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Author: Aleksander Kristiansen Ferkingstad	.... (signature author)

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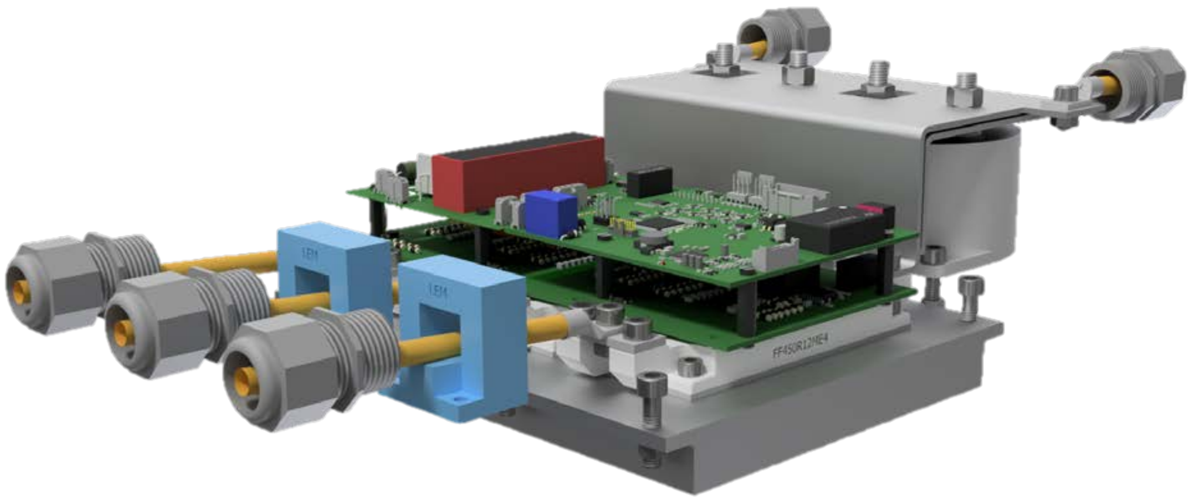

Design and testing of a voltage source inverter and three-phase motor controller system for use in a race car.

Aleksander K. Ferkingstad

Department of Electrical Engineering and Computer Science
University of Stavanger
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Abstract

ION Racing is a student organization that each year designs and tests a formula student race car. The goal is to compete in formula student , which is the largest student competition in the world for engineers. The objective of this thesis is to design and a motor controller for use in the race car. The race car is electric and uses a 400V battery for the main power source and a permanent magnet synchronous motor. The motor controller is the interface between the battery and the motor. The thesis includes the design of the small-signal electronics, power electronics, cooling of the power electronics and control software.

Acknowledgement

I would like to give my thanks to ION Racing and all the members. Without the financial support from ION Racing and all the sponsors for buying component, producing printed circuit boards and machining components this would not have been possible. The members of the team have been a great help in both teaching me different software i needed for the thesis work and generally to keep me motivated. I would also like to thank my supervisor Morten Tengesdal.

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Acknowledgement

ECU Engine Control Unit

BMS Battery Management System

PCB Printed Circuit Board

IGBT Isolated Gate Bipolar transistor

MOSFET Metal Oxide semiconductor field effect transitor

Chapter 1

Introduction

ION Racing designs and creates a one-seat-race car for competing in formula student each year. Formula student is the largest engineering competition for students in the world. The race car for this year is a one-motor electric race car, limited to 80kW. The drivetrain consists of a 400V battery, a motor-controller, an PMSM motor, a one-level gearbox and a mechanical differential. This thesis were about designing, creating and testing the motor controller system for the car. This includes design of the power electronics, small-signal electronics, casing, cooling of the power electronics and control software.

1.1 The competition

The competition consists of a dynamic part and a static part. Figure 1.1 shows the distribution of points that are awarded in the competition. The concept of the dynamic part is test how good the car drives while the static part is to evaluate the engineering effort of designing the car, the cost of the car and the teams business plan for mass production of the car. The competition have a relatively comprehensive set of rules that need to adhered to. As a part of the competition the teams needs to write several documents, whereof two are relevant for the work done in this thesis. These two documents are the Failures Mode and Effect (FMAE) and Electrical Safety Form (ESF). These documents are a team effort written by all the members of the electrical team. The electrical safety form is added to the appendix.

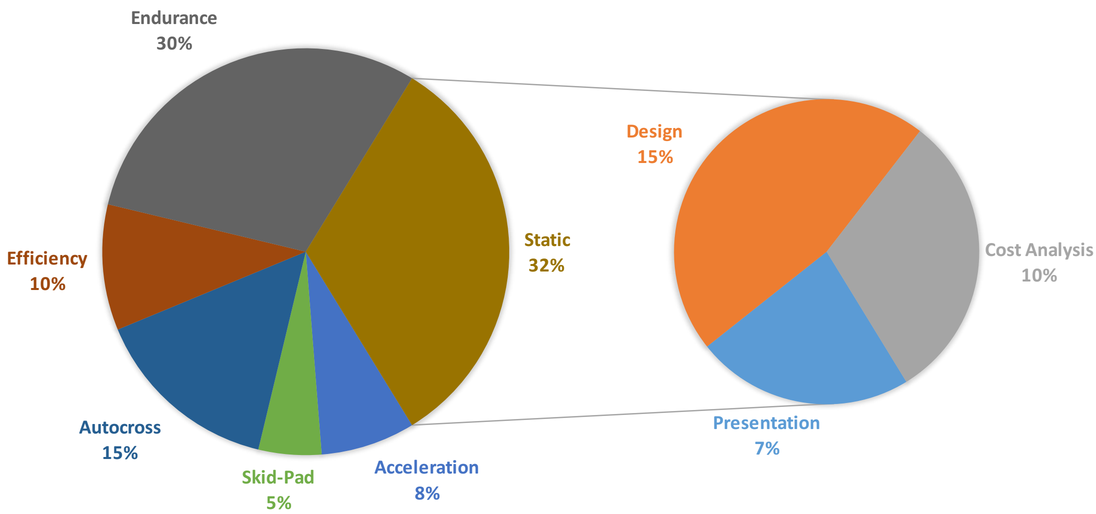

Figure 1.1: Score distrubution in Formula Student

1.2 The Motivation

Electrical vehicles are becoming more popular both in the consumer marked and the racing community. Combustion engine cars and electrical cars compete at formula student against each other. The tracks at formula student are small with many corners, which means that electrical cars with their high torque and acceleration excel. Many of the top teams creates electric cars with four motors driven independently by using torque vectoring algorithms. The motors are usually mounted in the wheel. Torque vectoring increases the handling of the car in corners by controlling each motor independently instead of relying a mechanical differential. The implementation of a four wheel drive race car is complex both in regards of the control algorithms and the hardware implementation of the system.

A four wheel drive car have been considered at ION Racing, but there are little to no complete solutions for such a system on the marked for the time being. The solution would be to design such a system in-house, but were for now disregarded as being to complex. The purpose of this thesis is to acquire a better understanding of inverter design and the control of permanent magnet synchronous machines by designing a VSI. Hopefully this thesis will serve to help if anybody in the future would like to design a four wheel drive system.

1.3 Electronics system in the car

Figure 1.2 shows a simplified overview of the electrical system in the car. All the small signal electronics in the car is powered by a 15V battery. The electronics communicate with each other over CAN-bus.

Engine Control Unit This is the brain of the car. It reads different sensors, including the throttle position, runs control algorithms and transmits a torque request to the motor controller. It runs safety checks, decides when the car can start and when it needs to shut down. Further it can transmit data to a external computer for live view of the data in the car. It also loggs sensor readings and CAN-bus messages for later analysis.

Data analysis software This software is written by the computer engineers on the team. It enables live view of desired data in the pit, and analysis of logged data. It runs on a normal computer and communicates with the car over telemetry using a team designed telemetry module.

7-segment display This display is used for showing information to the driver. It's not essential since the team monitors the live data over telemetry and relays important information to the driver via radio communication, but it can be helpful if the communication with the driver fails and under initial testing of the car. The display can be programmed to show any information broadcasted on the CAN-bus.

400V battery The High Voltage Battery (HVB) is the energy source for the drivetrain in the car. It uses a Battery Management System (BMS) which can stop the car and isolate the 400V from the rest of the system if it detects a fault.

Motor controller The motor controller is the subject for this thesis. It converts the 400V DC from the HVB to three phase AC to the motor. It's task is to take a torque request from the ECU and create three phase voltages on the output which generates the desired torque request.

Insulation monitor This is a bought module from Bender which monitors that that the high side (400V system) is isolated from the low side (15V system). If a ground fault is detected the 400V from the HVB will be isolated from the rest of the system, and the car stops.

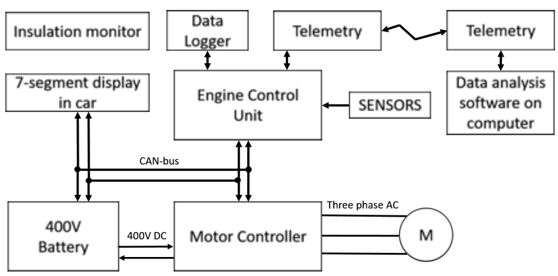

Figure 1.2: Simplified overview of the electrical system in the car

1.4 Drivetrain

It were decided to control the torque of the motor (instead of the speed of the motor), since this is the most natural response for the driver. The drivetrain consists of the 400V battery which is connected to the motor controller. The motor controller takes a torque request from the ECU, and controls the torque of the motor to that value. The motor is connected to a one level gear-box and then to a mechanical differential. This section describes the electrical components of the drivetrain in some more detail.

High Voltage Battery

The car uses a high energy battery designed by teammates at ION Racing, [[9]]. The battery is the energy source for the drivetrain.

As Per the rules of the competition [2] the power delivered by the battery must not exceed 80kW. If the delivered power exceeds 80kW for more than 100ms or it exceeds 80kW after a moving average filter for 500ms is applied it is considered a violation. A violation results in a disqualification for the event which it happened at. A disqualification at an event leads to zero points for that event. So even though the battery can deliver large amounts of power, the peak power is limited to $I_{peak} = \frac{80kW}{V_{battery}}$.

1.4.1 Engine Control unit

The ECU are also designed by teammates at ION Racing. In short the role of the ECU is to read the requested torque from the driver and other sensors. The ECU then processes the data and transmit a new torque request to the VSI. The processing includes safety algorithms, traction control and power limiting. It is the responsibility of the ECU to limit the maximum power to 80kW per the rules, so the VSI does not need to take measures to limit the peak output power to be below 80kW.

1.4.2 Motor

The car were designed to use a Emrax 228, which is a Permanent Magnet Synchronous Machine (PMSM). This is the same motor that were used for last years car and the team wanted to continue using this motor as they were pleased with it's performance. The PMSM type has the highest torque-to-weight compared to other motor types on the market, which is the desired characteristics for use in a race car. The cost of a PMSM is larger than that of other motor types, but are justified by the higher performance it delivers. Table 1.1 shows the characteristics of the Emrax 228 motor.

Table 1.1: Emrax 228 motor characteristics

Continuous power @ 3000-5000 RPM	28-42	kW
Peak power	100	kW
Mechanical speed limit	5500	RPM
Weight	12.3	kg

1.4.3 Motor controller

The Motor Controller (MC) is supplied by the high voltage battery. It needs needs to transform the DC voltage from the battery to three phase alternating currents to the motor in such a way to generate the torque requested by the ECU.

Table 1.2: Voltage source desired specifications

Continuous power	30	kW
Peak power	80	kW
Input Voltage	288-400	V

Chapter 2

Theory

This chapter explains some useful theory for controlling the torque generated by the motor. It includes some basic theory about permanent magnet AC (PMAC) motors, some important mathematics, popular control methods and their implementation in a microcontroller. Most of the content for the theory chapter were gathered from the following books: "High performance control of AC drives" [1], "Power electronics" [5] and "Power electronic converters: PWM strategies and current control techniques" [6].

2.1 Brushless Permanent Magnet Synchronous Motors

2.1.1 Permanent magnet synchronous motor construction

This section goes through the construction of the motor, different types of the motor and some useful math needed for understanding the control of them. The purpose of the PMSM motor is to generate mechanical energy. This is done by converting electrical energy to magnetic energy in the stator coils. The magnetic fields induced in the stator windings is attracted to the permanent magnets in the rotor, which generates mechanical energy.

Figure 2.1 illustrates the construction of a four pole brushless Permanent Magnet Synchronous Motor (PMSM) with glued on permanent magnets. It consists of a rotor with permanent magnets either glued on or embedded in the rotor, a wound stator and a sensor for sensing the rotation of the rotor. The position of the rotor is read from the sensor, and is used for controlling the torque and/or speed of the motor.

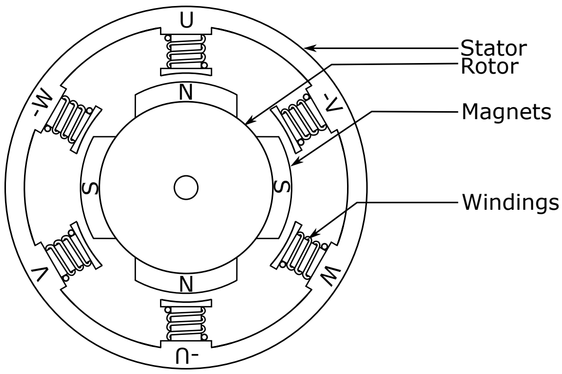

Figure 2.1: Permanent magnet motor with four rotor poles

The windings with the same labels illustrated in figure 2.1 are internally connected. The minus marking (-u, -v, -w) means that the current goes through these windings in the opposite direction than in the windings without a marking. The start of each winding are the phase connections of the motor (U, V, W). The end of the connections can either be star-connected or delta-connected, for the Emrax 228 they are internally connected in a star-configuration.

The direction of the current flow in, i.e U, is opposite of the direction of the current flow in the -U winding, so that the generated magnetic field is opposite for them. i.e a current flow in one direction would create a north pole towards the magnets for both windings. By applying different currents to each of the phases a combined magnetic vector can be generated at a desired angle. The relationship between the electrical position of the generated magnetic field and the mechanical position of the rotor is given by equation 2.1, where P is the number of rotor poles in the motor.

$$\Theta_e = \theta_m \cdot P \tag{2.1}$$

2.1.2 Torque generation

Figure 2.2 shows the equivalent electrical model for one phase of the motor. The resistor and inductor are the resistance and inductance of the windings respectively. The voltage source, called the Back-Electromotive Force (BEMF), is the induced voltage in the windings generated when the rotor rotates. The shape of the BEMF is determined by how the motor have been wound.

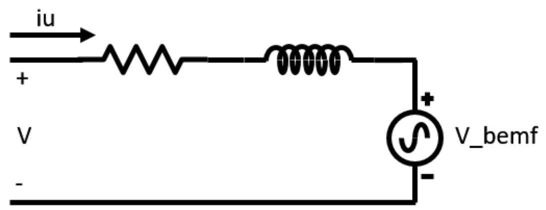

Figure 2.2: Per phase equivalent model of motor

The torque generated by the motor is given by equation 2.2, where P is the number of poles, ϕ is the flux linkages of the motor, K_U is the BEMF of phase U, K_V is the BEMF of phase V, K_W is the BEMF of phase W, i_U is the current in phase U, i_V is the current in phase V and i_W is the current in phase W.

$$T_e = P\phi[i_U K_U[\Theta_e] + i_V K_V[\Theta_e] + i_W K_W[\Theta_e]] \tag{2.2}$$

To generate constant torque the shape of the BEMF must be known. The shape of the BEMF is used for classifying the PMSM and can be roughly divided in two categories:

1. Trapezoidal type
2. Sinusoidal type

Figure 2.3 shows two ideal BEMF waves for a full 360 degrees rotation. The sinusoidal type will have a BEMF that resembles the ideal sinusoidal shape, while the trapezoid type will have a BEMF that resembles the ideal trapezoid shape. Motors wound to have a trapezoidal BEMF is often called Brushless DC (BLDC) Motors, and motors with a sinusoidal BEMF is often called sinusoidal PMSM or just PMSM. From now on the name PMSM will be used for the sinusoidal PMSM. The EMRAX 228 motor is a PMSM, and thus the rest of the theory chapter will have a focus on relevant theory for the PMSM.

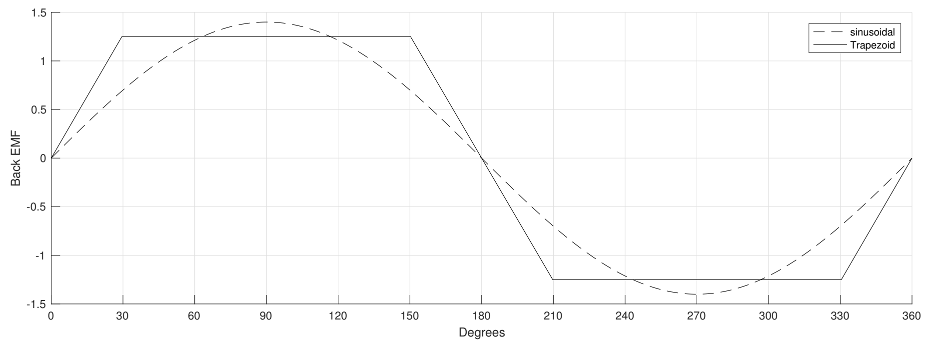

Figure 2.3: BEMF waves

The BEMF wave-shape of a PMSM (sinusoidal BEMF) is given by equation 2.3.

$$K_U[\Theta_e] = sin(\Theta_e) \tag{2.3a}$$

$$K_V[\Theta_e] = sin(\Theta_e - \frac{2\pi}{3}) \tag{2.3b}$$

$$K_W[\Theta_e] = sin(\Theta_e + \frac{2\pi}{3}) \tag{2.3c}$$

Figure 2.4 shows a simplified two pole motor. The Rotor direct axis is the direction of the magnetic field generated by the permanent magnets. The axis for Phase U, V, and W is the direction of generated magnetic field in each of the phases. The vectors of the magnetic fields produced by the windings are skewed from each-other by 120 degrees. Together they produce one magnetic field vector. The direct rotor field will lock on to the combined magnetic field of the phases. The angle of the combined magnetic field vector and the direct rotor axis is referenced to the phase U axis, given by Θ.

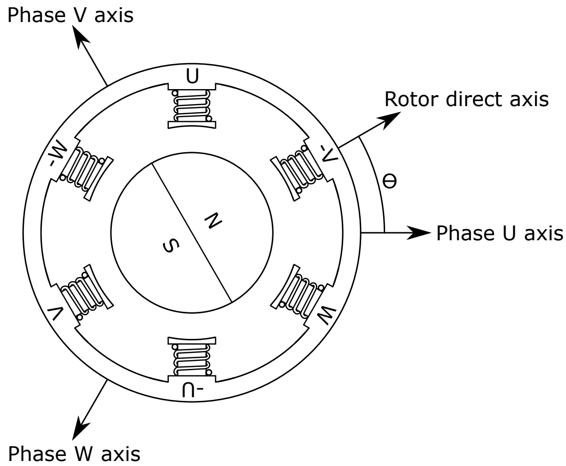

Figure 2.4: A simple two pole permanent magnet synchronous machine

The produced torque of the motor were calculated for a locked rotor (Θ = 0 for the direct rotor axis) and choosing currents for the three phases which generated a combined magnetic field vector for different angles. Figure 2.5 shows the result of the torque calculation for a full 360 degrees rotation of the combined magnetic field vector generated by the windings.

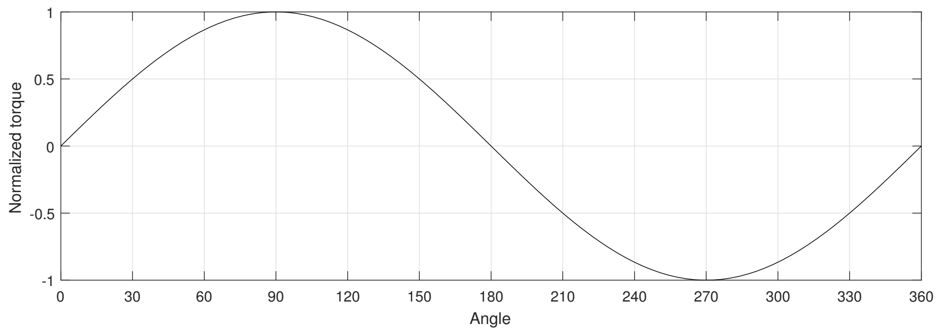

Figure 2.5: Illustration of maximum torque per ampere

As can be seen from figure 2.5 the maximum torque is achieved by generating a magnetic field that is skewed by 90 degrees from the rotor axis magnetic field. Thus to generate maximum torque per ampere the currents entering the phases should be equal to that of equation 2.4. If these input currents are used on a motor with sinusoidal BEMF the produced torque will be nearly constant (little torque ripple), but if a trapezoidal motor it would generate considerable torque ripple.

$$i_U = i_s sin(\Theta_e) \tag{2.4a}$$

$$i_V = i_s sin(\Theta_e - \frac{2\pi}{3}) \tag{2.4b}$$

$$i_W = i_s sin(\Theta_e + \frac{2\pi}{3}) \tag{2.4c}$$

If the BEMF of the motor is sinusoidal and input currents to the phases are equal to those given in equation 2.4 the torque generated by the motor can be simplified to that given by equation 2.5.

$$T_e = \frac{3}{2} P \phi i_s \tag{2.5}$$

The relationship between the electrical frequency of the currents and the mechanical frequency of the rotation is given by equation 2.6, where P is the number of poles , ω_e and ω_m is the electrical and mechanical rotational speed in rad/s respectively.

$$\omega_e = \omega_m P \tag{2.6}$$

2.2 Field oriented control of torque

This section describes the control-algorithm used for controlling the generated torque from the motor. It uses the torque equation (2.2) explained in the previous section. The control solutions presented in this section ignores the power electronics that is needed in practical systems. The power electronics will be explained in the next section. It starts with a simple solution for the control loop and explains the improvements that can be made by the use of some mathematical transformations. Figure 2.6 shows a simple approach to the control loop.

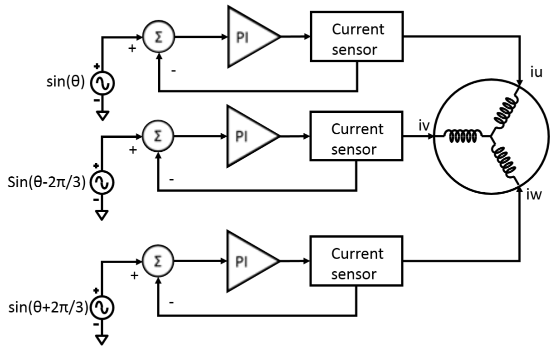

Figure 2.6: Field oriented control simple

This method uses three regulators, three set points and three current sensors. The difficuly of this approach is mainly that the reference values are sinusoidal for steady point, not constant. By using the mathematical transformation called the Clarke-transform the control loop can be simplified.

2.2.1 Clarke transform

The clarke transform takes the three phase values and transforms them in to two-phase values. The forward clarke transformation is given by equation 2.7 and the inverse clarke transformation is given by 2.8.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \end{bmatrix} \tag{2.7}$$

$$\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.8}$$

Figure 2.7 illustrates the Clarke transformation of the three phase currents given by equation 2.4. It takes advantage of the fact that the PMSM is a balanced system, which means that $i_u + i_v + i_w = 0$. Thus only two current sensors are needed.

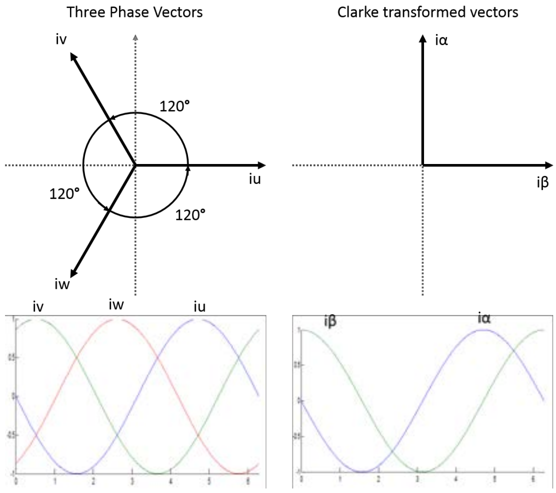

Figure 2.7: Clarke transformation illustration

A simplified control method utilizing the Clarke-transform are shown in figure 2.8. By using the clarke-transform one current sensor and one PI-regulator have been removed, but the reference values are still sinusoidal for steady-state. The control loop can be further simplified by using the Clarke and Park transform.

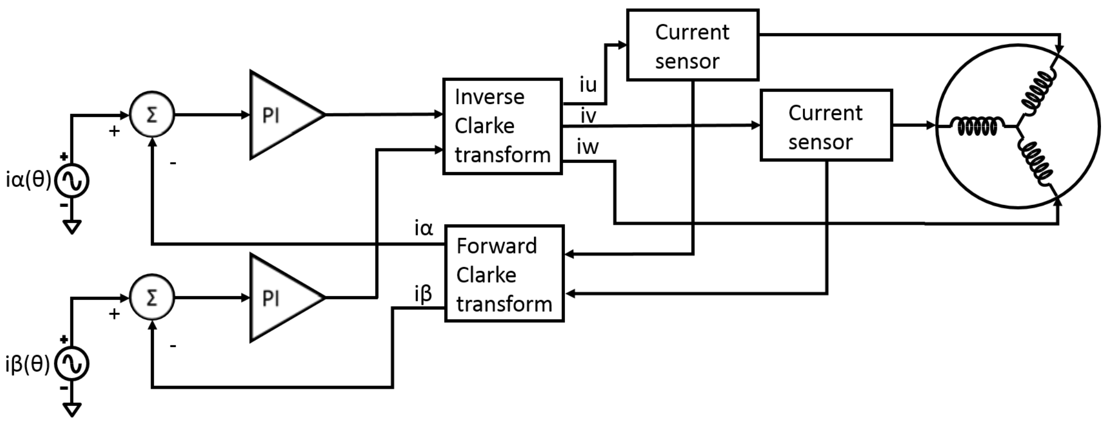

Figure 2.8: Field oriented control, improved by the use of Clarke-transform

2.2.2 Clarke and Park transform

The clarke transform takes the park transformed values and translates them by θ degrees, where Θ is the angle of the direct rotor axis referenced to the U-axis as previously shown in figure 2.4. Equation 2.9 shows the forward Park-transform and equation 2.10 shows the inverse Park-transform.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ i_\beta & -i_\alpha \end{bmatrix} \begin{bmatrix} cos\theta \\ sin\theta \end{bmatrix} \tag{2.9}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_d & -i_q \\ i_q & i_d \end{bmatrix} \begin{bmatrix} cos\theta \\ sin\theta \end{bmatrix} \tag{2.10}$$

Figure 2.9 shows the Clarke and park transformation of the three phase currents given by equation 2.4. It is important to note that the transformed values are constants, this means that for steady state the reference values are constant.

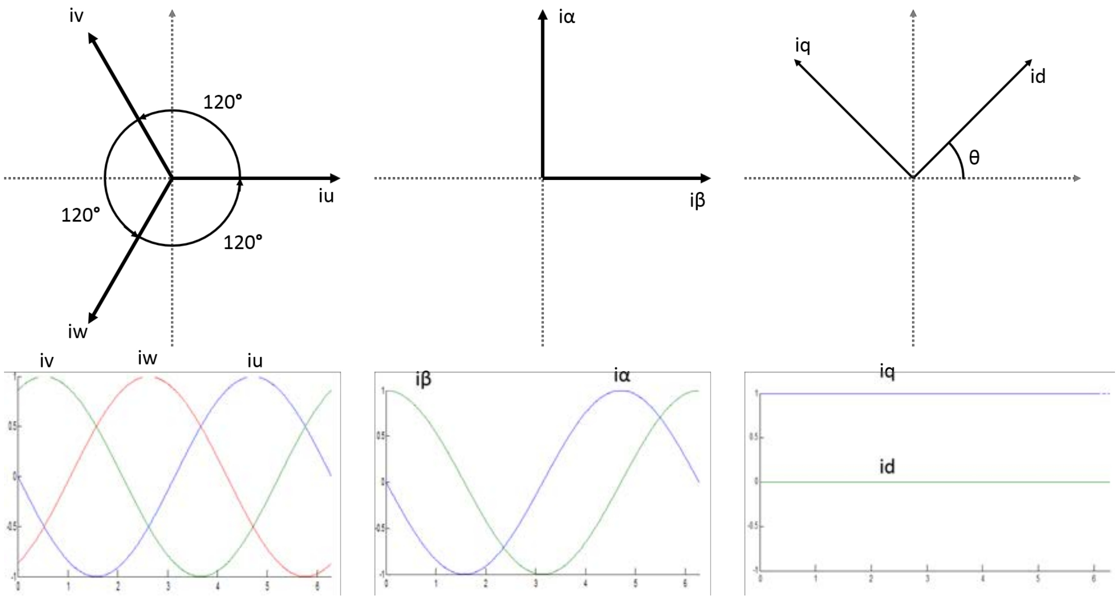

Figure 2.9: Clarke and Park transformation illustration

The generated torque of the motor can be rewritten as shown in equation 2.11. The value i_q controls the torque, but the value of i_d needs to be controlled to zero as illustrated in figure 2.9.

$$T_e = \frac{3}{2} P\phi i_q \tag{2.11}$$

The value of i_q then controls the amplitude of the magnetic field that is rotated 90 degrees referenced to the direct rotor axis, and the value of i_d controls the amplitude of the generated magnetic field that is on the direct rotor axis. By controlling the current in the d-axis to a negative value the permanent magnets in the motor can be temporarily weakened (called flux weakening). In a practical system the BEMF of the motor will restrict the maximum RPM that the motor can reach. This is because the voltage generated by the BEMF creates a opposing voltage to the control voltage, thus limiting the input current to the motor. The peak voltage amplitude of the BEMF wave can be calculated with equation 2.12 where k_e is the BEMF-constant and ω is the electrical frequency of the rotor.

$$V_{pk} = k_e\omega \tag{2.12}$$

If flux weakening is used care must be taken to limit the negative d-axis current amplitude to not permanently weaken the magnets. Also the speed must not exceed the rated speed of the motor bearings. Flux weakening were not used in the system designed for this thesis to not accidentally destroy the motor.

Figure 2.10 shows the control loop using the Clarke and Park transformation. By using these transformations the flux generated in direct rotor axis and the generated flux which is rotated by 90 degrees from the direct rotor axis have been decoupled. Further it simplifies the control method by removing one PI-regulator, one current sensor and by making the references constants for steady-state operation.

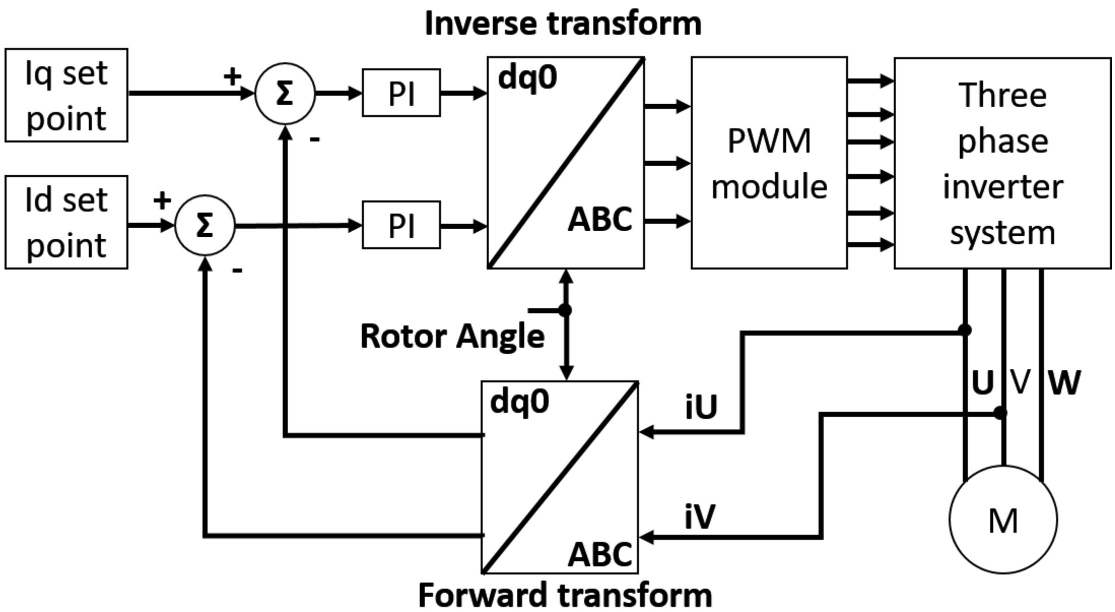

Figure 2.10: Proposed field oriented control method

2.3 Motor controller

The previous explanations have disregarded the practical problems of the implementation. The 400V DC voltage from the battery needs to be converted to three phase currents to the motor. This can be done by using a voltage source inverter. The schematics for a Voltage Source Inverter (VSI) is shown in figure 3.15. It consists

A Voltage Source Inverter (VSI) is a electrical circuit used for converting DC to AC. Figure 3.15 shows the configuration for a three phase 2-level VSI. It consists of six switches and six diodes. The six switches are grouped in three poles; Pole U (U and nU), pole V (V, nV) and pole W (W, nW). The output voltage of the VSI can be controlled by modulating the transistors.

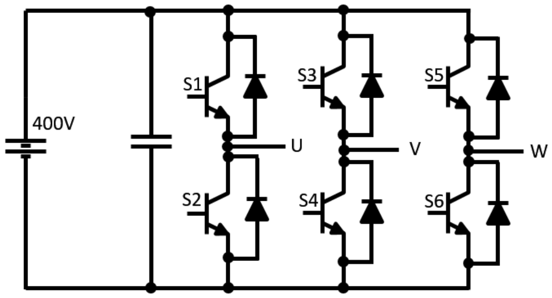

Figure 2.11: Voltage source inverter

The task of the motor controller is to take an input in form of a torque request or RPM request and regulate the motor to generate the desired value by switching the transistors in the correct manner. The other task is to keep the system safe. It does this by monitoring for any faults in the system and set it in limp mode or shut it down if necessary. The common method for switching the transistors are using Pulse Width Modulation (PWM).

