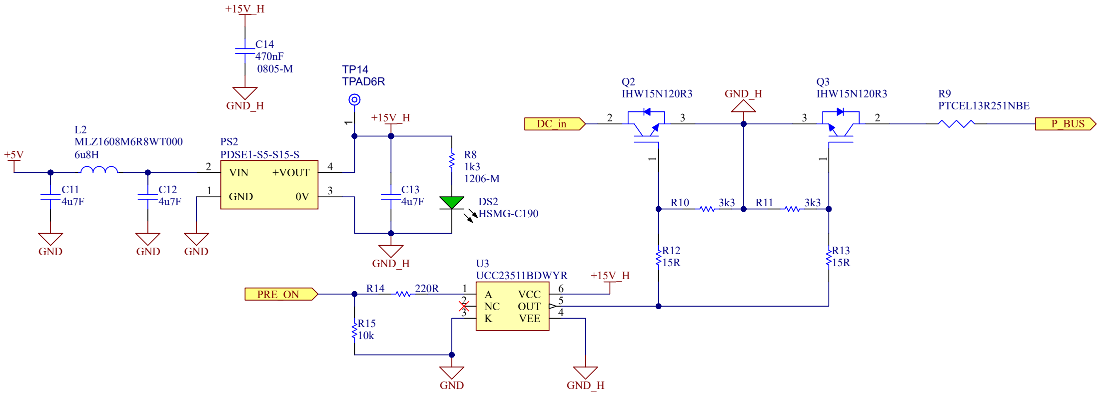

Figure 2.7: Precharge system.

The system is paralleled with the Kilovac switch and Fig, 2.7 shows the precharge circuitry. 5V supply is filtered by a CLC and stepped up to 15V by the PDSE1-S15 in order to give the right voltage to the gate of the two anti-series IGBTs. Isolated converters like the PDSE1-S15 provide electrical isolation between the input and output circuits. This isolation is important for safety reasons, to prevent ground loops and to protect sensitive circuitry (gate of th IGBTs) from noise and voltage spikes. The system has also an LED to quickly check whether the supply is working properly. "PRE-ON" signal given by the MCU enables the gate driver U3 and then IGBTs start conducting. These two are connected between the high voltage source and the positive side of the DC-link through a PTC. A positive temperature coefficient (PTC) ceramic resistor, is a type of resistor whose resistance increases with an increase in temperature. In PTC thermistors, the resistance typically rises rapidly beyond a certain temperature threshold, making them useful for various applications such as inrush current protection. In this case is useful because when the DC-link capacitors are almost fully charged and the Kilovac is closed the current stops flowing through the precharge and passes only through the Kilovac.

2.3 Discharge system

The discharge system is a circuit whose main task is to dissipate the energy of the DC-link. It is a key part of the DC side management because is one of the main safety features. When is necessary to shut down the system, capacitors can be fully charged at 800V, so discharging the stored electrical energy is essential to ensure safety conditions around the inverter.

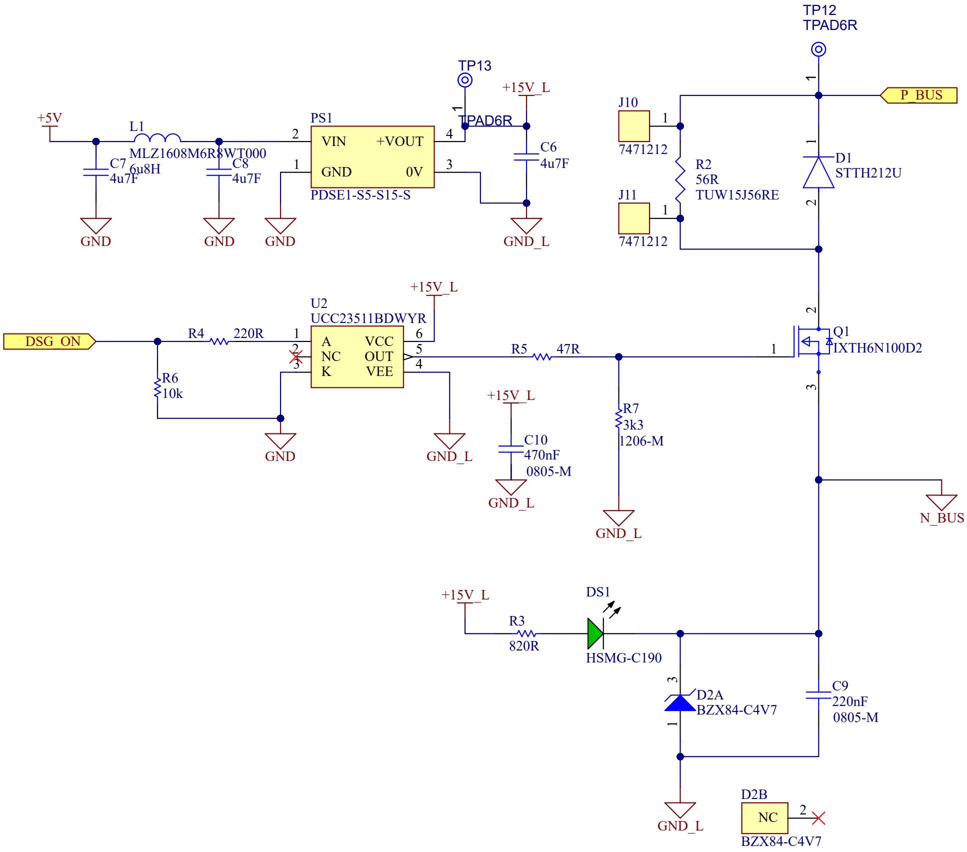

Figure 2.8: Discharge system.

Supply is the same as the precharge system, so there is the PDSE1 which turns 5V to 15V isolated to feed the Gate driver U1. When the Pbus is at steady-state Vgate is zero. Vgs instead is kept negative by the circuit shown in Fig. 2.8 forcing the depletion-mode MOSFET (IXTH6N100D2) to be opened. R3 helps control the current that flows into the zener diode BZX84 and allows a 4.7V drop across it.

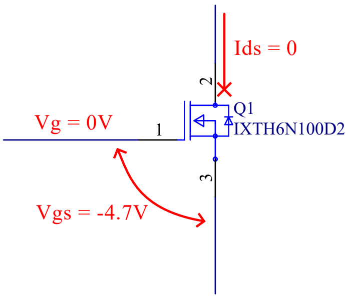

Figure 2.9: Off-state.

In the condition shown by Fig. 2.9 Vgs is kept at -4.7V and the MOSFET is not conducting. When the inverter is turned off, DSG-ON MCU signal turns on the gate driver, Vgate will be around 12V and Vgs will be:

$$V_{gs} = V_{gate} - 4.7 = 12 - 4.7 = 7.3V \tag{2.4}$$

This voltage level is enough to guarantee the conduction of the depletion MOSFET and as a consequence the DC-link discharge (Fig. 2.10).

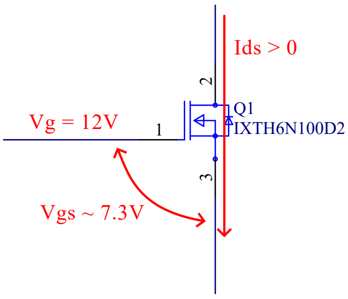

Figure 2.10: On-state.

The advantage of using this scheme is that if a fault for 15V or 5V occurs, the MOSFET will have Vgs=0V but for its intrinsic characteristic will conduct in any case and will ensure a path for the dclink current. The Bulk resistor was chosen to be able to dissipate the energy stored in the capacitors. Resistance value is 56 Ω enough to limit the current to a value suitable for the depletion-mode MOSFET. The DC-link capacitors have a capacitance C of 300μF so the storage energy will be so far:

$$E_{DCbus} = 0.5 \cdot C \cdot V^2 = 0.5 \cdot 300 \cdot 10^{-6} \cdot 800^2 = 96J \tag{2.5}$$

It’s known that the in an RC circuit the capacitor totally discharge itself in around 6 τ so:

$$\tau = R_{bulk} \cdot C = 56 \cdot 300 \cdot 10^{-6} = 0.168s \tag{2.6}$$

So the maximum power that the resistor has to dissipate is:

$$P_{max} = \frac{E_{DCbus}}{6 \cdot \tau} = \frac{96}{6 \cdot 0.168} \cong 960W \tag{2.7}$$

The system dissipate 960 W in around 0.1 seconds, the nominal continuous power that the resistor is able to dissipate is 15W (P_{nom}). With this power rate capacitors will be discharged in 6.4 seconds according to:

$$T_{min} = \frac{E_{DCbus}}{P_{nom}} = \frac{96}{15} = 6.4s \tag{2.8}$$

So to keep the thermal balance is necessary to wait a minimum time of 6.4 seconds after the discharge.

2.4 Relays

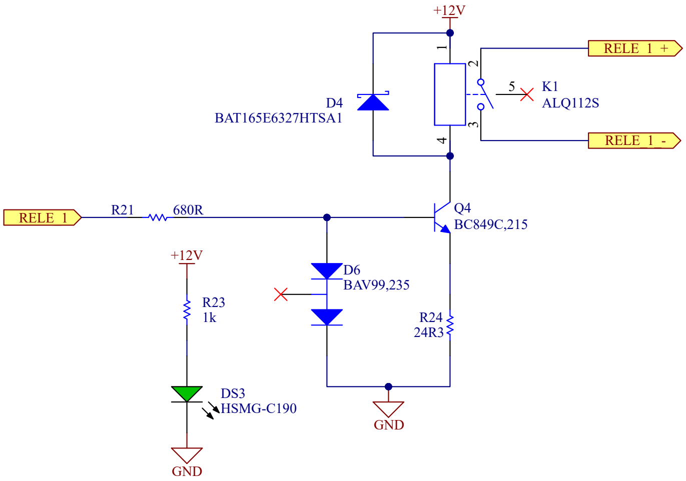

Figure 2.11: Relay 1 schematic.

The relays command block is used to control auxiliary devices such as additional cooling systems and or some external equipment that could be involved during experiments. Also in this case there an LED to check the 12V supply. In parallel with the coil there is a free-wheeling diode to dissipate the magnetic energy.

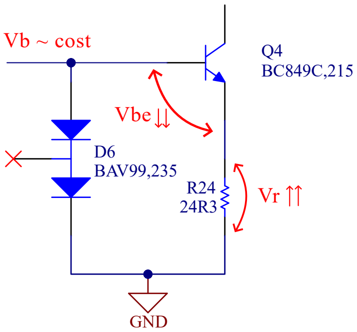

Figure 2.12: Current limit system.

The structure of Fig.2.12 is used to limit the current flowing in the NPN transistor in case of a fault in the coil. If an overcurrent passes through the transistor, the resistor below it increase the voltage drop. This decrease the gate-emitter voltage (Vge) and as result the transistor will limit the current.

2.5 Fan command

An additional fan has been added to the design in order to have a better thermal dissipation and so in this block there is the enabling circuitry.

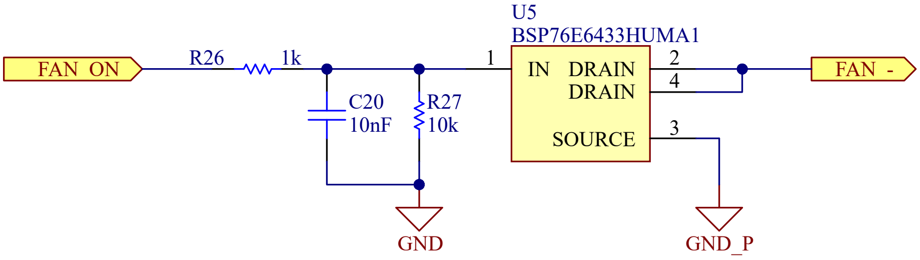

Figure 2.13: Fan command schematic.

The BSP76E6433HUMA1 is a smart low-side switch with embedded protection circuits.

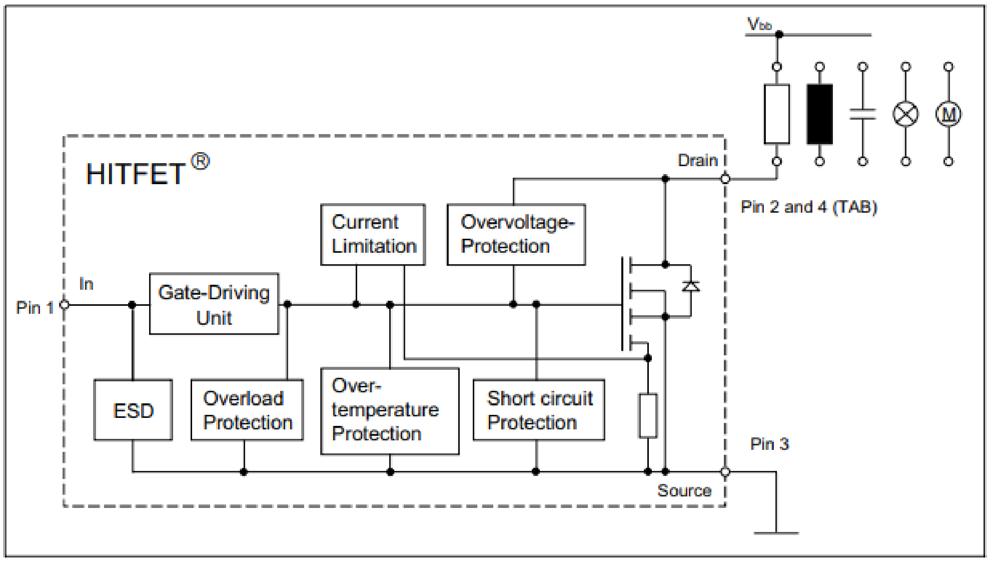

Figure 2.14: BSP76 internal scheme[4].

It has gate driver and the N-FET in the same case. It suits particularly well for this application because does not require so much space, the typical input threshold voltage is 1.7V (small enough for the FAN-ON signal from the MCU) and it can handle a V_{DS} of 42V (drain-source voltage is 12 from connector J6 Fig. 2.2).

2.6 PCB layout and 3D model

Once the schematics are made, the following step is creating the physical model of the PCB. Designing a printed circuit board layout involves several key steps:

1. **PCB Footprint Creation**: For each component in the schematic, it's necessary to create or select a corresponding footprint, which defines the physical dimensions and placement of the component's pads on the PCB.
2. **PCB Layout**: Arrange the components on the PCB according to the schematic diagram considering factors such as signal integrity, power distribution, and thermal management during placement.
3. **Routing**: Connecting the components using copper traces on the PCB. This involves routing signal traces between components while sticking to design rules such as minimum trace width, clearance, and impedance control.

4. **Ground and Power Planes**: Allocating dedicated layers on the PCB for ground and power planes to ensure proper signal integrity, noise reduction, and power distribution.

5. **Design Rule Check (DRC)**: Run a design rule check to identify and correct any violations of design rules, such as inadequate clearances or trace widths.