2.3.1 Pulse Width Modulation Techniques

The theory governing this section were mainly acquired from the book "Power electronic converters: PWM strategies and current control techniques" [6]. PWM is used to vary the output voltage of the Voltage Source inverter. This section briefly explains the concept of PWM and some methods for implementing it in a motor controller.

Sine Pulse Width Modulation

Sine PWM is a common method and fairly easy to implement in a microcontroller. It works by having carrier wave and a reference wave. The carrier wave and the reference are compared to each other. If the value of the reference signal is larger than the carrier signal the output goes high and otherwise it goes to low. The carrier wave is usually a form of triangle wave (sawtooth or center aligned triangle wave). The frequency of the carrier wave determines the switching frequency of the system. The reference signal is the signal which gets modulated on the output. The modulated output voltage or frequency can be changed by changing the carrier wave amplitude or frequency respectively. Figure 2.13 shows a plot of the carrier signal, reference signal and the modulated output for a single transistor system. The output is a modulated square wave which needs to filtered if only the fundamental frequency is of interest. In motor applications the filter is not crucial since the motor acts as a filter. If a filter is not used in motor applications the fundamental frequency and some harmonics are left in the signal.

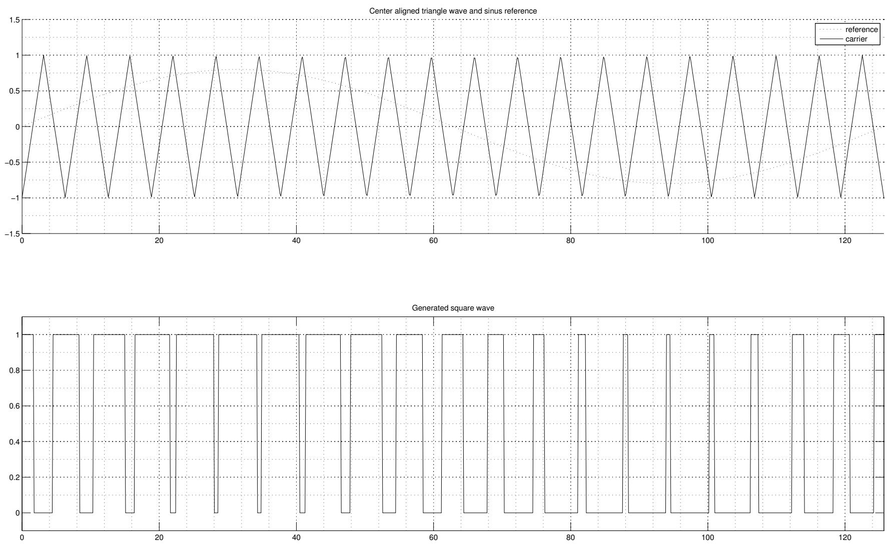

Figure 2.12: Sine Pulse Width Modulation for single transistor

The implementation of sine-PWM for a three phase inverter is done by using one triangular carrier wave and three sinusoidal reference waves, which are displaced from each other by 120 degrees (as shown in equation 2.13). The two PWM signals to one pole are complementary with a added dead-time. The dead-time is a small time delay between switching one of the transistors on before switching the other transistor off. This is needed to not short circuit the pole.

$$V_u = V_s sin(wt) \tag{2.13a}$$

$$V_v = V_s sin(wt - \frac{2\pi}{3}) \tag{2.13b}$$

$$V_w = V_s sin(wt + \frac{2\pi}{3}) \tag{2.13c}$$

Figure 2.13 shows the sine-PWM signals for a three phase VSI. V_{UN} are the voltage between the phase and the negative side of the DC supply. V_{UV} is the voltage between phase V_U and V_V, given by $V_U - V_V$.

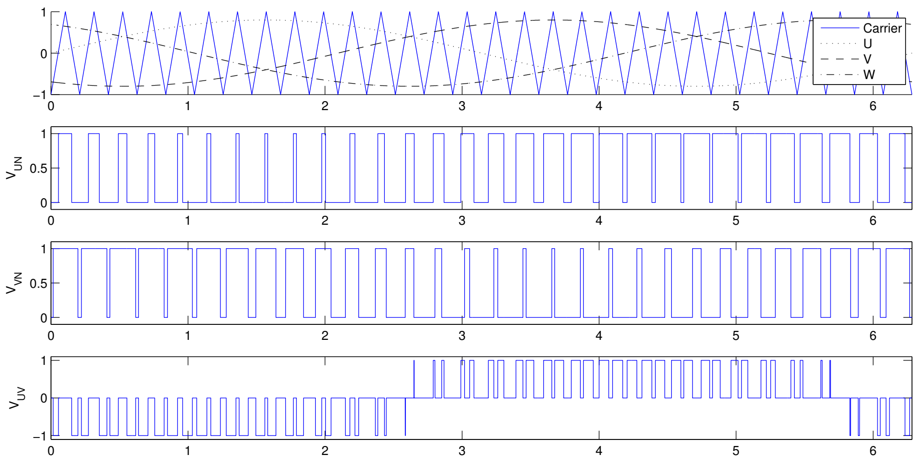

Figure 2.13: VSI Sine PWM

The modulation index is given by equation 2.14, where V_{ref} is the amplitude of the reference wave and $V_{carrier}$ is the amplitude of the carrier wave.

$$m_a = \frac{V_{ref}}{V_{carrier}} \tag{2.14}$$

The line to line RMS voltage of the fundamental frequency voltage of the output is given by equation 2.15, where m_a is the modulation index and V_d is the supply voltage.

$$V_{LL-RMS} = \frac{\sqrt{3}}{2\sqrt{2}}(m_a V_d) \tag{2.15}$$

The carrier signal can be implemented in a microcontroller by the use of a internal timer. The same timer that creates the carrier wave can be used to create a interrupt for calculating the new reference values, by doing this the control loop gets synchronized to the update rate of the PWM.

2.4 Other methods for torque-control

2.4.1 Six step control

Six step control works by switching the transistors in a repeating pattern. Each transistor conducts for 120 degrees and only two transistors remains on at any time. It's the most popular method for controlling low-performance motors. Figure 2.14 illustrates the phase voltages generated and the switching states. The output waves shown in the figure gets low-pass filtered by the motor. The low-pass filtered waves will resemble trapezoidal waves, and are thus suitable for controlling fans, hard-disks or other low performance motors with trapezoidal BEMF. Another disadvantage of this method is that only two transistors are on at the same time, so only two thirds of the copper in the motor is utilized. For a high performance drive control methods using the Iq and Id vectors are more suitable.

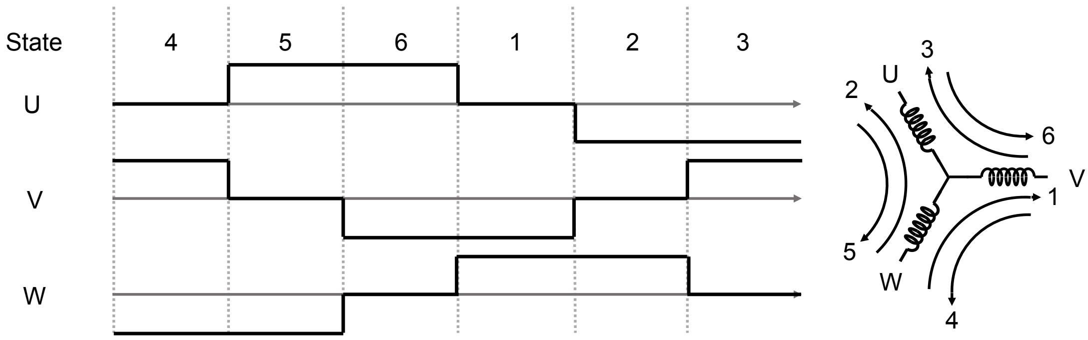

Figure 2.14: Six step control method

Chapter 3

Hardware

This chapter goes through the design choices and implementation of the hardware for the motor controller. This includes DC-link capacitor, switching transistors, gate-driver, current sensors, resolver interface, control electronics and cooling of the switching transistors.

3.1 Clearance requirements

The system contains both 400V and 15V. The 400V system is categorized as high side and the 15v system as low side. Components that interface both sides must implement some form of insulation. The rules for the competition have clearance requirements on PCB's which contains high side and low side. Table 3.1 lists the clearance values required by the rules.

Voltage	Over surface	Through air	Under coating
0-50VDC	1.6mm	1.6mm	1mm
50-150V	6.4mm	3.2mm	2mm
150-300V	9.5mm	6.4mm	3mm
300-600V	12.7mm	9.5mm	4mm

Table 3.1: Clearance requirements between high side and low side

The PCB's which contains both high side and low side will be conformally coated. The rules does not state any clearance or creepage values between components with high voltage potential but were both components are high side. The IPC-2221B standard values have been used for the spacing requirements between high voltage potentials on high side connections.

3.2 Bamocar D3

On the previous electric cars the Bamocar D3 motor controller have been used. The self designed inverter is designed to be compatible with the Bamocar. This were done as a precaution if the self-designed does not work or fails, it should be swappable with the Bamocar D3 motor controller.

3.3 System overview

In this section the system as a whole will be briefly explained. The sections afterwards will go in more detail on each subject. The whole system is shown in figure 3.1.

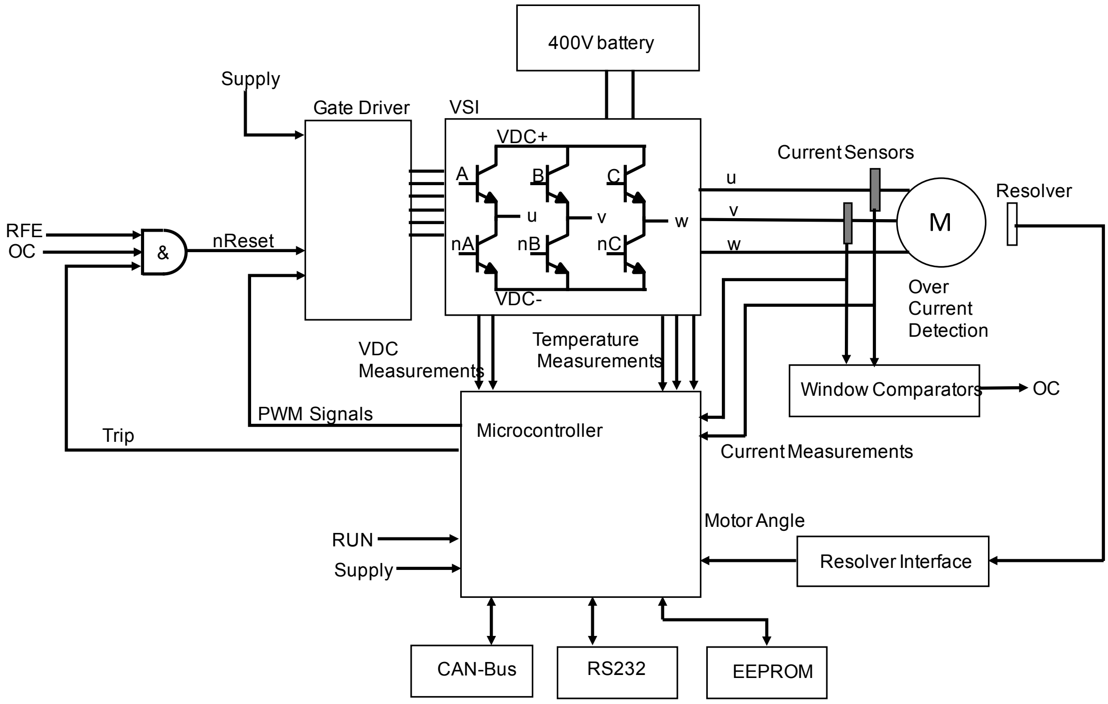

Figure 3.1: System overview

The following functionality were desired:

1. Gate driver electronics to properly drive the gates of the switching transistors.
2. A resolver interface to read the motor position from the resolver sensor on the Emrax 228.
3. Read the current in two of the phases.
4. CAN-bus to communicate with the rest of the car.
5. RS232 for debugging and logging data under bench testing.
6. Non-volatile storage for storing parameters.
7. A microcontroller to run the control algorithm, protect against over-temperatures,under/over voltage and over-current.
8. Hardware protection against over-current for a more robust protection scheme.
9. Hardware protection against short-circuit in legs.
10. Hardware protection against faulty PWM signals (Trying to turn on both transistors in a leg should not short circuit the supply, but be ignored).

For ease of design and space restriction the system were divided in three separate PCB's. It were desirable that the cards should be easily mounted and with as little as possible wired connections between them. This was wanted to keep the assembly time lower, and minimize faults from occurring during assembly.

1. Auxiliary card
2. Driver card
3. Logic card

Auxiliary card

The rules from Germany and England demands some functionality for the motor-controller. The Bamocar D3 does not fulfill these rules, as such the auxiliary card were designed to fit in both the Bamocar D3 motor-controller and the self-designed motor controller. This were deemed as the easiest solution to make both motor-controllers rule-applicant. The auxiliary card needed the following functionality:

1. When the system is shutdown the voltage on the capacitors needs to be discharged to below 60V within five seconds.
2. VDC measurement circuit for detecting if the voltage on the capacitors are above 60V.

Driver card & Logic card

The rest of the electronics were decided to be split up in two cards. The reasoning behind these are space restrictions and clearance restrictions between the low side and high side system. The reason for the space restriction is that it's desirable to have the driver electronics as close as possible to the gates of the switching transistors, preferably mounted on top of the transistor to minimize stray inductance.

The driver card contains the components that interface to the high side of the system, while the logic card contains the low side components.

3.4 Switching transistors

3.4.1 Switching transistor technologies

Most of the theory for this section is gathered from the book "The Art Of Electronics" [3]. It goes through some important aspects of the different transistor technologies for use in switching applications.

Bipolar Junction Transistor

Bipolar Junction Transistors (BJTs) are in essence a current amplifier. Equation 3.1 explains the relationship between the base current and the current through the collector to emitter. This means that for large current through the collector to emitter a large control current is needed. This means that the driver circuitry needs to be complex and large, thus the BJT technology is not a good choice for the motor controller.

$$I_{ce} = I_b \cdot \beta \tag{3.1}$$

On the other hand a characteristic of the bipolar transistor which does make it useful is the collector to emitter voltage (V_{ce}), which varies little with collector current (I_c). The on power loss of the BJT is given by equation 3.2.

$$P_{on} = I_s \cdot V_{ce} \tag{3.2}$$

Power Metal Oxide Semiconductor Field-Effect Transistor

Power Metal Oxide Semiconductor Field-Effect Transistors (MOSFETs) are suitable for use in switching applications because of their low on resistance (R_{on}), High input impedance and negative tempco at high drain currents. When used in switching applications MOSFETs can be paralleled without a balancing ballast resistor because of the negative tempco at high drain currents. The voltage drop from source to drain (V_{sd}) is determined by the source current (I_s). The on power loss of the MOSFET is given by equation 3.3. As can be seen the power loss increases by the square of the current, thus for high currents the BJT technology can have lower conduction-losses than that of a MOSFET. Even so the MOSFET is good solution for a power application because of the low on-loss and low switching losses.

$$P_{on} = R_{on} \cdot I_s^2 \tag{3.3}$$

Insulated Gate Bipolar Transistor

The Insulated Gate Bipolar Transistor (IGBT) can be modelled as a MOSFET driving a BJT. The IGBT has the advantageous characteristics of the MOSFETs high input impedance as well as the BJTs low saturation voltage. The disadvantage of the IGBT compared to the MOSFET is that the turn-on time is larger, which means that the switching power losses in the IGBT is larger than that of the MOSFET.

3.4.2 Choice of switching transistor technology

The MOSFET were of interest because of low switching losses, but solutions using MOSFET ended up being expensive compared to IGBT solutions. The IGBT technology were chosen because there are plentiful of modules to chose from for the current/voltage range of the system, and the fact that they are cheaper than the MOSFETs.

3.4.3 IGBT selection

The IGBT used in the Bamocar were used as a reference for the selection of IGBT for the motor-controller. Table 3.2 compares some different IGBT's, FF600R06ME3 is the IGBT module used in the Bamocar D3.

Since the manufacturers differs in how they specify the IGBT's a maximum DC-current through the diode and through the IGBT were calculated for the table. The maximum currents were calculated by using equation 3.4, where $T_{j\_op\_max}$ is the maximum operation temperature of the junction in degrees Celsius, T_{j_op} is the operation temperature in degrees Celsius, R_{jc_igbt} is the thermal resistance from the junction to case in Kelvin/Watt and V_{ce_sat} is the saturation voltage of the component. $T_{j\_op} = 80$ were used for all the calculations.

$$I_{c_max} = \frac{T_{j\_op\_max} - T_{j\_op}}{R_{jc} * V_{sat}} \tag{3.4}$$

MPN	V_{ce_max}	I_{c_max}	I_{d_max}	Price (NOK)
FF600R06ME3	600V	458A	239A	1094
SEMiX303GB12E4p	1200V	324A	202A	1722
FF300R12ME4_B11	1200V	363A	283A	1084
MIXA300PF1200TSF	1200V	383A	254A	1114
FF450R12ME4	1200V	517A	424A	1542
MIXA450PF1200TSF	1200V	543A	368A	1456
MG06600WB-BN4MM	600V	438A	292A	1262
FF600R07ME4_B11	600V	511A	333A	1080
FF450R12ME4_B11	1200V	517A	424A	1158
MG12450WB-BN2MM	1200V	352A	234A	1692
MG12300WB-BN2MM	1200V	250A	176A	1262
MG12225WB-BN2MM	1200V	188A	141A	1120
FS800R07A2E3_B31	1200V	516A	399A	2026

Table 3.2: IGBT specification comparison

The FF450R12ME4 were chosen since it had roughly the same specifications as the FF600R06ME3 used in the Bamocar D3, and that RS online stocked the FF450R12ME4. RS online sponsors ION Racing by giving good discounts on their components.

3.5 Cooling system

The excess heat generated by the power loss in the IGBT needs to be removed. There needs to be a water cooling system in the car since the EMRAX228 motor is water cooled. It were therefore chosen to also water cool the IGBT transistors. This section describes the design of the water cooling block for the transistors. It were 3D-modeled in Autocad Inventor and simulated in Autocad CFD. The CFD simulation gives thermal results, flow results and pressure drop.

3.5.1 Calculation of inlet temperature

To find a rough estimate to the inlet temperature a thermal analysis of the whole cooling loop where done. Figure 3.2 shows the order which the components are placed in the cooling loop. The motor comes before the motor controller in the loop since it requires a maximum inlet water temperature of 50 degrees Celsius.

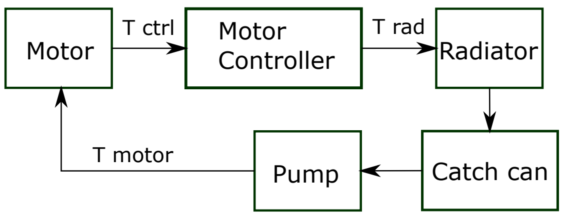

Figure 3.2: Cooling loop in the car

The steady state temperature out of the motor were calculated with equation 3.5, where T_{in} is the input tempetaure in degrees Celsius, ω is the flow in kg/s, P is the power loss in the motor, and is the specific heat constant of water.

$$T_{out} = \frac{T_{in} \cdot \cdot \omega + P}{\omega} \tag{3.5}$$

To calculate the inlet temperature T_{ctrl} the flow of the water must first be calculated. Further to calculate the water flow the pressure drop through the different components must be known.

Pressure drop calculations

The pressure drop calculations over the motor and radiator are based upon measurement from last year, reference **??**. The radiator for the 2017 car were unknown. Using data from last years radiator were chosen as a rough estimate. The pressure drops are calculated by using equation 3.6, where ω is the mass flow of the water in kg/s and b is a constant determined from measurements. The formula is for calculating pressure drops where the flow is laminar.

$$\Delta P_{drop} = b \cdot \omega^{1.75} \tag{3.6}$$

The cooling block were designed and simulated for pressure drop to calculate the constant b. Figure 3.3 shows the results of the first simulation. The cooling block were designed with 13mm inner channels. The simulations shows particle traces of the water, which shows how the water particles have moved through the cooling block. The simulation were done with a water flow of 0.08kg/s. The b value were calculated using equation 3.6.

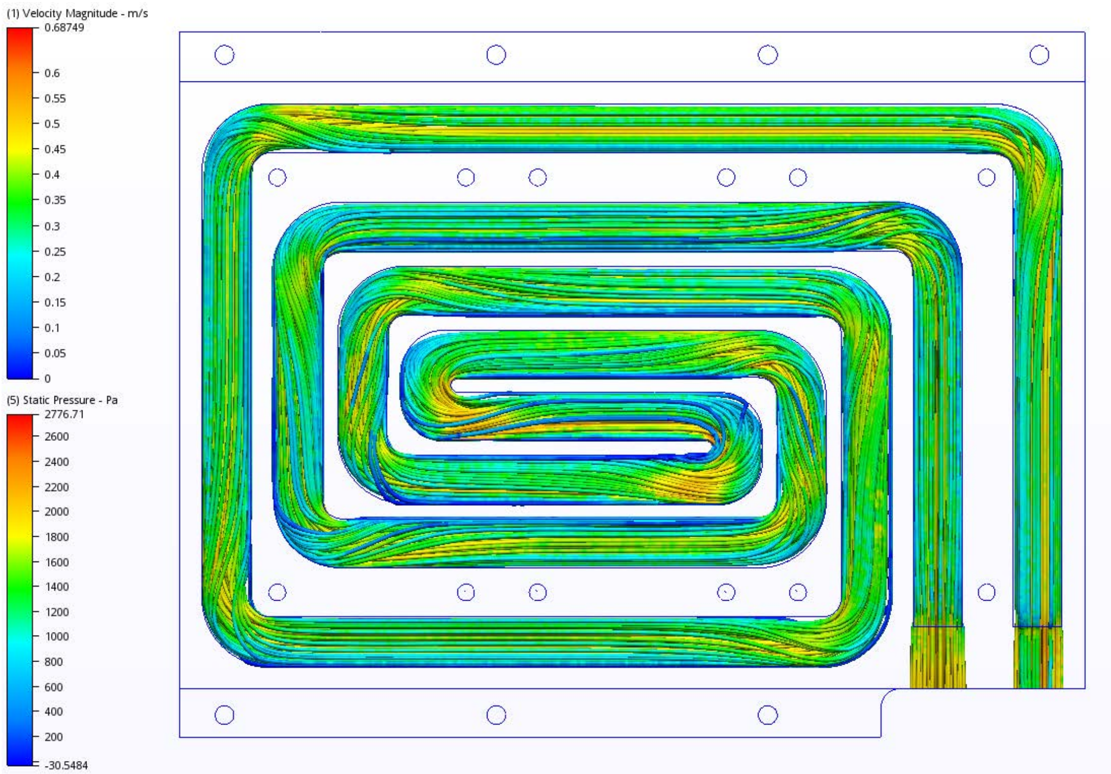

Figure 3.3: Cooling block pressure simulation

Table 3.3 lists the b constants for the different components.

Component	b
motor	2527473.6
cooling block	230719.3
radiator	360532

Table 3.3: Pressure drop constant b

Pressure drop in hoses

The hoses also introduce a pressure drop. Larger inner diameter of the hose reduces the pressure drop. To decide which inner diameter should be used for the hoses, the pressure drop for three different sizes were calculated (10mm, 12.7mm, 17mm). For a rough estimation the calculations were done for only for straight paths. First the Reinolds number were calculated using equation 3.7, where Q is the volume metric flow in m^3/s, v is the kinematic viscosity of water in m^2/s, and D is the inner diameter of the hoses in meters.

$$R_e = \frac{4Q}{v\pi D} \tag{3.7}$$

Then the Moody friction factor were calculated according to equation 3.8, where E is the absolute roughness of the hose, R_e is the Reinolds number, and D is the inner diameter in meters.

$$f = \frac{1.325}{log(\frac{E}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}).^2} \tag{3.8}$$

Finally the pressure drop in KPa were calculated according to equation 3.9, where ρ is the specific weight of water, Q is the volume metric flow in m^3/s, f is the moody friction factor, D is the inner diameter of the hoses in meters, and L is the length of hose in meters. A total length of 2.5 meters were estimated based upon manual measurements in the car.

$$\Delta P = [\rho \frac{8Q^2}{\pi^2 \cdot D^4} \cdot \frac{f \cdot L}{D}]/1000 \tag{3.9}$$

A Matlab script was created to calculate the pressure drop vs flow. The result is shown in figure 3.4. The matlab script are added in appendix ?.

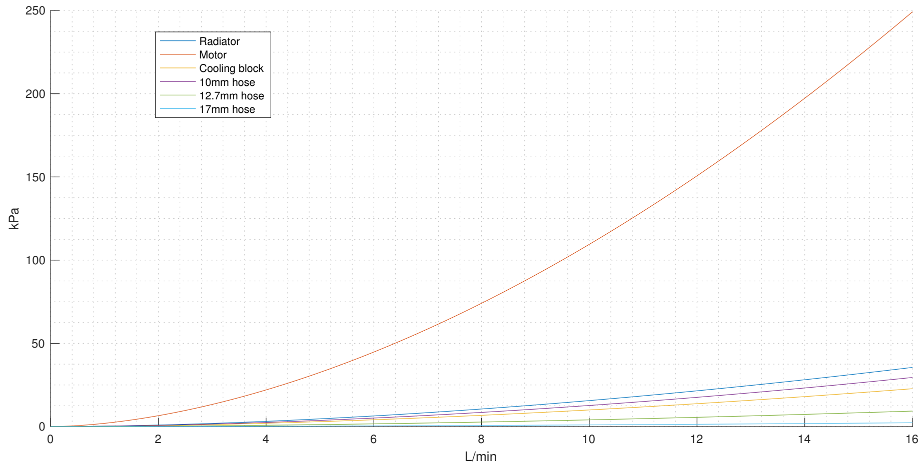

Figure 3.4: Pressure drops for the different components and different inner diameter for the cooling hose

Pump choice

Last year a Bosch 0 392 023 232 water pump were used. It were of interest to compare it with a more powerful pump. The weak pump from Bosch (0 392 023 232) and a more powerful pump from Bosch (0 392 024 058) are compared in this section. A plot were created in Matlab by interpolating data points from the data-sheets characteristics. The results are shown in figure 3.5.

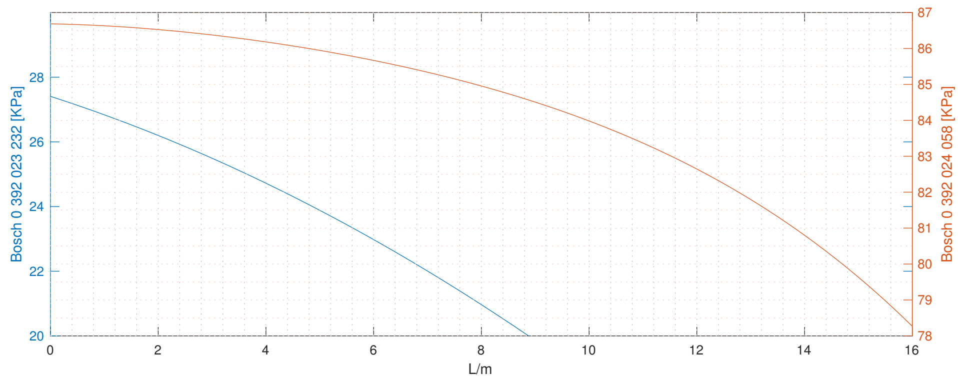

Figure 3.5: Pump characteristics

To find the flow in the system the intersection between the total pressure drop in the system and the pump characteristics must be found. Figure 3.6 shows a plot of the total pressure drop for the different hose sizes and both pump characteristics.

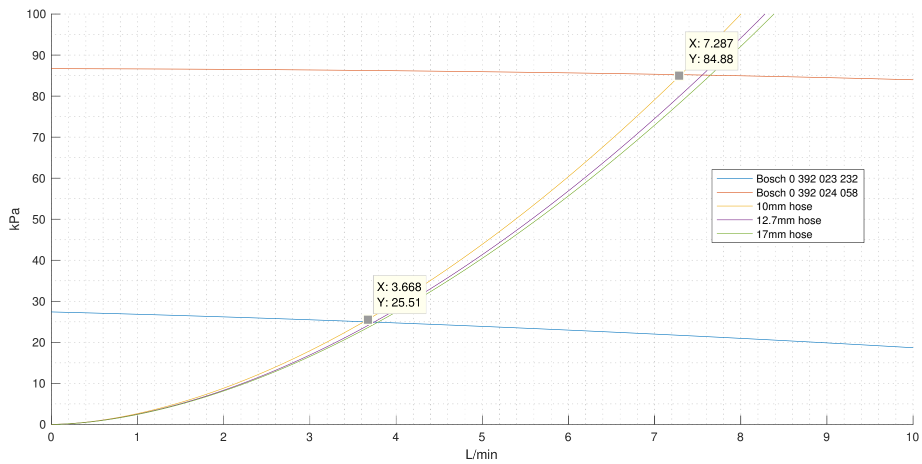

Figure 3.6: Pump characteristics vs total for loss for different inner diameter for the cooling hose

As shown in the figure 3.6 the hose size does not have a major effect on the achieved flow. A 10mm inner diameter hose were chosen, since this size fits on the motor coolant fittings. Further for a 10mm inner hose diameter the flow ends up being 3.668 L/min for the weak pump and 7.287 L/min for the more powerful pump. Emrax recommends a flow of 8L/min, therefor the more powerful model (0 392 024 058) were chosen as the pump for this years car.

The inlet temperature can now be calculated. To find the power loss of the motor, it were estimated that the average motor power were 45kW. A worst case efficiency from the Emrax228 datasheet of 86% efficiency were used for calculating the power loss. Further it were anticipated that the radiator were able to cool the water to 50 degrees Celsius. The inlet temperature where then calculated to be: $To = \frac{50 \cdot 4186 \cdot 0.1212 + 45000 \cdot (1-0.86)}{0.1212 \cdot 4186} = 62.42$ degrees Celsius.

3.6 Power dissipation in IGBTs

A Matlab script which estimates the power losses numerically were created. The script is added in the appendix. The peak output current were set to 166A for the calculations, which corresponds to a appareant motor power of 45KW with a modulation index of 0.9. The power loss in each IGBT-module were estimated to be about 282W. Each IGBT Module contains two transistors and two diodes. The maximum heathsink surface temperature can be calculated using equation 3.10, where $T_j max$ is the maximum junction temperature of the IGBT, $R_{\theta jH}$ is the thermal resistance from junction to heatsink in K/W, and P is the power loss.

$$T_H < T_{jmax} - R_{\theta jH} \cdot P \tag{3.10}$$

The $R_{\theta jH}$ is equal to 150 degrees Celsius and the $R_{\theta jH}$ is equal to 0.096 for one IGBT. Both values are read from the datasheet. The value $R_{\theta jH}$ is for one IGBT, so the calculated power loss of 282W needs to halved for the calculations. The maximum heatshink surface temperature were calculated to be $T_H < 150 - 0.096 \cdot 282/2 = 136$ degrees Celsius.

3.6.1 Thermal analysis of cooling block

A thermal analysis of the cooling block where done in CFD. The result of the simulation is shown in figure 3.7. The simulation where done with a inlet temperature of 70 degrees Celsius to give some headroom for faults in the calculations. The temperature that is shown is the maximum casing temperature, which is well below the maximum allowed temperature of 136 Degrees Celsius.

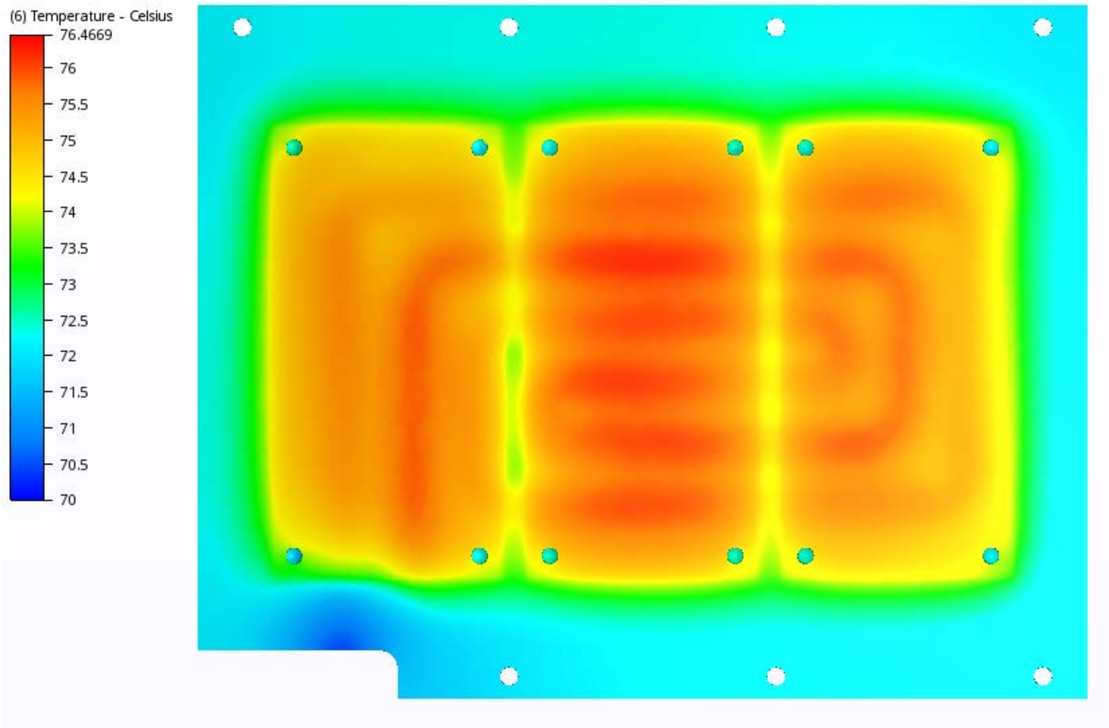

Figure 3.7: Thermal analysis of cooling block

3.6.2 DC-Link Capacitor

First the RMS-current draw of the VSI were calculated. This is needed to know how much heath is generated in the capacitor. The research "Analytical calculation of the RMS current stress on the DC-link capacitor of voltage-PWM converter systems" paper proved to be helpful for calculating the RMS-current stress of the capacitor bank [4]. The methods in the paper ignores the affect of dead-time and recovery current of the diodes, which it states are minor influences. Further a purely sinusoidal output current is considered.