2.7 DC-side PCB

The first step is to place the electronic components on the PCB canvas. Components are represented by symbols or footprints, and they need to be arranged in a way that optimizes space, minimizes signal interference and ensures proper electrical connectivity. The layout design is shown by Fig.2.15

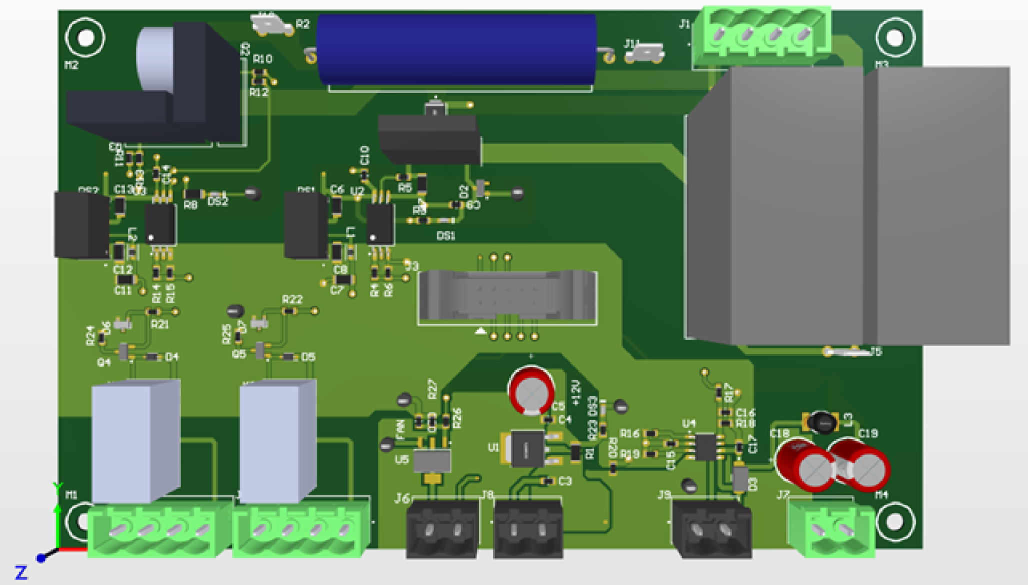

Figure 2.15: DC-side board 3D model

The board is 6350x3950 mils and it has four conductive layers. The structure of the layers is:

	Material	Name	Thickness [mil]
1	/	Top Overlay	/
2	Solder resistant	Top Solder	0.4
3	Copper	Top layer	1.4
4	PP-006	Dielectric 2	2.8
5	CF-004	Layer 1	1.4
6	FR-4	Dielectric 1	12.6
7	CF-004	Layer 2	1.4
8	PP-006	Dielectric 3	2.8
9	Copper	Bottom layer	1.4
10	Solder resistant	Bottom Solder	0.4
11	/	Bottom overlay	/

Table 2.4: PCB layers

This board it's been divided in 7 main regions (Fig.2.16) and also there is a separation between low and high voltage components.

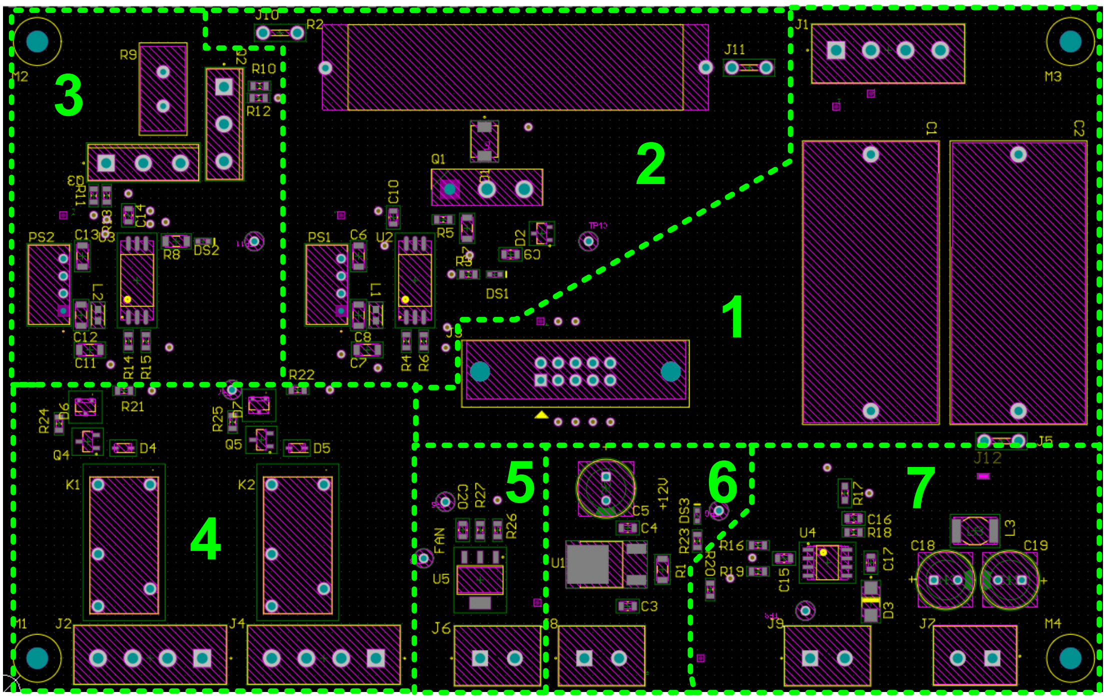

Figure 2.16: Regions footprint

1. **Interfaces**: In the middle of the board there is the XG4 connector that interfaces with the control board. On the right there are the two capacitors Cy that directly

interfaces with the DC-link bank capacitors and the connector J1 responsible of connecting the high voltage supply (ex. battery).

2. **Discharge system**: In this region there is the big bulk resistor on the edge of the board so that it's easier to dissipate the heat.

3. **Precharge system**: In the lower part of the region there is the signal processing circuits (low voltage side) and in the upper part there are the two antiseries IGBTs arranged in an L shape for the high voltage side

4. **Relays**: K1 and K2 are the two relays for the external auxiliaries

5. **Fan command**: Here is the circuitry of the external fan used for cooling purposes, There is the connector, the smart power switch and the condenser and resistors.

6. **Supply**: The supply for this board comes from this region where there is the connector and then the linear voltage regulator with its filters. As previuos explained if the supply is already 12V from the connector, there is a bypass 0R resistor (R1).

7. **Kilovac regulator**: On the left side of this region there is the kilovac contactor is represented by connector J9 with its voltage regulator circuitry. The 12V supply for the Kilovac can be provided through the connector J7 by an external source or through the jumper with the internal 12V supply.

Routing

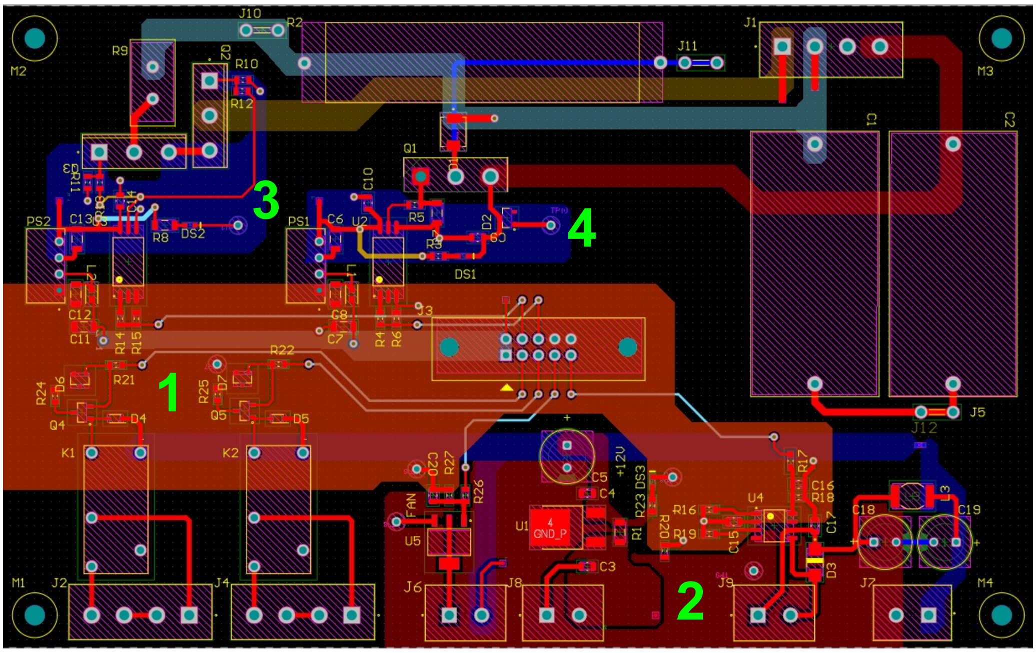

Figure 2.17: DC-side board 3D model

In Fig. 2.17 it is shown the general routing of the board, on the different layers:

- Top layer → Red
- Layer 1 → Ocher
- Layer 2 → Light Blue
- Bottom layer → Red

Furthermore, the ground planes are numbered. It is evident from the layout that power signals are directed through broader tracks to mitigate the risk of overheating the PCB.

Table 2.5: Ground planes.

	Type
1	GND
2	GND-P
3	GND-H
4	GND-L

Chapter 3

Control Board

A control board for an inverter gate driver is a circuit board designed to manage and control the operation of gate drivers in an inverter system. The main functions are:

- Gate Driver Interface: The control board interfaces with one or more gate drivers, which are responsible for controlling the switching of power MOSFETs in the inverter.

- Control Signals Generation: It generates control signals necessary for driving the gate drivers. These signals typically include PWM (Pulse Width Modulation) signals for controlling the switching frequency and duty cycle of the power devices.

- Feedback Circuitry: The control board includes feedback circuitry to monitor various parameters such as current, voltage, temperature, and fault conditions within the inverter system. This feedback is essential for closed-loop control and protection mechanisms.

- Microcontroller: the microcontroller used to implement control algorithms, process sensor data, and generate control signals with precise timing and accuracy.

- Communication Interface: the control board feature communication interfaces such as UART, and CAN bus for external communication with other devices or systems, enabling monitoring, configuration, and diagnostics.

- Protection Circuits: To ensure safe and reliable operation, the control board uses protection circuits to detect and respond to overvoltage, overcurrent, overtemperature, and short-circuit conditions. These circuits trigger fault shutdowns or activate protective measures to prevent damage to the inverter system.

- Power Supply: The control board requires a stable and reliable power supply to operate. This power supply includes voltage regulation and filtering to ensure clean power is delivered to the control electronics.

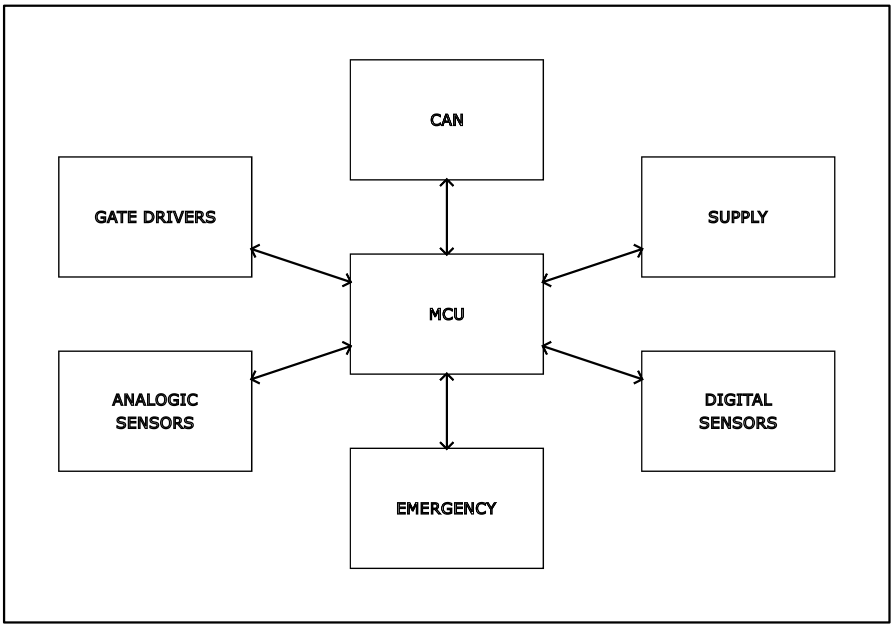

Figure 3.1: Block diagram of the control board.

3.1 Connectors

Current connectors

Connectors are the interface between the external equipment and he control board. For the new board some of the old connector were kept in place, such as the ones for current and voltage sensing and also the ones for internal fans. Starting from the current connectors, they are 0022232031 Molex connectors (Fig.3.2) with a pitch 2.54 mm and they can handle voltages around 500VDC enough for a signal range between -15V and +15V.

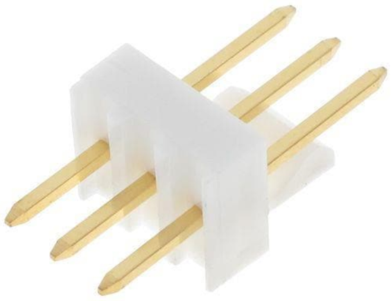

Figure 3.2: 0022232031 Molex current connector [5].

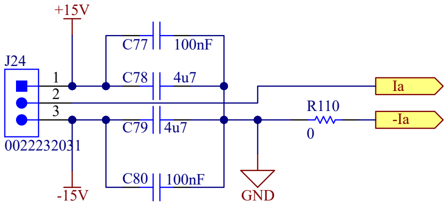

Figure 3.3: Current connector schematic symbols.

DC-link connector

For the DClink voltage there is a dedicated housing for two pins directly connected to the DC BUS capacitors and to connect these pins to the connector (J14) placed on the board there are two specific cables. The connector is the GMSTBV 2,5/ 2-G-7,62 with a rated current of 12A and a pitch of 7.62 mm and since the minimum space required between two pins to handle 1000V is 5 mm this is component is good for the application.

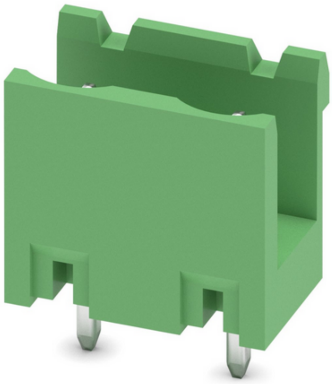

Figure 3.4: GMSTBV 2,5/ 2-G-7,62 VDC connector[6].

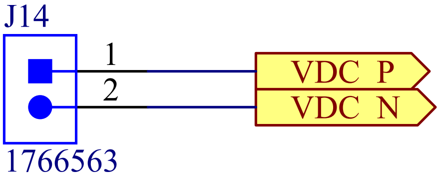

Figure 3.5: VDC connector schematic symbol.