The ripple current stress of the capacitor bank where calculated using equation 3.11.

$$I_{crms} = I_{nrms}\sqrt{2M \cdot [\frac{\sqrt{3}}{4\pi} + cos(\phi)^2 \cdot (\frac{\sqrt{3}}{\pi} - \frac{9}{15}M))]} \tag{3.11}$$

The power factor of the system where not known so a worst case analysis were done with the power factor equal to 1. The worst case normalized RMS current is then equal to 0.6497. The

RMS current ripple were calculated to be 155.928 Arms by taking 240A rms and multiply by the normalized factor.

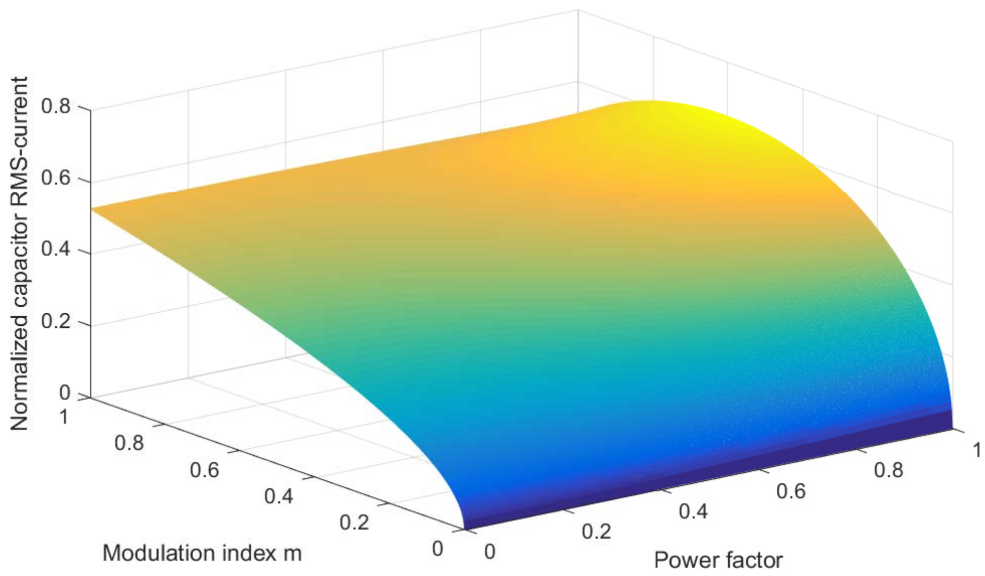

Figure 3.8: Three dimensional representation of the normalized current stress of the capacitor bank as function of modulation index and power factor.

Two C4DEFPQ6380A8TK film capacitors were used in parallel. They are rated for 400V and 100Arms ripple current each, which means that two in parallel can handle a ripple current of 200Arms.

3.7 Bus-bars

The capacitors needs to be connected to the IGBT's in some manner. This could be done by the use of cables or bent sheet-metal bus-bars. To prevent high switching voltages, which can destroy the IGBT's, the inductance of the connection must be as low as possible. To lower the inductance a two-layer busbar were designed **??** . A sandwich structure consists of two metal plates isolated from each other by a isolating material. The plates gets mounted as close to each-other as possible, so that they act as a capacitor. Figure 3.9 shows a rendered side image of the construction, and figure 3.10 shows a angled image of the construction. The bus-bars were isolated using Capton tape. Technical drawings of the bus-bars are added in appendix A.

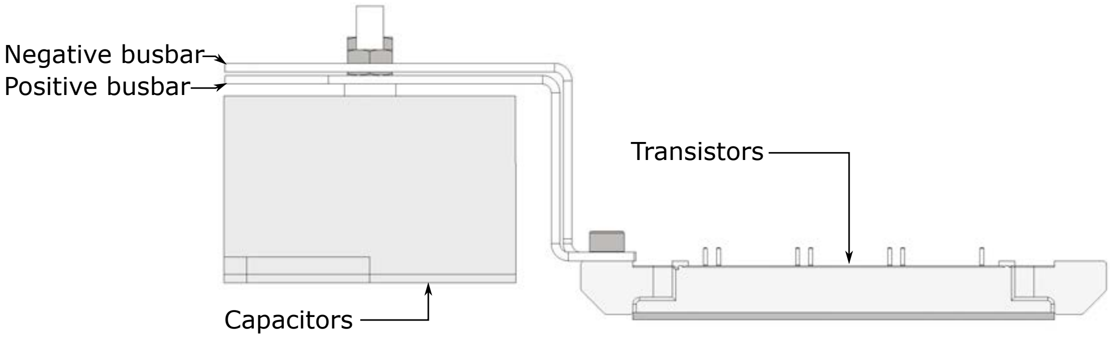

Figure 3.9: Bus-bar construction side view

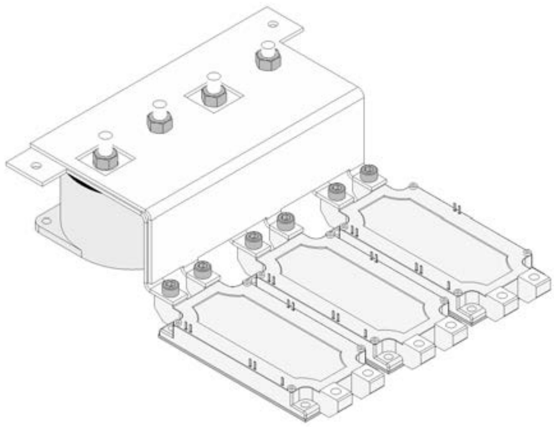

Figure 3.10: Bus-bar construction angled view

3.7.1 Current sensor

The control algorithm needs current measurement of two phases. It is not uncommon to measure the current in all three phases for detecting ground fault, but this is unnecessary for this design since the car have a insulation monitor installed. It were decided that measuring the current of two phases were good enough.

There are different methods for measuring the current. Two of the most popular are to measure either the phase currents or the current going in the legs of the switching transistors. Measuring the current in the phases offers the benefit of constant motor current through the sensor independent of the transistor switching state. It were decided to measure the current in the phases because of this reason. There are different types of sensors to be used for current measurement. The two most common types are:

1. Current transducer.

2. Shunt resistor.

The shunt resistor works by measuring the voltage drop over a precise and known low resistance resistor. The current transducer works by measuring the magnetic field in the cable. There are some trade-offs between the technologies. The current transducer offer the following advantages:

1. They offer isolated measurement.
2. They can be placed anywhere in the current path, which sometimes can simplify the construction of the system.
3. They have very little effect on the system they measure.

Some disadvantages for the current transducer are:

1. They are expensive compared to shunts.
2. They can be affected by nearby magnetic fields, which would need to be compensated for.
3. They have limited bandwidth compared to the shunt and thus (for some sensors) considerable delay.

The advantages of the shunt resistor are:

1. They are usually very cheap compared to current transducers.

The disadvantages are:

1. They can dissipate a lot of heat. A trade-off between heat dissipation and accuracy must be made.
2. They affect the measured circuit by introducing a voltage drop.

The high current of the system introduces a problem with using shunts. It were difficult to find shunt resistors rated for such high current. The ones which were rated for the high current were both large and expensive. The current transducer were chosen because of the larger selection of sensors for high current and the smaller size of them. Table 3.4 compares the specification of some sensors.

Name	LF 305-S	HASS 50 200	HAL 200S
Supply voltage	+/-12V	5v	+/-15V
Supply current	170mA peak	25mA	80mA peak
Output signal	150mA RMS	2.5 +/- 0.625V	+/-4V
Total un-adjusted error	0.836%	11.8%	4%
Response time	$1\mu s$	$4\mu s$	$3\mu s$
Nominal measurement range	+/-300A RMS	+/- 600A	+/- 200A
Price	94$	22.77$	56.5$

Table 3.4: Current transducers comparison

The total un-adjusted error were calculated as the sum of the different errors for the sensor. It were calculated with a delta in temperature of 40 degrees Celsius. The current transducer sensors can be roughly put in two categories: compensated and uncompensated. The compensated type offers better accuracy, higher immunity to external interference and higher bandwidth, but needs a bipolar supply. The HASS 50 200 are of the uncompensated type while the other two are compensated. The HASS 50 200 were dismissed because of it's low accuracy.

The HAL 200S series were chosen instead of the LF 305-S because of it's lower price, lower supply current compared to LF 305-S and the fact that the output is a voltage signal. HAL-transducers can measure a larger area than the nominal measurement range, but the accuracy specifications are only valid for the nominal measurement range. The HAL 400S were chosen as the current sensor for the system. It has the same specifications as the HAL 200S, but a nominal measurement range of 400A RMS.

3.8 Driver card

This section describes the design choices for the electronics on the driver card. The driver card have the following functionality:

1. Drive the gates of the switching transistors.
2. galvanic isolation of temperature sensors.
3. Short circuit protection.
4. Logic for opening all the transistors.
5. Bus voltage measurement.

Figure 3.11 shows a top sheet diagram of the gate driver schematics. S1 is the connector to the logic card. S3 contains the connections to the IGBT, shown in figure 3.12 and 3.13. Two of the phase connections are identical to the one shown in figure 3.12, while one of the phases have added connections for the voltage measurement as shown in figure 3.13.

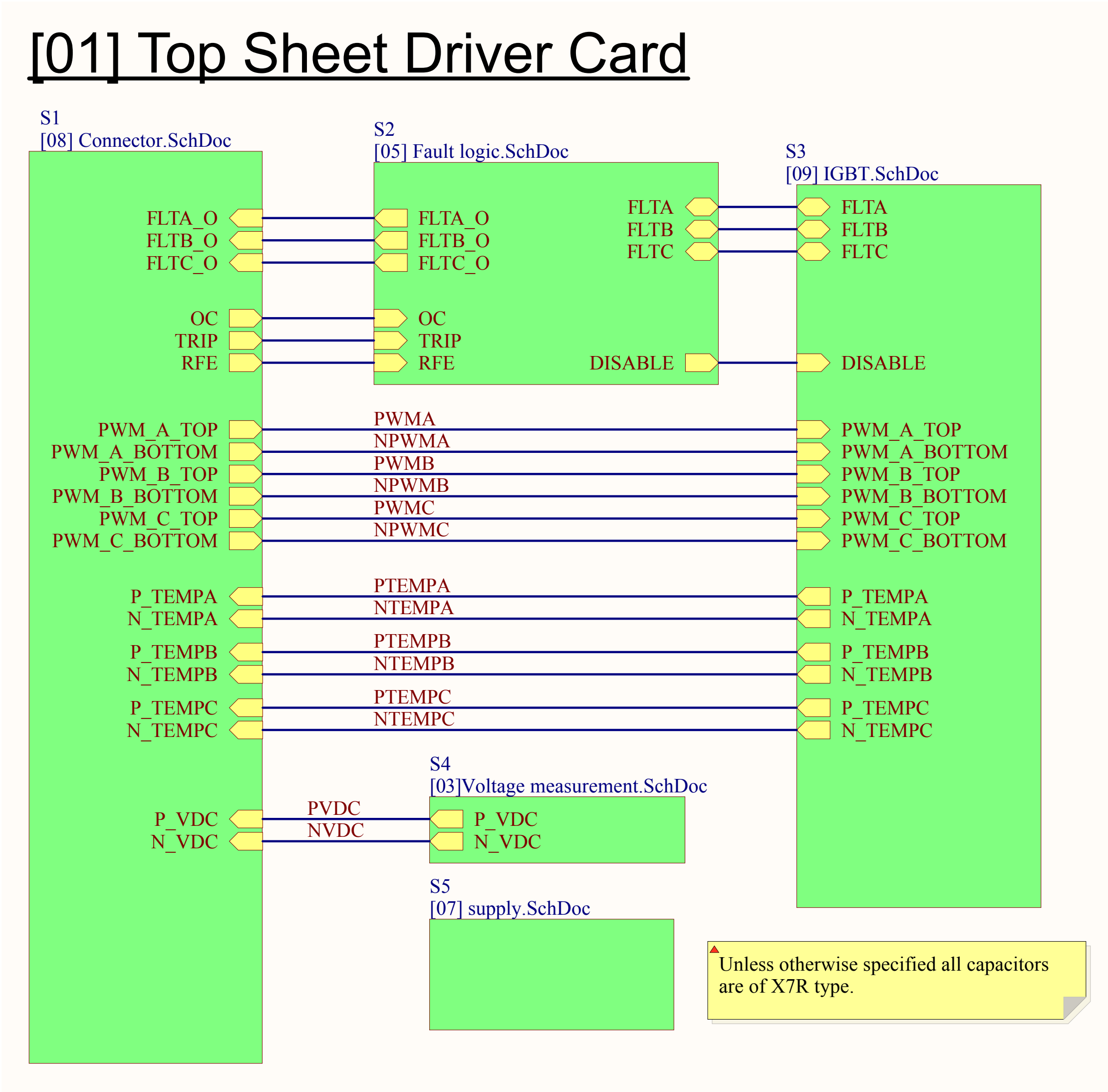

Figure 3.11: Top sheet connection for driver card

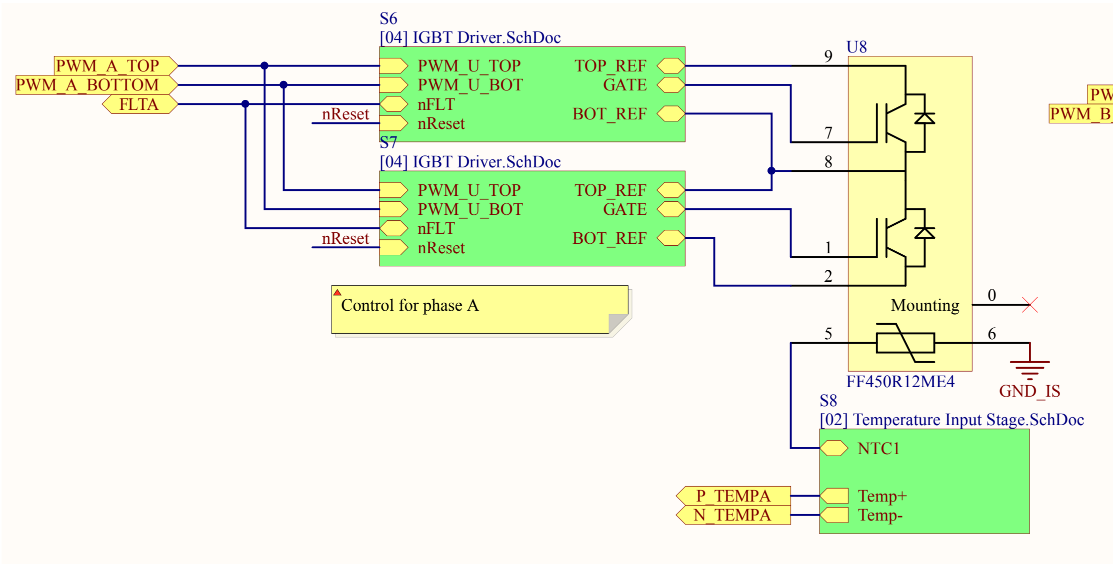

Figure 3.12: Driver card phase A connections

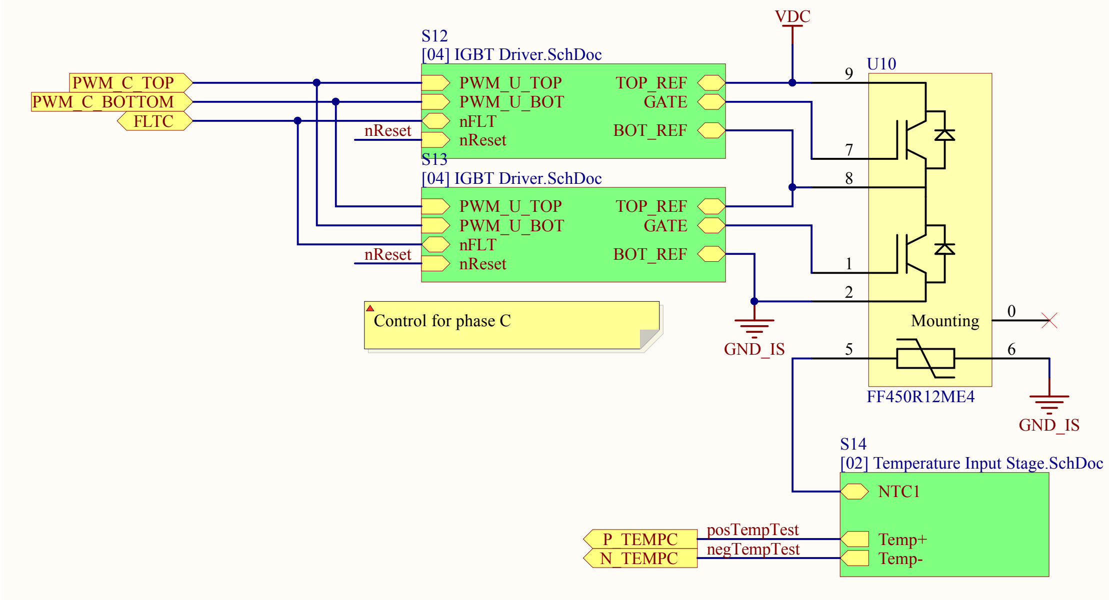

Figure 3.13: Driver card phase C connections

3.8.1 Gate driver

The gate driver electronics receives the PWM signals from the microcontroller; amplifies them and isolates them. The application note "external booster for driver IC" [8] were a helpful resource for the calculations done in this section. Schematics for a general gate driver is shown in figure 3.14.

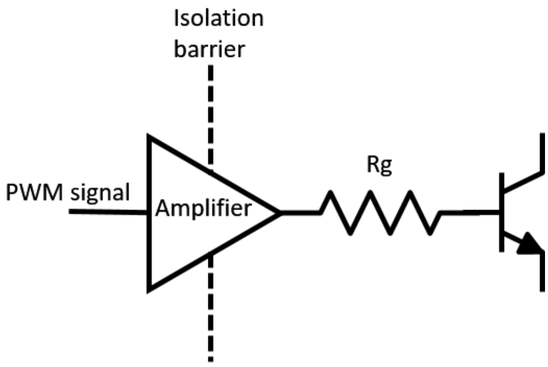

Figure 3.14: Bus-bar construction angled view

Since the signal going out of the amplifier is on the high-side it needs to be isolated from the control signal, which is on the low side of the system. Further it must be able to deliver enough current to turn the transistor on/off quickly enough for the given PWM frequency. The circuitry can either be made by discrete components or by the use of a gate driver IC. A gate driver IC often includes more advanced functionality, such a short circuit protection. A gate driver IC solution were chosen for its simplicity compared to a discrete solution.

Supply voltages

To properly turn on the transistor a typical voltage of 15 is applied to the gate. For turning off the transistor a negative voltage is usually applied. A more economical method is to use a electronic clamp, which shunts the resistor Rg shown in figure 3.14. The clamp method, while economical, is not sufficient to keep the gate off. It were chosen to use bipolar supply with voltage levels of +15V and -8.7V. The reason for this specific voltage level were that Murata delivered a series of isolated DC/DC supplies designed for IGBT applications.

Current demands of gate driver

Gate drivers are specified for peak output currents. Even tough the average current demand for switching the transistor on/off are low, the transient current can be quite large. The peak output current are given by equation 3.12, where R_{int} is the internal resistance of the module. The external resistor Rg can not be calculated, but must be tested in with the real hardware. It's desirable to have it as low as possible to minimize switching losses, but to low a value and there will be overshoot in the gate voltage signal which can destroy the IGBT. Infineon states that rough estimation for the the external resistor value is a value between the internal resistance value and two times the internal resistance value. The internal resistance of the IGBT module is 1.7Ω. To give some headroom it were chosen to calculate the peak current using a external resistance value of 1.3Ω. The peak current that the driver must be capable of delivering is then equal to $I_{out} = \frac{15V+8.7V}{1.3\Omega+1.7\Omega} = 7.9A$.

$$I_{out} = \frac{\Delta V_{gate}}{R_{int} + R_g} \tag{3.12}$$

Power demands of gate driver

The power requirements for the gate driver is given by equation 3.13, where Q_gate is the gate charge for a given voltage swing, f_{sw} is the switching frequency and ΔV_{gate} is the voltage swing. The datasheet of the IGBT states that Q_gate is $3.3\mu C$ for a voltage swing of 30V. For a voltage swing of $15 + 8.7 = 23.7$ the gate charge will be smaller, but is not linear. The gate charge value of $3.3\mu C$ where used for the calculations since the relationship between voltage swing and gate charge were unknown.

$$P = Q_{gate} f_{sw} \Delta V_{gate} \tag{3.13}$$

The power demands for the gate driver were calculated to be $P = 3.3\mu \cdot 15KHz \cdot 23.7V = 1.17315W$.

Average current demand

The average current demand is given by equation 3.14, where P is the power needed to switch the transistor (previously calculated as the power demand of the gate driver) and ΔV_{gate} is the voltage swing. The average current demand were calculated to be $I_{avg} = 1.17315W/23.7V = 49.5mA$.

$$I_{avg} = \frac{P}{\Delta V_{gate}} \tag{3.14}$$

Power supply choice

The transistor arrangement for a two-level VSI is shown in figure 3.15. Each of the transistors needs a individual gate driver. All of the drivers for the top transistors (S1, S3 and S5) must have individual isolated supplies. The bottom transistors can have a common supply, since they share a common ground potential.

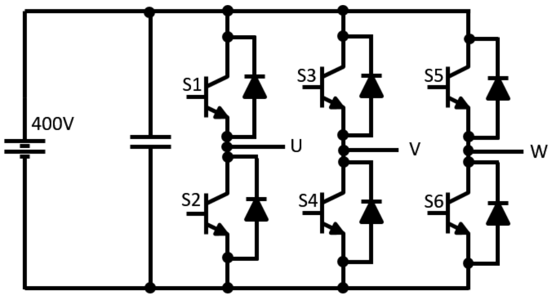

Figure 3.15: Bus-bar construction angled view

Three methods were considered for implementing the supply:

Bootstrap The bootstrap method creates the isolated supply from the bottom supply. This method is a economical way to implement the isolated top supplies. The downside is that a 100% duty ratio is not possible if a bootstrap supply is used.

Multi tap transformer Design a discrete isolated DC/DC converter using a multi tap transformer. One tap for every gate driver, or one tap for each top driver and a common tap for the bottom drivers.

Individual isolated DC/DC modules One DC/DC module for each driver, or one for each top driver and a common for each bottom. This method is more expensive than the multi tap transformer solution, but is simpler to implement. Another benefit of this method is that the PCB-layout is simplified since there will be less crossing of high voltage signals.

The individual isolated DC/DC module solution were chosen for it's simplicity. It were further decided to use one DC/DC module per driver, since the same DC/DC module could then be used for all the drivers. The supply has to deliver the average current demand of the gate driver, which were calculated to be $49.5mA$. The MGJ2D151509SC isolated +15V/-8.7V DC/DC module from Murata where chosen. The needed power for the system is 1.17315W, the Murata DC/DC module is rated for 2W, which should give some headroom for other incidental power losses.

Bulk decoupling capacitors

Since the supply is not capable of delivering the transients currents of the driver, bulk decoupling capacitors must be added to deliver these currents. The total gate drive energy for one cycle is given by equation 3.15.

$$E = Q_{gate}\Delta V_{gate}. \tag{3.15}$$

The total gate drive energy for one cycle were calculated to be $E_{tot} = 3.3\mu C \cdot 23.7V = 75.9\mu J$. This is the energy that both the rails need to supply. The 15V rail then needs to supply

$E = 75.9\mu J \frac{15V}{23.7V} = 48\mu J$. The needed capacitance value of the bulk decoupling capacitor can then be calculated using equation 3.16. Given a voltage drop of 0.5V the capacitance needs to be $C = \frac{2 \cdot 48\mu J}{15V^2 - 14.5V^2} = 6.51\mu F$.

$$C = \frac{2E}{V_{init}^2 - V_{final}^2} \tag{3.16}$$

Another source for voltage drop is the ESR of the capacitor. It's important that high quality capacitors with low ESR is used. X7R capacitor, tantalum capacitor or other high quality capacitors are suitable. It were decided to use X7R ceramic capacitors for the bulk capacitors. Table 3.8.1 shows some specifications for a X7R $4.7\mu F$ ceramic capacitor from Kemet. An important downside of ceramic capacitors are that the capacitance are voltage dependant.

ESR @ 15Khz	$12.808 m\Omega$
Capacitance @ 15V	$3.25851\mu F$
Tolerance	10%
Worst case capacitance	$3.25851 \cdot 0.9 = 2.933\mu F$

Table 3.5: Specifications for Kemet X7R $4.7\mu F$, C1206C475K3RACTU

If the capacitors are paralleled the ESR is lowered and the capacitance increases. By using three capacitors in parallel the worst case total capacitance would be $8.799\mu F$ which leads to a voltage drop of 0.37V. The total ESR would be $4.27m\Omega$ which leads to a voltage drop of $V_{drop} = I_{peak} \cdot ESR = 7.9A \cdot 4.27m\Omega = 0.034V$

Choice of gate driver IC

The required peak current of 7.9A severely limits the choices of suitable gate driver IC's. There are some IC's which can deliver such large peak currents, but they typically lack in other features. It were decided to find a gate driver with suitable extra features, and add a boost stage after it. The single gate driver 1ED020I12-B2 were chosen. It were chosen for the following features:

Desat protection By measuring the saturation voltage of the IGBT it detects short circuit fault in the leg and turns the IGBT off. The response time is from desat detection to output low is 430ns.

Galvanic isolation Required to isolate the low side and high side.

Complementary PWM input It requires complementary PWM input, if both inputs are high or both inputs are low the output state goes low. For one leg in the VSI the positive input of one of the gate drivers are connected to the negative of the other gate driver. This ensures that the microcontroller generating the PWM signals does not accidentally turn on both transistors in one leg.

Fault output If the IC detects any faults this is signaled to the microcontroller.

Bipolar supply capability it were desired to use a bipolar supply of +15V/-8.7V.

Reset input Hardwired signal for turning off the transistor. All of the reset inputs of the gate drivers are connected together. This is used to turn off all the transistor in the VSI if a fault is detected.

Current booster stage

To boost the output current of the gate driver IC a push pull stage using complimentary bipolar transistors were used. A benefit of using a current booster stage is that it enables using two gate resistors; one resistor for turning on the gate and one for turning off the gate. This can be useful since the IGBT takes longer to turn off than on. The power loss in the transistor are given by equation 3.17.

$$P_d = \frac{1}{2}\Delta V_{gate} f_{sw} Q_{gate} - (R_g + R_i nt)(f_{sw} Q_{gate})^2 \quad (3.17)$$

The power loss in the transistors were calculated to be $P_d = 0.5 \cdot 23.7V \cdot 15KHz \cdot 3.3\mu C - (1.7\Omega + 1.3\Omega) \cdot (3.3\mu C \cdot 15KHz)^2 = 0.58W$. The NPN transistor zxtn2010z and the pnp transistor zxtp2012z were used for the boost stage. Table **??** shows the required specifications for transistors and the actual specifications for the transistors.

Specification	required value	zxtn2010z	zxtp2012z
$V_{(BR)ceo})$	23V	60V	60V
i_{peak}	7.9A	20A	-15A
$P_m ax$	0.58W	1.5W	1.5W

Table 3.6: Current booster transistor specifications

A maximum ambient temperature the transistors can handle with the given power dissipation is calculated using equation 3.18.

$$T_{a-max} = T_{j-max} - R_{\theta ja} \cdot P \quad (3.18)$$

For the NPN transistor the maximum ambient temperature is calculated to be $T_{a-max} = 150 - 0.58 \cdot 80 = 103.6$ degrees Celsius,and for the PNP $T_{a-max} = 150 - 0.58 \cdot 83 = 101.86$ degrees Celsius. Both temperatures are much larger than what the temperature inside the enclosure should reach. The base resistance value were difficult to calculate since the gain of the transistors vary a lot, testing with the real hardware were deemed necessary.

Schematics for final design

Figure 3.16 shows the final schematics for the gate driver circuit, including the current booster and supply. There are in total six of thse on one driver board (one for each transistor in the VSI).

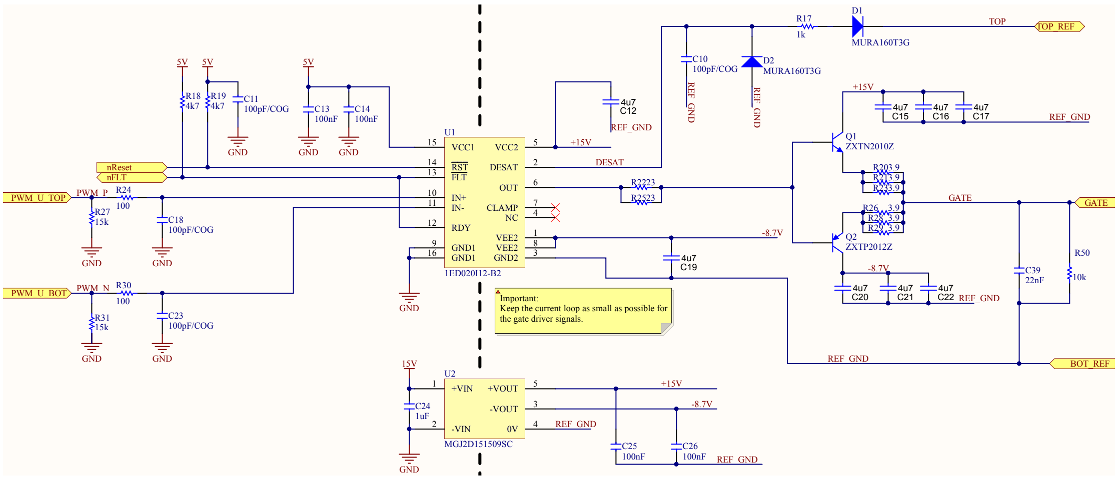

Figure 3.16: Final schematics for gate driver

3.8.2 Temperature measurement

To protect the IGBT's against over-temperature the temperature of the modules needs to measured. The chosen IGBT-modules have an internal Negative Temperate Coefficient (NTC)-resistor. The NTC resistor have a temperature dependent resistance, equation ?? gives an approximation to the resistance. There are several methods for measuring a resistance, the three most popular are:

Current source The resistance can be indirectly read by reading the voltage drop created from sending a precise current through the resistor.

Voltage divider Using a current limiting resistor in series with the NTC. This method linearizes the the sensor to some degree.

Bridge measurement A bridge measurement is the same approach as a voltage divider, but does a much better job at linearizing the sensor.

Since in the end a microcontroller processes the reading, the bridge measurement type were not considered. This is simply because it's easier, cheaper and more precise to linearize the readings digitally in the microcontroller. The voltage divider solution were chosen instead of the current source method, since it's cheaper and easier to implement.

In application notes from Infineon it were stated that the sensor were isolated from the rest of the circuitry, but if the IGBT should be destroyed under use the high voltage could break through to the sensor connections. It were chosen to measure the resistance using isolating amplifiers to give an extra level of insulation. The schematics of the circuit is shown in figure 3.17.

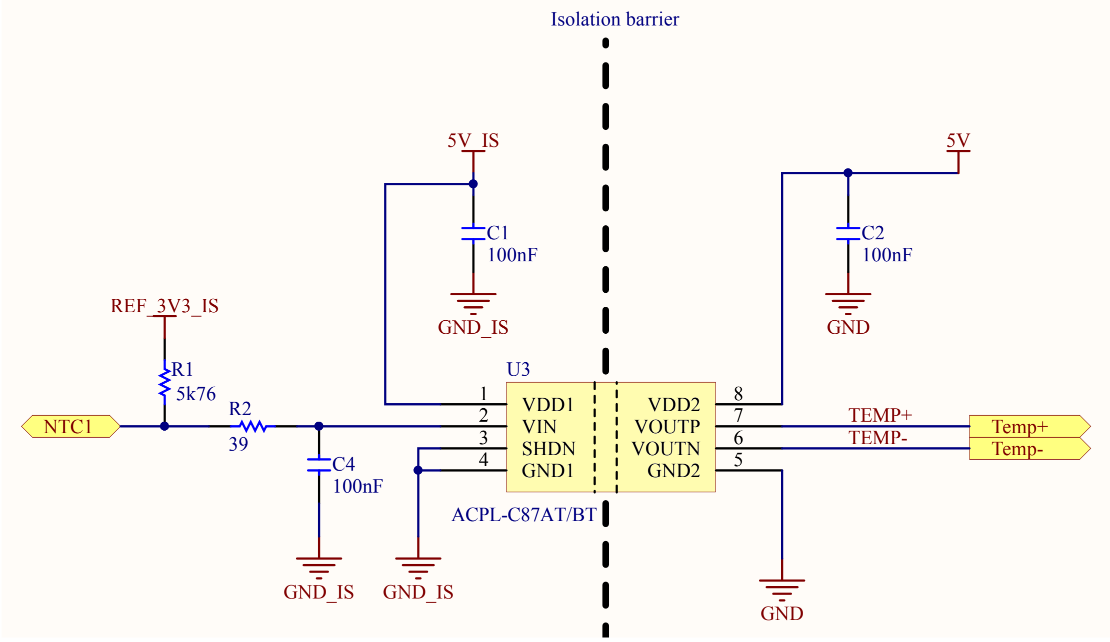

Figure 3.17: Temperature measurement electronics on driver card

Component description

R1 pull-up resistor for the NTC resistor voltage divider.

C1 Decoupling capacitor high side.

C2 Decoupling capacitor low side.

R2 & C4 Input low pass filter.

U3 Isolated amplifier.

Operational description

The pull-up resistor R1 forms a voltage divider with the NTC-resistor. The signal is low pass filtered and isolated through the isolation amplifier (U3). The output of the isolation amplifier is differential. The differential signal is wired to the logic card, where it's converted to a single ended signal and read by the internal ADC in the microcontroller. The microcontroller linearizes the signal in software and protects against over/under voltage.

3.8.3 bus voltage measurement

The bus voltage is measured to detect if the bus voltage is to high or to low. Also it is used for detecting if the bus voltage is above 60V, which is required by the rules for the TSAL. The measurement were done by using a voltage divider circuit. Figure 3.18 shows the schematics for the bus voltage electronics on the driver card.

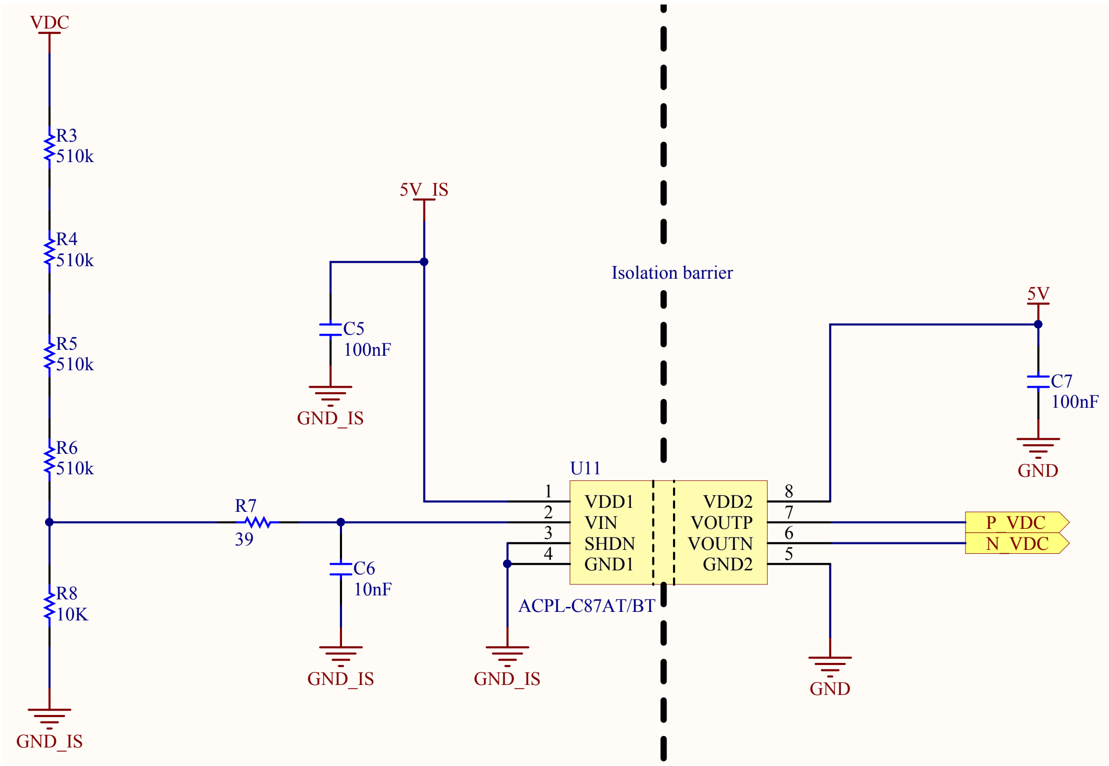

Figure 3.18: Schematics of the bus voltage measurement.

The resistors R3, R4, R5 and R6 are from the Vishay's MMB MELF resistors. Four resistors were used for the top resistor to increase the creepage and clearance of the voltage divider. Each of the resistors are rated for a operational voltage of 350V, which means that the voltage divider should have no problem with handling the maximum voltage of 400V. Again the ACPL-C87AT/BT isolated amplifier are used for isolating the voltage from the voltage divider. The amplifier have unity gain. The relationship between the bus voltage and the output voltage is given by equation 3.19.

$$V_o = V_{bus} \frac{10k}{4 \cdot 510k} \tag{3.19}$$

3.8.4 Isolated supply for temperature measurement and voltage measurement

The circuitry for all three temperature measurements and the voltage measurement shares one supply isolated supply for the high side, and one supply for the low side. The low side is supplied with 5V from the logic card, and the high side is supplied by a isolated DC/DC supply. The schematics for the isolated supply is shown in figure 3.19

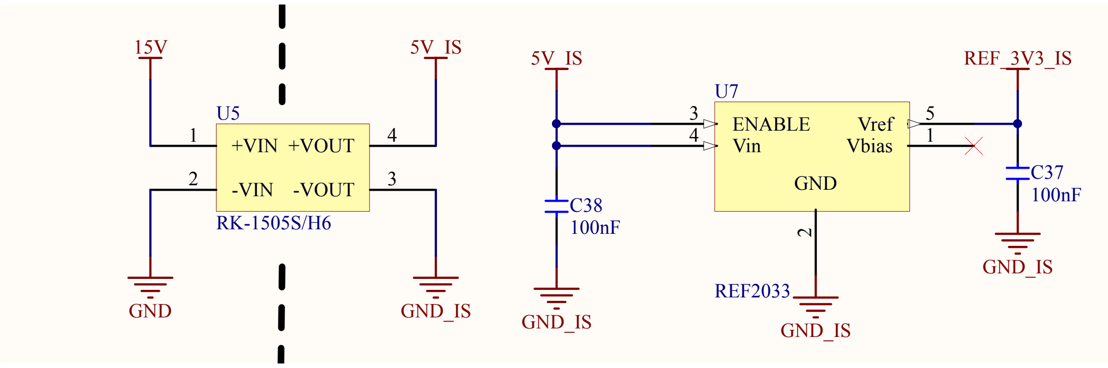

Figure 3.19: Schematics of the isolated supply for the sensor measurements.

3.8.5 Driver card Logic

Each of the phase legs have their error output signal tied together. All of the signals are wired to the microcontroller so that errors can be read and responded to. Figure 3.20 shows the schematic for three LED's added on the driver card. These light up a error occurs and are intended for visual aid under testing.

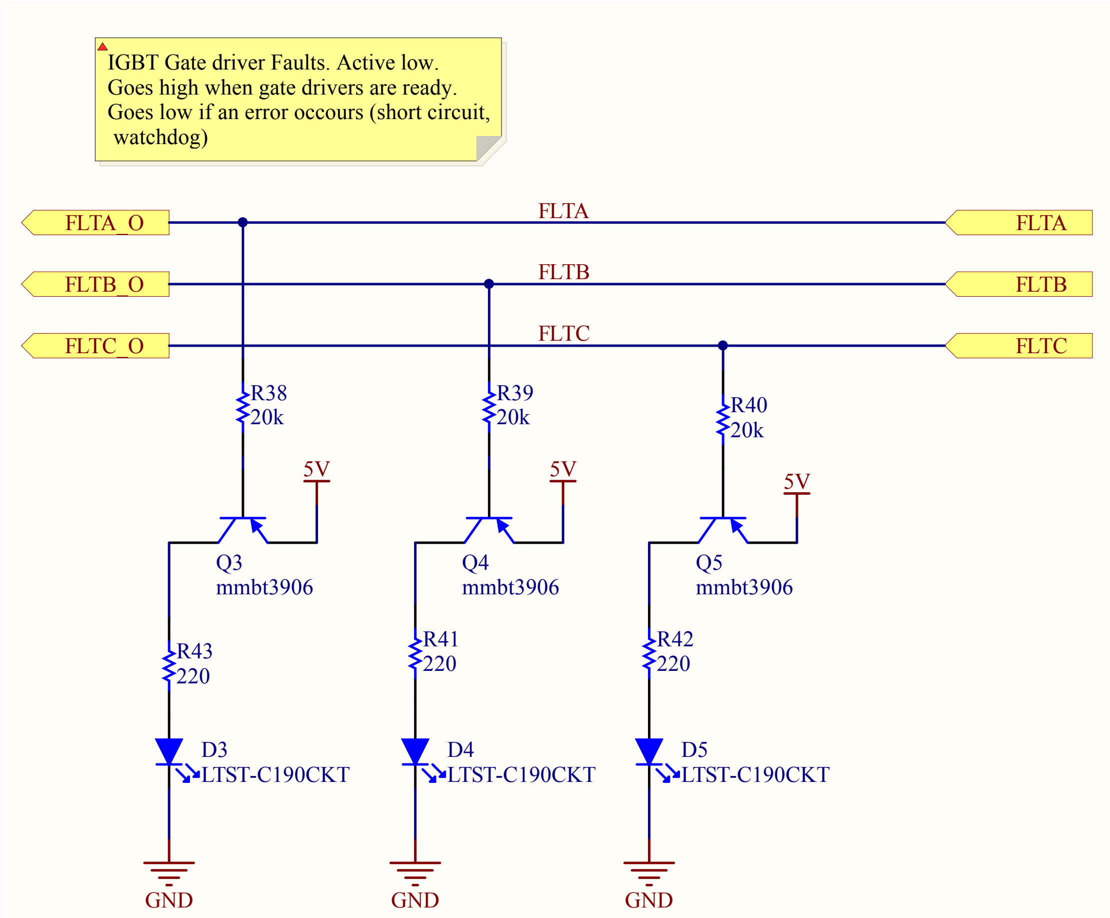

Figure 3.20: Schematics Fault connections and LED indicators.

Figure 3.21 shows how the reset signal to all the gate drivers are connected. If any of the error signals (RFE, OC or TRIP) goes low all the switching transistors are turned off. The RFE signal is hardwired to the ECU and is there as a extra precaution in the case ECU looses communication with the motor controller. The OC connection is the hardware overcurrent protection implemented on the logic card. TRIP is connected to the microcontroller and is used by the software to turn off all the transistors if it detects a error.

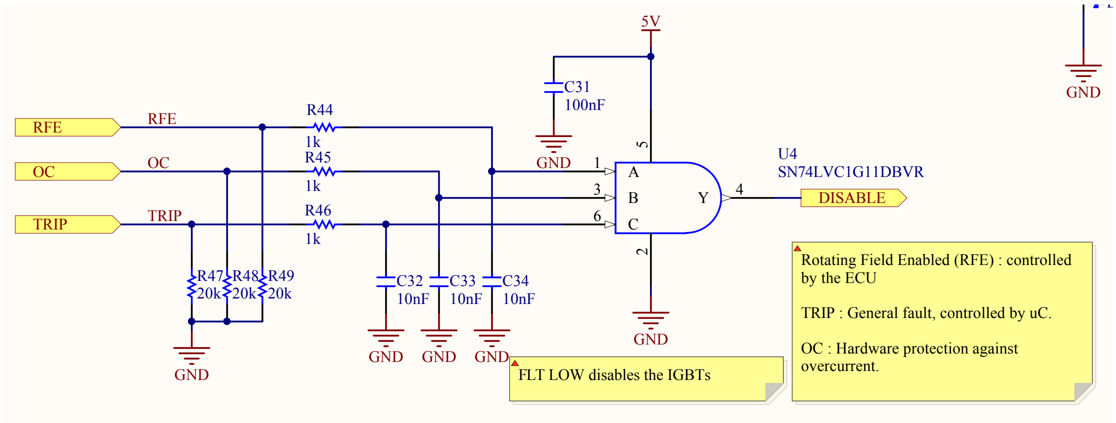

Figure 3.21: Schematics fault logic

3.8.6 PCB clearance

Since the PCB contains both high side and low side connections there are requirements for spacing between them to keep the creepage and clearances within allowed range. Figure ?? shows the PCB layout with added dimensions for the clearances.

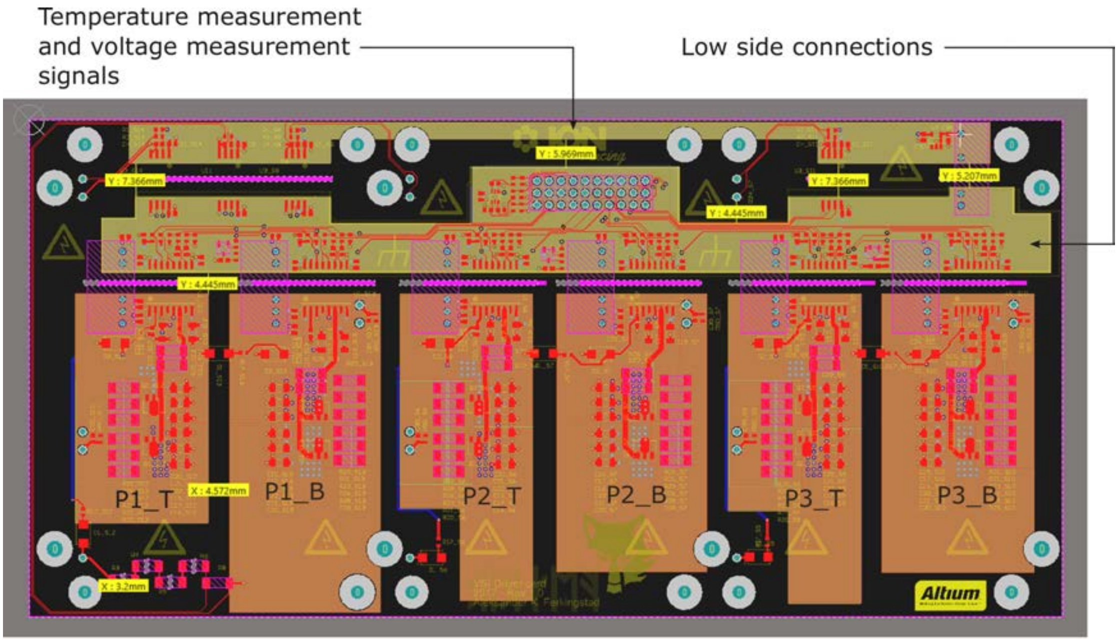

Figure 3.22: Spacing dimensions on driver card.

3.9 Logic card

3.9.1 Differential to single ended stage

Figure ?? shows the schematic for the differential to single ended stage on the logic card. It's used for converting the differential signals from the temperature sensors and voltage measurement to single ended. The output is connected to the internal ADC of the microcontroller.

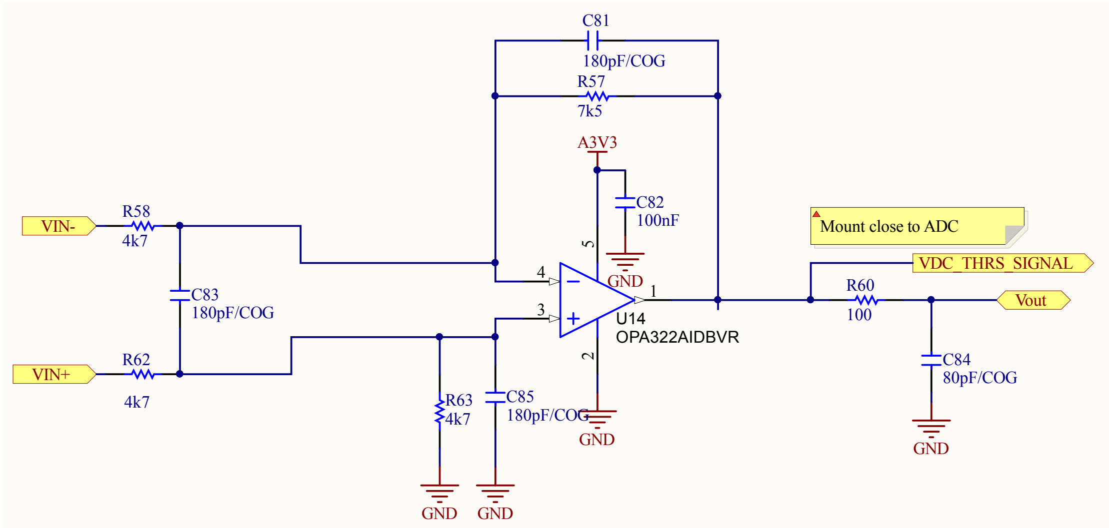

Figure 3.23: Differential to single ended input stage

3.9.2 Non volatile storage

Non volatile storage where added for storing motor controller parameters. The internal flash memory of the microcontroller could have been used, but the author have had some technical problems using this method on previous designs, so it were decided to add an external EEPROM. The schematics for the EEPROM circuit is shown in figure 3.24

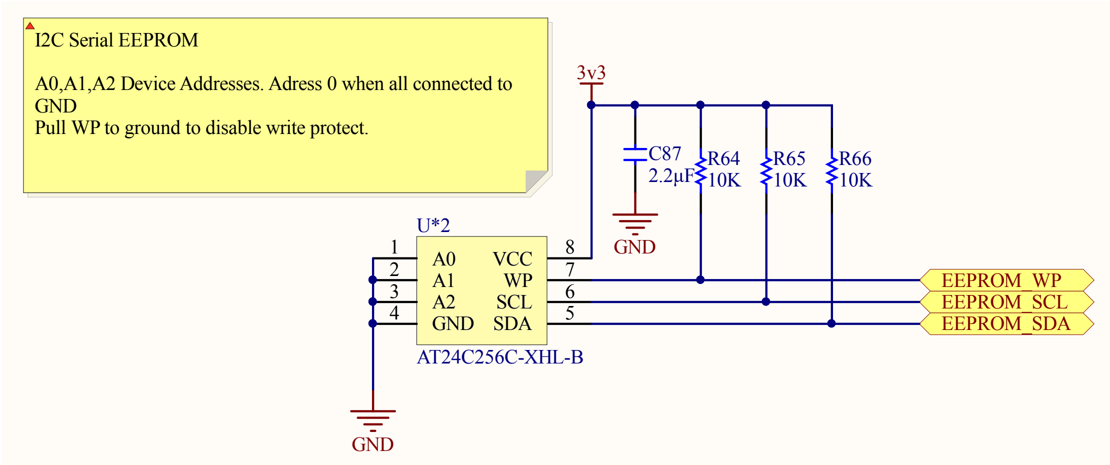

Figure 3.24: EEPROM schematics

3.9.3 Motor temperature input stage

The motor has built in resistive temperature sensor. Fig 3.25 shows the schematics for the input stage of the motor temperature sensor. The output is connected to internal ADC of the microcontroller. Over temperature is protected against in software.

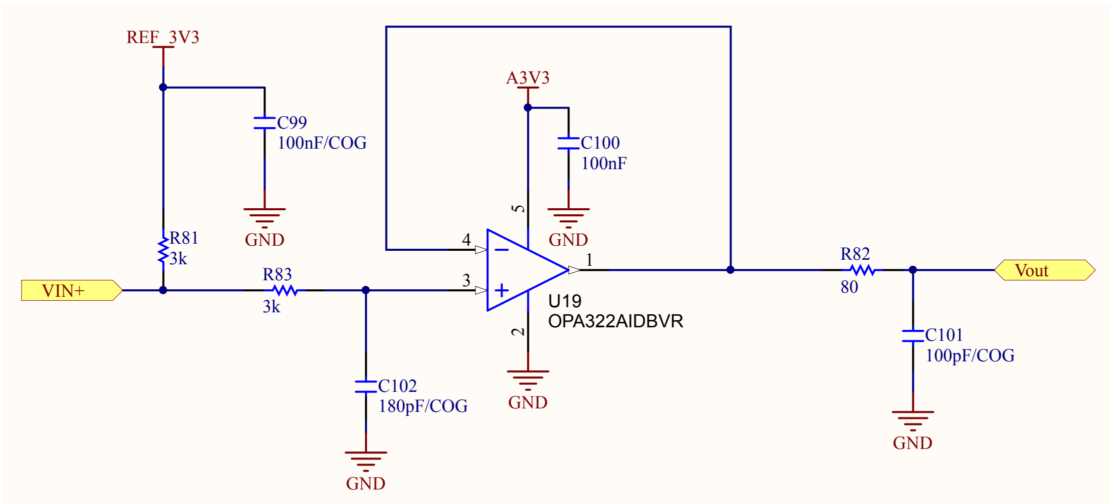

Figure 3.25: Motor temperature input stage

3.9.4 Current sensor input stage

The control algorithm needs to know the currents of two phases. Preferably the two currents should be read with as little latency as possible, and simultaneously. It were chosen to use the internal ADC of the microcontroller for reading the senors. The internal ADC of the microcontroller is of the Successive Approximation ADC (SAR), which offers zero cycle latency and low latency time. Further it has the capability of simultaneous sampling. What the internal ADC lacks is the ability to read bipolar signals, which the output from the sensors are. To remedy this problem the input stage had to add a positive offset on the sensor output voltage, so that it never goes negative.

The second desired functionality for the input stage were to detect over currents, and send a reset signal to the driver card. The reason for protecting against over current in hardware, were added robustness to the protection scheme. The software will also protect against over currents, but the maximum current for the software protection can be programmed to any desired value below the hardware protection value. Under testing the software limit can then be adjusted to a much lower value.

Figure 3.26 shows the schematic for one of the input stages. Both of the input stages are identical. The output, OUC, of both stages gets tied together so that it performs a logic or operation.

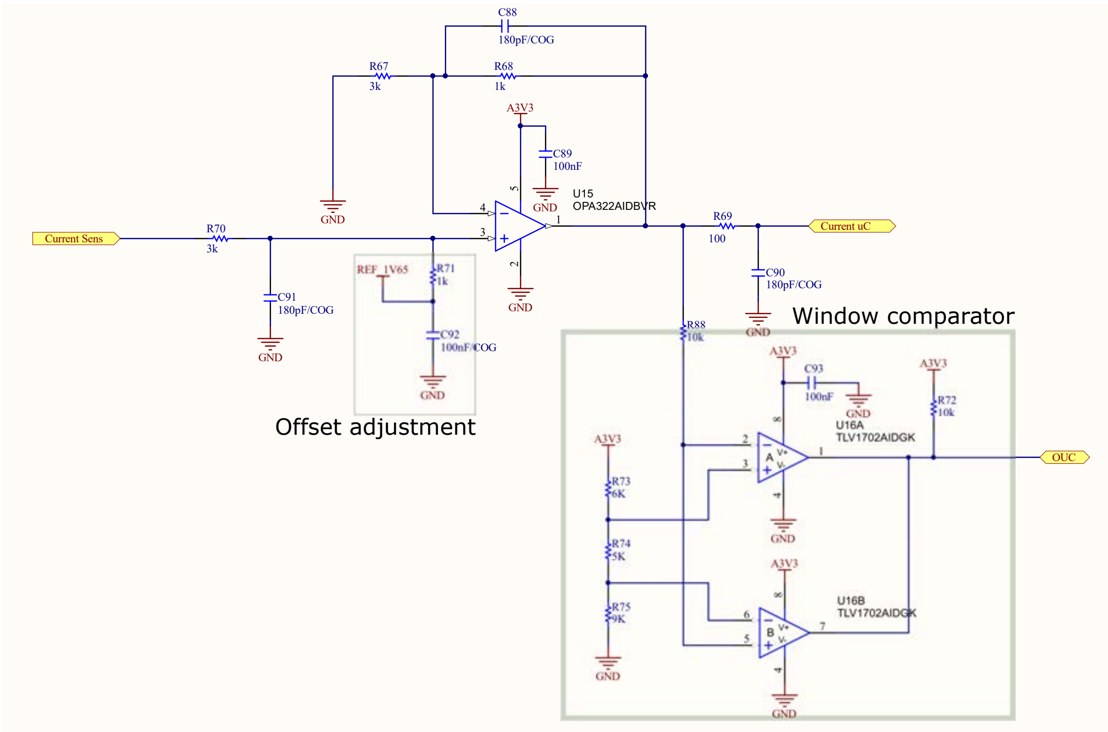

Figure 3.26: Input stage for current sensor

3.9.5 Casing temperature measurement

The microcontroller protects against over temperature inside the enclosure. Figure 3.27 shows the schematics for temperature sensor. It's PCB mounted sensor and is directly connected to the internal ADC of the microcontroller.

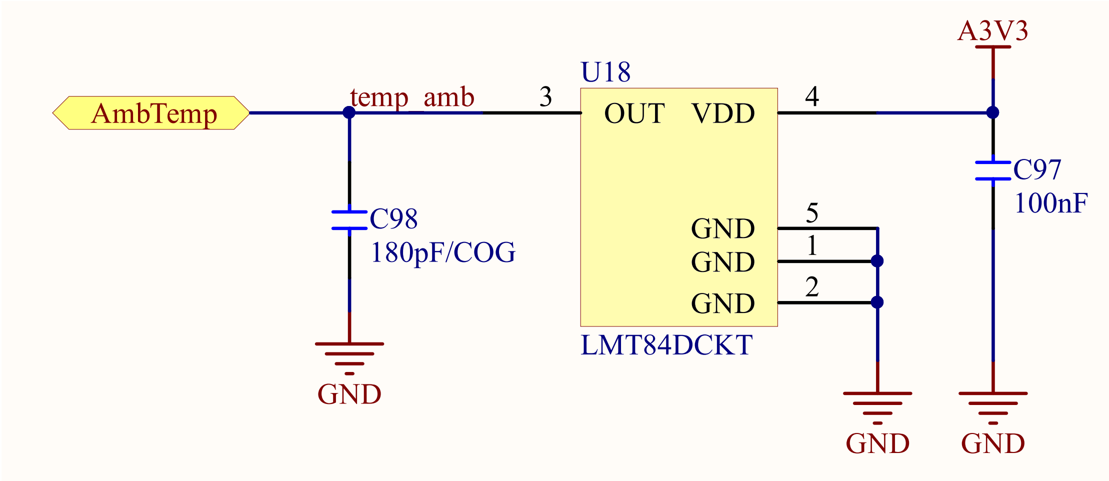

Figure 3.27: Temperature sensor inside enclosure

3.9.6 Inputs

The motor controller have two inputs controlled by the ECU. Both uses optocoupler input stages as shown in figure 3.28. The two inputs are RFE and RUN. The RFE is directly connected to gate driver reset signal, while the run signal is connected to the microcontroller to tell it when it can enable the PWM output.

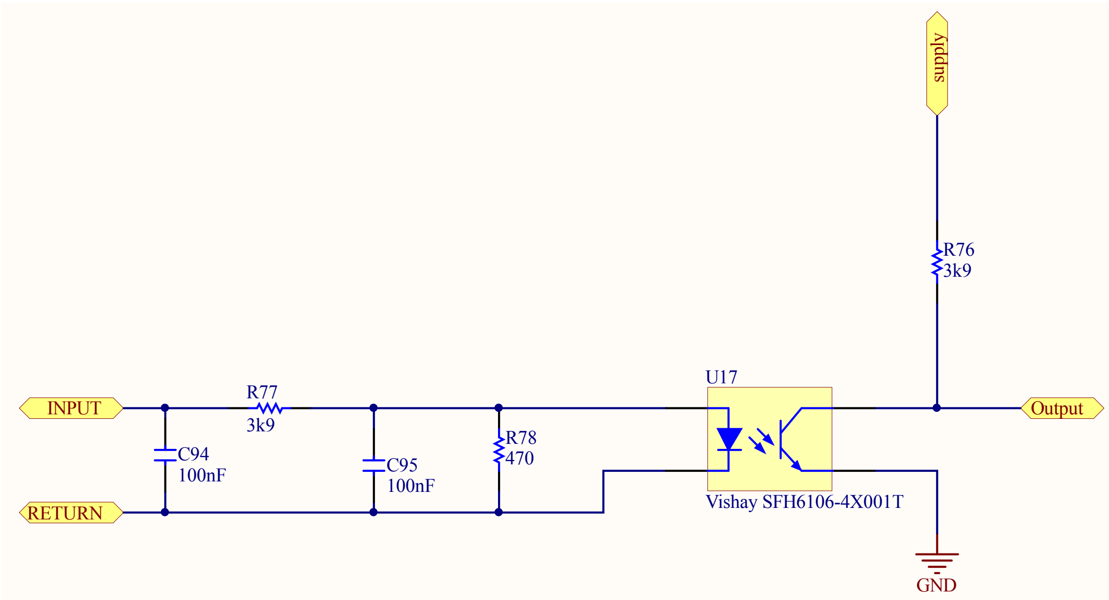

Figure 3.28: Optocoupler input stage

3.9.7 Bus voltage threshold detection

The German rules demands that a circuit needs to detect if there are a voltage greater than 60V on the capacitor bank. The circuit is shown in figure 3.29. The input is the single ended signal from the differential to single ended input stage. The output is connected to the high voltage battery which uses the signal as a part of the Tractive system active light circuit.

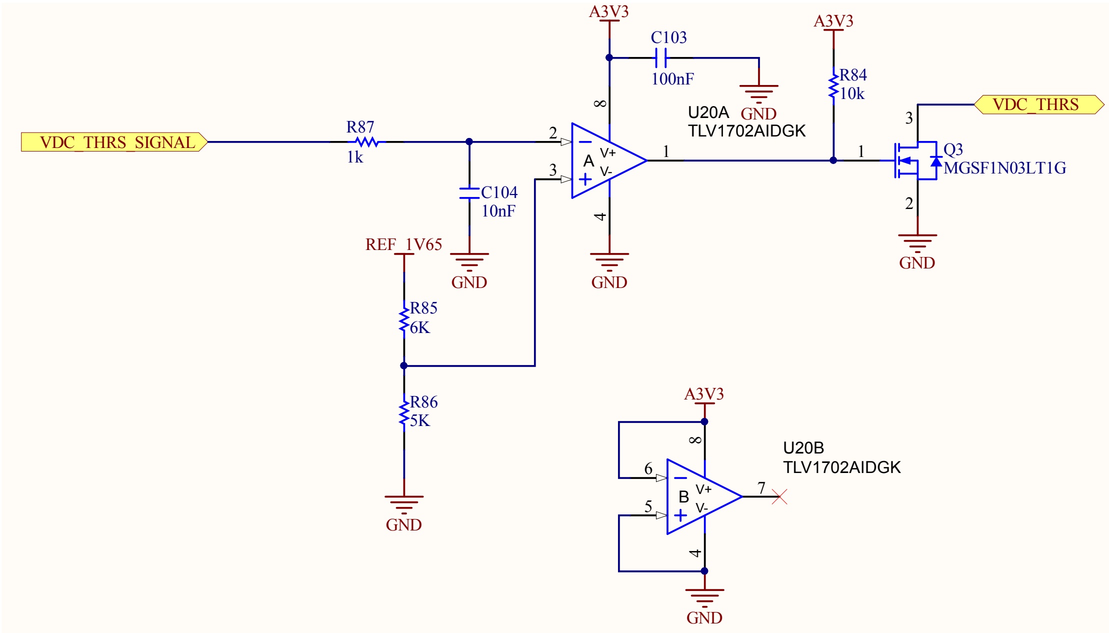

Figure 3.29: Voltage Threshold detection circuit

3.9.8 Pilot-line

A pilot-line stage were added to the motor controller so that it can shut down the whole car if necessary. The pilot-line goes through the relay, and the microcontroller can open or close the relay. The schematics are shown in figure 3.30.

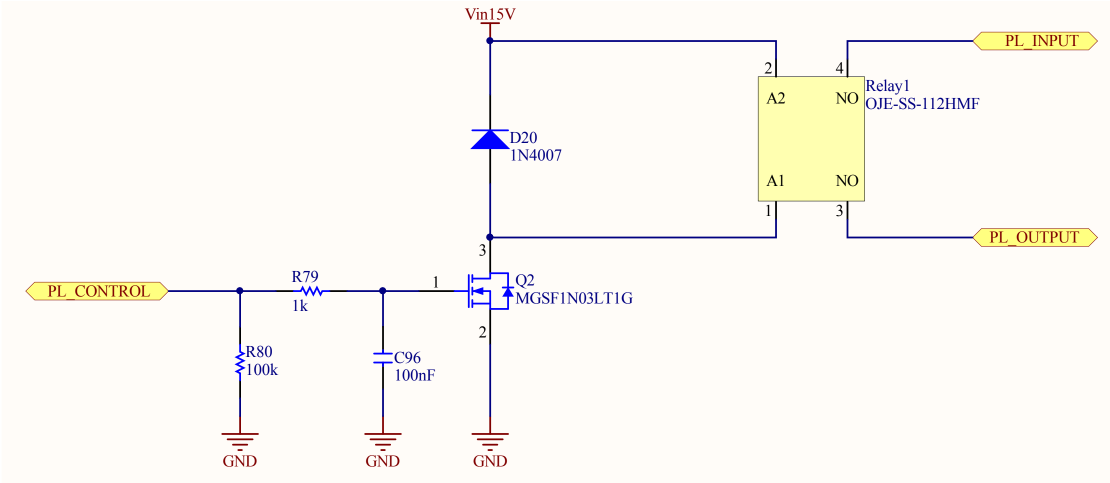

Figure 3.30: Pilot line control circuit

3.9.9 Communication interfaces

The motor controller have to communication interfaces. CAN-bus for communicating with the car and a RS232 interface for debugging/testing purposes. Figure 3.31 shows the schematics for the CAN-bus. Figure 3.32 shows the schematics for the RS323.