Fan connectors

The two internal fan connectors are responsible only of supplying the power, indeed they're connected only to the 12V supply, in this way fans will start as soon as the board is turned on. The connectors are 640456-2 AMP MODU from TE connectivity appropriate for 12V power supply.

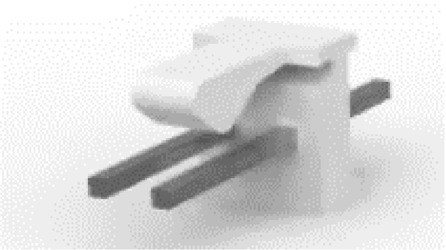

Figure 3.6: 640456-2 AMP MODU Fan connector[7].

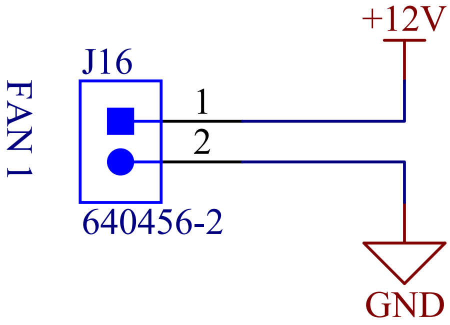

Figure 3.7: Fan conector schematic symbol.

Torquemeter connector

The torquemeter has two connectors. In this application torquemeter 24V supply is provided by an external source through J15 connector (5-104363-7) as shown by Fig.3.8. Then is filtered by a simple EMI filter made with L12, C90, C91 and C90 and it goes in J19, the connector that interfaces the board with the torquemeter round connector.

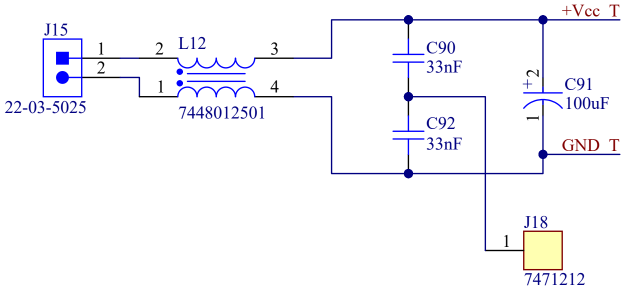

Figure 3.8: Torque supply schematic.

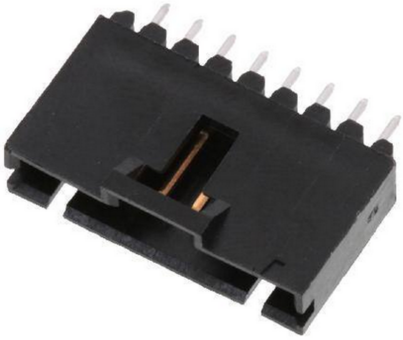

Figure 3.9: 5-104363-7 torque connector[8].

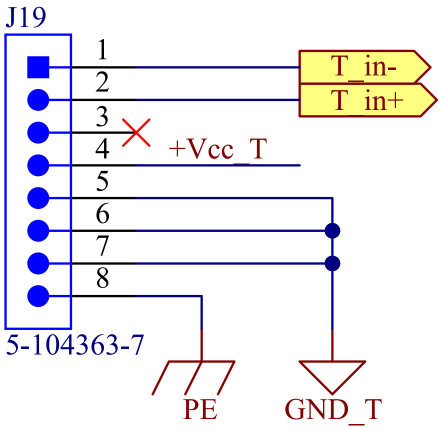

Figure 3.10: Torque connector schematic symbol.

Pin 3 is not used, instead pin 6 and 7 correspond to a shunt signal trigger, but in this application they're not involved so they're pulled down to GND.

Encoder connectors

There are two encoder connectors, one for receiving signals and one for transmitting them to external equipment. This connectors provide also the isolated 5V supply used by the encoder. A and B (and their negates) are the primary output signals of the encoder. They are typically square waves that are out of phase by 90 degrees. This phase difference allows the controller to determine the direction of rotation (clockwise or counter-clockwise) by analyzing the sequence of the A and B pulses.

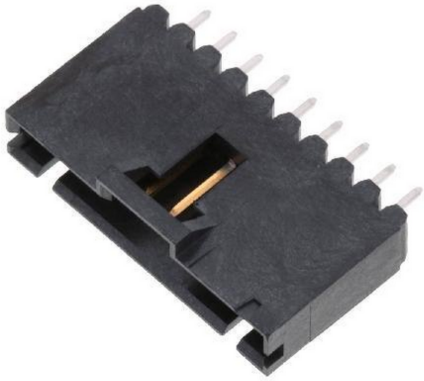

Figure 3.11: 5-103735-8 Encoder connector[9].

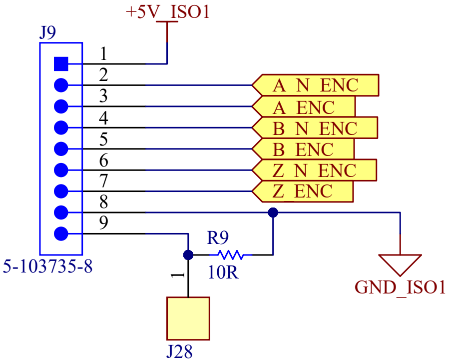

Figure 3.12: Encoder connectors schematic.

Z (and its negate) is an optional signal that provides a single pulse per revolution. It acts as a reference point and is used to establish the absolute position of the shaft at the beginning of operation. The connectors used are J9 and J11 that are AMP MODU Headers suitable for signaling purposes (Fig.3.11). There is also a faston connector represented by J28 that is connected directly to the protection earth (PE).

DC side connector

This connector is the link between the DC side board and the control board. Signals come from the MCU and goes into this connector that is the same one of the other board. Also this connector has two pins responsible for the 5V supply of the DC-Side

Figure 3.13: DC-Side connector[10].

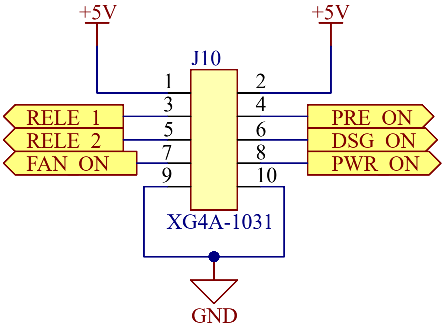

Figure 3.14: DC-Side connector schematic symbol.

Water flow connector.

The water flow connector is a 3 pin connector, 2 for supplying power to the sensor (114991176 by Seeed technology) and one for the effective flow read.

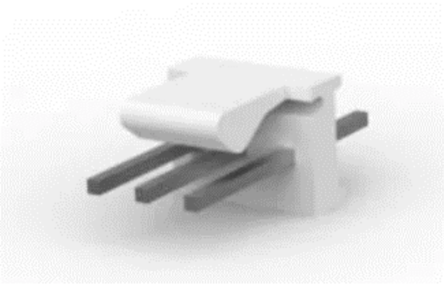

Figure 3.15: Water flow connector [11].

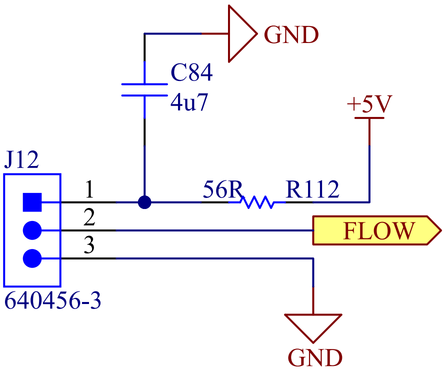

Figure 3.16: Water flow connector schematic symbol.

CAN connectors.

CAN connectors act as a physical gateway for devices to integrate into the CAN bus network, facilitating the exchange of data and signals with other nodes on the bus. The connectors used are the same as the one of the water flow sensor.

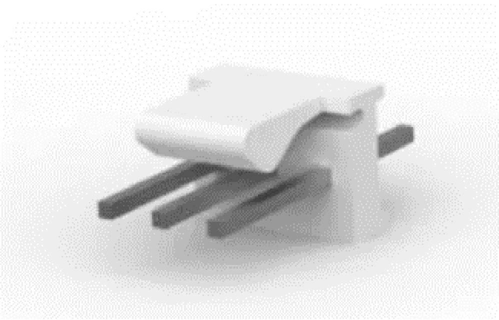
Figure 3.17: CAN connector[11].

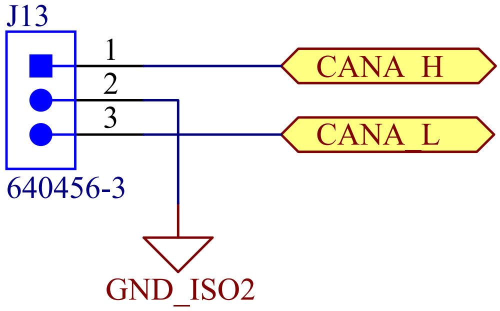

Figure 3.18: CAN connector schematic symbol.

Driver connectors

These three connectors (J20, J21, J21) send and receive the inverter leg signals. There is also the 12V supply for the MOSFET gate drivers, there are also safety signals that will be explained later. These connectors are the same as the ones of the original control board, to ensure the compatibility with the inverter and for dimensional reasons.

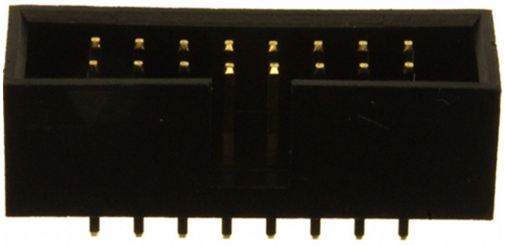
Figure 3.19: Driver connector[12].

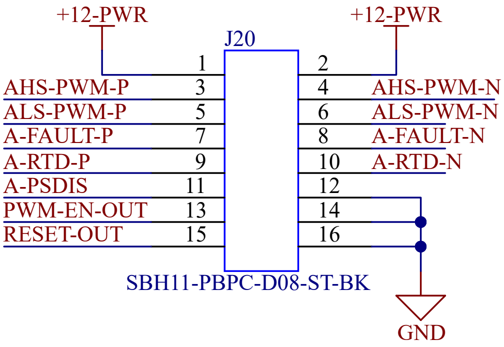

Figure 3.20: Driver connectors schematic symbol.

Temperature connectors

J5, J6, J7, J8 are the temperature connectors added on the new control board to provide additional information of the electric motor, cooling fluid and other components that could be connected to the setup. These are MTA-100 from TE connectivity with a pitch of 2.54 mm, the same as the water flow and CAN connectors

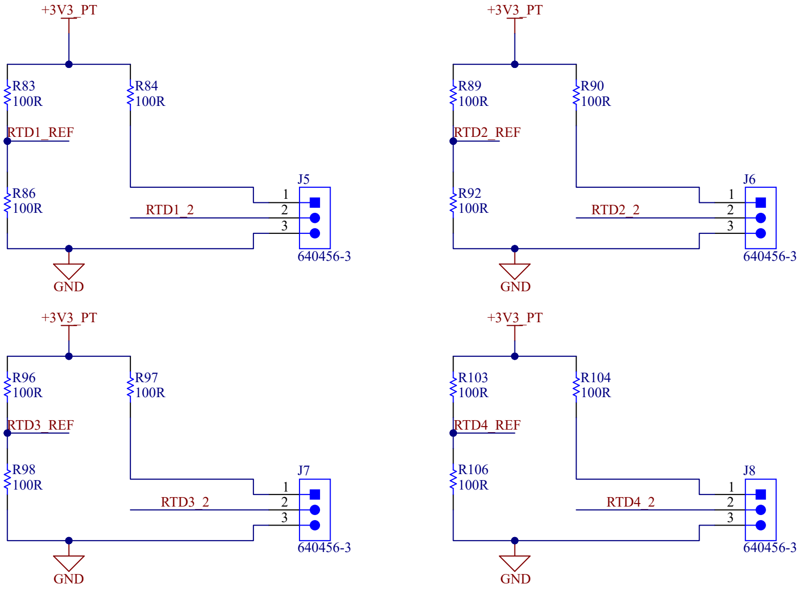

Figure 3.21: Temperature connector.

3.2 Supply

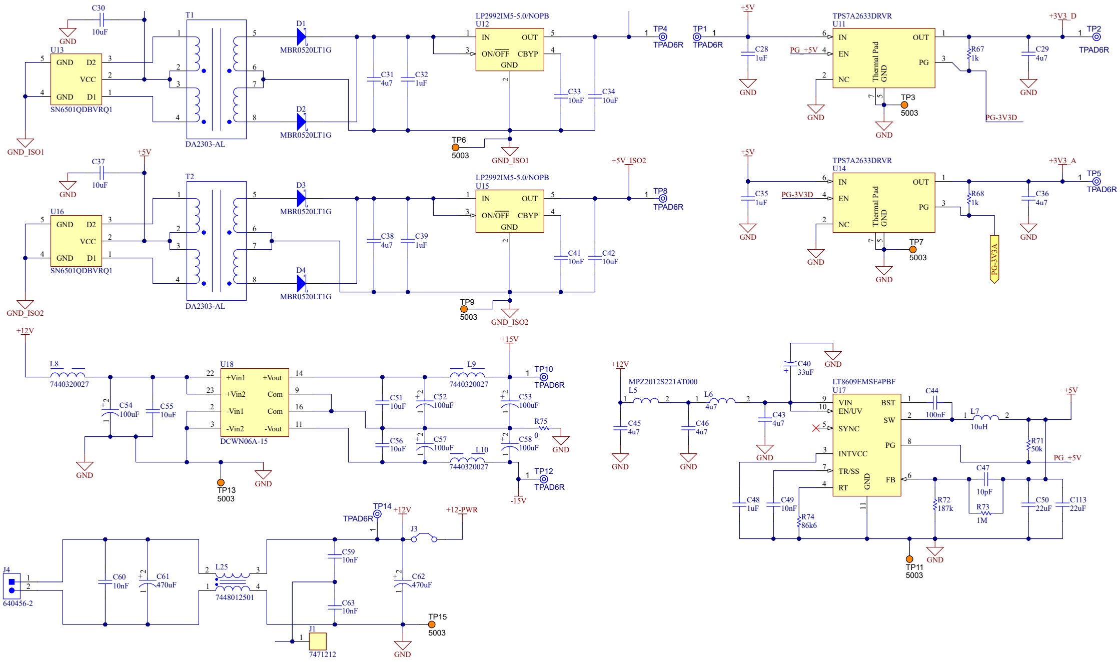

Figure 3.22: Supply schematic.

The starting point of the supply circuitry is the connector J4 as shown in Fig.3.22 where an external 12V supply comes. After that there is a CLC filter with a cut-off frequency of around 2.2 kHz for differential mode noise. It is estimated a current consumption of around 1.5A - 1.8A, so in order to have a good margin and for powering hypothetical new components, The inductor current rating is 2.8A. There is also a jumper after this filter to separate the 12V for the gate drivers, this for having the possibility of disconnecting the drivers when commissioning and testing the control board.

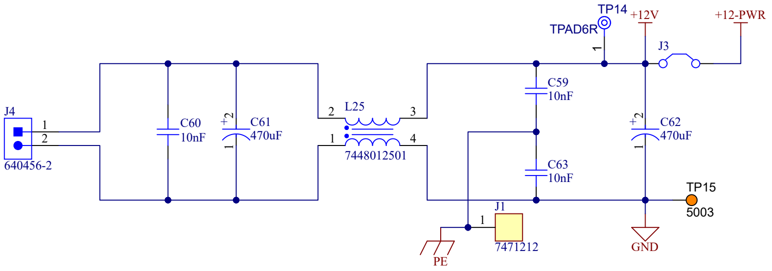

Figure 3.23: 12V supply filtered.

When the 12V connection is established this voltage has to be transformed in various levels.

1. 12V to 5V: 5V supply is used by several components such as the ones for encoder signal conditioning.
2. 12V to ±15V: current sensor supply
3. 5V to 5V isolated: there are to different 5V isolated used inside the encoder conditioning block
4. 5V to 3.3V: there are two same blocks, one for the analog and one for the digital devices

3.2.1 12V → 5V

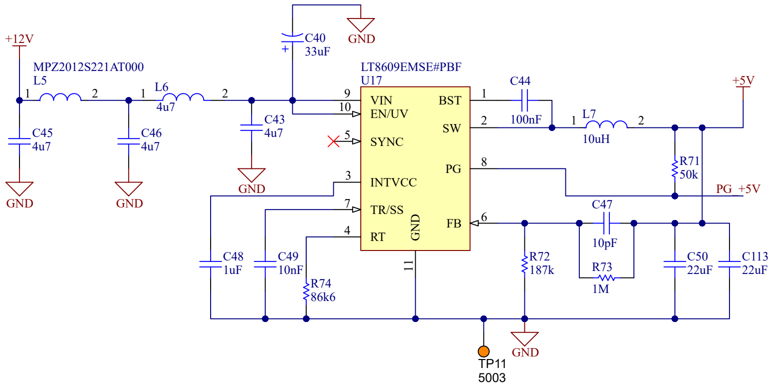

Figure 3.24: 12V→5V.

This voltage drop is made with the LT8609 (U17). The LT8609 is a compact, high efficiency, high speed synchronous monolithic step-down switching regulator and it can deliver 3A of continuous current[13]. It's configured in ultra-low EMI mode and it can be seen from Fig.3.24 that there is a series of two CLC filters on the supply input pin that help reduce noise.

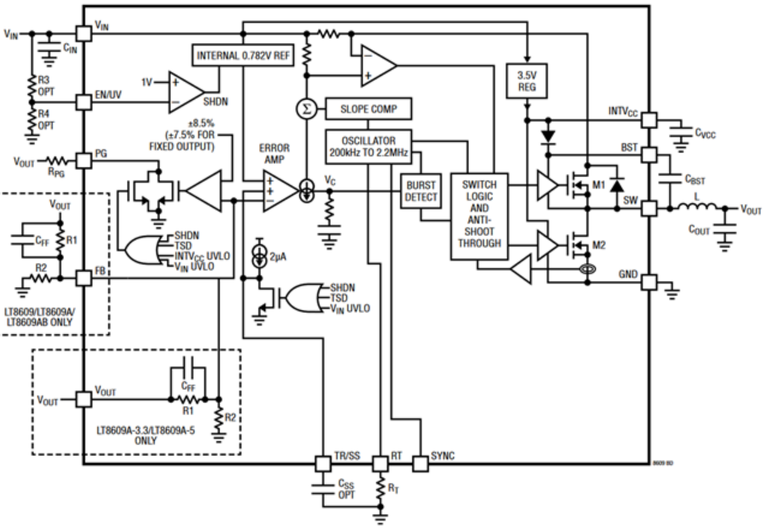

Figure 3.25: LT8609 internal schematic[13].

The componentS surrounding the LT8609 were chosen based on the datasheet outline such as input and output capacitors (C45, C46, C43, C40, C50, C113), enable pin, soft start (C49) and internal reference voltage capacitor (C48). PG is a pin for verifying the correct operation of the LT8609. When the LT8609/LT8609A/LT8609B's adjustable output voltage is within the ±7.5% window of the regulation point, which is a VFB voltage in the range of 0.716V to 0.849V (typical), the output voltage is considered good and the open-drain PG pin goes high impedance and is typically pulled high with an external resistor (R71). The PG pin is also actively pulled low during several fault conditions: EN/UV pin is below 1V, INTVCC has fallen too low, VIN is too low, or thermal shutdown[13]. The PWM switching frequency chosen is 500kHz for faster response times in voltage regulation, reducing output voltage ripple and improving the dynamic response of the converter to load changes. To enable this frequency operation it is necessary to choose between different values of resistor RT (R74) based on table 3.1.

SW Frequency (MHz)	**RT Value (kΩ)**
0.2	221
0.3	143
0.4	110
0.5	86.6
0.6	71.5
0.7	60.4
0.8	52.3
0.9	46.4
1.0	40.2
1.2	33.2
1.4	27.4
1.6	23.7
1.8	20.5
2.0	18.2
2.2	16.2

Table 3.1: SW Frequency vs RT Value[13].

To achieve a frequency of 500 kHz, an 86.6 kΩ resistor is required. The output voltage is programmed with a resistor divider between the output and the FB pin. Input voltage is 12V and the output desired is 5V so the resistor values should be according to:

$$R_{72} = R_{73} \cdot \left(\frac{V_{OUT}}{0.782V} - 1 \right) \tag{3.1}$$

The total resistance of the FB resistor divider should be selected to be as large as possible when good low load efficiency is desired where R72 is 1MΩ and as a consequence of 3.1 R72 will 187KΩ.

3.2.2 12V → ±15V

±15V is the voltage required for hall effect current sensor to run. To perform this voltage rise, it has been chosen the DCWN06A-15, a 6W isolated and regulated DC-DC converter with DIP24 package. It can handle currents of up to 200mA and according to the datasheet of the lf510s (current sensor) the maximum current that the three sensors will absorb will be around 150mA. The electrical isolation can help reduce noise and interference in the measurement system. By isolating the sensor supply, the impact of electromagnetic interference (EMI) can be minimized and ensure more reliable and accurate current measurements. Moreover, there is a PI-filter either on +15V and on -15V to further lower interferences as shown in Fig.3.26.

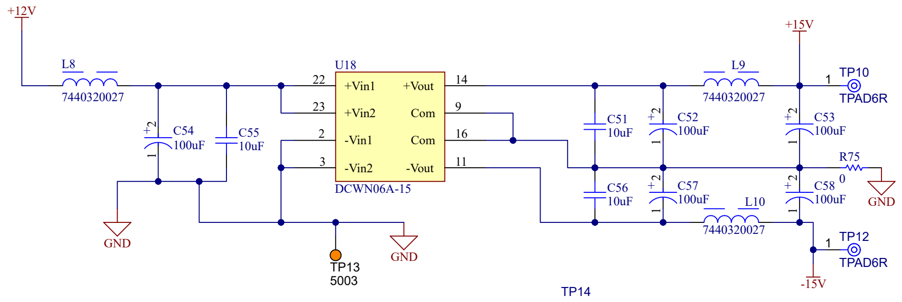

Figure 3.26: 12V → ±15V schematic.

3.2.3 5V → 5V isolated

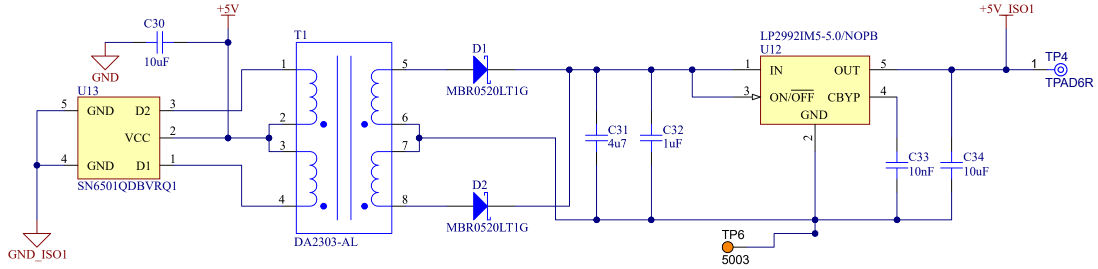

Figure 3.27: 5V isolated supply schematic.

Encoder and CAN bus circuitry require isolated supply for the correctness of signals, since they are key components for controlling the motor and inverter parameters. In principles one isolated supply is for the signals that comes from the encoder to the control board and the other one is for the signals that come out from it. Fig.3.27 shows the component required to isolate 5V. Starting from the SN6501, it is a monolithic oscillator/power-driver, specifically designed for small form factor, isolated power supplies in isolated interface applications. The device drives a low-profile, center-tapped transformer primary from a 5-V DC power supply. The secondary can be wound to provide any isolated voltage based on transformer turns ratio. The DA2303-AL transformer, optimized for the SN6501, isolates and step up the voltage from 5V to 6V. There are then the two schottky rectifiers MBR0520L used for their low forward voltage and short recovery time. At the end to have again 5V there is an LDO LP2992IM5, required to provide a stable and load-independent supply while keeping maximum efficiency[14].

3.2.4 5V → 3.3V

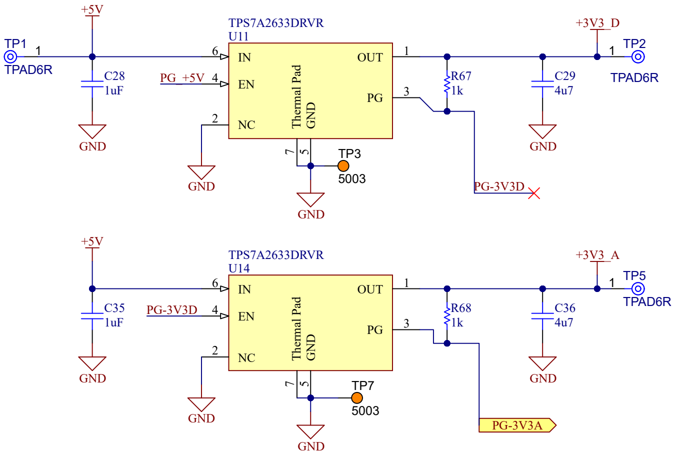

Figure 3.28: 5V → 3.3V schematic.

The last voltage stage is 5V to 3.3V. 5V is stepped down by two TPS7A2633, a voltage regulator by Texas Instruments, to create two different supplies, one for analog devices and one for digital ones, keeping them separated to prevent interference between signals. From Fig.3.28 it can be noticed that each regulator has an enable pin used to switch on and off the devices. For the digital 3.3V supply the enable pin signal is the "power good" output from the LT8609 (12V to 5V), then the 3.3 V power good output signal is sent to the enable pin of the U14 (5V to 3.3V analog). In this way if there's a fault on the 5V supply U11 (digital) is turned off and as a consequence U14 (analogic) turns off. The 3.3V analog power good signal is then sent to other components for emergency reasons.

3.3 Encoder

This part of the control board deals with the encoder signals, it receives, conditions and sends back them to other peripherals. The whole circuitry is shown in Fig.3.29 and all starts from A, B, Z and their negates signals coming from the encoder connectors to this part of the board.

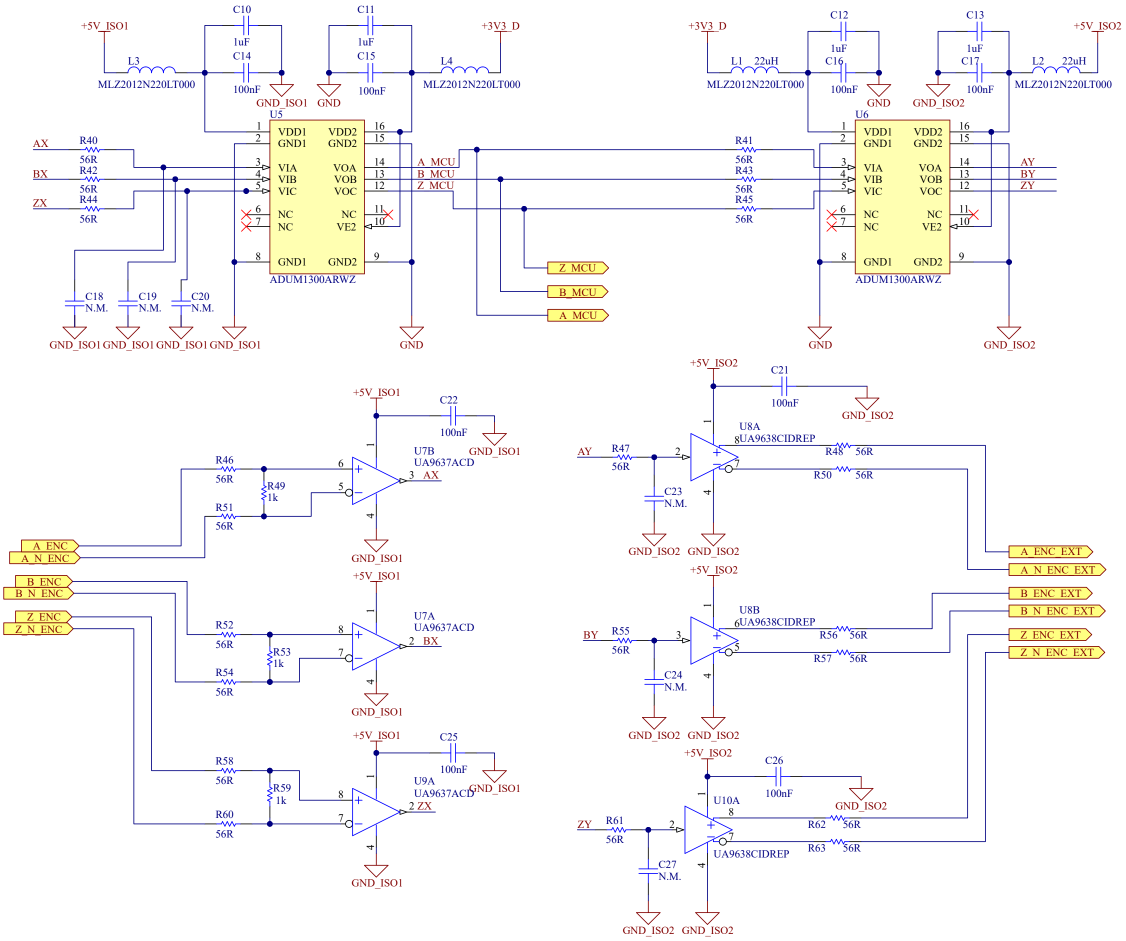

Figure 3.29: Encoder schematic.