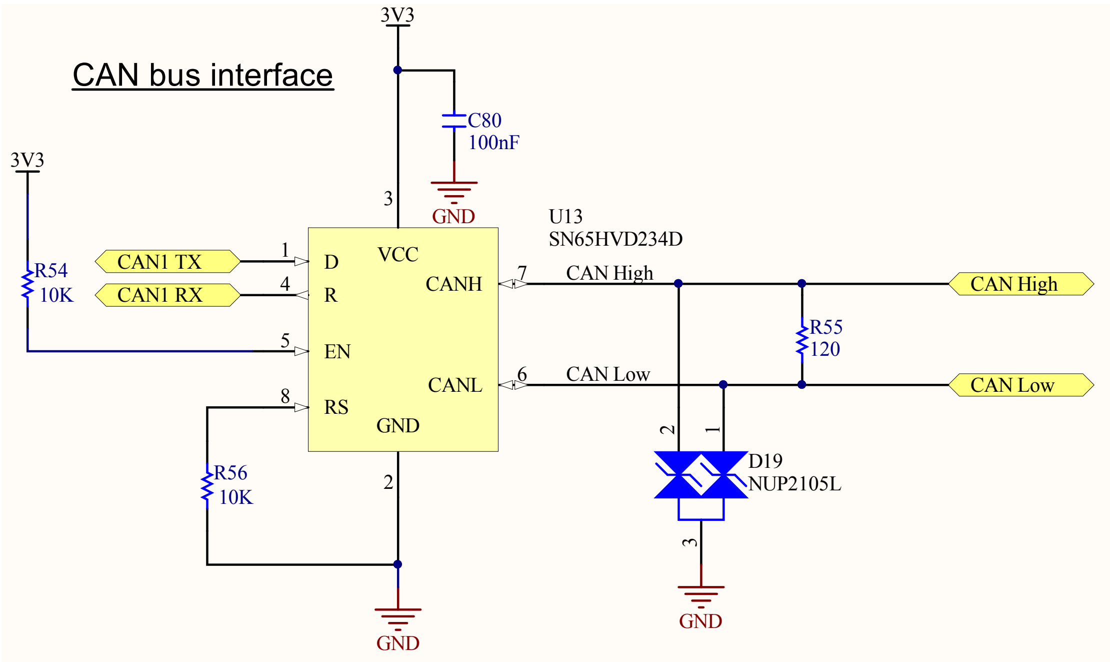

Figure 3.31:

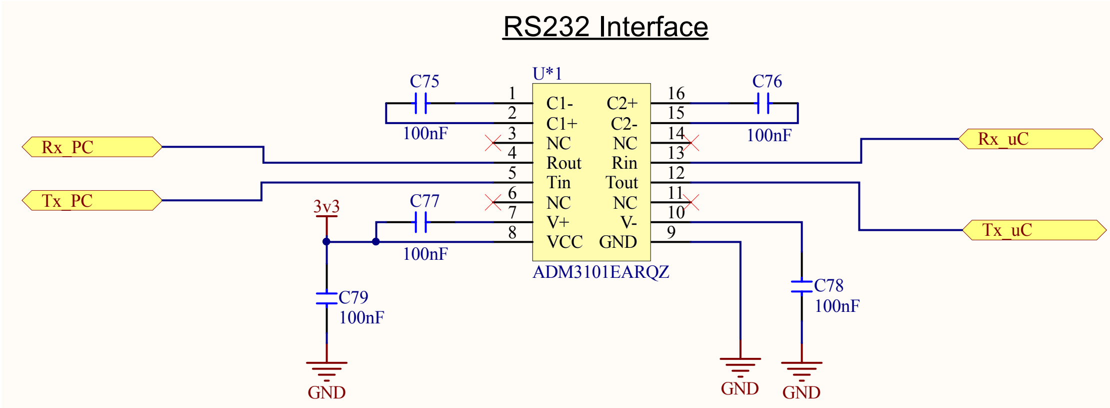

Figure 3.32:

3.9.10 Resolver interface

A chip from Texas instruments called PGA411 were used for interfacing the resolver sensor in the motor. It has most of the needed hardware inside the IC, so only some passive components had be added. It generates the sinusoidal reference and calculates the angle from the two feedback sinusoidal waves. It has programmable frequency and amplitude of the reference wave. It has a SPI communication interface for programming it and a parallel interface for reading the angle. The full schematics of it are shown in the appendix.

3.9.11 Microcontroller

The STM32f405vgt6 were chosen as the microcontroller for the motor controller. It has a clock frequency of 168Mz. This were done since this microcontroller have amble resources, functionality and the fact that it have been used for two years at ION-Racing. The complete schematics for the microcontroller are in the appendix.

3.10 Auxiliary card

The Auxiliary contains the discharge circuit, the Tractive System Measurement Point (TSMP) resistors and a HV-detection circuitry. The design of auxiliary card will be explained here. The card is designed to conform to both the rules for Germany and England. The Bamocar motor-controller does not fulfill all the rules of the competition. This card is designed to be installed in both the Bamocar inverter and the self-designed motor-controller so that both will fulfill the rules.

3.10.1 Discharge circuitry

The role of this circuit is to discharge the energy stored in the DC-link capacitor within a given time frame. The FSAE rules sets the following criteria for the discharge circuit:

1. The discharge circuit must discharge the capacitor bank of the motor-controller to a voltage below 60V within 5 seconds.

2. The discharge resistor must be able to handle the maximum discharge current for 15 seconds.

The discharge circuit were kept as simple as possible. It consists of a discharge resistor in series with a normally closed relay as shown in figure 3.33.

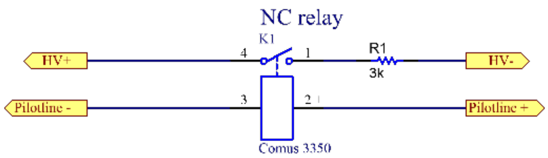

Figure 3.33: Discharge schematics

The relay is supplied by the pilot-line connected as shown in figure 3.34. The relay will be closed if no faults are detected in the car. If a fault is detected or the tractive system of the car is shut of the pilot-line will open, thus discharging the capacitor bank. For the system to be fail-safe the discharge must occur even if power is lost which is why the normally closed type relay were chosen.

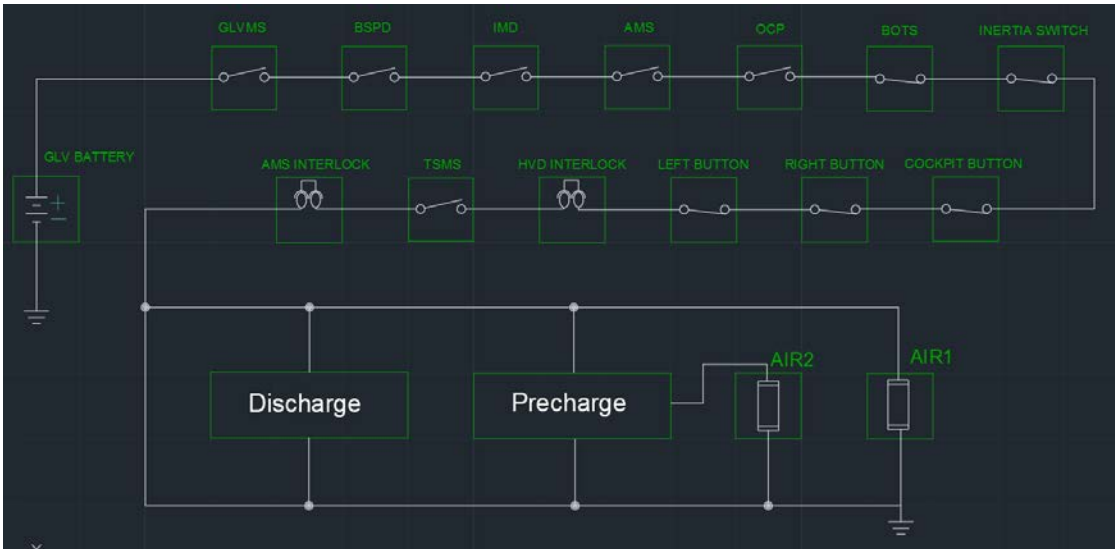

Figure 3.34: Pilot-line wiring

Discharge resistor

To find the maximum allowable resistance value the standard equation for capacitor discharge where used, see equation 3.20. For the discharge to be compatible with both the self-designed system and the Bamocar the it must be able to discharge the largest capacitor bank from 400V to 60V within 5 seconds. The maximum allowable resistance where calculated to be: $R = \frac{-5s}{800\mu F \cdot ln(60V/400V)} = 3294.467\Omega$.

$$R = \frac{-t}{C \cdot ln(\frac{v}{v_0})} \tag{3.20}$$

A standard resistor value of $3K\Omega$ where chosen. The resistor does not need to be rated for the maximum power of the discharge cycle, but it must be of sufficient size to handle peak power. Wire wound resistor or similar would be suitable. According to Vishay Dale [add citation] the power specification for the resistor can be conservatively derated for use in pulsed operation. The derating factor is equal to $\sqrt{D}$ where D is the duty ratio of the pulsed operation. Given that the resistor must be able to handle the peak power for 15 seconds (according to the rules), this is chosen as the on time of the surge. Given that we only discharge every five minutes the derating factor becomes : $K = \sqrt{\frac{15}{5\cdot 60}} = 0.2236$. The peak power is equal to $P_{max} = \frac{400^2}{3000} = 53.3W$. The derated maximum power is then equal to $P_d = 53.3 \cdot 0.2236 = 11.9253W$. A power-resistor rated for a continuous power of 20W where chosen to give some headroom. A suitable resistor from Vishay Dale where chosen, table 3.7 shows the specifications for the resistor.

MPN	CP00203K000JE14-ND
Resistance	$3K\Omega$
Power	20W
Short time overload	$5 \cdot$ P for 5 s

Table 3.7: Discharge resistor specifications

This resistor fulfilled the requirements of the rules, but it were desirable to discharge more often than every five minutes under testing. A more thorough calculation for the resistor were done.

In reality it the resistor does not need to handle the peak power for 15 seconds, but the dissipated energy of the discharge. The energy that the resistor had to dissipate were calculated according to equation 3.21 and equal to 64J.

$$E = 0.5CV^2 \tag{3.21}$$

Given a discharge time of 5 seconds and that the capacitor bank are discharged every 10 seconds, the average power that have to be dissipated is equal to 6.4W. This is within the specifications of the resistor.

A safety issue which needs to be addressed is if the discharge circuit should fail in such a way that it continuously discharges. The discharge resistor is of a fusible-flameproof type, which means that it will fail open like a fuse. The capacitor bank voltage is monitored under use of the car and a open discharge resistor would be noticed.

Discharge relay

A NC reed relay from Comus were chosen as the discharge relay. Table 3.8 lists the required specification for the relay and the specifications for the comus 3350 relay.

Specifications	Required	Comus 3350
Switching voltage	>400V	3500V
Switching capacity	$> 400V^2/3K\Omega = 54W$	200W
Carrying current	$> 400V/3K\Omega = 133mA$	3A

Table 3.8: Discharge relay specifications

3.10.2 Tractive system measurement point resistors

The tractive system measurement points and the current limiting resistors are required by the rules. The tractive system measurement points are two banana-jacks mounted on the side of the car. The two measurement points are connected to the positive and negative capacitor terminals in the motor-controller. They are used for testing the functionality of the discharge, precharge and insulation monitor. The value of the resistors are specified by the rules to be $15K\Omega$.

3.10.3 Voltage measurement

The German rules states that the tractive system active light circuitry (Located in the high voltage battery) needs to detect if there are above 60V present in the capacitor bank. The circuitry for this are included in the logic-card and driver-card for the self designed motor-controller, but for the Bamocar to fulfill the rules it had to be included on the auxiliary-card as well. The circuitry for this section will only be soldered on the PCB which are mounted in the Bamocar.

The complete schematics for the voltage measurement are shown in figure **??**. The design of the voltage measurement are identical to that explained previously for the logic-card and driver-card, and are therefore not explained again here.

Chapter 4

Software design

This chapter explains the software of the microcontroller. All the source code for the system is included in the appendix. The software utilizes the Standard Peripheral library created by STM to configure the hardware.

4.1 Program structure

Three different methods for structuring the program were considered:

Super-loop A super-loop is the simplest approach for system design. In a super-loop all the code for the system is in the main loop and often implements state-machines to control what to do. It is a deterministic system and often results in a robust solution, but can become very complex to implement for larger systems.

Background and Foreground tasks The background and foreground approach splits the code in two tasks namely the foreground and background task. It's a common technique for control systems. Usually the foreground task is created by a interrupt at a certain interval, while the background task is written in the main code. The code that needs to executed regularly are then in the foreground task, while all the other code for the system is in the background task. The background task gets executed as often as the system has time to.

Real Time Operating Systems Real time operating systems are created to minimize the input/output delay of the system. It does this by creating tasks which it switches quickly between. It is a suitable solutions for systems which needs to handle many tasks simultaneously.

The background and foreground method where chosen. The reason for this choice is the ease of debugging the code compared to more sophisticated scheduling techniques (like RTOS) and the authors previous experience with creating systems with this approach. A super-loop solution, although more deterministic, where not chosen because of the complexity involved in implementing it. The foreground task handles all the control-code, while the background task handles the rest of the code. Figure 4.1 shows flow charts for the background task and the foreground task. The background task updates the torque set point in the foreground task, if a new torque request were received on the CAN-bus.

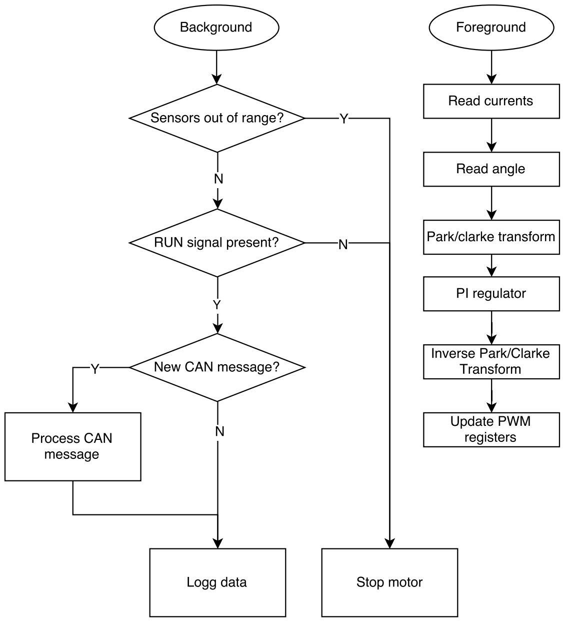

Figure 4.1: Simplified flowchart for background and foreground task

The foreground code is handled by a interrupt while the background tasks are handled in the main code. Thus the code handles all the background tasks when it has time for it, while the foreground tasks are executed at a certain interval. The foreground task is synchronized to the PWM update rate and thus runs at the same frequency of 15KHz.

4.2 Clarke and Park transformations

The forward clarke and park transformations were created as one function, since the control algorithm only needs the iq and id values, as following:

```
void inline parkClarke_forward(
        uint16_t theta,
        float ia,
        float ib,
        float* iq,
        float* id
){
        /* Clarke transformation */
        float ibeta;
        /* ialpha = ia; */
        ibeta = sqrt3Inv * (ia + 2*ibeta);

        /* Park transformation */
        *id = ia * LUT_COSINE(theta) + ibeta * LUT_SINE(theta);
        *iq = ibeta * LUT_COSINE(theta) - ia * LUT_SINE(theta);
}
```

The square root calculations were pre-calculated and added as a define. The same procedure were done for the inverse transformation, as following:

```
void inline parkClarke_inverse(
        uint16_t theta,
        float vq,
        float vd,
        float* va,
        float* vb,
        float* vc
){
        float vAlpha, vBeta;

        /* Inverse Park transformation */
        vAlpha = vd * LUT_COSINE(theta) - vq*LUT_SINE(theta);
        vBeta = vq * LUT_COSINE(theta) + vd*LUT_SINE(theta);

        /* Inverse clarke transformation */
        *va = vAlpha;
        *vb = (-vAlpha + sqrt3 * vBeta )/2;
        *vc = (-vAlpha - sqrt3 * vBeta) /2;
}
```

4.2.1 Sine calculation

To keep the execution time low a 12-bit sin Look Up Table (LUT) were implemented. The following macros were defined for interfacing the LUT.

```
#define nbrOfPoints 4096
#define nintyDeg 1024 /* (90/360) * 4096 */

/*------------------------ Macros -----------------------------------------*/
#define LUT_SINE(angle) (LUT_sin[ WRAP_ANGLE(angle) ])
#define LUT_COSINE(angle) (LUT_sin[ ( WRAP_ANGLE(
                                angle + nintyDeg) ) ])

/* If the angle is larger than 4095 (360 degrees) it wraps to around.
* It skips zero when wrapping around (360 = 0).
* 4097 -> 1, 4098 ->2.. 4096 + 1024 = 1024.
*/
#define WRAP_ANGLE(angle)   (angle > nbrOfPoints ?
                                angle-nbrOfPoints : angle)
```

4.3 PI regulator

The PI regulator were implemented as pointer based structure. This were done so that several PI regulator instances could easily be made.

```
/* Macros ----------------------------------------------------------------*/
#define MAX(val1,val2) (val1 > val2 ? val1 : val2)
#define MIN(val1, val2) (val1 < val2 ? val1 : val2)

/* Public functions ------------------------------------------------------*/
void PI_update(PIregulator_t *PI)
{
        float iMax, iMin; /* min and max values for
                             integrator anti-windup */

        PI->error = PI->setPoint - PI->plantValue;
        PI->proportionalTerm = PI->error * PI->Ka;
        PI->integralSum += PI->Kb * PI->proportionalTerm;

        /* Integral Anti windup */
        iMax = MAX(PI->outputMax - PI->proportionalTerm, 0);
        iMin = MIN(PI->outputMin - PI->proportionalTerm, 0);
        if(PI->integralSum > iMax){ PI->integralSum = iMax;}
        else if(PI->integralSum < iMin){ PI->integralSum = iMin;}

        /* Calculate and limit output */
        PI->output = PI->proportionalTerm + PI->integralSum;
        if(PI->output > PI->outputMax){PI->output = PI->outputMax;}
        else if(PI->output < PI->outputMin){PI->output =
                                                PI->outputMin;}
}
```

The PI regulator implements a dynamic anti windup method. It works by setting the limits of the integral sum dynamically, based upon the proportional output and maximum allowed output. The dynamic anti windup method is described by equation 4.1 and 4.2, where I_{max} is the maximum sum of the integral, I_{min} is the minimum output of the integrator sum, P_{out} is the proportional output, H is the maximum allowed output value for the regulator and L is the minimum allowed output value of the regulator. This method offers less overshoot compared to static clamping.

$$I_{max} = MAX(H - P_{out}, 0) \tag{4.1}$$

$$I_{min} = MIN(L - P_{out}, 0) \tag{4.2}$$

4.4 Pulse Width Modulation

To generate the PWM pulses to the driver-card TIM1 were used. TIM1 were configured to run in center aligned mode with a frequency of 15KHz. Three compare registers were configured with complementary outputs (six-channels in total) and adjustable dead-time. The timer hardware compares the running timer with the three compare registers and automatically sets the PWM outputs high or low based upon if timer value is larger or lower than the register value. A interrupt were configured to happen when the timer counter reaches 50% of the maximum values.

This interrupt is the foreground task of the code. Figure 4.2 illustrates the PWM configuration scheme.

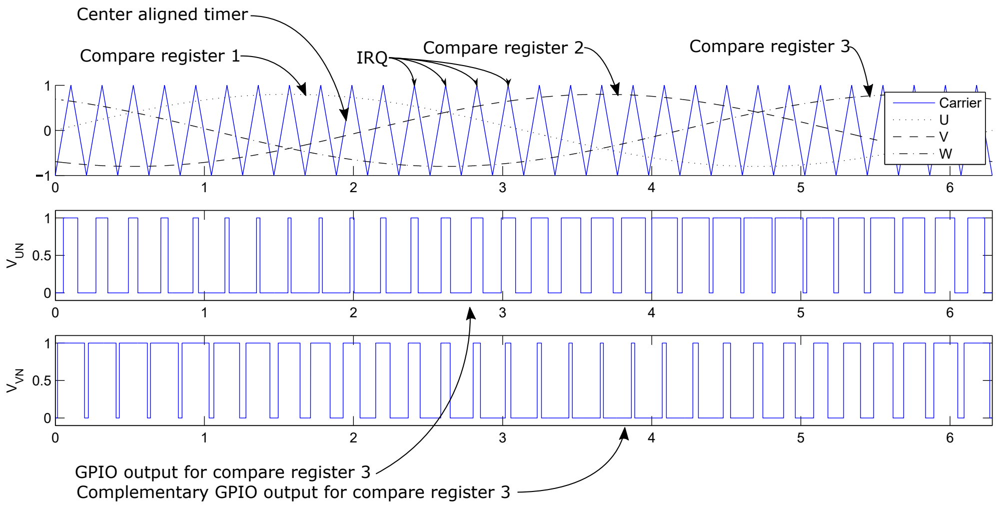

Figure 4.2: Pulse width modulation confiuration

The task of the controller is to update the PWM registers to the correct value after every Interrupt. As can be seen from figure 4.2 the compare register values end up having three phase sinusoidal shape as the motor rotates.

4.5 Protection procedure

To protect against overvoltage a function were created which locks the PWM output to set all the bottom transistors on and all the top transistors off, which stops the motor from charging the capacitor bank.

```
void HAL_PWM6channel_OvervoltageProtection(PWM_state_t state)
{
        if(state == enable)
        {
                overvoltageProtection_f = enable;
                TIM1->CCR1 = (period * 0)/100;
                TIM1->CCR2 = (period * 0)/100;
                TIM1->CCR3 = (period * 0)/100;
        }else if(state == disable)
        {
                overvoltageProtection_f = disable;
        }
}
```

If a over current or over temperature is detected all of the transistors is locked in a off state:

```
void HAL_PWM6channel_disableOutput(void)
{
        TIM_CtrlPWMOutputs(TIM1, DISABLE);
        TIM_ITConfig(TIM1, TIM_IT_CC4, DISABLE);
}
```

4.6 Foreground task psuedo code

```
void TIM1_CC_IRQHandler()
{
        if (TIM_GetITStatus(TIM1, TIM_IT_CC4) != RESET)
                {
                        TIM_ClearITPendingBit(TIM1, TIM_IT_CC4);

                        /* Start Conversion of readings (currents,
                                        voltage, temperatures) */
                        /* Read Angle */
                        /* Wait for current conversion complete */
                        /* Park Clarke transformation */
                        /* PI-calculations*/
                        /* Inverse transformation */
                        /* Scale output */
                        /* Update PWM registers*/

                        /*
                        if current > max current ->
                                disable output, turn on led.
                        if voltage > max voltage ->
                                overvoltage  protection enabled.
                        if any temperature > max temperature ->
                                disable output.
                        */
                }
}
```

The rest of the code is added in the appendix.

Chapter 5

Results

5.1 Hardware

All of the hardware were finished designed and produced. The driver card still needs to be soldered and tested before the system as a whole can be tested.

Busbar

Figure 5.1 shows the assembled bus-bars without the isolating Kapton tape. And figure 5.2 shows the bus bar with the added Kapton tape.

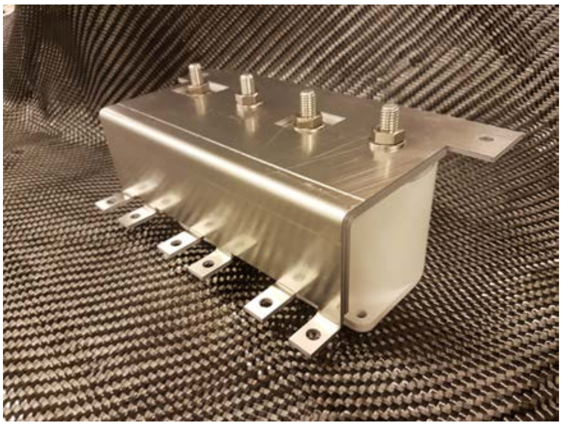

Figure 5.1: Busbar without added Kapton tape

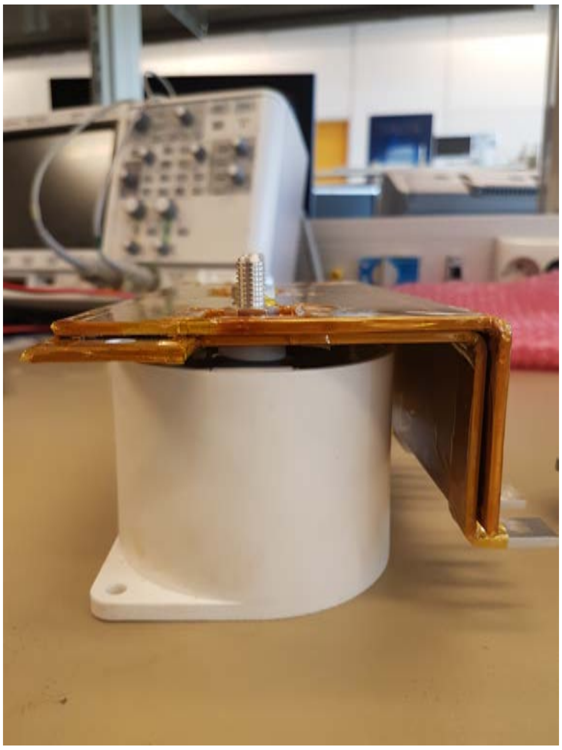

Figure 5.2: Busbar with added Kapton tape

Water block

The machined water block are shown in figures 5.3 and 5.4.

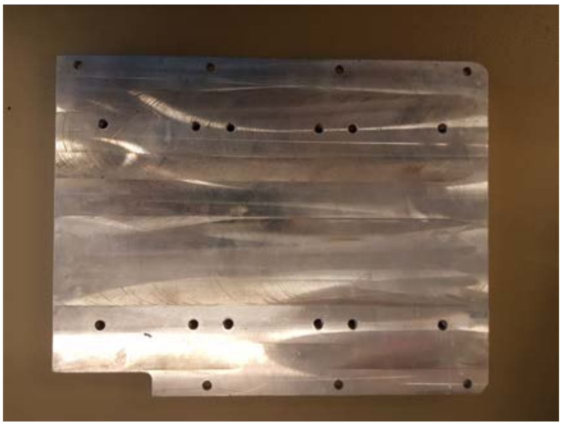

Figure 5.3: Water block IGBT mounting side

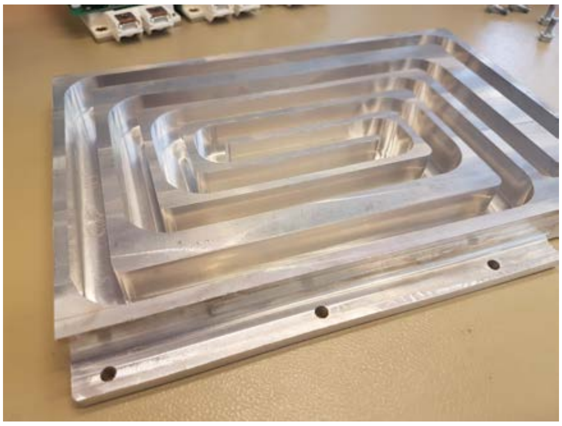

Figure 5.4: Water block channels

Auxiliary PCB

Figure 5.5 shows the top side of the auxiliary PCB and figure 5.6 shows the bottom side.

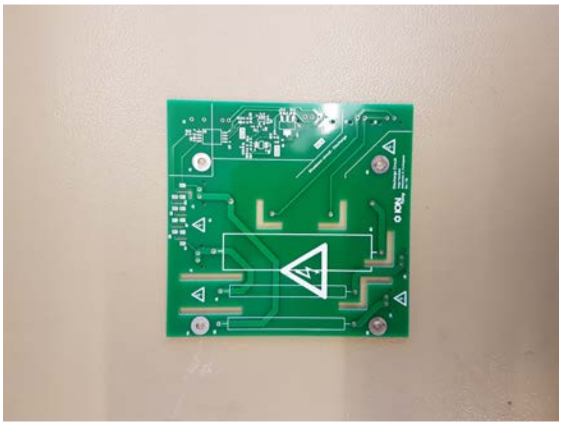

Figure 5.5: Auxiliary PCB top

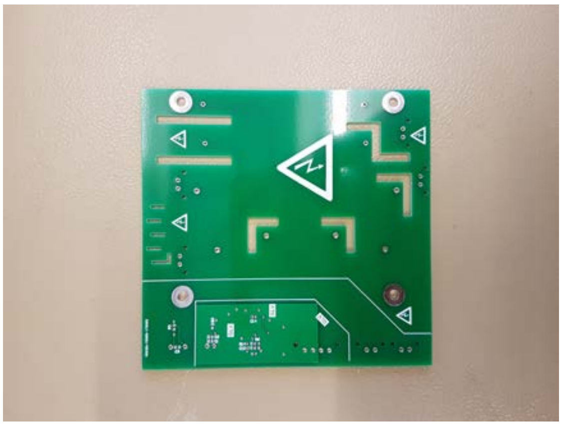

Figure 5.6: Auxiliary PCB bottom

Gate Driver PCB

Figure 5.7 shows the top side of the driver card PCB and figure 5.8 shows the bottom side.

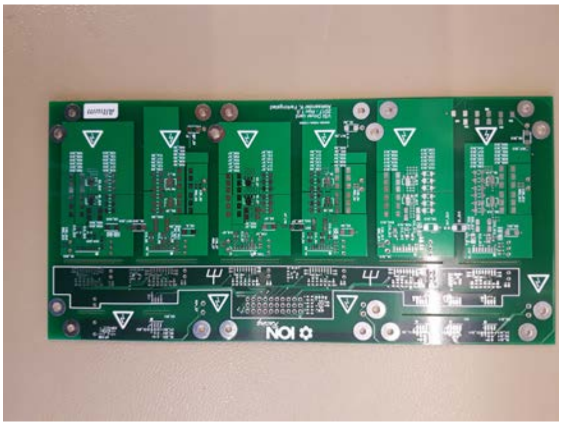

Figure 5.7: Gate driver PCB top

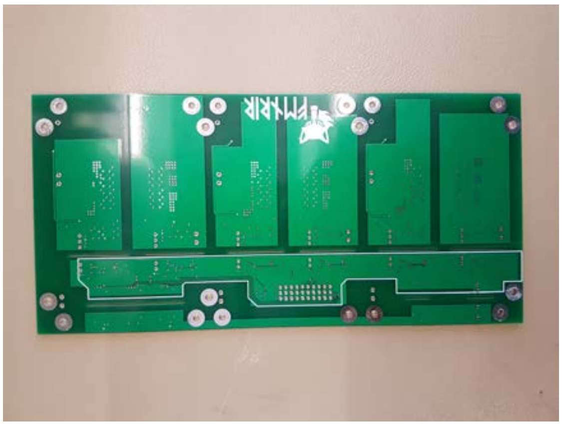

Figure 5.8: Gate Driver PCB bottom

Logic card PCB

Figure 5.9 shows the top side of the logic card PCB and figure ?? shows the bottom side.

Figure 5.9: Logic PCB top

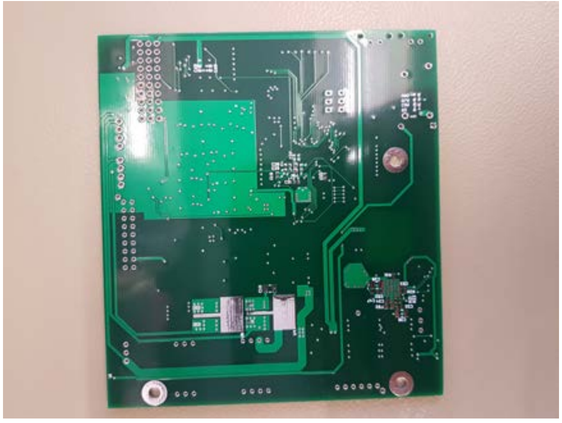

Figure 5.10: Logic PCB bottom

Two errors were found on the logic card when soldering it. Figure 5.11 shows the first error where the enable signal to the 3.3V supply had not been added, this were fixed by adding a jumoper wire as shown. Figure 5.12 shows the second error where the pins of the -15V supply for the current sensor had been mixed up. This were fixed by using some jumper wires.

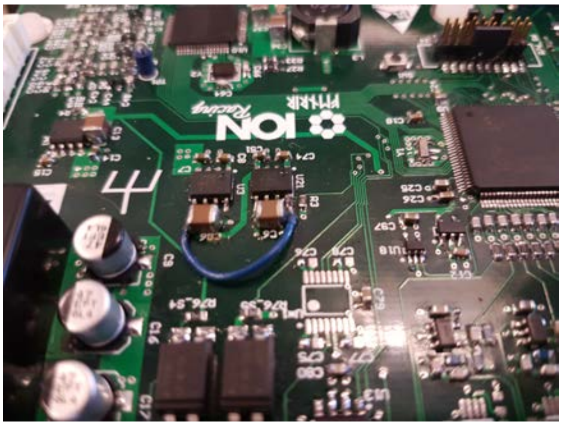

Figure 5.11: Logic PCB error

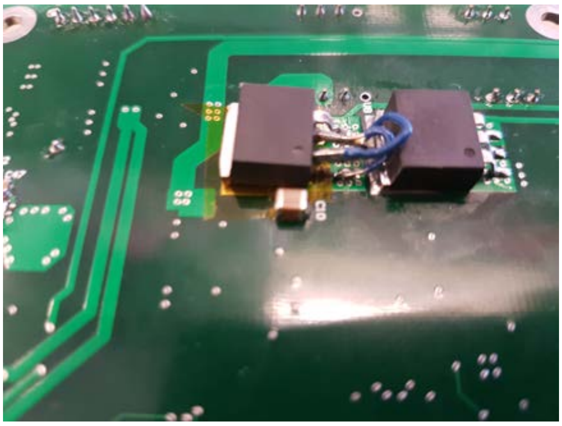

Figure 5.12: Logic PCB error

Electronics assembly

Figure 5.13: Top view of the electronics assembly

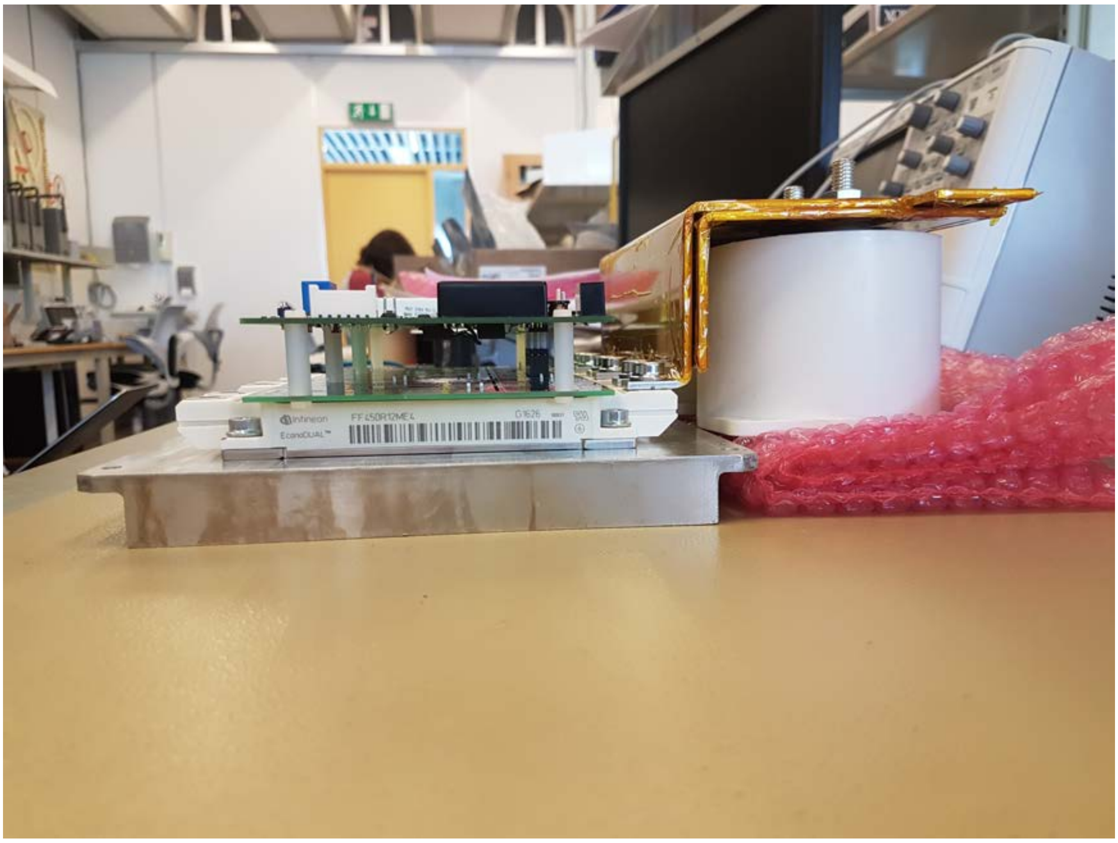

Figure 5.14: Side view of the electronics assembly

5.2 Software

Some minor code have to be written to start testing the system, but there are still a lot of software that needs to be written before the motor controller can be used in the car.