Differential signals A, B and Z are conditioned by U7 and U9, these are UA9637A dual differential line receivers operating with a single 5V supply. A differential line receiver is a type of electronic circuit used to receive and process differential signals. It is commonly employed in applications where noise immunity, signal integrity, and high-speed data transmission are really important. The differential receiver compares the voltage levels between two signal lines (usually a real signal and its negate). It amplifies the voltage difference between these lines while rejecting common-mode noise, which is noise that appears on both lines simultaneously. By amplifying only the voltage difference, the receiver effectively "extracts" the original signal from the noise, improving the overall signal quality. Then the output signal is sent to the ADUM1300A triple-channel digital isolator.

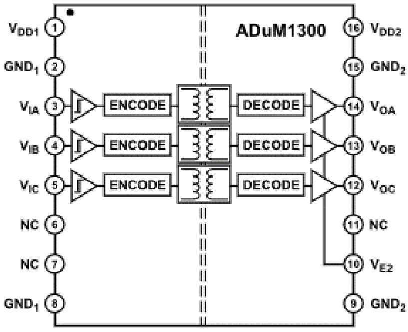

Figure 3.30: ADUM1300 internal representation[15].

The first ADuM1300 isolator (U5) provides three independent isolation channels and operates at 5V(ISO), separates the input signals and gives as output A, B and Z at 3.3V level. These last will be sent to the MCU to be processed (A-MCU, B-MCU, Z-MCU).A-MCU, B-MCU, Z-MCU now will pass through another ADUM1300 (U6) to be isolated from external sources and for stepping up the voltage again to 5V level. It is important to notice that the two isolators are supplied with the two different isolated 5V described in 3.2.3 with additional LC filters for every Vdd port. Lastly the output of U6 (AY, BY, ZY) must be sent to The UA9638C, a dual high-speed differential line driver that has the opposite purpose of the UA9637A, so it has to convert digital signals into differential signals suitable for transmission over communication lines for the same reasons as before (noise immunity and signal integrity). After this operations the signals are ready to be sent outside of the board through the connector J11.

3.4 Current and voltage sensing

In this application there are 3 LF510-s hall effect current sensors right after the inverter output pads. A Hall effect current sensor is a type of sensor used to measure the flow of electrical current in a conductor. It operates based on the Hall effect, which is the production of a voltage difference (the Hall voltage) across an electrical conductor when a magnetic field is applied perpendicular to the direction of the current flow. In a Hall effect current sensor, a Hall sensor is placed in close proximity to the conductor through which the current flows. When current flows through the conductor, it generates a magnetic field around it. This magnetic field interacts with the Hall sensor, causing a voltage difference to be produced across the sensor. This voltage difference is proportional to the strength of the magnetic field, which in turn is proportional to the current flowing through the conductor. By measuring the Hall voltage, the current flowing through the conductor can be determined. Hall effect current sensors are commonly used in various applications such as power monitoring, motor control, and energy management systems. They offer advantages such as high accuracy, low insertion loss, and galvanic isolation between the current-carrying conductor and the measurement circuit.

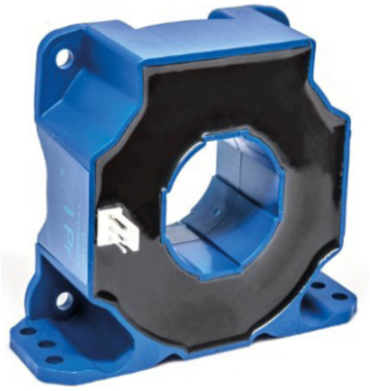

Figure 3.31: LF-510-S hall effect current sensor[16].

The lf510-s has a maximum primary current of 500 A, but for laboratory purposes the current is limited to 250A peak. The secondary winding has 5000 turns so based on (3.2):

$$I_s = \frac{I_p}{Nturns} = \frac{\pm 250}{5000} = \pm 50mA \tag{3.2}$$

This is the max current value that flows to the 3 connectors J24, J32, J33. Now the problem is that this current could be either positive or negative and when passes through a shunt resistor (R21) could create a negative voltage. Since this signal will be sent to the MCU and it cannot receive negative voltages it is used a combination of a differential and a voltage adder circuitry for operational amplifiers. A differential operational amplifier with feedback resistors is a common setup that employs resistors in the feedback path to control the gain and performance characteristics of the op-amp. It consists of two input terminals (non-inverting and inverting), a single output terminal, and resistors connected in the feedback path. Feedback resistors are connected between the op-amp's output and its inverting input terminal. These resistors determine the gain and other performance parameters of the amplifier.

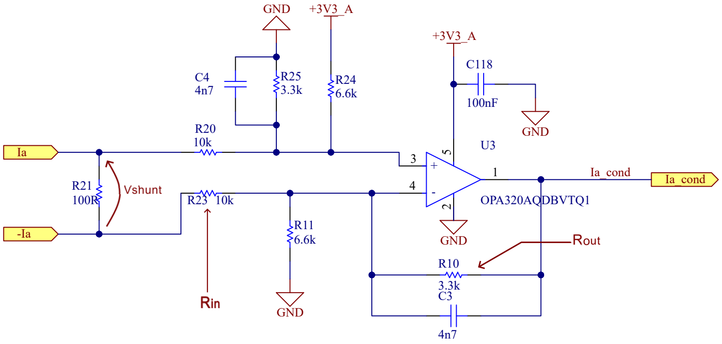

Figure 3.32: Current sensing schematic.

The differential voltage will be the one across the shunt resistor and according to Ohm's law the max voltage will be:

$$V_{shunt} = R_{shunt} \cdot I_s = 100 \cdot (\pm 0.05) = \pm 5V \tag{3.3}$$

The gain of the amplifiers is determined by the feedback resistorR_{10} and the input resistor R_{20} for Ia signal and so the output voltage will be:

$$V_{out} = \pm V_{shunt} \cdot \frac{R_{10}}{R_{20}} = \pm 5 \cdot \frac{3300}{10000} = \pm 1.65V \tag{3.4}$$

As explained before the microcontroller can accept only signals in the 0V → 3.3V so it is necessary to add an offset to the circuit in order to obtain the right output voltage and this can be done with a voltage adder circuit. In Fig.3.32 the voltage offset adder is represented by the additional 3.3V analog supply plus the resistor R24. The voltage offset V_{off} must be 1.65V (to offset -1.65V) and as a consequence the resistor R24 will be:

$$V_{off} = V_s \cdot \frac{R_{10}}{R_{24}} \tag{3.5}$$

$$R_{24} = V_s \cdot \frac{R_{10}}{V_{off}} = 3.3 \cdot \frac{3300}{1.65} = 6.6k\Omega \tag{3.6}$$

3.4.1 Voltage measurement

DC-link bus measurements is directly detected through two pins directly connected to the capacitor bank as shown in the fig below. The high voltage signal is not isolated but it will flow through a high impedance path to guarantee safety operations. VDC signal ranges between 0V → 800V and to be transformed within the range 0 → 3.3V to be suitable for the MCU, a differential operational amplifier is needed.

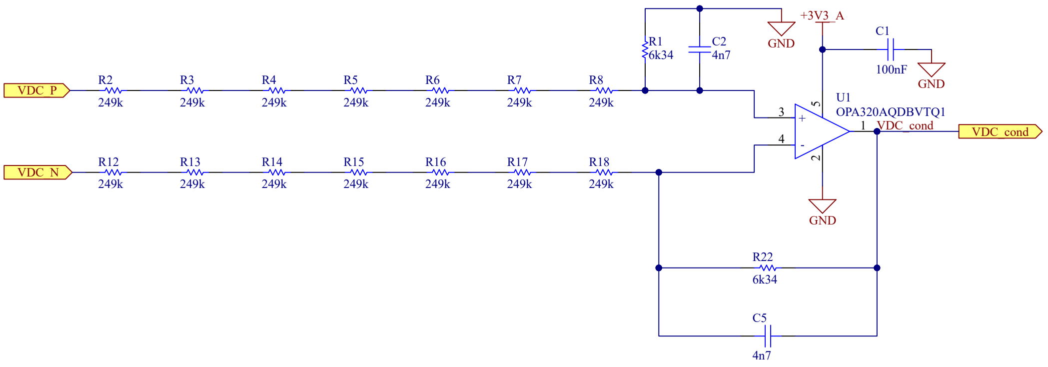

Figure 3.33: VDC conditioning schematic.

The input resistance in this case is the sum of the seven 249KΩ resistors and the output one is R22. So based on the circuit above (Fig.3.33) the maximum output voltage is calculated with:

$$V_{out} = V_{DC} \cdot \frac{R_{out}}{Rin_{eq}} = 800 \cdot \frac{6340}{249 \cdot 7} = 2.9V \tag{3.7}$$

There is also a low pass filter, for a better signal processing, represented by R22 and C5 with a cut-off frequency of:

$$F_{cutoff} = \frac{1}{2\pi \cdot RC} = \frac{1}{2\pi \cdot 6340 \cdot 4.7 \cdot 10^{-7}} \cong 5300Hz \tag{3.8}$$

3.5 Temperature sensing

The additional temperature sensors used are three-wired PT100. The PT100 sensor is a type of Resistance Temperature Detector (RTD) that changes resistance with temperature. As the temperature increases, the resistance of the PT100 sensor also increases. The three-wire connection helps compensate for the resistance of the wires themselves, ensuring more accurate temperature measurements. The Wheatstone bridge consists of four resistors, forming a bridge-like structure with the PT100 sensor placed within the bridge as shown in Fig.3.34.

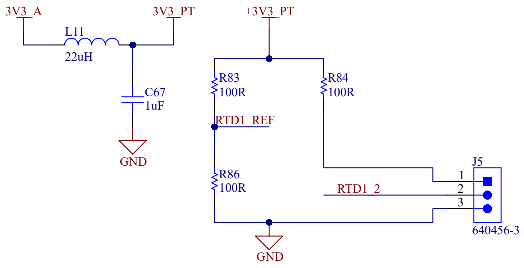

Figure 3.34: Temperature bridge schematic.

There are three 100 Ω fixed resistors composing the bridge and the sensor is represented by the 3 pins connector as shown by Fig.3.21. Due to the extremely sensitive measure it's necessary to filter the voltage for reducing noise and fluctuations in the signal. By applying 3.3V across the bridge, a voltage difference appears between two points of the bridge (A = RTD1-REF and B = RTD2-2). This voltage difference, or output voltage, is proportional to the change in resistance of the PT100 sensor, which is related to the temperature change. In particular R_{PT100} changes it's value according to the simplified equation:

$$R_{PT100} = R_0 \cdot (1 + \alpha \cdot \Delta T) \tag{3.9}$$

With R_0 equal 100 °C and $\alpha = 3.9083 \times 10^{-3}$ °C^{-1}. Using the following scheme is possible to calculate the output voltage V_G.

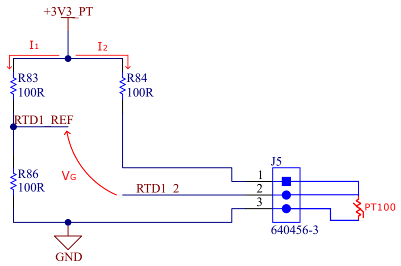

Figure 3.35: Temperature bridge circuit.

Currents will be:

$$I_1 = \frac{1}{R_1 + R_2} \cdot V_s \; I_2 = \frac{1}{R_3 + R_{PT100}} \cdot V_s \tag{3.10}$$

So the voltage V_G is:

$$V_G = R_2 \cdot I_1 + R_{PT100} \cdot I_2 \tag{3.11}$$

Based on (3.9) at 0 °C R_{PT100} is 100 Ω and at 150 °C $R_{PT100} \cong 157.57$ Ω So the voltage range (using (3.11)) that it's possible to measure is 0V at 0°C and 0.3659V at 150°C. This voltage needs to be amplified to be readable by the ADC of the MCU and the conditioning is made with the differential operational amplifiers circuit shown in Fig.3.36

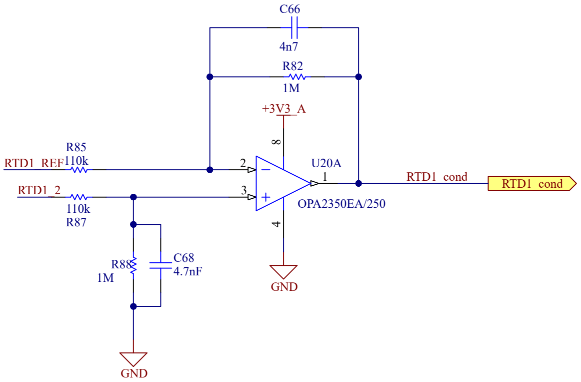

Figure 3.36: Temperature conditioning schematic.

To obtain 3.3V as maximum output the gain must be:

$$G = \frac{V_{in}}{V_{out}} = \frac{R_{out}}{R_{in}} \cong 9 \tag{3.12}$$

So the resistor chosen are $R_{out}(R_{82})$ $1M\Omega$ and $R_{in}(R_{85})$ $110k\Omega$.

3.6 Torque sensing

The torque is measured through the T40B torquemeter attached to the induction motor. The sensor can measure torque until 20000 rpm and it sends back a voltage between -10V and 10V proportional to the torque. This signal has to be conditioned because the MCU must receive only positive signals. The circuit is similar to the current sensing one and it is shown in Fig.3.37

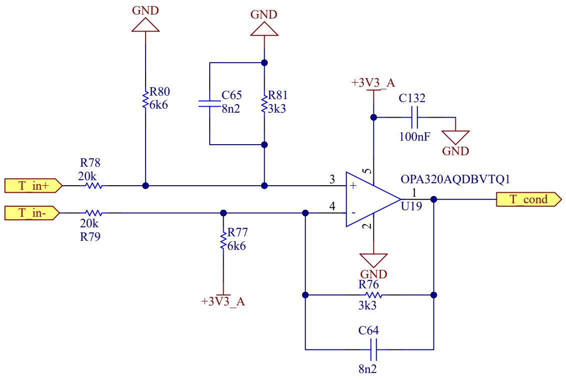

Figure 3.37: Torque conditioning schematic.

The torque signal is manipulated following the same principles used for the current signals, so:

$$V_{out} = \pm V_{in} \cdot \frac{R_{76}}{R_{78}} = \pm 10 \cdot \frac{3300}{20000} = \pm 1.65V \tag{3.13}$$

Also there is the voltage offset circuit to change the output voltage range to 0 → 3.3V.

3.7 Drivers Wolfspeed

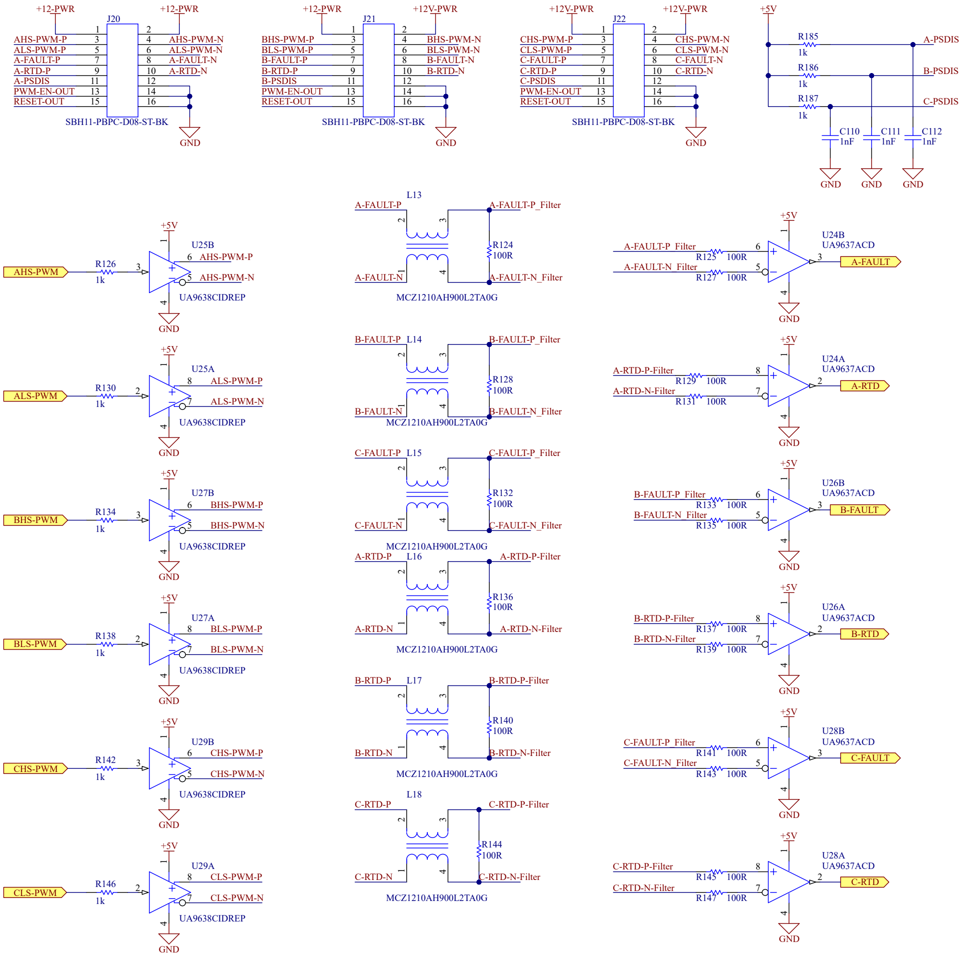

Figure 3.38: drivers schematic.

Wolfspeed's CGD12HBXMP is a form-factor-fitting two-channel gate driver for the XM3 power module platform. Each of the two gate drive channels is protected against over-current and reverse polarity. The on-board 2 W isolated power supplies support 80 kHz switching frequency [1]. It can handle a DC-BUS voltage of up to 1000V. In this applications there are 3 of these components and they interface with the control board through the connectors J20, J21, J22 (Fig.3.38). Signals are:

- AHS-PWM-P and AHS-PWM-N: these are the signals used for modulating the upper inverter leg and it has also its negate for interference immunity. The same is for BHS-PWM-P, BHS-PWM-N, CHS-PWM-P and CHS-PWM-N.
- ALS-PWM-P and ALS-PWM-N: these are the signals for the lower inverter leg.
- PSDIS: The PSDIS signal disables the output of the isolated DC/DC converter for the two channels. It is a single-ended input that must be pulled low to turn off the power supplies. This signal can be used for startup sequencing.
- RTD: RTD output is a differential signal that measures the resistance of the temperature sensor integrated in the CAB450M12XM3 modules. The signal is frequency modulated and it encodes the resistance of the temperature sensors.
- FAULT-EN-OUT: The fault signal is a RS422 compatible differential output. A High signal means there are no fault conditions for either gate driver channel.
- PWM-EN-OUT: This is a single-ended input that enables the PWM inputs for both channels. When this signal is pulled down the differential receiver for both channel are disabled and the gates will both be pulled low through a resistance. All protection circuitry and power supplies continue top operate including FAULT and RTD
- RESET-EN-N: This input must be held low for the normal running, but when a fault exists, this pin is brought high to clear the fault.

3.7.1 Leg signals

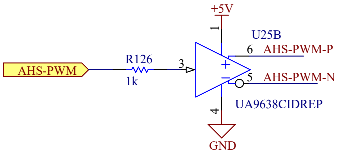

Figure 3.39: Leg A high-signal conditioning schematic

The MCU creates the leg signals based on the rotor speed and position. This signal needs to be stepped up to 5V to make it readable for the gate driver. To do that it's used the UA9638CIDREP, a dual high-speed differential line driver and after that the signals are sent to the connectors.

3.7.2 Safety signals

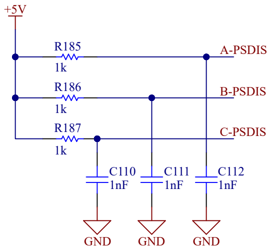

Figure 3.40: PSDIS direct supply schematic.

PSDIS signal is kept high through the circuit shown in Fig. 3.40. When the system starts up PSDIS goes directly high to 5V and can be sent to the driver.

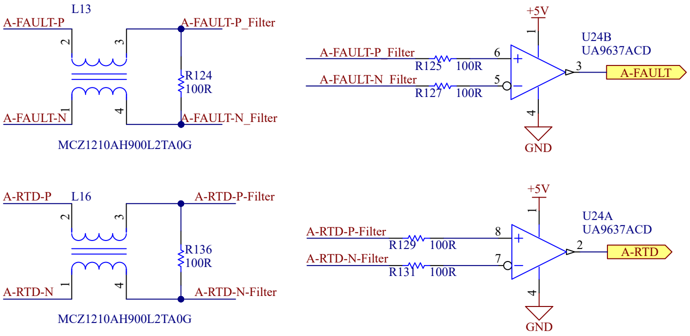

Figure 3.41: Fault and RTD signals schematic.

Fault and RTD signals come from the gate drivers and go through the filters (Fig.3.41). This part of the circuit has been changed with respect to the original board. Before there were two inductors with the resistor, now there is a coupled inductor and a resistor as a filter. After that the differential signals must be read by the MCU so there is the UA9637ACD that translates the differential inputs in a single output. This output is now at 5V, to step down this voltage is used a simple voltage divider with two resistors respectively of 2.2 $k\Omega$ and of 3.3 $k\Omega$ so that:

$$V_{out} = 5 \cdot \frac{2200}{3300} \cong 3.3V \tag{3.14}$$

3.7.3 PWM and Reset signals

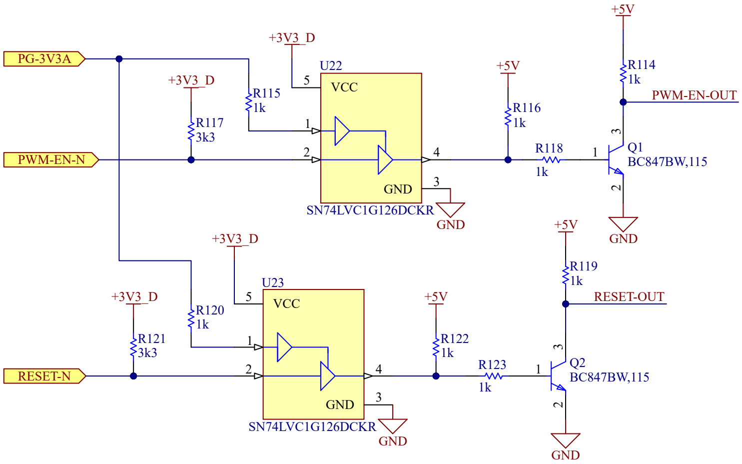

Figure 3.42: PWM and Reset schematic

Fig.3.42 is the scheme used for controlling the PWM and RESET signals. As said before PWM-EN-OUT signal must be held high in order to ensure the correct functioning of the gate driver modules. U22 is a single buffer driver. It is enabled by the power good signal from TPS7A2633DRVR (3.3V analog). If U22 is enabled, depending on PWM-EN-N signal from the MCU the driver input signal PWM-EN-OUT can be around 5V or 0V. If PWM-EN-N is pulled high (using inverted logic) the output of U22 (V_{U22}) is high, in this way a current passes through the NPN transistor Q1 base (Fig.3.43). The base current (I_b) is defined by:

$$I_b = \frac{V_{U22} - V_{be}}{R_{122}} = \frac{3.3 - 0.6}{R_{122}} = 2.7mA \qquad (3.15)$$

So the transistor is closed, the PWM-EN-OUT signal goes low (0.2V that is the V_{ce}) and the inverter gate driver PWM is disabled.

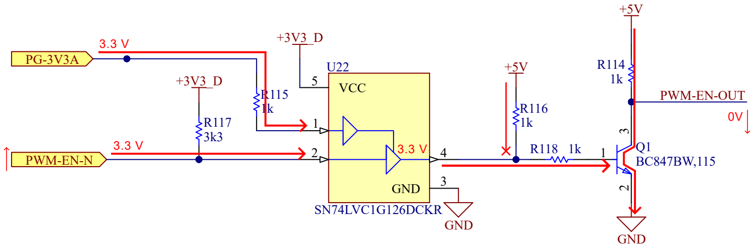

Figure 3.43: PWM-EN-N high state schematic.

On the other hand when PWM-EN-N is pulled low, the output of the SN74 is 0V and the 5V path is shown in Fig.3.44 There will be no I_b and the NPN transistor pulls up the the output signal to 5V, as a consequence the inverter gate driver will start modulating the inverter MOSFETs.

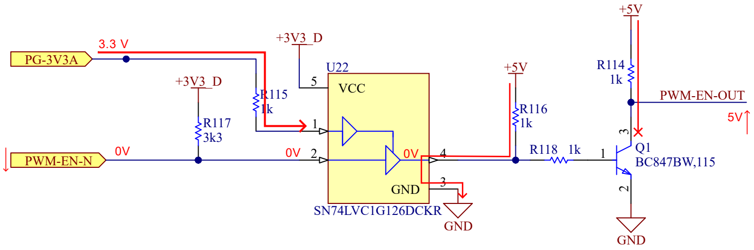

Figure 3.44: PWM-EN-N low state schematic.

5V supply is useful during the startup phase when the PG-3V3A signal is not ready. Indeed if there's no power good signal, the output of the SN74 goes to high impedance mode, in that way the 5V supply preferred path is shown in Fig.3.45 and there will be a base current and so PWM-EN-OUT will be held low to ensure safety operations.

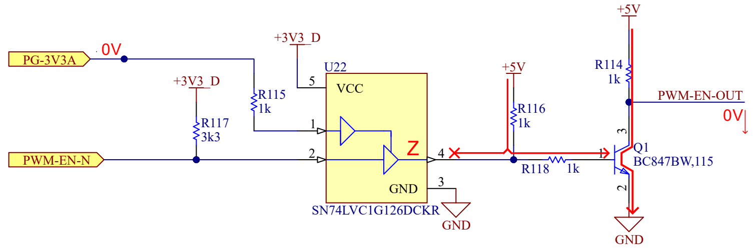

Figure 3.45: PG-3V3A disabled schematic.

Reset

The RESET-OUT signal circuitry uses the same principles as the PWM-EN-OUT. When the system is in normal conditions RESET-OUT signal must be held low therefore following the same logic as before the MCU signal RESET-N must be high. After a fault, to reset the gate driver, RESET-OUT must go high and as a consequence RESET-N must go low.

3.8 Emergency circuit

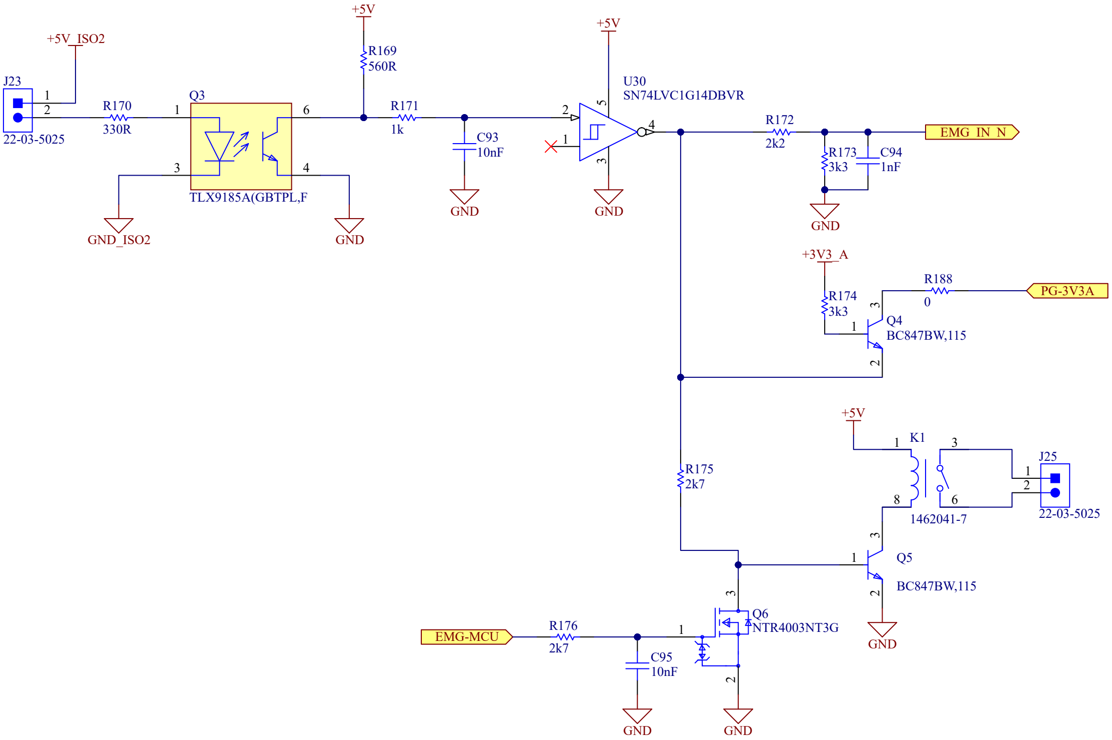

Figure 3.46: Emergency schematic circuit.

Laboratories often deal with lot of people, equipment, and processes. Having an emergency button helps ensure the safety of personnel by stopping operations in case of imminent danger. For those reasons it's been implemented a circuit that manages the shutdown of the inverter and its peripherals. Fig 3.46 shows how the logic circuit is realized on the control board. J23 connector represents the normally closed emergency button.

Normal conditions

During regular operations, represented by Fig. 3.47, a current passes through the diode of the optoisolator Q3 and the NPN transistor inside is closed. The current from 5V supply will flow through the NPN and the pin 2 of U30 is held low. SN74LVC1G14DBVR is an independent inverter with Schmitt-trigger inputs which makes it tolerant to slow or noisy input signals. As the input (pin 2) is low ($\cong 0V$) the output (pin 4) will be high ($\cong 5V$). Pin 4 is then connected to three different parts:

1. EMG-IN-N: It is the signal that goes to the MCU and to be compatible with the MCU input pin there is a voltage divider (5V → 3.3V and a filter capacitor. This signal uses negate logic so if it is high means that everything is fine and no emergency routines are called.