Chapter 6

Discussion and further work

The sheer amount of work needed to design a motor controller and get grasp of all the theory were not anticipated. The work have not gotten as far as were planned. There are still more work left before a complete working system is finished, mainly what is missing is more testing of the system. Undoubtedly there are more minor errors that needs to fixed. Some errors have been found and fixed.

6.1 The cooling system

The cooling system of the car were meant to be done by a another member of the team, but he left the team with little work done. The Author had little choice but to try and do some rough estimations for the cooling system. The calculations done were based upon a thesis on the cooling system for 2016 car. A more thorough analysis of the cooling should be done.

6.1.1 The cooling block

The weight of the motor controller is a essential specifications since it is to be used in a race car. The cooling block can be improved upon by making it smaller and lighter. It were decided that the cooling block should be mounted on the outside of the enclosure, as to let excess heath out instead of trapping it inside the enclosure. Since the cooling block were to be mounted on the outside, the minimum dimensions of it were set because of the mounting arrangement. If the cooling block could be mounted inside the enclosure, the cooling block could also be made smaller. Problems with heath build-up in the enclosure could be fixed by using some venting holes or a fan.

6.1.2 Assembly

The dimensions of the enclosure were decided early on since the motor controller should be compatible with the Bamocar. If this were not the case a more compact solution could be made.

6.1.3 Electronics

Many of the solutions for electronics were chosen on the basis of it being simpler/quicker to implement. The electronics could have been made cheaper by using more economical solutions. A lot of time were spent on the power electronics, in hindsight this were not as fruitful as one would have wished. The focus should have been on designing the hardware as simple as possible, and spend more time on the software and testing of the system.

When the car is done and have been thoroughly tested there will be more data on the system, which could be used for optimization of the hardware (escpecially the power electronics). Future work for ION-Racing could be to downscale the system for a 4-wheel drive system. That would also open up work to be done on torque-vectoring control methods and design of light-weight efficient PMSM motors.

6.1.4 Software

When the system is up and running the most interesting part for further work would be on the software, Especially on the control-system. More advanced control techniques can be tested and compared with the designed hardware. For example: Direct torque control [1], sensor-less control [10], dynamic switching-frequency control [7].

Bibliography

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[2] FSAE. 2017-18 formula sae® rules, 2017.

[3] Paul Horowitz, Winfield Hill, and Ian Robinson. *The art of electronics*, volume 2015. Cambridge university press Cambridge, 2015.

[4] Johann W Kolar and Simon D Round. Analytical calculation of the rms current stress on the dc-link capacitor of voltage-pwm converter systems. *IEE Proceedings-Electric Power Applications*, 153(4):535–543, 2006.

[5] Ned Mohan, Tore M Undeland, and William P Robbins. Power electronics. *Wiley*, 1988.

[6] Eric Monmasson. *Power electronic converters: PWM strategies and current control techniques*. John Wiley & Sons, 2013.

[7] KOICHI OKUBO, MAKIO MASUDA, YOSHIKI KATO, and YUTAKA NAKATANI. Development of low-loss inverters for electric vehicle (ev) motors. *Mitsubishi Heavy Industries Technical Review*, 45(3), 2008.

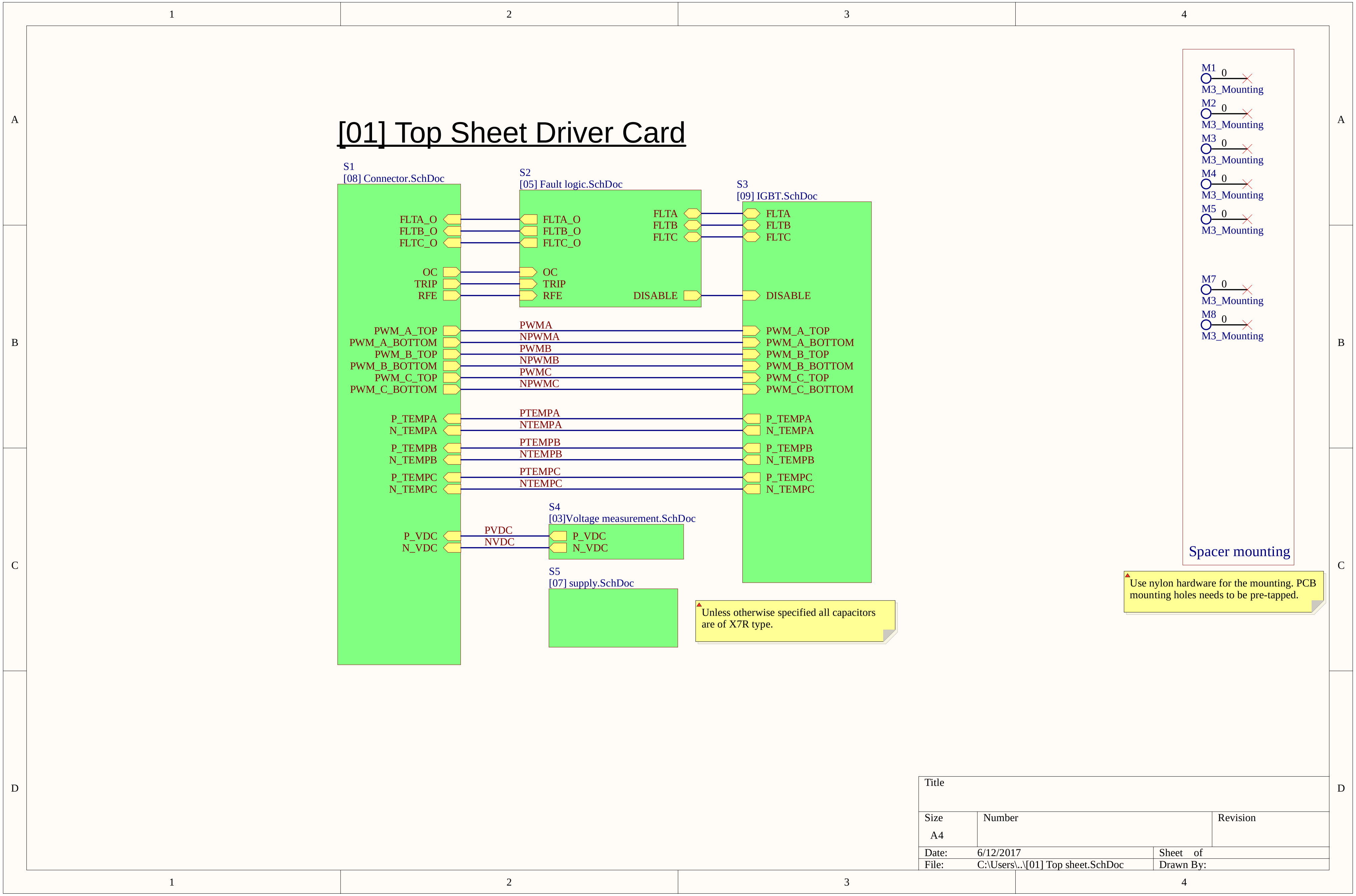
[8] Jinsheng Song. External booster for driver ic. *Infineon*, 2014.

[9] Helge Vassbakk and Olav Risa. Design og testing av batteri styrings system (bms) til bruk i en formula student bil., 2017.

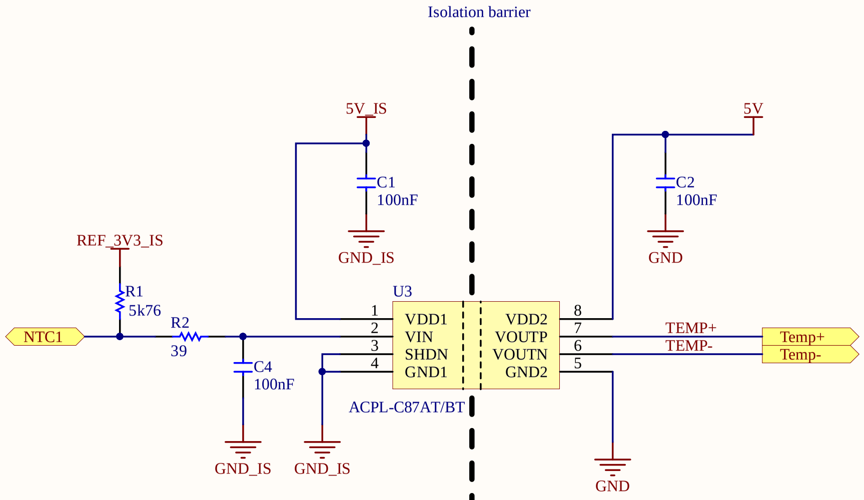
[10] Jorge Zambada. Sensorless field oriented control of pmsm motors. *Microchip AN1078*, pages 1–30, 2007.

Appendix A

Full schematics for driver card



[01] Top Sheet Driver Card
S1
[08] Connector.SchDoc
FLTA_O
FLTB_O
FLTC_O
OC
TRIP
RFE
PWM_A_TOP
PWM_A_BOTTOM
PWM_B_TOP
PWM_B_BOTTOM
PWM_C_TOP
PWM_C_BOTTOM
P_TEMPA
N_TEMPA
P_TEMPB
N_TEMPB
P_TEMPC
N_TEMPC
P_VDC
N_VDC
S2
[05] Fault logic.SchDoc
FLTA_O
FLTB_O
FLTC_O
OC
TRIP
RFE
FLTA
FLTB
FLTC
DISABLE
S3
[09] IGBT.SchDoc
FLTA
FLTB
FLTC
DISABLE
PWM_A_TOP
PWM_A_BOTTOM
PWM_B_TOP
PWM_B_BOTTOM
PWM_C_TOP
PWM_C_BOTTOM
P_TEMPA
N_TEMPA
P_TEMPB
N_TEMPB
P_TEMPC
N_TEMPC
PWMA
NPWMA
PWMB
NPWMB
PWMC
NPWMC
PTEMPA
NTEMPA
PTEMPB
NTEMPB
PTEMPC
NTEMPC
PVDC
NVDC
S4
[03]Voltage measurement.SchDoc
P_VDC
N_VDC
S5
[07] supply.SchDoc
Unless otherwise specified all capacitors are of X7R type.
M1 0 M3_Mounting
M2 0 M3_Mounting
M3 0 M3_Mounting
M4 0 M3_Mounting
M5 0 M3_Mounting
M7 0 M3_Mounting
M8 0 M3_Mounting
Spacer mounting
Use nylon hardware for the mounting. PCB mounting holes needs to be pre-tapped.
Title
Size A4
Number
Revision
Date: 6/12/2017
Sheet of
File: C:\Users\..\[01] Top sheet.SchDoc
Drawn By:



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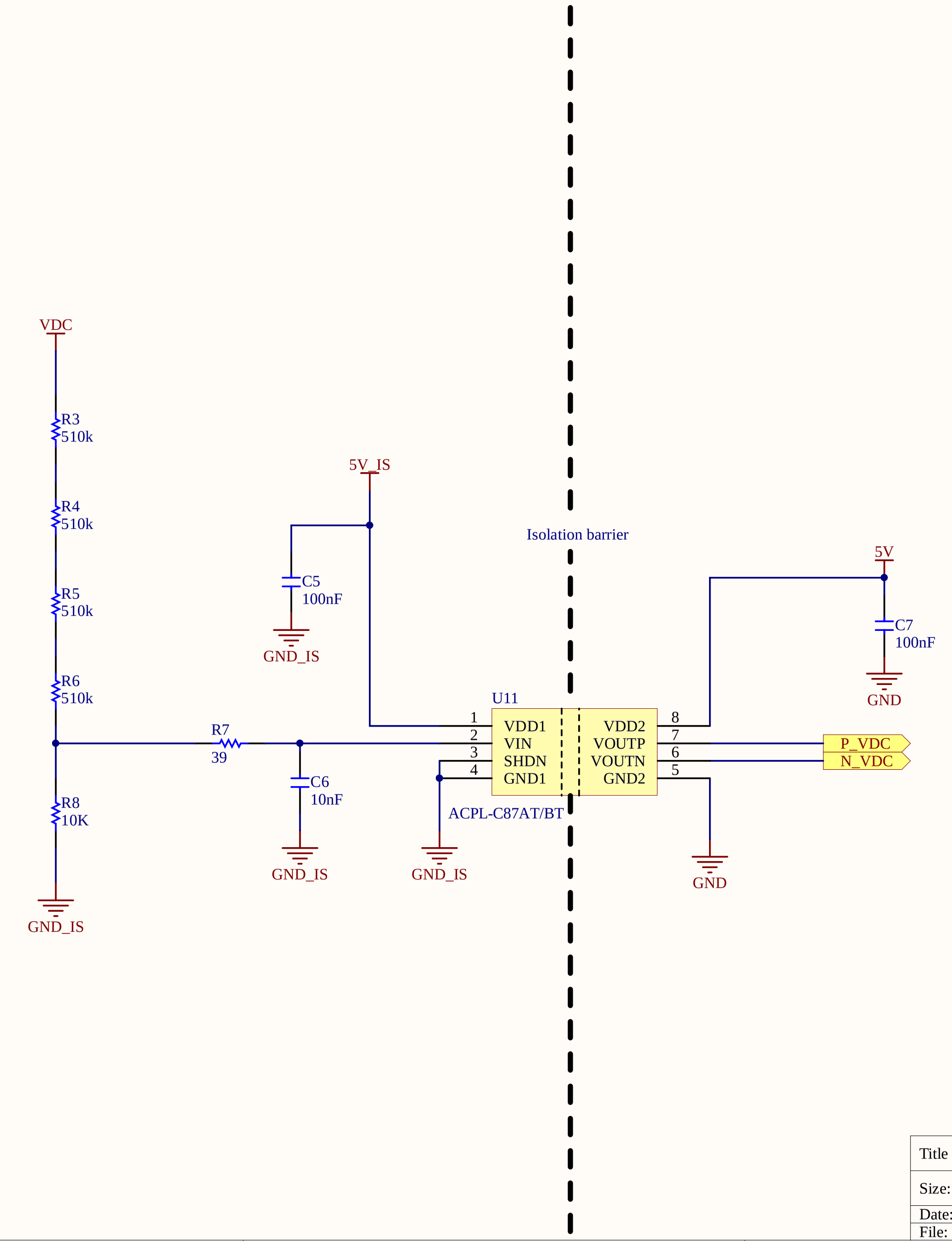

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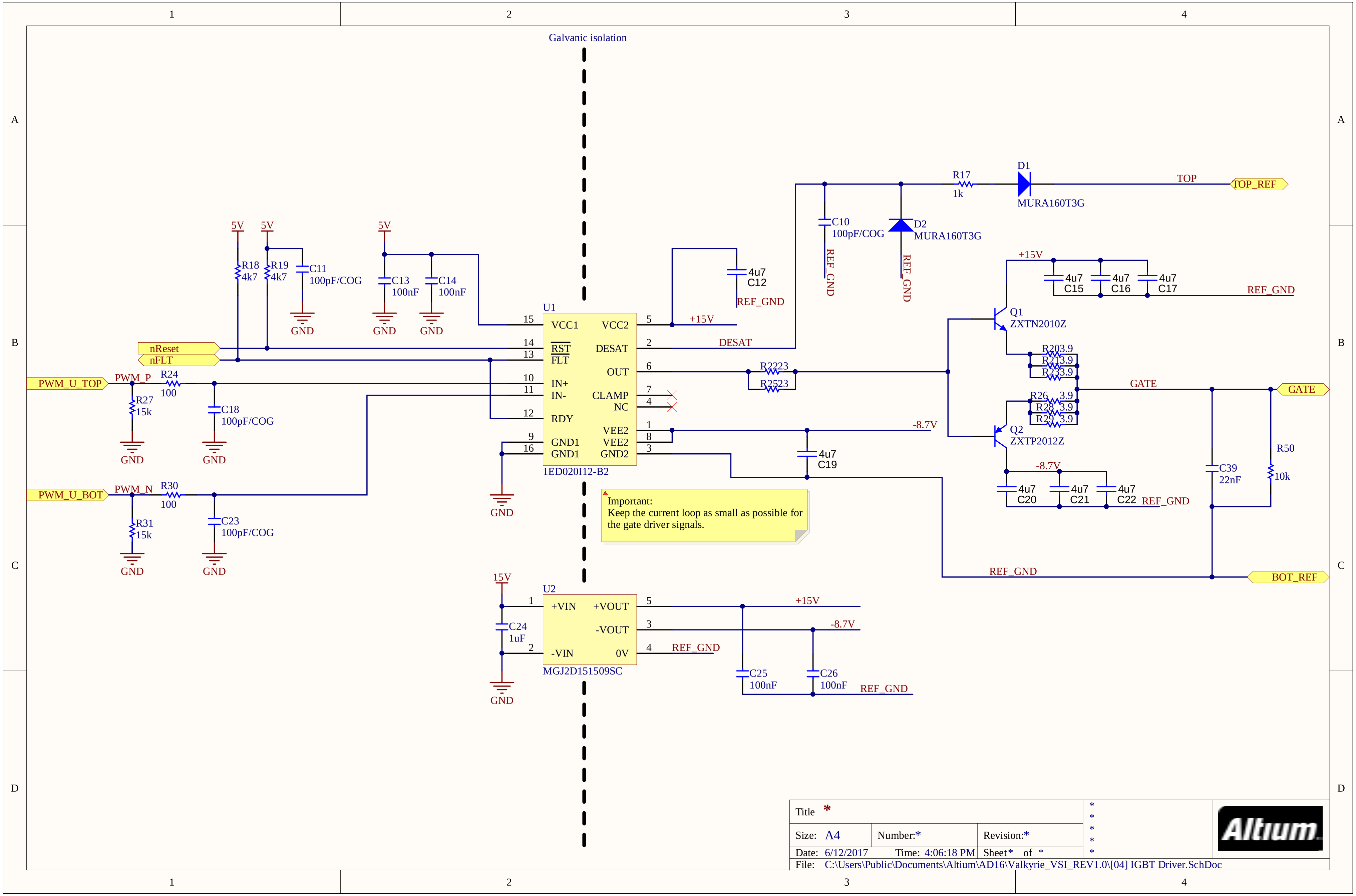
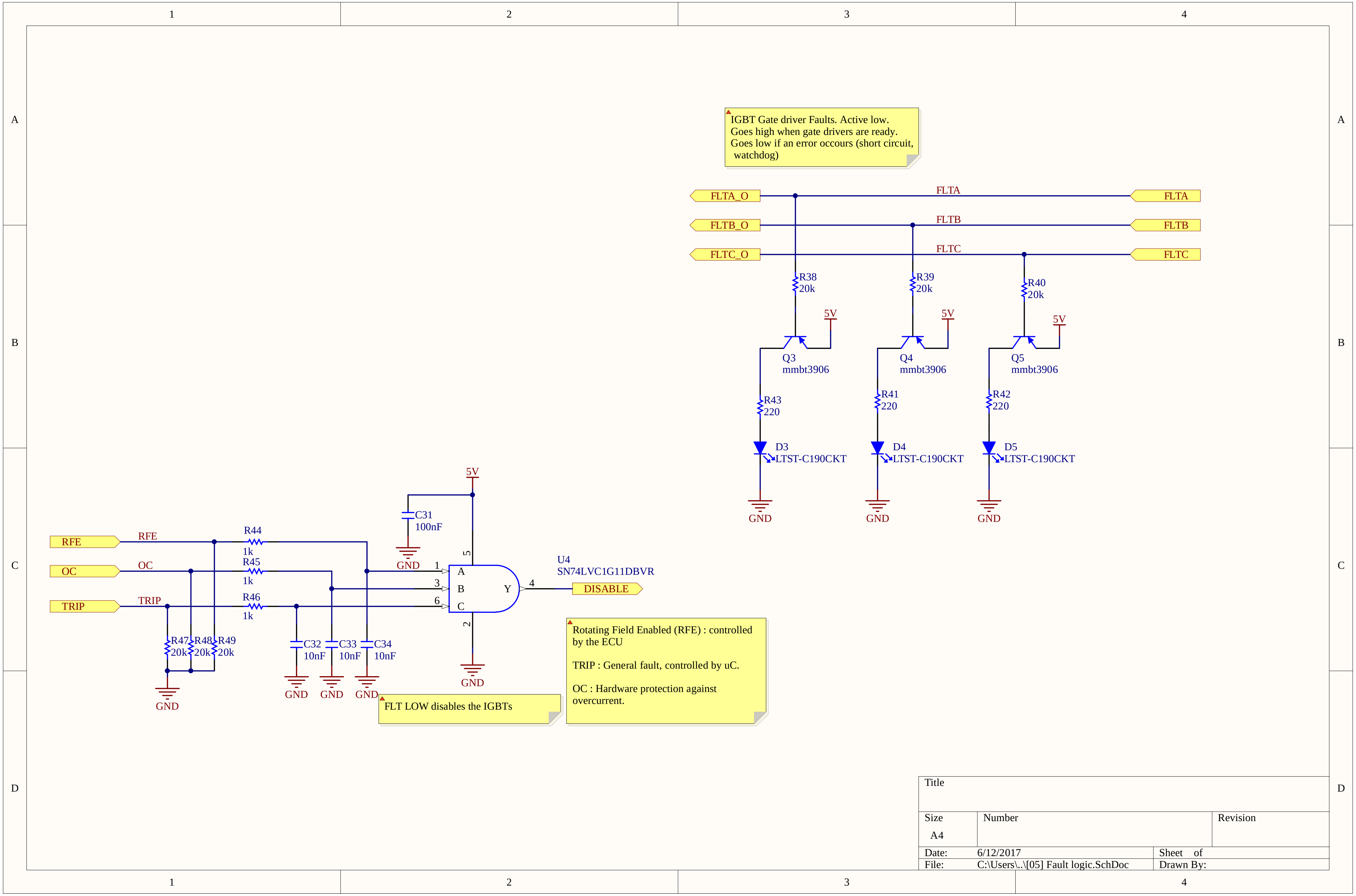

Galvanic isolation
U1
1ED020I12-B2
VCC1
RST
FLT
IN+
IN-
RDY
GND1
GND1
VCC2
DESAT
OUT
CLAMP
NC
VEE2
VEE2
GND2
U2
MGJ2D151509SC
+VIN
-VIN
+VOUT
-VOUT
0V
nReset
nFLT
PWM_U_TOP
PWM_U_BOT
PWM_P
PWM_N
R18 4k7
R19 4k7
C11 100pF/COG
C13 100nF
C14 100nF
R24 100
R27 15k
C18 100pF/COG
R30 100
R31 15k
C23 100pF/COG
C24 1uF
5V
15V
GND
+15V
-8.7V
REF_GND
4u7 C12
DESAT
R2223
R2523
4u7 C19
C25 100nF
C26 100nF
R17 1k
D1 MURA160T3G
D2 MURA160T3G
C10 100pF/COG
TOP
TOP_REF
Q1 ZXTN2010Z
Q2 ZXTP2012Z
4u7 C15
4u7 C16
4u7 C17
R203.9
R213.9
R233.9
R26 3.9
R28 3.9
R29 3.9
4u7 C20
4u7 C21
4u7 C22
GATE
C39 22nF
R50 10k
BOT_REF
Important:
Keep the current loop as small as possible for the gate driver signals.
Title *
Size: A4
Number:*
Revision:*
Date: 6/12/2017
Time: 4:06:18 PM
Sheet * of *
File: C:\Users\Public\Documents\Altium\AD16\Valkyrie_VSI_REV1.0\[04] IGBT Driver.SchDoc


IGBT Gate driver Faults. Active low.
Goes high when gate drivers are ready.
Goes low if an error occours (short circuit, watchdog)
FLTA_O
FLTB_O
FLTC_O
FLTA
FLTB
FLTC
R38 20k
R39 20k
R40 20k
5V
Q3 mmbt3906
Q4 mmbt3906
Q5 mmbt3906
R43 220
R41 220
R42 220
D3 LTST-C190CKT
D4 LTST-C190CKT
D5 LTST-C190CKT
GND
RFE
OC
TRIP
R44 1k
R45 1k
R46 1k
R47 20k
R48 20k
R49 20k
C31 100nF
C32 10nF
C33 10nF
C34 10nF
U4
SN74LVC1G11DBVR
A
B
C
Y
DISABLE
FLT LOW disables the IGBTs
Rotating Field Enabled (RFE) : controlled by the ECU
TRIP : General fault, controlled by uC.
OC : Hardware protection against overcurrent.
Title
Size A4
Number
Revision
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Sheet of
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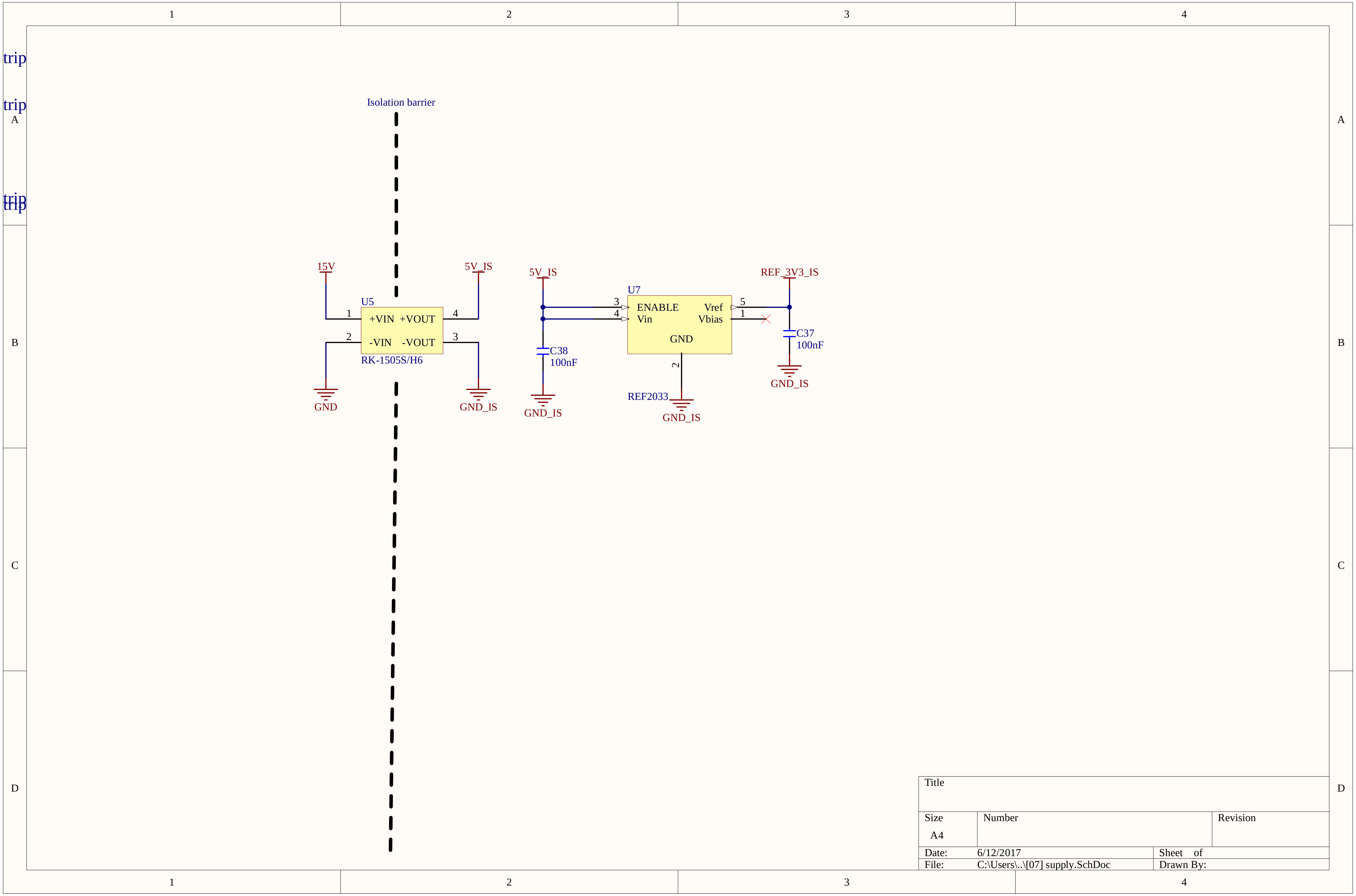
trip
trip
trip
trip
Isolation barrier
15V
5V_IS
U5
+VIN +VOUT
-VIN -VOUT
RK-1505S/H6
GND
GND_IS
5V_IS
C38
100nF
GND_IS
U7
ENABLE
Vin
Vref
Vbias
GND
REF2033
GND_IS
REF_3V3_IS
C37
100nF
GND_IS
Title
Size
A4
Number
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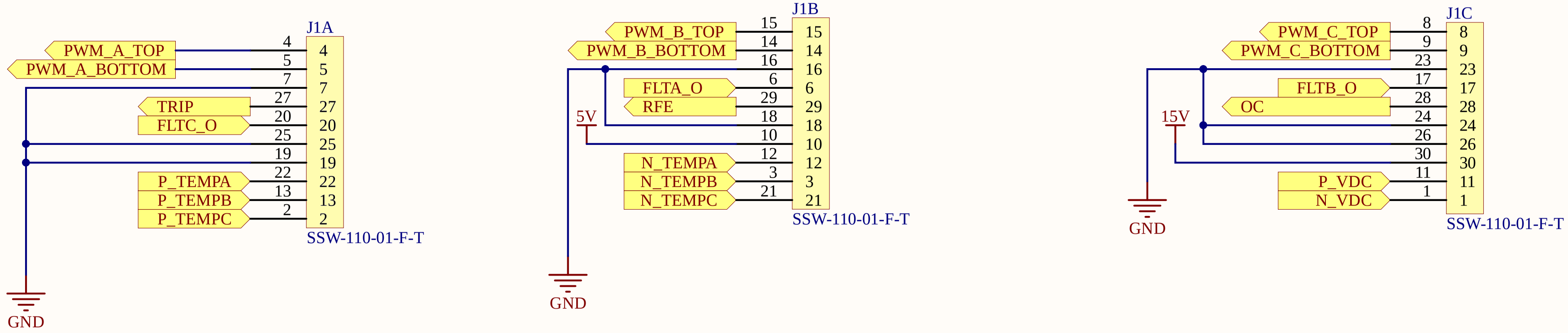

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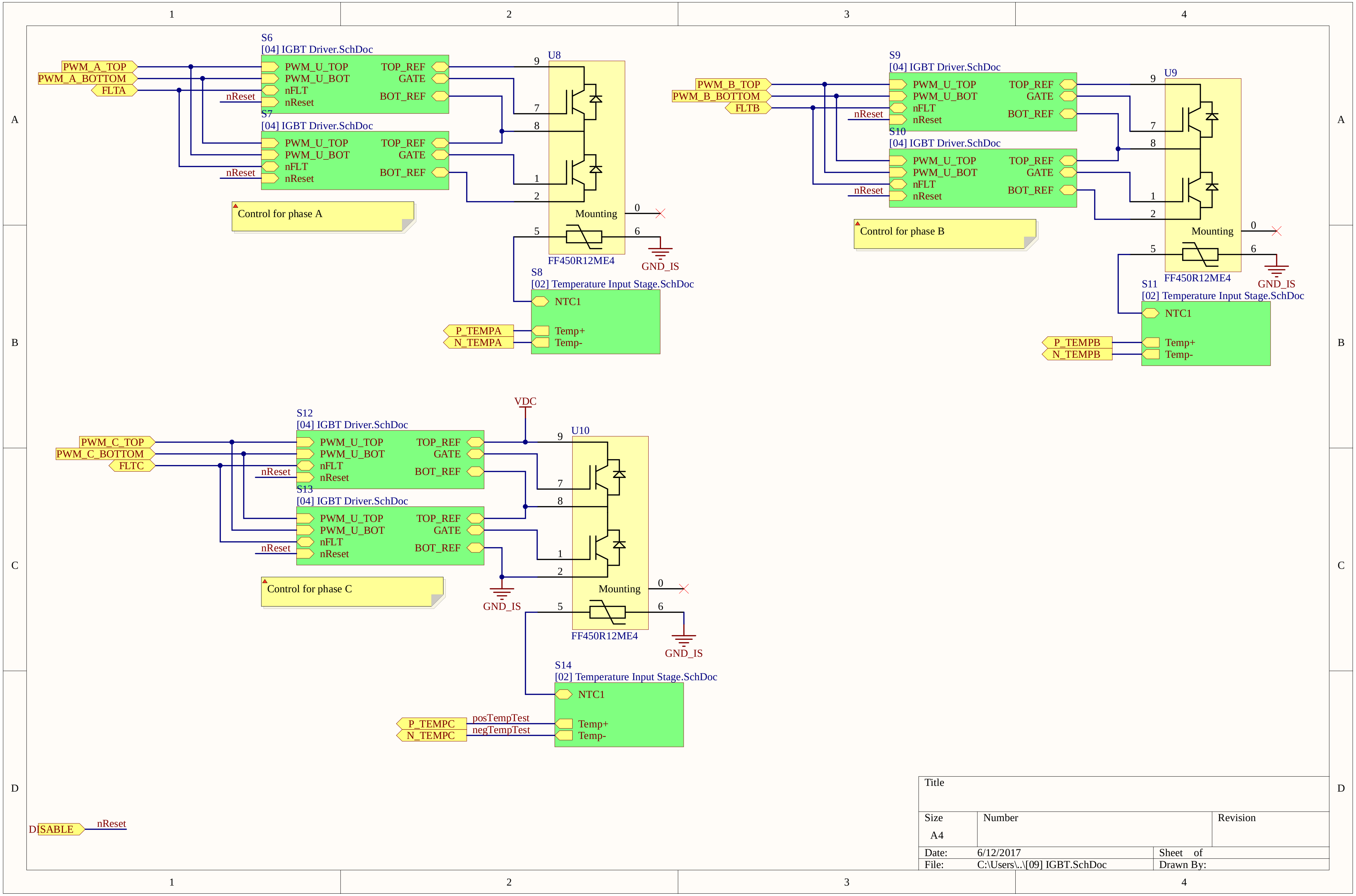