2. Q4 emitter: this circuit is used to eventually pulls down PG-3V3A signal but during normal conditions V_{be} will be:

$$V_{be} = V_b - V_e \cong 3.3 - 5 \cong -1.7V \tag{3.16}$$

   Since V_{be} is negative the current cannot pass through the NPN.

3. Q5 base: Q5 works as a switch for K1 relay, an auxiliary connected to external equipment through j25 connector. Q5 is kept closed by the base current provided by the high state of pin 4 through R175 resistor. If Q5 is closed K1 coil is excited and the contact is closed.

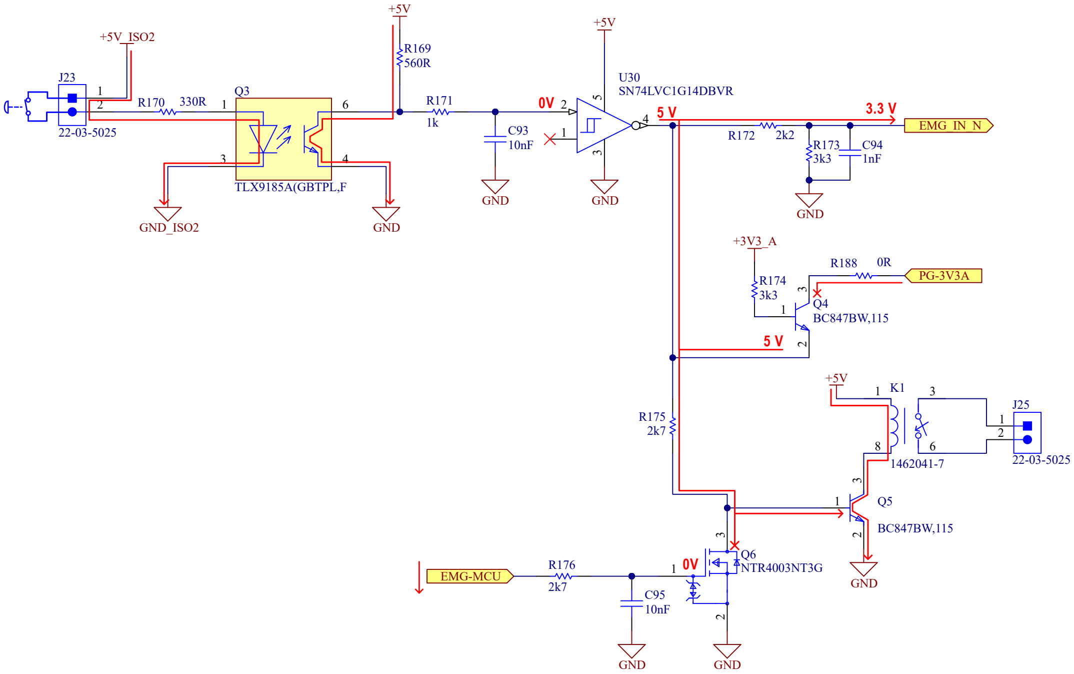

Figure 3.47: Normal-operation emergency schematic.

There is another emergency input that is the EMG-MCU signal, a signal that comes from the MCU in case the microcontroller detects failures in the system. During normal operations this is low, so Q6 MOSFET will remain open.

Emergency conditions

Depending on which emergency input is involved the circuit will behave in two different manners:

- J25 (Emergency button): If the emergency button is pushed, the contact will open and no current can flow through the diode of the optoisolator. The NPN transistor will open and the pin 2 of U30 will go to high state (5V). Since is an inverting trigger, pin 4 will go to zero. EMG-IN-N signal will be zero and the MCU will detect that and will act accordingly. PG-3V3A will be pulled down by Q4 because now V_{be} will be greater than 0.6V and Q4 will close. Lastly there won't be any base current in Q5, the NPN will open and also the auxiliary contact will open, transmitting the emergency to the external equipment.

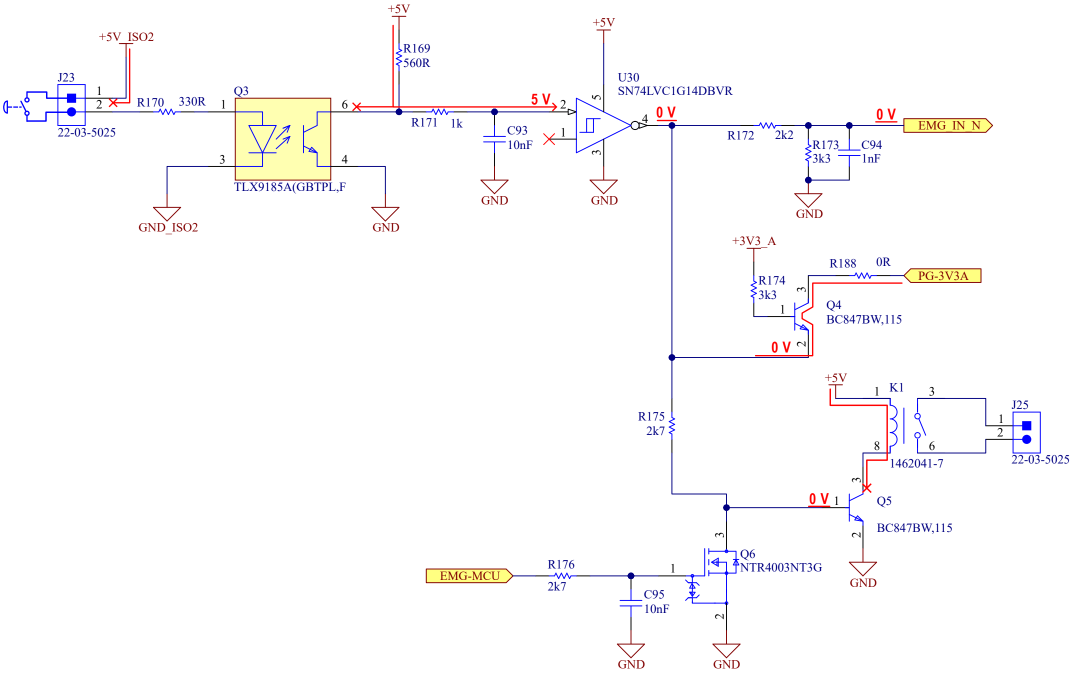

Figure 3.48: Emergency-ON schematic.

- EMG-MCU signal in high state: Assuming that the emergency button is not pushed and as consequence pin4 of U20 is in high state, the MCU can detect problems and must be able to shut down all the critical parts of the setup. When EMG-MCU is pulled up, a voltage is applied at the Q6 gate, closing the MOSFET. 5V from pin 4 will be pulled to 0V through Q6 and as consequence EMG-IN-N, PG-3V3A and Q5 will behave as the emergency button is pushed.

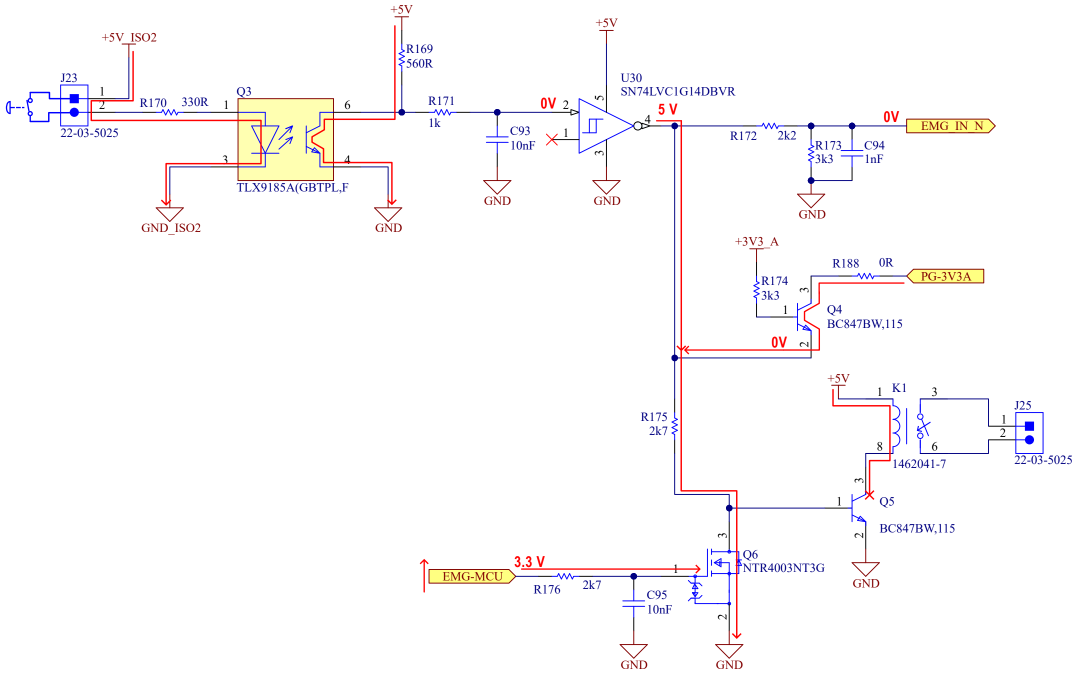

Figure 3.49: Emergency MCU schematic.

3.9 CAN

The Controller Area Network (CAN) bus is a widely used communication protocol in automotive and industrial applications for connecting various electronic control units (ECUs) within a vehicle or a system. It's designed for high reliability, real-time operation, and robustness in noisy electrical environments. CAN bus signals are transmitted differentially over two wires: CAN High (CANH) and CAN Low (CANL). This differential signaling helps in noise immunity and allows for reliable communication even in electrically noisy environments. CAN bus typically employs a bus topology, where multiple nodes are connected to the same two-wire bus and supports different speeds ranging from 10 kbit/s to 1 Mbit/s, depending on the specific implementation and requirements of the application. Onto the control board there are two different CAN channels, CAN-A and CAN-B. This is useful for laboratory test, for letting the different components to communicate with each other, as well as for automotive applications. The setup in shown in Fig.3.50

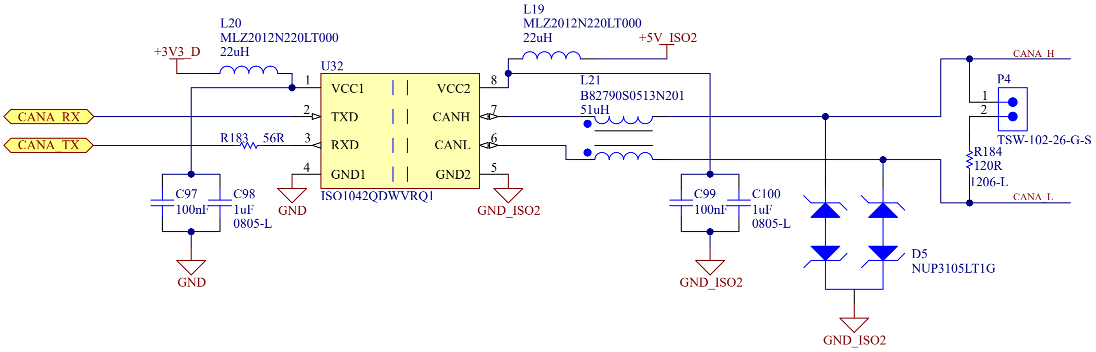

Figure 3.50: CAN-A circuit.

The ISO1042-Q1 device is a galvanically-isolated controller area network (CAN) transceiver. The device supports up to 5-Mbps data rate and uses a silicon dioxide (SiO 2) insulation barrier with a withstand voltage of 5000 VRMS and a working voltage of 1060 V RMS (Fig. 3.51). Used in conjunction with isolated power supplies, the device protects against high voltage, and prevents noise currents from the bus from entering the local ground[17].

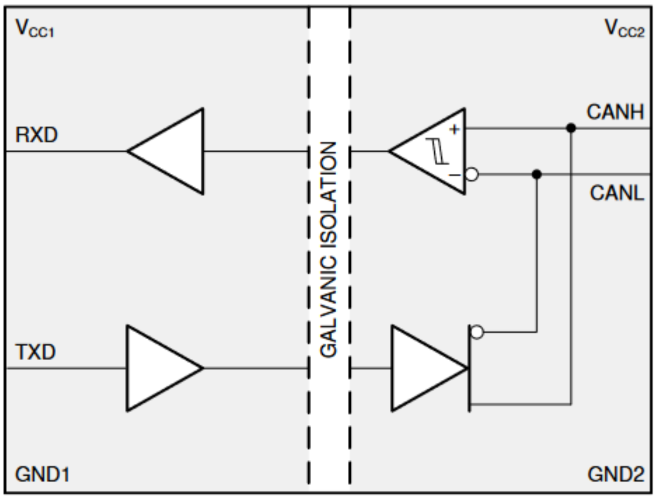

Figure 3.51: ISO1042 internal scheme[17].

CAN-RX, CAN-TX are signals that come from the MCU passes through the ISO1042 that encode them in a differential signal (CANH, CANL) the two signals then goes to the connectors and to the external devices. In the scheme 3.50 it can be also notice R184 that is resistor used as a terminator of the line.

3.10 Microcontroller

This control board was created with the initial main purpose of integrating the MCU on it. The original control board provided by Wolfspeed had an external microcontroller attached over it through specific connectors. Now the new MCU by STM, the STM32G474VET LGFP100, is surface mounted on the board and it has better integration with the I/O of the system.

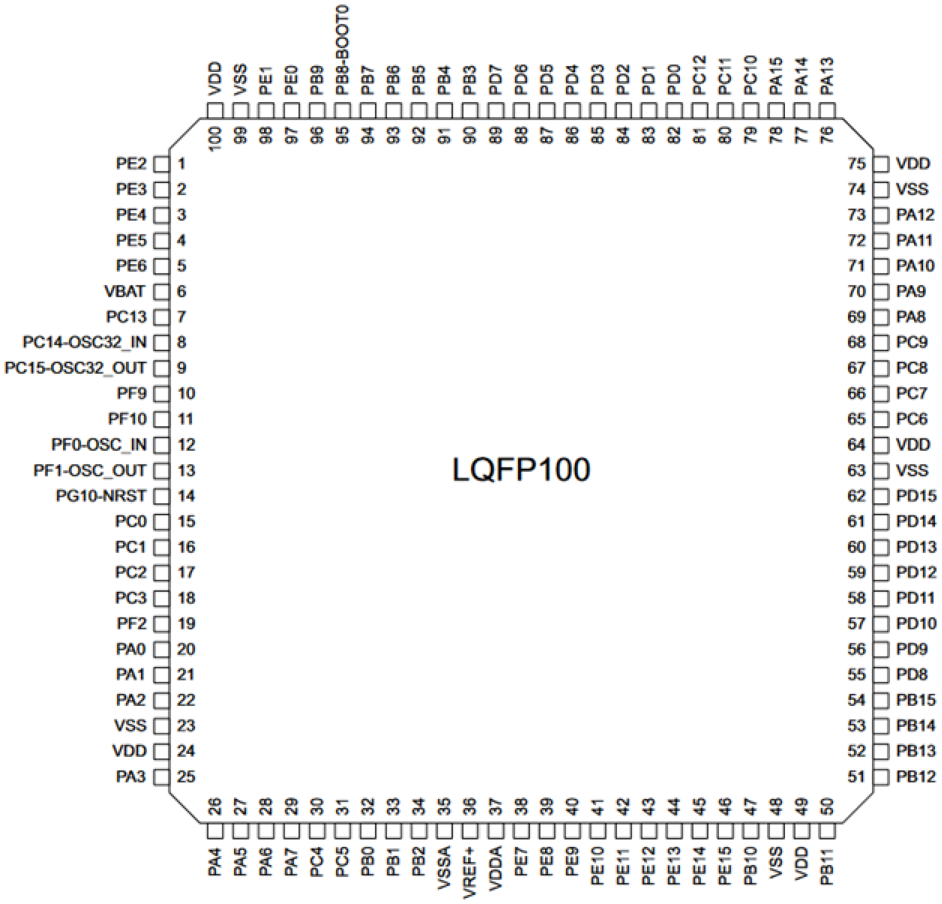

Figure 3.52: package top view[18].

3.10.1 STM32G474VET

The STM32G474 device is based on the high-performance Arm® Cortex®-M4 32-bit RISC core. They operate at a frequency of up to 170 MHz. The Cortex-M4 core features a single-precision floating-point unit (FPU), which supports all the Arm single-precision data-processing instructions and all the data types. It also implements a full set of DSP (digital signal processing) instructions and a memory protection unit (MPU) which enhances the application's security. These devices embed high-speed memories (up to 512 Kbytes of Flash memory, and 128 Kbytes of SRAM), a flexible external memory controller (FSMC) for static memories (for devices with packages of 100 pins and more), a Quad-SPI Flash memory interface, and an extensive range of enhanced I/Os and peripherals connected to two APB buses, two AHB buses and a 32-bit multi-AHB bus matrix. They offer five fast 12-bit ADCs (4 Msps), seven comparators, six operational amplifiers, seven DAC channels (3 external and 4 internal), an internal voltage reference buffer, a low-power RTC, two general-purpose 32-bit timers, three 16-bit PWM timers dedicated to motor control, seven general-purpose 16-bit timers, and one 16-bit low-power timer, and high resolution timer with 184 ps resolution. The devices operate in the -40 to +85 °C (+105 °C junction) and -40 to +125 °C (+130 °C junction) temperature ranges from a 1.71 to 3.6 V power supply. A comprehensive set of power-saving modes allows the design of low-power applications. Some independent power supplies are supported including an analog independent supply input for ADC, DAC, OPAMPs and comparators[18].

3.10.2 Supply

The STM32G474VET6 run on 3.3V, in Fig.3.53 is shown the circuit to provide power to the internal digital and analog circuits. Moreover for every pin there are two input filters represented by capacitor in Fig.3.54

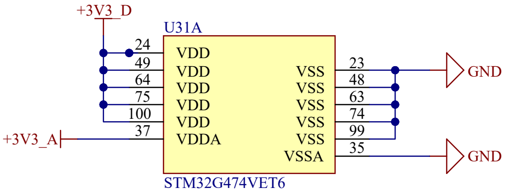

Figure 3.53: MCU supply pin.

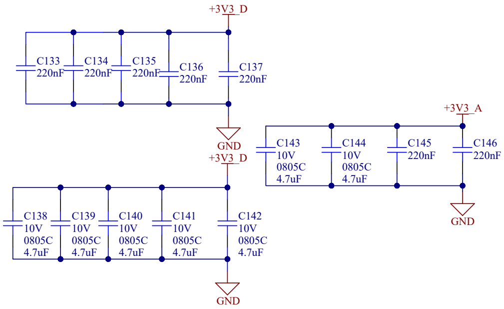

Figure 3.54: MCU supply filters.

3.10.3 Input and Output pin

The STM32G474VET6 in LQFP100 package typically has 82 general-purpose I/O (GPIO) pins. These pins can be configured for various functions such as digital input, digital output, analog input, PWM output, USART, SPI, I2C. Additionally, some pins might have specific functions dedicated to particular peripherals like timers, analog peripherals andcommunication interfaces. In this application, pins are configured as shown by the following tables:

Table 3.2: Drivers pin.

Pin	**Name**	**Type**	**I/O**
PA8	AHS-PWM	PWM	OUTPUT
PA9	ALS-PWM	PWM	OUTPUT
PC6	A-FAULT	DIGITAL	INPUT
PD3	A-RTD	DIGITAL COUNTER	INPUT
PC10	A-PSDIS	DIGITAL	OUTPUT
PA10	BHS-PWM	PWM	OUTPUT
PA11	BLS-PWM	PWM	OUTPUT
PC7	B-FAULT	DIGITAL	INPUT
PE2	B-RTD	DIGITAL COUNTER	INPUT
PC11	B-PSDIS	DIGITAL	OUTPUT
PB12	CHS-PWM	PWM	OUTPUT
PB13	CLS-PWM	PWM	OUTPUT
PC8	C-FAULT	DIGITAL	INPUT
PD12	C-RTD	DIGITAL COUNTER	INPUT
PC12	C-PSDIS	DIGITAL	OUTPUT
PD1	PWM-EN-N	DIGITAL	OUTPUT
PD2	RESET-EN-N	DIGITAL	OUTPUT

Inverter RTD internal signals are frequency signals, so to decode them the corresponding pin must be configured as digital counter input so that it can count the digital pulses. The frequency of these signals can vary from 4.6 kHz to 30.1 kHz.

Table 3.3: Analog pin.

Pin	**Name**	**Type**	**I/O**
PA1	Ia_cond	ANALOG	INPUT
PA0	Ib_cond	ANALOG	INPUT
PB1	Ic_cond	ANALOG	INPUT
PA6	VDC_cond	ANALOG	INPUT
PE9	T_cond	ANALOG	INPUT
PB14	RTD1_cond	ANALOG	INPUT
PB15	RTD2_cond	ANALOG	INPUT
PE8	RTD3_cond	ANALOG	INPUT
PD10	RTD4_cond	ANALOG	INPUT

Table 3.3 shows all the analog pins. These signals must be filtered before being physically connected to the MCU and Fig. 3.55 shows only the circuit for VDC signal filtering but is the same for the others.

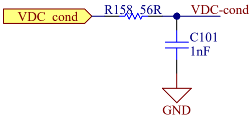

Figure 3.55: Analog pin filter.

Table 3.4: CAN Pin Configuration.

Pin	Function	Type	Direction
PD0	CANA_RX	I/O	-
PA12	CANA_TX	I/O	-
PB5	CANB_RX	I/O	-
PB6	CANB_TX	I/O	-

CAN signals use dedicated bidirectional communication lines and MCU pins must be properly configured.

Table 3.5: Encoder pin.

Pin	Function	Type	Direction
PC0	A_MCU	DIGITAL COUNTER	INPUT
PC1	B_MCU	DIGITAL COUNTER	INPUT
PE7	Z_MCU	DIGITAL COUNTER	INPUT

Table 3.6: DC-side pin.

Pin	Function	Type	Direction
PE3	PRE-ON	DIGITAL	OUTPUT
PE4	DSG-ON	DIGITAL	OUTPUT
PE5	PWR-ON	DIGITAL	OUTPUT
PF9	RELE-1	DIGITAL	OUTPUT
PF10	RELE-2	DIGITAL	OUTPUT
PE6	FAN-ON	DIGITAL	OUTPUT

Table 3.7: Emergency Pin Configuration.

Pin	Function	Type	Direction
PD15	EMG-MCU	DIGITAL	OUTPUT
PC9	EMG-IN-N	DIGITAL IRQ	INPUT
PD14	PG-3V3A	DIGITAL	INPUT

PG-3V3A signal is particularly important because it ensures the correct work of the temperature, current and voltage circuitry. EMG-IN-N pin is configured as a "DIGITAL IRQ INPUT" because when up it can automatically call an interrupt request.

Table 3.8: Water-flow sensor pin.

Pin	Function	Type	Direction
PB2	FLOW	DIGITAL COUNTER	INPUT

The water sensor outputs a frequency (F) proportional to the flow rate ($Q = \frac{L}{min}$) and since the maximum flow rate measurable is $30\frac{L}{min}$:

$$F = 6.6 \cdot Q = 198Hz \tag{3.17}$$

Table 3.9: LED Pin Configuration.

Pin	LED	Type	Direction
PC2	LED1	DIGITAL	OUTPUT
PC3	LED2	DIGITAL	OUTPUT
PF2	LED3	DIGITAL	OUTPUT

These three output pins are connected with three general purpose LED.

Table 3.10: Debug Pin Configuration.

Pin	Function	Type	Direction
PA4	DEBUG-1/SPI1_CS	DIGITAL	INPUT/OUTPUT
PA5	DEBUG-2/SPI1_CLK	DIGITAL	INPUT/OUTPUT
PA7	DEBUG-3/SPI1_MOSI	DIGITAL	INPUT/OUTPUT
PB4	DEBUG-4/SPI1_MISO	DIGITAL	INPUT/OUTPUT
PC4	USART1_TX_DBG	DIGITAL	OUTPUT
PC5	USART1_RX_DBG	DIGITAL	INPUT
PA2	USART2_TX_DBG	DIGITAL	OUTPUT
PB0	DBG_SYNC	DIGITAL	OUTPUT
PA14	SWCLK	DIGITAL	OUTPUT
PA13	SWDIO	DIGITAL	I/O
NRST	NRST	DIGITAL	INPUT
PF0	CLK_IN	DIGITAL	INPUT

Debug pins on a microcontroller unit (MCU) are used for debugging and programming purposes. These pins provide an interface for connecting the microcontroller to external tools, such as an in-circuit debugger or a programming tool, to facilitate software development, testing, and troubleshooting.

3.11 Control Board PCB

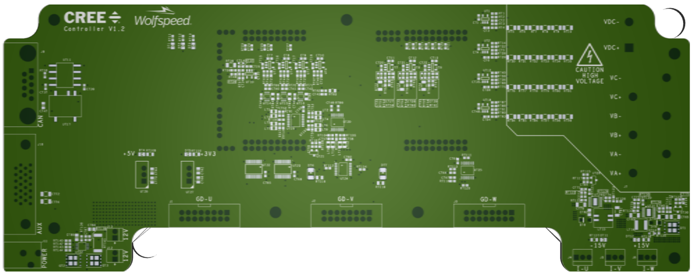

Figure 3.56: Original control board shape [1].

Fig.3.56 illustrates the original control board, designed to fit inside the confines of the inverter box. However, due to the addition of numerous new components, it is evident that this board is now too small to accommodate them all. Therefore, the new control board has been redesigned to be accommodated in a higher position with the possibility to be extended beyond the boundaries of the inverter box.

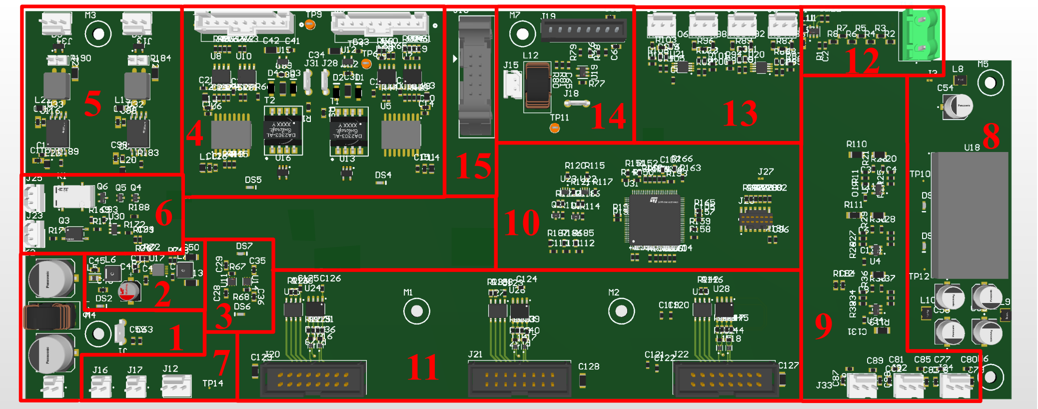

Figure 3.57: New control board.

The new board (Fig. 3.57) keeps the same mounting hole and similar position for the VDC conditioning, the driver connectors, current connectors and internal fan connectors. It is worth noting that the microcontroller is now situated on the board through which all signals are routed. On the left part of the board there are all the digital signals and on the left the analog ones, moreover there are, as for the DC-Side board, different regions of the board with the following functions:

1. 12V supply filters;
2. 12V → 5V supply;
3. 5V → 3.3V supply either for digital and analogic circuits;
4. 5V → 5V isolated supply and Encoder circuitry with connectors;
5. CAN circuitry;
6. Emergency circuits and connectors;
7. Fan and water flow sensor connectors;
8. 5V → ±15V supply for current sensors;
9. Current sensing circuits and connectors;
10. Microcontroller and debug circuit;
11. Gate driver connectors and circuitry;
12. DC-link connector and voltage sensing circuit;
13. Temperature sensing circuitry;
14. Torque sensing and 24V supply filters;
15. DC-side board connector;

Chapter 4

Conclusions

In conclusion, this thesis has examined essential topics of power electronics, focusing on the design and enhancement of a control board for an 800V inverter. With the increasing demand for higher voltage systems, such as the 800V inverter examined here, particularly in automotive applications, the need for robust control mechanisms becomes paramount.

The control board, as explained, acts like the brain of the inverter, making sure it does its job well by managing many important tasks. From power control to temperature regulation, from communication interfaces to the implementation of optimization algorithms, the control board plays a pivotal role in ensuring the seamless operation of the inverter while maintaining safety and efficiency standards.

The shortcomings identified in the previous configuration of the inverter and its control board underscore the necessity for innovation and improvement. By addressing issues such as single-ended encoder signaling, lack of EMI filters, inadequacy of external connectors and the absence of emergency circuitry as well as management mechanisms for the high-voltage DC side, this thesis has taken big steps toward fixing these problems.

The redesigned control board, as proposed, represents a comprehensive solution aimed at mitigating the identified shortcomings. By integrating the MCU directly onto the board, redesigning power supply systems, and incorporating safety features such as emergency sequences and circuit breakers, the new control board enhanced functionality, versatility, and safety.

Overall, I contributed to this project by creating the required circuitry for the DC-side board, reshaping and designing the new control board, searching and choosing the right components that hit the electrical and thermal requirements, creating the emergency circuit. Future improvements to this work could be the physical realization of these two boards, testing and implementing them in the PEIC laboratory.

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