S6
[04] IGBT Driver.SchDoc
PWM_A_TOP
PWM_A_BOTTOM
FLTA
nReset
PWM_U_TOP
PWM_U_BOT
nFLT
TOP_REF
GATE
BOT_REF
S7
[04] IGBT Driver.SchDoc
U8
FF450R12ME4
Mounting
GND_IS
Control for phase A
S8
[02] Temperature Input Stage.SchDoc
NTC1
Temp+
Temp-
P_TEMPA
N_TEMPA
S9
[04] IGBT Driver.SchDoc
PWM_B_TOP
PWM_B_BOTTOM
FLTB
S10
[04] IGBT Driver.SchDoc
U9
Control for phase B
S11
[02] Temperature Input Stage.SchDoc
P_TEMPB
N_TEMPB
VDC
S12
[04] IGBT Driver.SchDoc
PWM_C_TOP
PWM_C_BOTTOM
FLTC
S13
[04] IGBT Driver.SchDoc
U10
Control for phase C
S14
[02] Temperature Input Stage.SchDoc
P_TEMPC
N_TEMPC
posTempTest
negTempTest
DISABLE
Title
Size
A4
Number
Revision
Date: 6/12/2017
Sheet of
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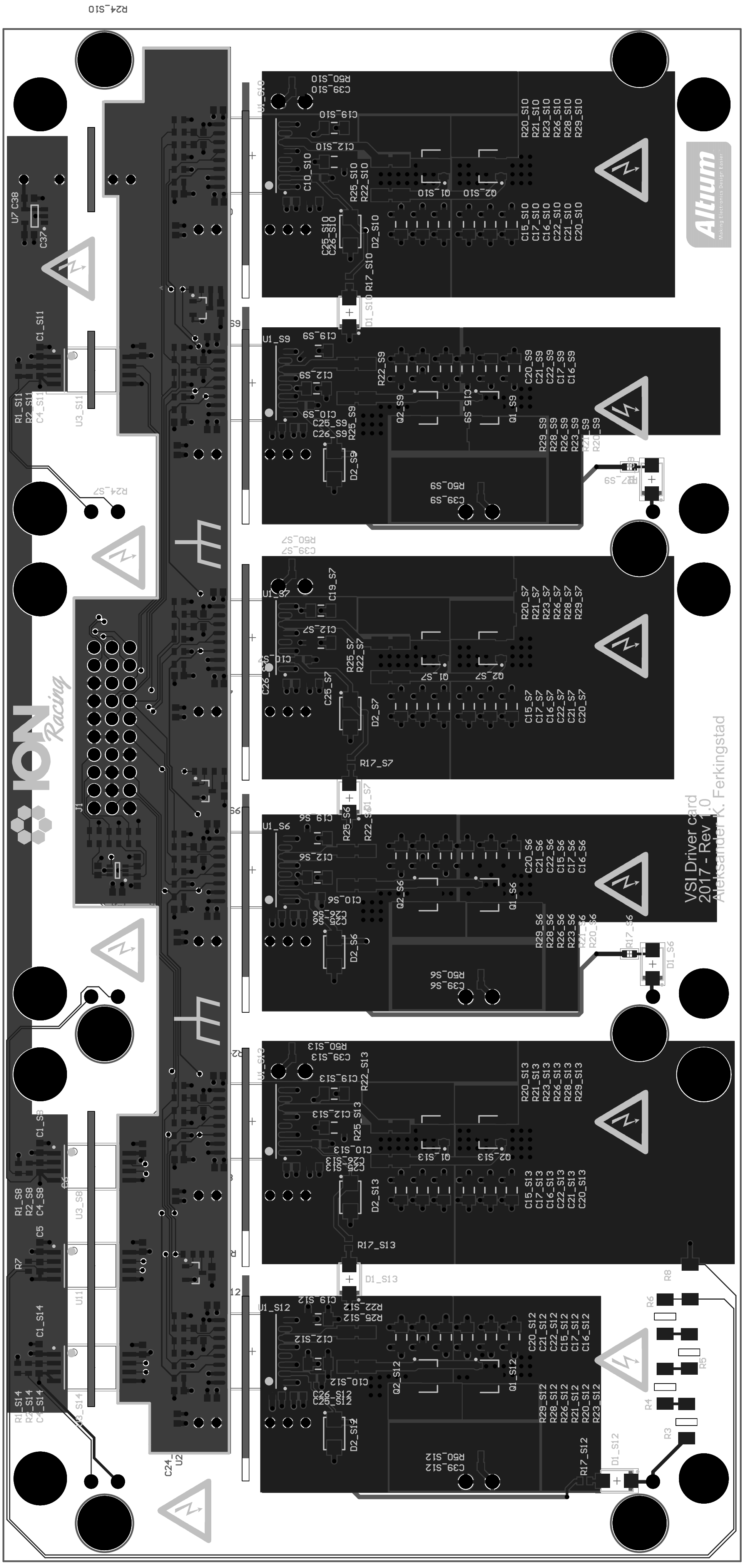
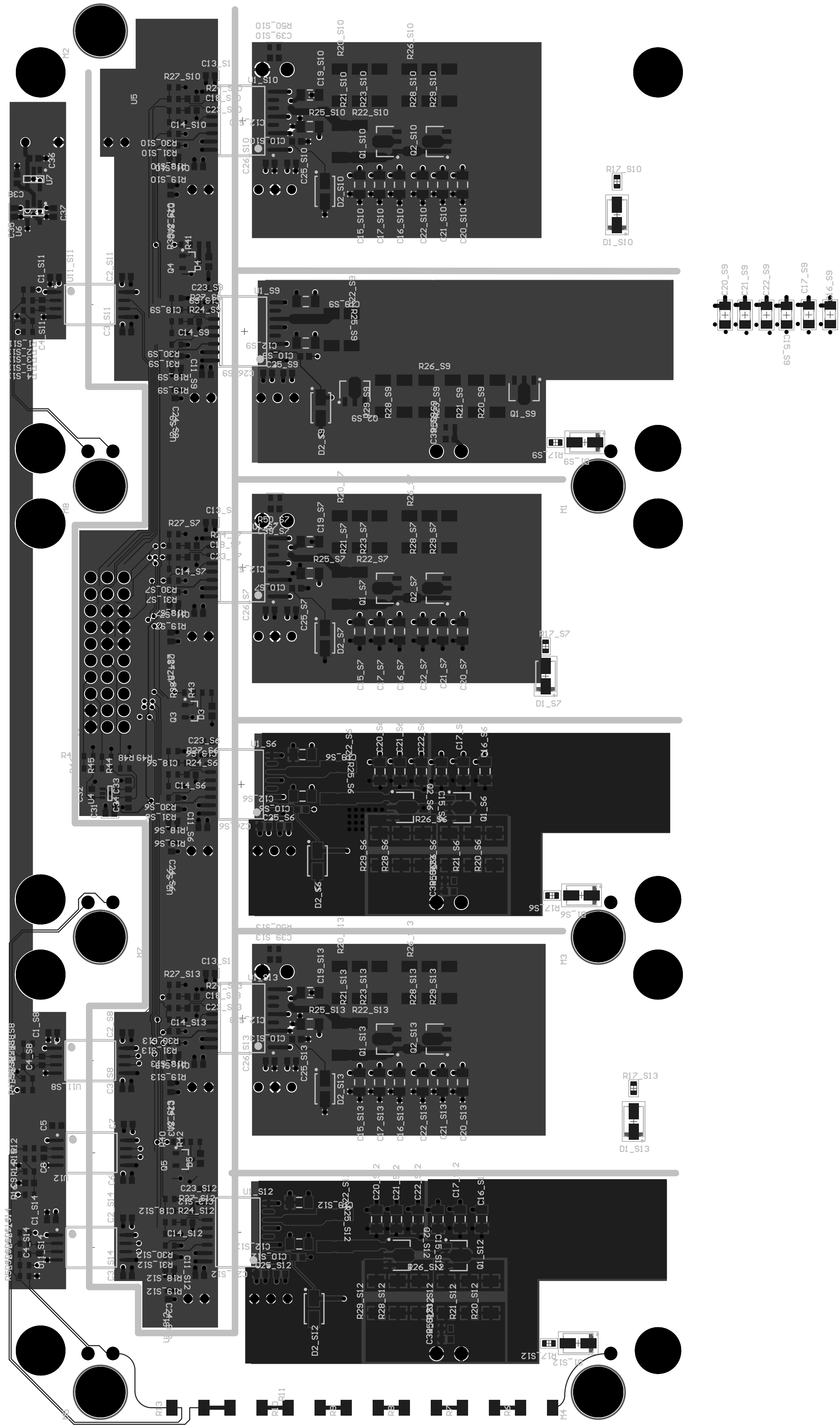

VSI Driver card
2017 - Rev 1.0
Aleksander K. Ferkingstad



Appendix B

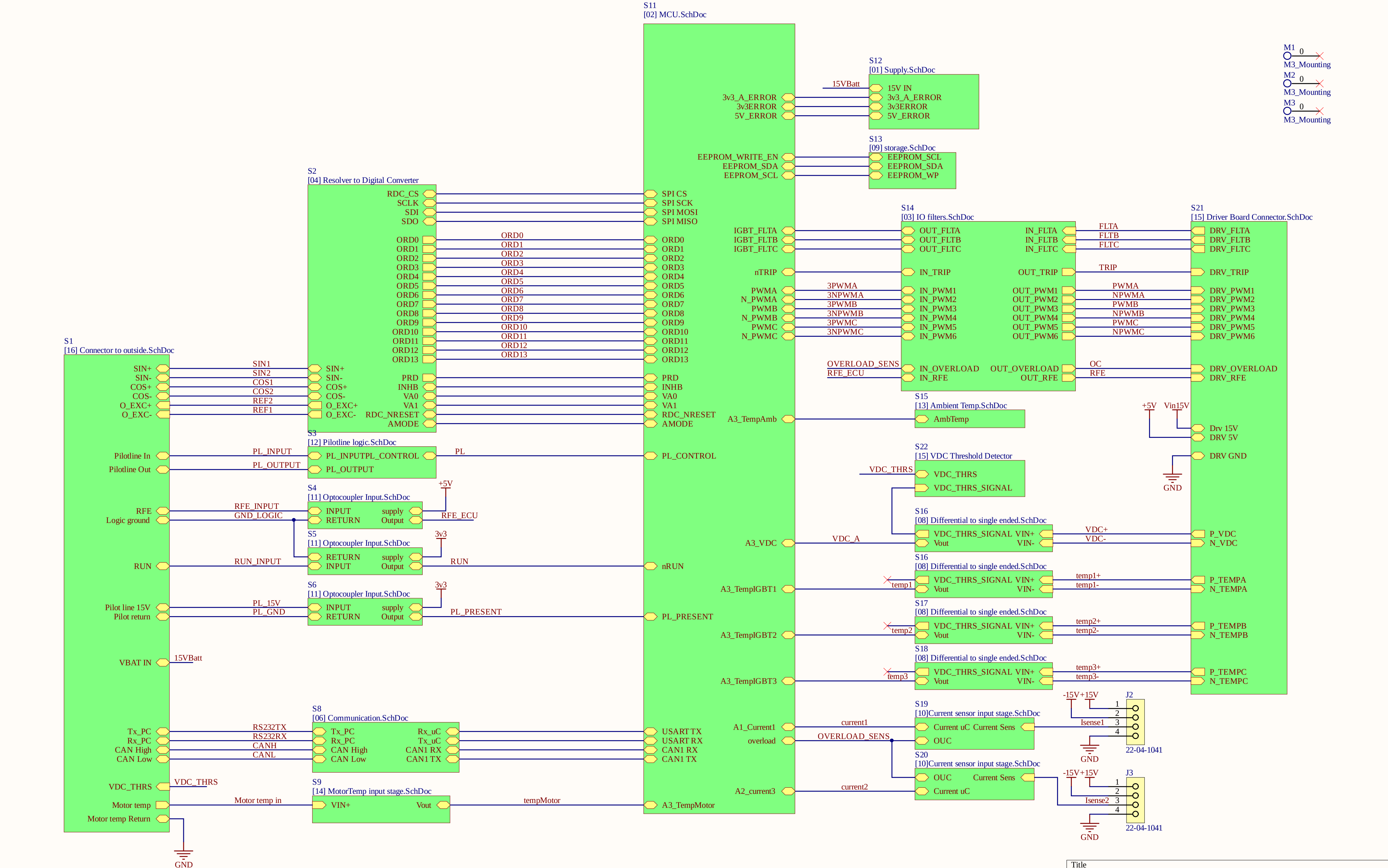
Bill of materials driver card

Comment	Description	Designator	MPN	Quantity
100nF	KEMET 100nF Multilayer Ceramic Capacitor MLCC 50 V 10% X7R Dielectric 0603 Max. Op. Temp. +125C	C1_S8, C1_S11, C1_S14, C2_S8, C2_S11, C2_S14, C4_S8, C4_S11, C4_S14, C5, C7, C13_S6, C13_S7, C13_S9, C13_S10, C13_S12, C13_S13, C14_S6, C14_S7, C14_S9, C14_S10, C14_S12, C14_S13, C25_S6, C25_S7, C25_S9, C25_S10, C25_S12, C25_S13, C26_S6, C26_S7, C26_S9, C26_S10, C26_S12, C26_S13, C31, C37, C38	C0603C104K5RACTU	38
10nF	Murata 10nF Multilayer Ceramic Capacitor MLCC 25 V dc ±10% B*1	C6, C32, C33, C34	GRM188R71E104KA01D	4
100pF/COG	KEMET 100pF Multilayer Ceramic Capacitor MLCC 50 V dc 5% C0G Dielectric 0603 Max. Op. Temp. +125C	C10_S6, C10_S7, C10_S9, C10_S10, C10_S12, C10_S13, C11_S6, C11_S7, C11_S9, C11_S10, C11_S12, C11_S13, C18_S6, C18_S7, C18_S9, C18_S10, C18_S12, C18_S13, C23_S6, C23_S7, C23_S9, C23_S10, C23_S12, C23_S13	C0603C101J5GACTU	24
4u7	KEMET 4.7F Multilayer Ceramic Capacitor MLCC 25 V dc 10% X7R Dielectric 1206 Max. Op. Temp. +125C	C12_S6, C12_S7, C12_S9, C12_S10, C12_S12, C12_S13, C15_S6, C15_S7, C15_S9, C15_S10, C15_S12, C15_S13, C16_S6, C16_S7, C16_S9, C16_S10, C16_S12, C16_S13, C17_S6, C17_S7, C17_S9, C17_S10, C17_S12, C17_S13, C19_S6, C19_S7, C19_S9, C19_S10, C19_S12, C19_S13, C20_S6, C20_S7, C20_S9, C20_S10, C20_S12, C20_S13, C21_S6, C21_S7, C21_S9, C21_S10, C21_S12, C21_S13, C22_S6, C22_S7, C22_S9, C22_S10, C22_S12, C22_S13	C1206C475K3RACTU	48
1uF	Multilayer Ceramic Capacitors MLCC - SMD/SMT 0603 1uF 50volts X5R 10%		GRM188R61H105KAALD	6
22nF	Vishay 22nF Multilayer Ceramic Capacitor MLCC 50 V 10% X7R Dielectric 0603 Max. Op. Temp. +105C	C39_S6, C39_S7, C39_S9, C39_S10, C39_S12, C39_S13	VJ0603Y223KNAAO	6
MURA160T3G	ON Semi MURA160T3G SMT Switching Diode, 600V 2A, 75ns, 2-Pin DO-214AC	D1_S6, D1_S7, D1_S9, D1_S10, D1_S12, D1_S13, D2_S6, D2_S7, D2_S9, D2_S10, D2_S12, D2_S13	MURA160T3G	12
LTST-C190CKT	Lite-On LTST-C190CKT Red LED, 638 nm 1608 (0603), Re	D3, D4, D5	LTST-C190CKT	3
SSW-110-01-F-T	Board board connector - sample from samtec	J1		1
M3_Mounting	RS Pro Nylon Hex Standoff Female/Female, 20mm, M3 x M3	M1, M2, M3, M4, M5, M7, M8	325-700	7
ZXTN2010Z	Diodes Inc ZXTN2010ZTA NPN Transistor, 5 A, 60 V, 3-Pin SOT-89	Q1_S6, Q1_S7, Q1_S9, Q1_S10, Q1_S12, Q1_S13	ZXTN2010ZTA	6
ZXTP2012Z	Diodes Inc ZXTP2012ZTA PNP Transistor, 4.3 A, 60 V, 3-Pin SOT-89	Q2_S6, Q2_S7, Q2_S9, Q2_S10, Q2_S12, Q2_S13	ZXTP2012ZTA	6
mmbt3906	Fairchild MMBT3906T PNP Transistor, 0.2 A, 40 V, 3-Pin SOT-523F	Q3, Q4, Q5	MMBT3906T	3
5k76		R1_S8, R1_S11, R1_S14		3
39		R2_S8, R2_S11, R2_S14, R7		4
510k		R3, R4, R5, R6		4
10K		R8		1
1k		R17_S6, R17_S7, R17_S9, R17_S10, R17_S12, R17_S13, R44, R45, R46		9
4k7		R18_S6, R18_S7, R18_S9, R18_S10, R18_S12, R18_S13, R19_S6, R19_S7, R19_S9, R19_S10, R19_S12, R19_S13		12
3.9		R20_S6, R20_S7, R20_S9, R20_S10, R20_S12, R20_S13, R21_S6, R21_S7, R21_S9, R21_S10, R21_S12, R21_S13, R23_S6, R23_S7, R23_S9, R23_S10, R23_S12, R23_S13, R26_S6, R26_S7, R26_S9, R26_S10, R26_S12, R26_S13, R28_S6, R28_S7, R28_S9, R28_S10, R28_S12, R28_S13, R29_S6, R29_S7, R29_S9, R29_S10, R29_S12, R29_S13		36
23		R22_S6, R22_S7, R22_S9, R22_S10, R22_S12, R22_S13, R25_S6, R25_S7, R25_S9, R25_S10, R25_S12, R25_S13		12
100		R24_S6, R24_S7, R24_S9, R24_S10, R24_S12, R24_S13, R30_S6, R30_S7, R30_S9, R30_S10, R30_S12, R30_S13		12
15k		R27_S6, R27_S7, R27_S9, R27_S10, R27_S12, R27_S13, R31_S6, R31_S7, R31_S9, R31_S10, R31_S12, R31_S13		12
20k		R38, R39, R40, R47, R48, R49		6
220		R41, R42, R43		3
10k		R50_S6, R50_S7, R50_S9, R50_S10, R50_S12, R50_S13		6
1ED020I12-B2	Infineon 1ED020I12-B2 Half Bridge MOSFET Power Driver 2.4A, 4.5 ? 5.5 V, 16-Pin DSO-16-15	U1_S6, U1_S7, U1_S9, U1_S10, U1_S12, U1_S13	1ED020I12-B2	6
MGJ2D151509SC	Murata Power Solutions Through Hole Isolated DC-DC Converter, Vin 13.5 ? 16.5 V dc, I/O isolation 5200V dc	U2_S6, U2_S7, U2_S9, U2_S10, U2_S12, U2_S13	MGJ2D151509SC	6
ACPL-C87AT/BT	Broadcom ACPL-C87AT-000E, Isolation Amplifier, 3 ? 5.	U3_S8, U3_S11, U3_S14, U11	ACPL-C87AT-000E	4
SN74LVC1G11DBVR	Texas Instruments SN74LVC1G11DBVR, 3-Input AND Lo	U4	SN74LVC1G11DBVR	1
RK-1505S/H6	Recom Through Hole 1W Isolated DC-DC Converter, I/O isolation 4kV, Vout 5V dc	U5	RK-1505S/H6	1
REF2033		U7	REF2033AIDDCT	1
FF450R12ME4	Infineon FF450R12ME4_B11, ECONOD Series IGBT Module, 675 A max, 1200 V, PCB Mount	U8, U9, U10	FF450R12ME4_B11	3

Appendix C

Full schematics for logic card

[00] Valkyrie Control Card Top Sheet



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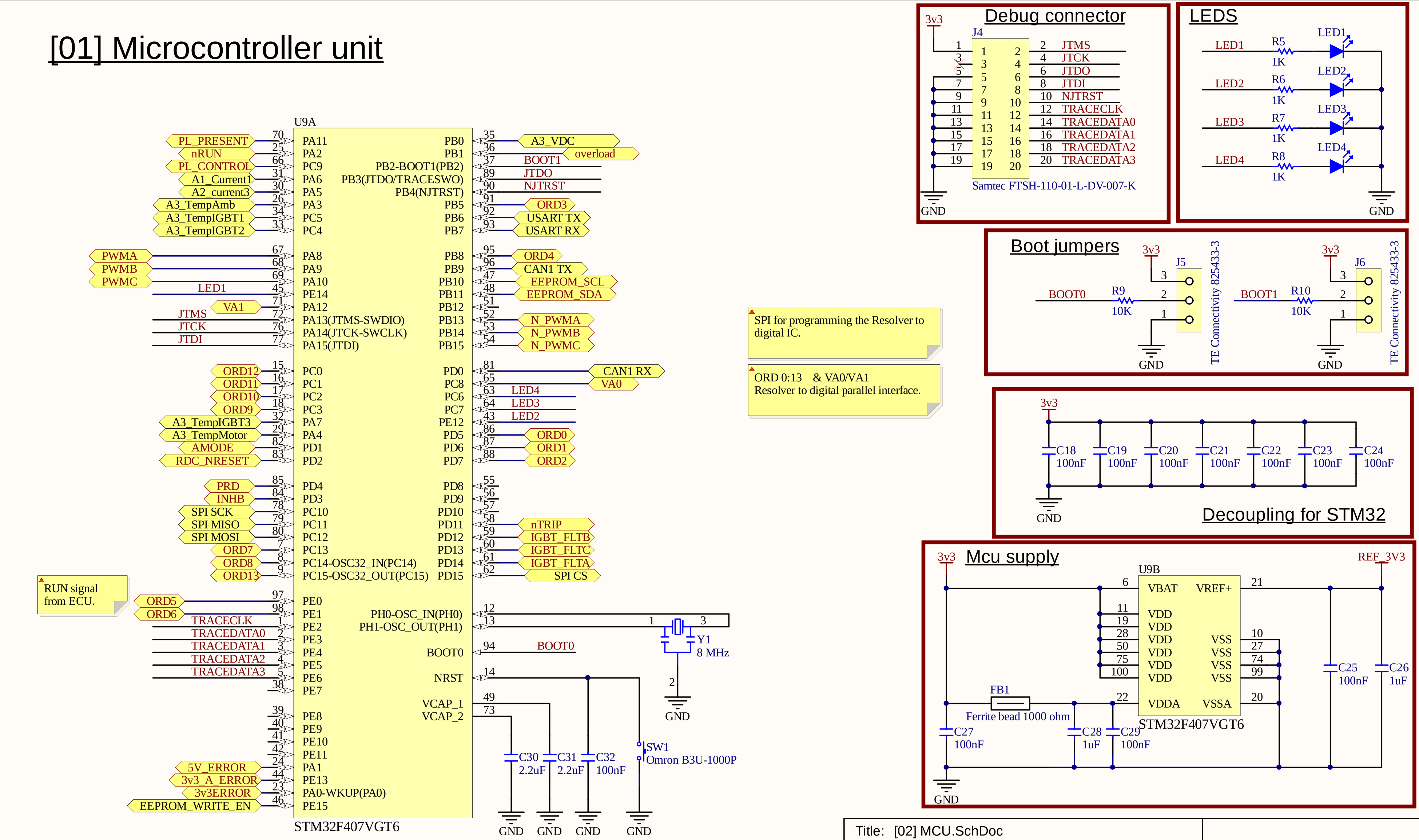
[01] Microcontroller unit



Title: [02] MCU.SchDoc		
Project name: Valkyrie_VSI_REV1.0.PrjPcb		
Date: 6/12/2017	Sheet: 1 of 10	Revision: 1.00
Size: A4	Drawn by: Aleksander K. Ferkingstad	

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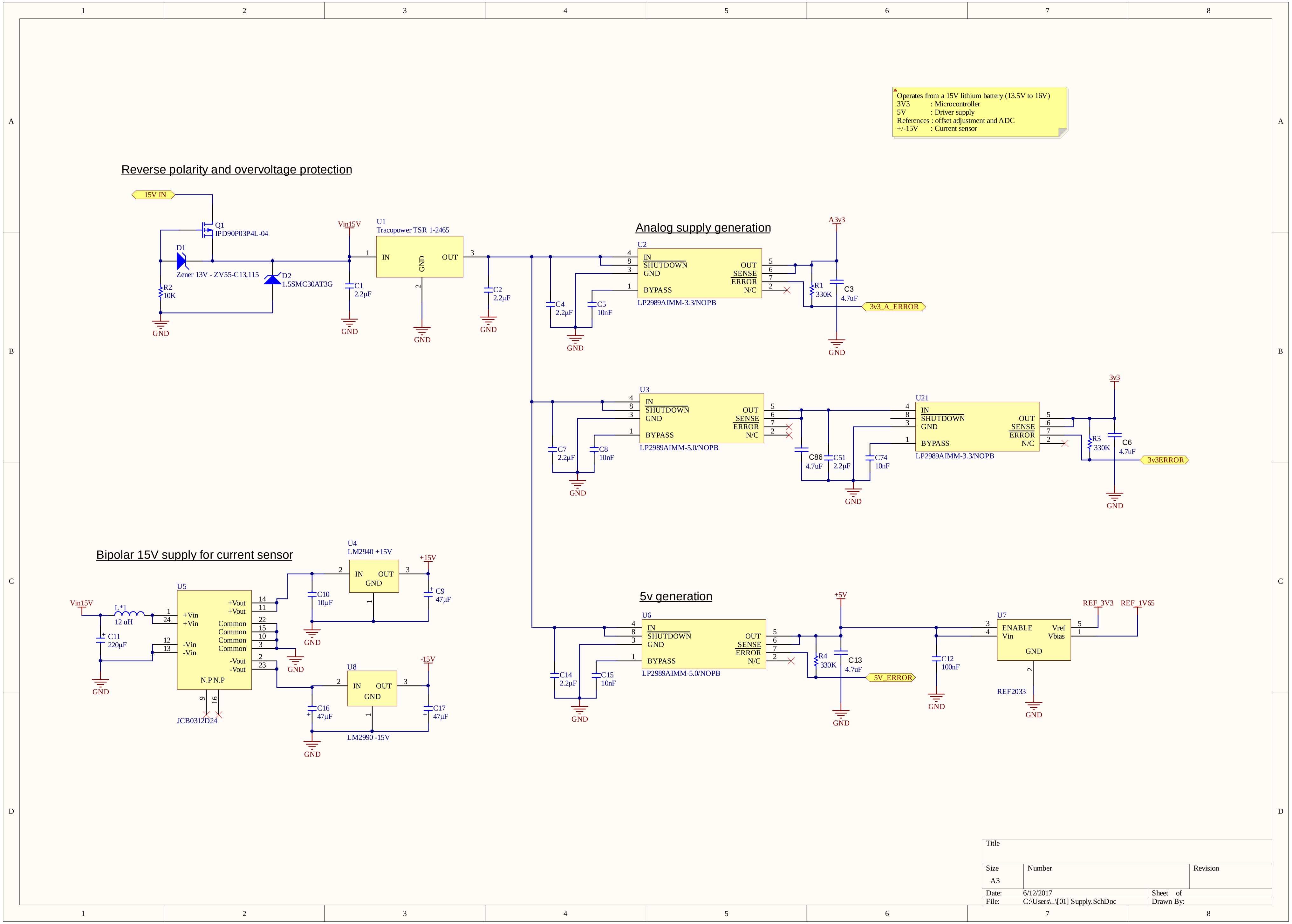
Operates from a 15V lithium battery (13.5V to 16V)
3V3 : Microcontroller
5V : Driver supply
References : offset adjustment and ADC
+/-15V : Current sensor
Reverse polarity and overvoltage protection
15V IN
Q1 IPD90P03P4L-04
D1 Zener 13V - ZV55-C13,115
D2 1.5SMC30AT3G
R2 10K
Vin15V
C1 2.2µF
U1 Tracopower TSR 1-2465
IN GND OUT
C2 2.2µF
Analog supply generation
U2 LP2989AIMM-3.3/NOPB
IN SHUTDOWN GND BYPASS OUT SENSE ERROR N/C
C4 2.2µF
C5 10nF
A3v3
R1 330K
C3 4.7uF
3v3_A_ERROR
U3 LP2989AIMM-5.0/NOPB
C7 2.2µF
C8 10nF
C86 4.7uF
C51 2.2µF
C74 10nF
U21 LP2989AIMM-3.3/NOPB
3v3
R3 330K
C6 4.7uF
3v3ERROR
5v generation
U6 LP2989AIMM-5.0/NOPB
C14 2.2µF
C15 10nF
+5V
R4 330K
C13 4.7uF
5V_ERROR
C12 100nF
U7 REF2033
ENABLE Vin Vref Vbias GND
REF_3V3 REF_1V65
Bipolar 15V supply for current sensor
Vin15V
L*1 12 uH
C11 220µF
U5 JCB0312D24
+Vin +Vin -Vin -Vin +Vout +Vout Common Common Common Common -Vout -Vout N.P N.P
U4 LM2940 +15V
C10 10µF
+15V
C9 47µF
U8 LM2990 -15V
C16 47µF
-15V
C17 47µF
GND
Title
Size A3
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Revision
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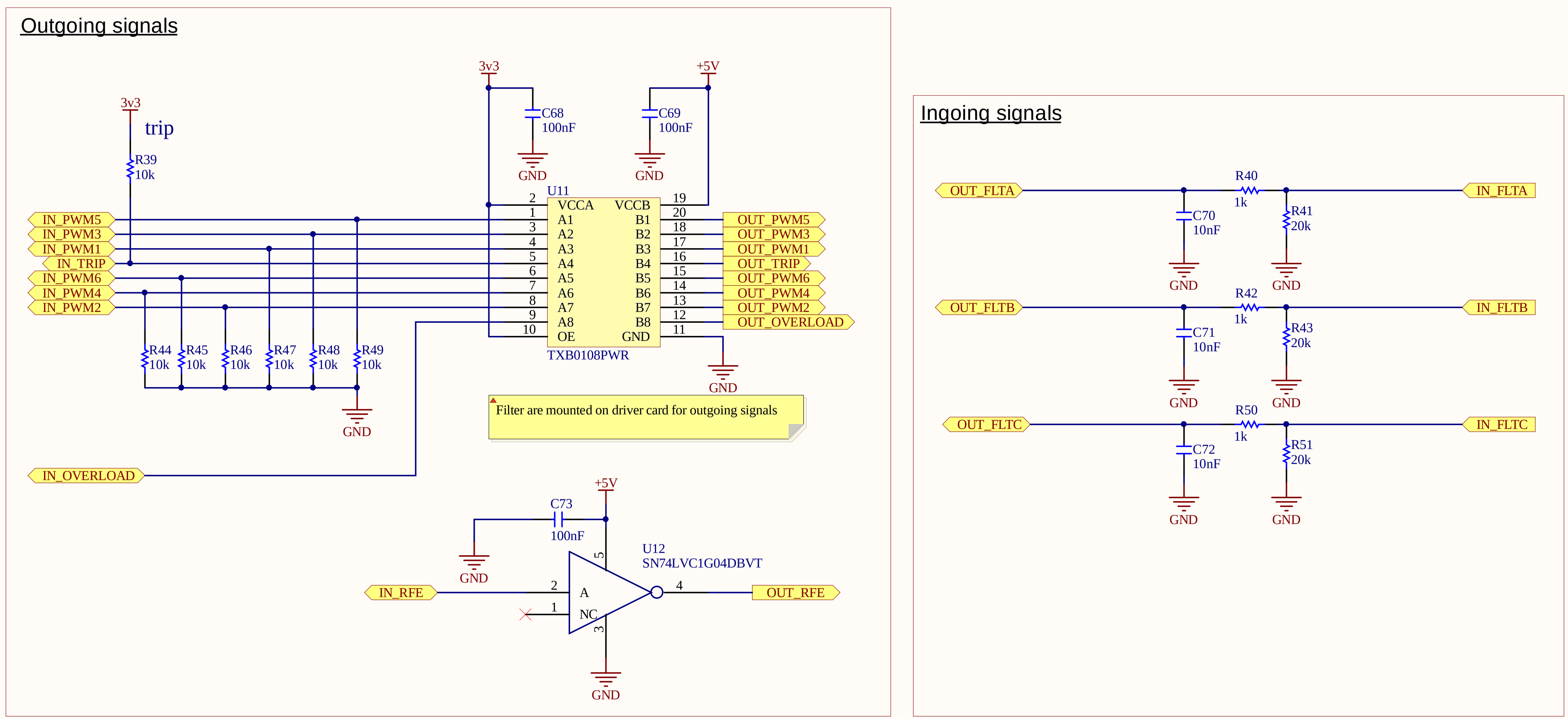
Sheet of
Drawn By:



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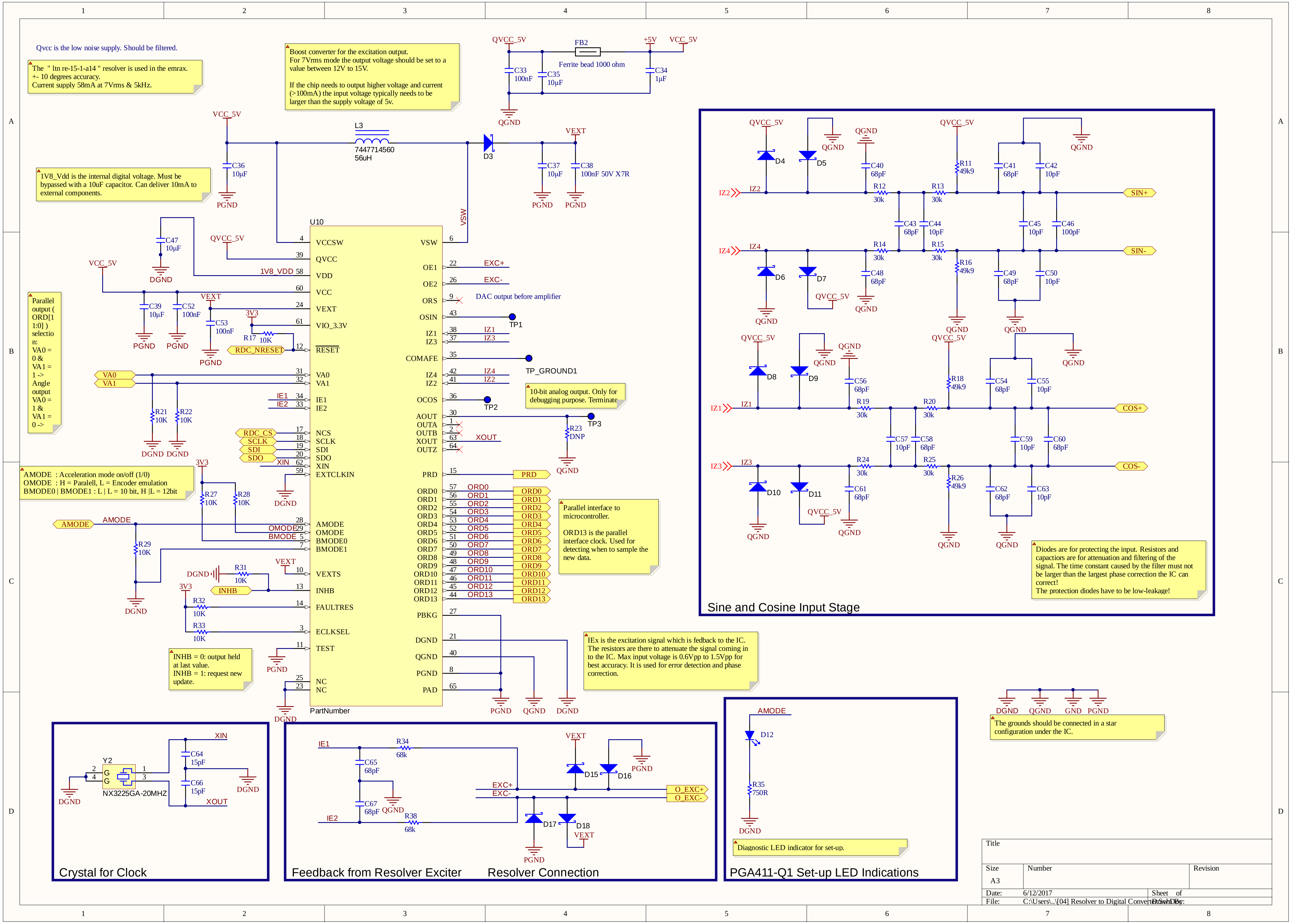
Qvcc is the low noise supply. Should be filtered.
The " ltn re-15-1-a14 " resolver is used in the emrax. +- 10 degrees accuracy. Current supply 58mA at 7Vrms & 5kHz.
Boost converter for the excitation output. For 7Vrms mode the output voltage should be set to a value between 12V to 15V. If the chip needs to output higher voltage and current (>100mA) the input voltage typically needs to be larger than the supply voltage of 5v.
1V8_Vdd is the internal digital voltage. Must be bypassed with a 10uF capacitor. Can deliver 10mA to external components.
Parallel output (ORD[11:0]) selection: VA0 = 0 & VA1 = 1 -> Angle output VA0 = 1 & VA1 = 0 ->
AMODE : Acceleration mode on/off (1/0)
OMODE : H = Paralell, L = Encoder emulation
BMODE0 | BMODE1 : L | L = 10 bit, H |L = 12bit
INHB = 0: output held at last value. INHB = 1: request new update.
DAC output before amplifier
10-bit analog output. Only for debugging purpose. Terminate
Parallel interface to microcontroller. ORD13 is the parallel interface clock. Used for detecting when to sample the new data.
IEx is the excitation signal which is fedback to the IC. The resistors are there to attenuate the signal coming in to the IC. Max input voltage is 0.6Vpp to 1.5Vpp for best accuracy. It is used for error detection and phase correction.
Diodes are for protecting the input. Resistors and capactiors are for attenuation and filtering of the signal. The time constant caused by the filter must not be larger than the largest phase correction the IC can correct! The protection diodes have to be low-leakage!
The grounds should be connected in a star configuration under the IC.
Diagnostic LED indicator for set-up.
Sine and Cosine Input Stage
Crystal for Clock
Feedback from Resolver Exciter
Resolver Connection
PGA411-Q1 Set-up LED Indications
U10
FB2 Ferrite bead 1000 ohm
L3 7447714560 56uH
NX3225GA-20MHZ
Title
Size A3
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Revision
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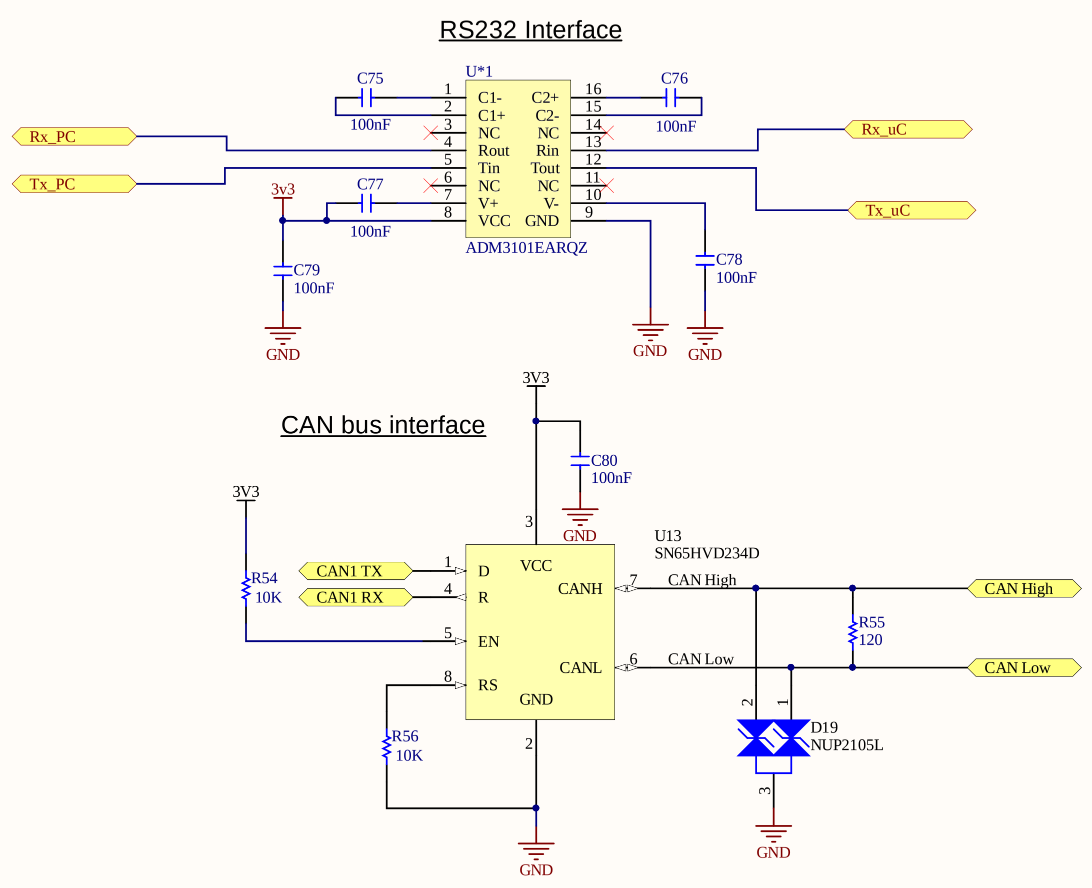
[06] Communication



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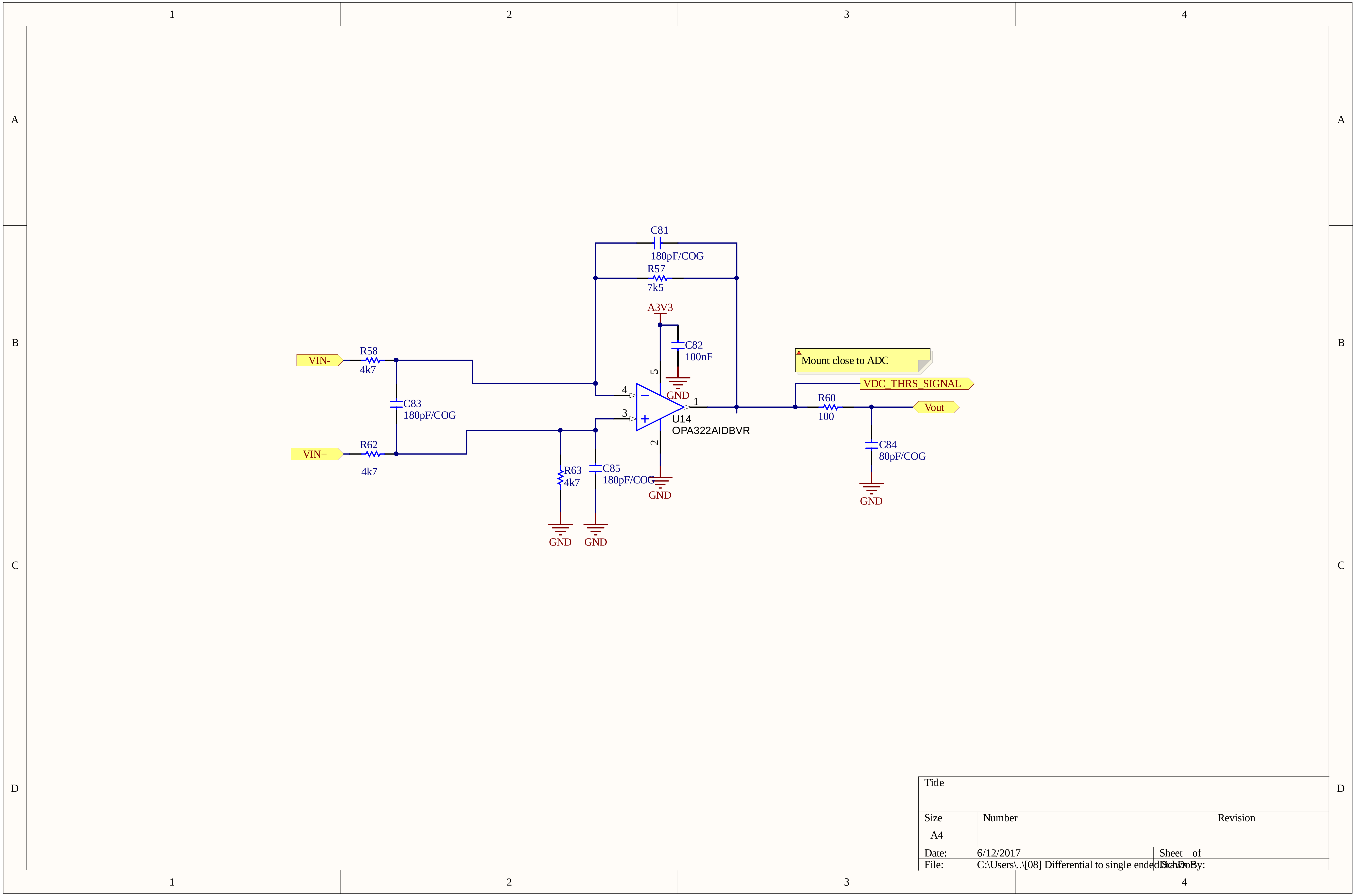
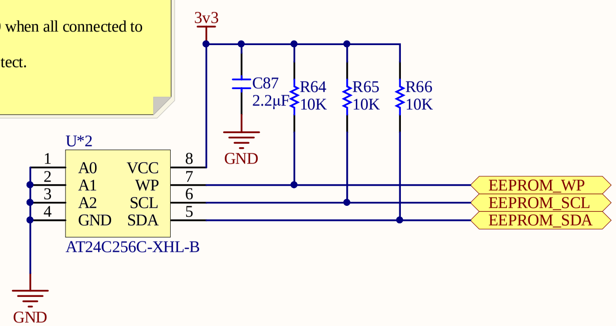

C81
180pF/COG
R57
7k5
A3V3
C82
100nF
GND
Mount close to ADC
VDC_THRS_SIGNAL
VIN-
R58
4k7
C83
180pF/COG
VIN+
R62
4k7
4
3
5
1
2
U14
OPA322AIDBVR
R60
100
Vout
C84
80pF/COG
GND
R63
4k7
C85
180pF/COG
GND
GND
GND
Title
Size
A4
Number
Revision
Date: 6/12/2017
Sheet of
File: C:\Users\..\[08] Differential to single ended.SchDoc
Drawn By:

I2C Serial EEPROM

A0,A1,A2 Device Addresses. Adress 0 when all connected to GND
Pull WP to ground to disable write protect.



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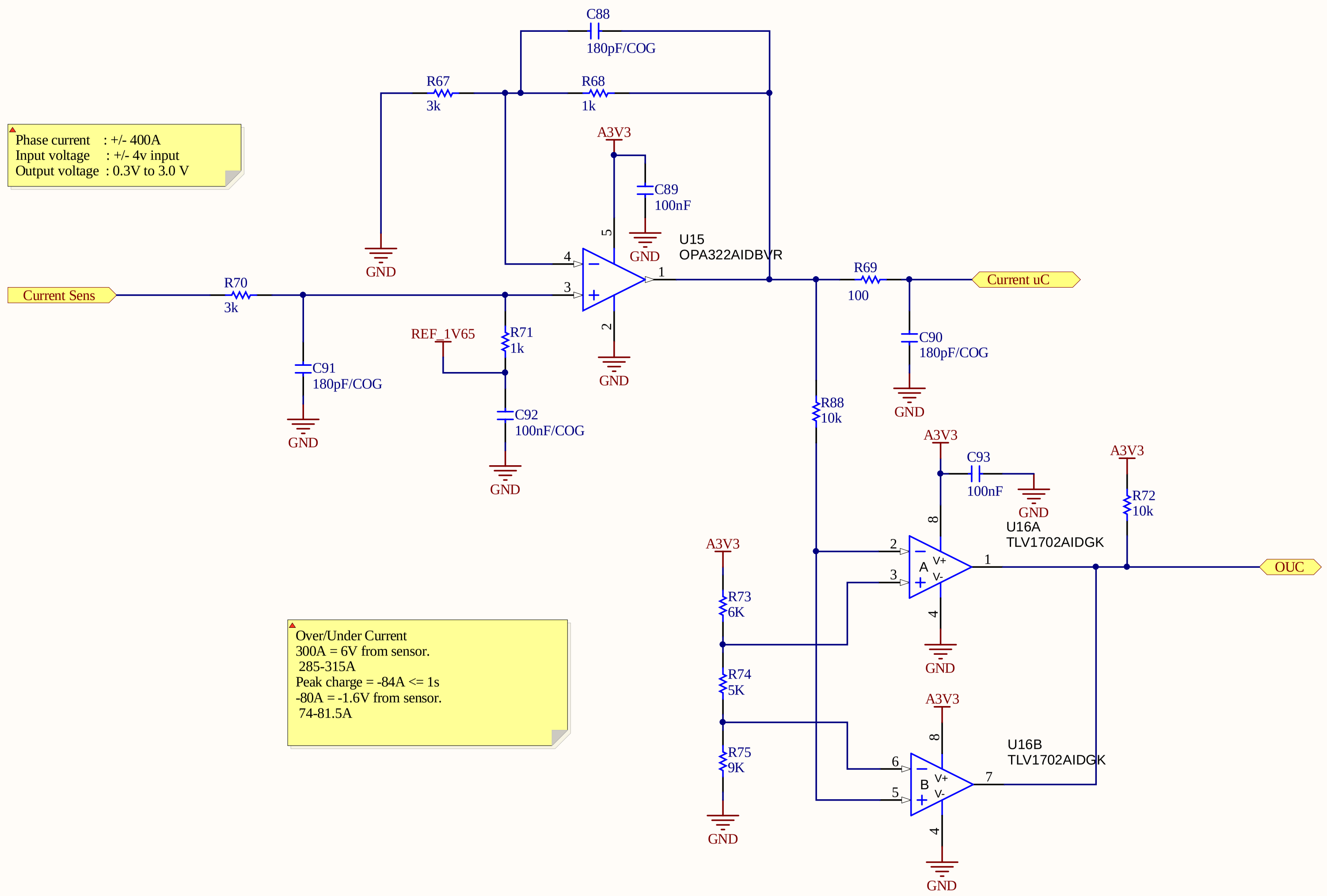

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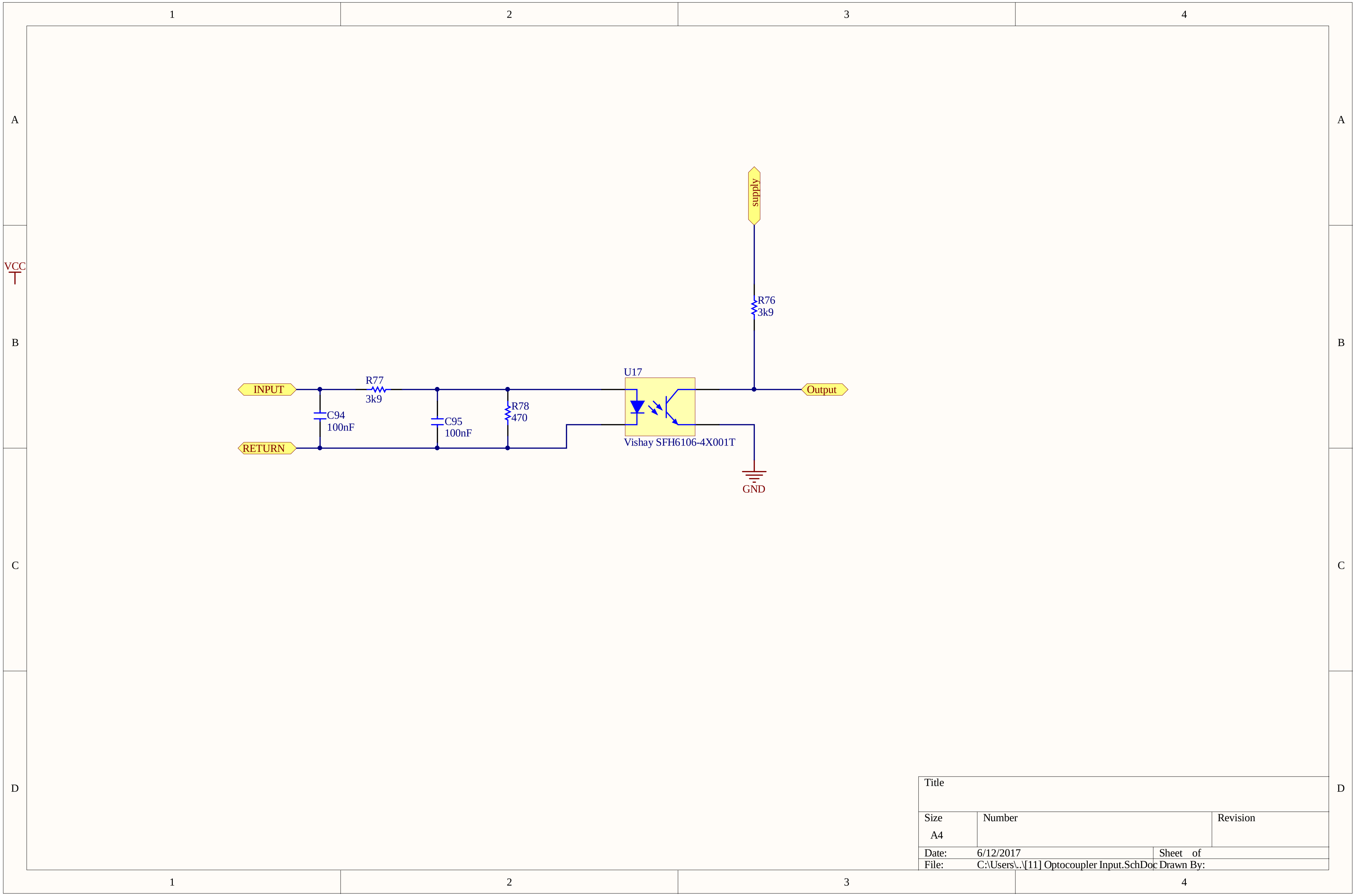

supply
R76
3k9
INPUT
R77
3k9
U17
Output
C94
100nF
C95
100nF
R78
470
RETURN
Vishay SFH6106-4X001T
GND
VCC
Title
Size
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Number
Revision
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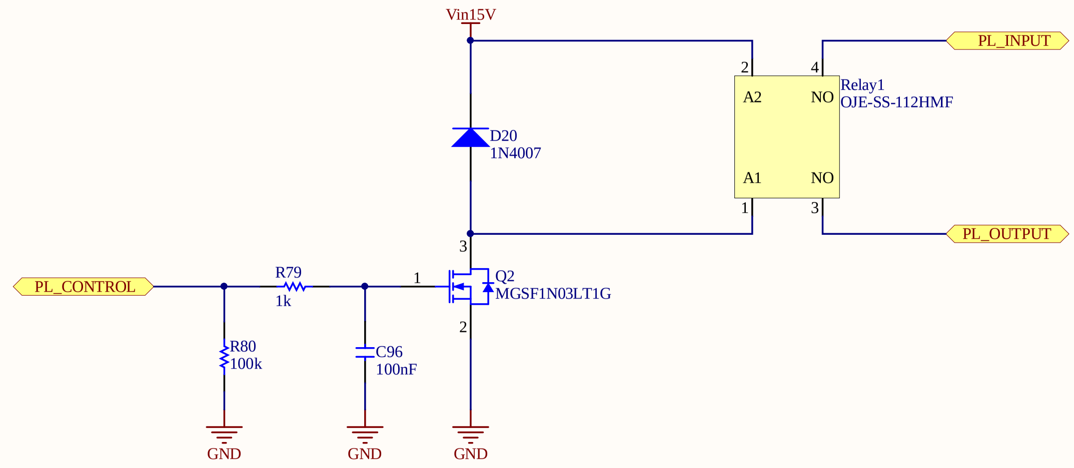

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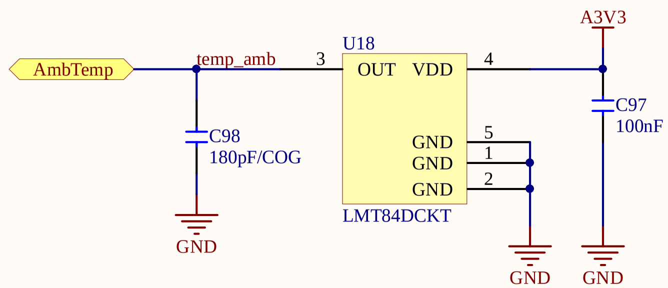

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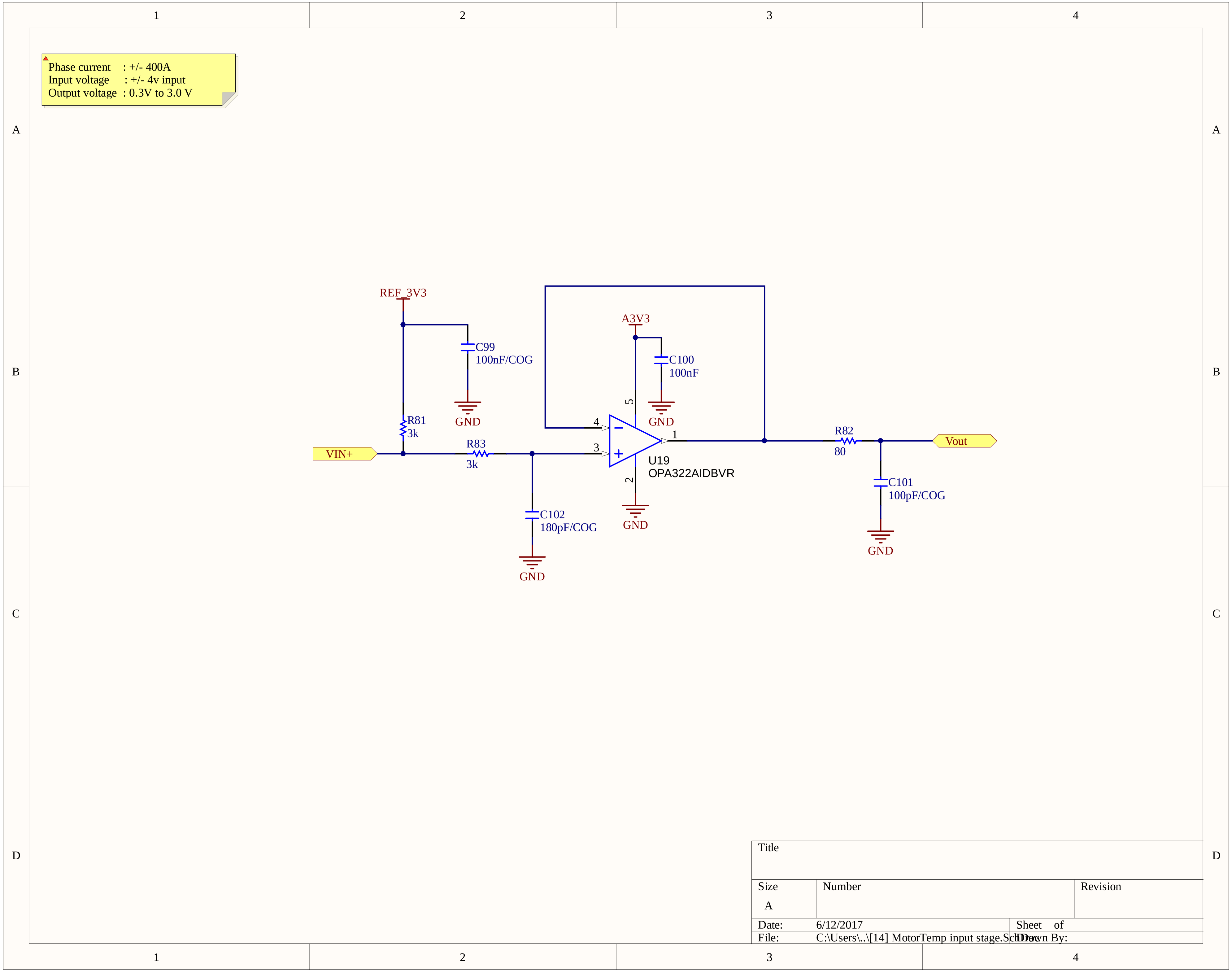

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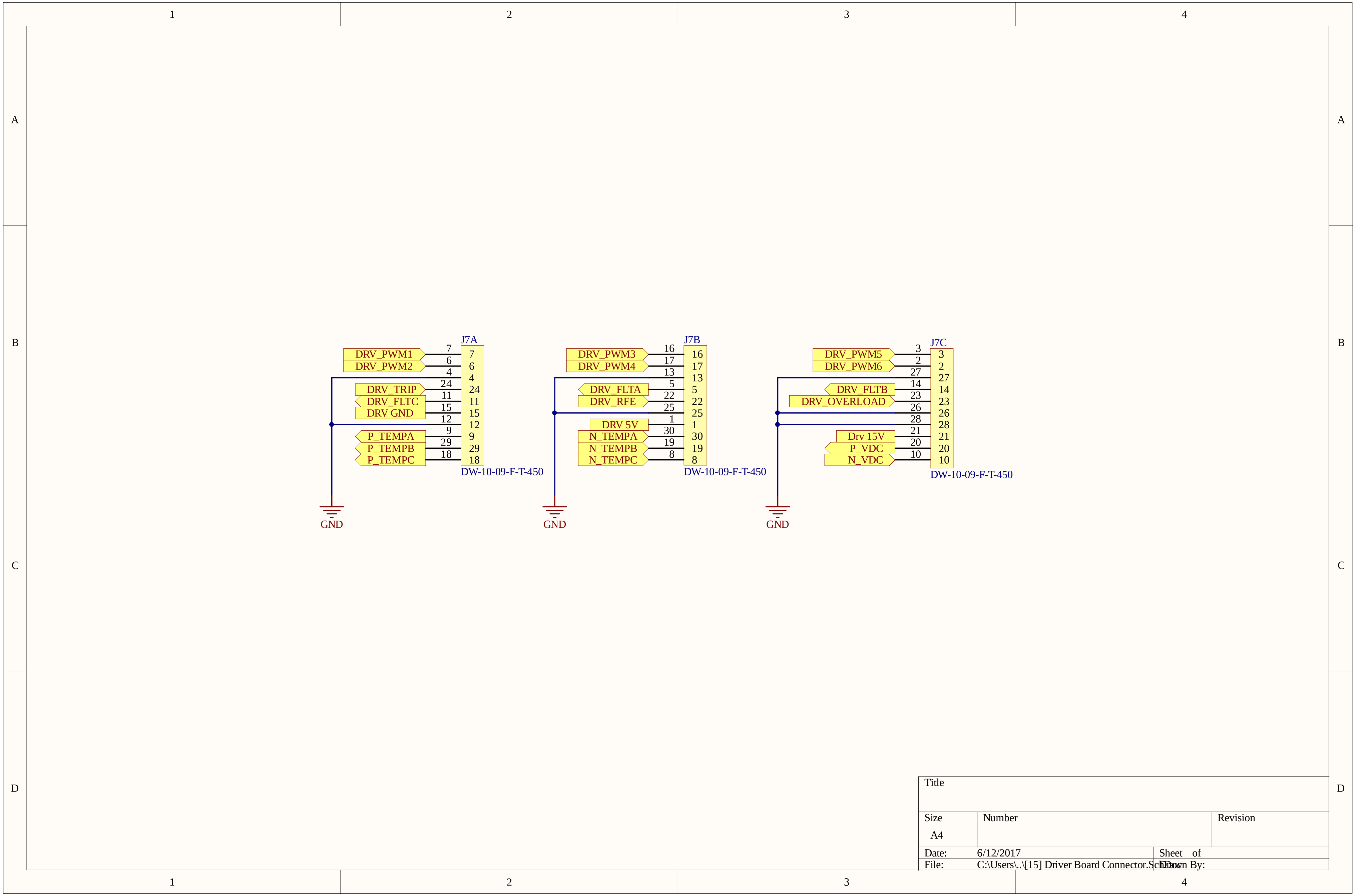
J7A
DRV_PWM1
DRV_PWM2
DRV_TRIP
DRV_FLTC
DRV GND
P_TEMPA
P_TEMPB
P_TEMPC
DW-10-09-F-T-450
GND
J7B
DRV_PWM3
DRV_PWM4
DRV_FLTA
DRV_RFE
DRV 5V
N_TEMPA
N_TEMPB
N_TEMPC
DW-10-09-F-T-450
GND
J7C
DRV_PWM5
DRV_PWM6
DRV_FLTB
DRV_OVERLOAD
Drv 15V
P_VDC
N_VDC
DW-10-09-F-T-450
GND
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Number
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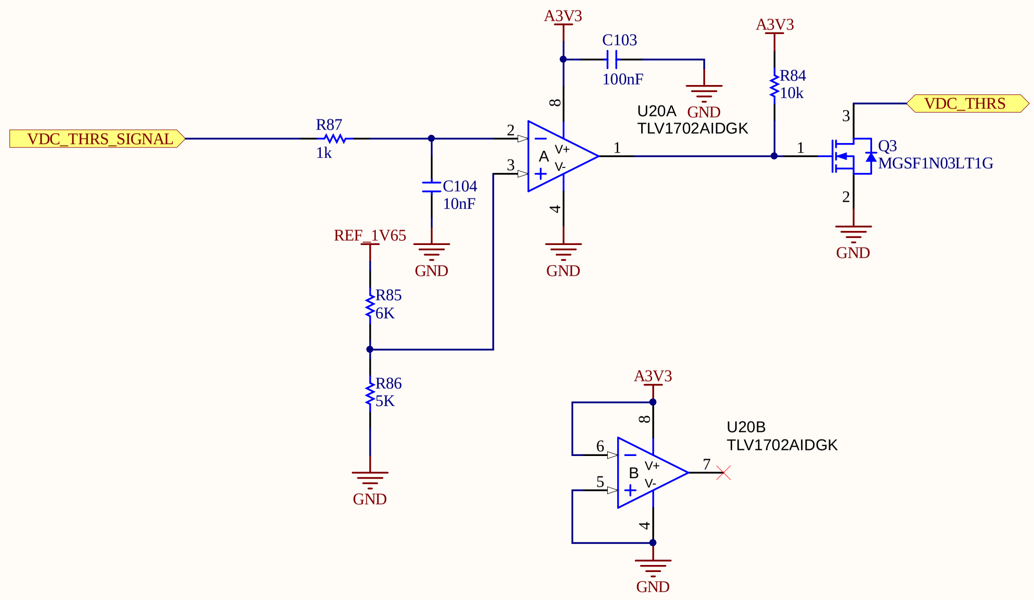
VDC_THRS_SIGNAL
R87
1k
C104
10nF
GND
REF_1V65
R85
6K
R86
5K
GND
A3V3
C103
100nF
GND
U20A
TLV1702AIDGK
GND
A3V3
R84
10k
VDC_THRS
Q3
MGSF1N03LT1G
GND
A3V3
U20B
TLV1702AIDGK
GND
Title
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Number
Revision
Date: 6/12/2017
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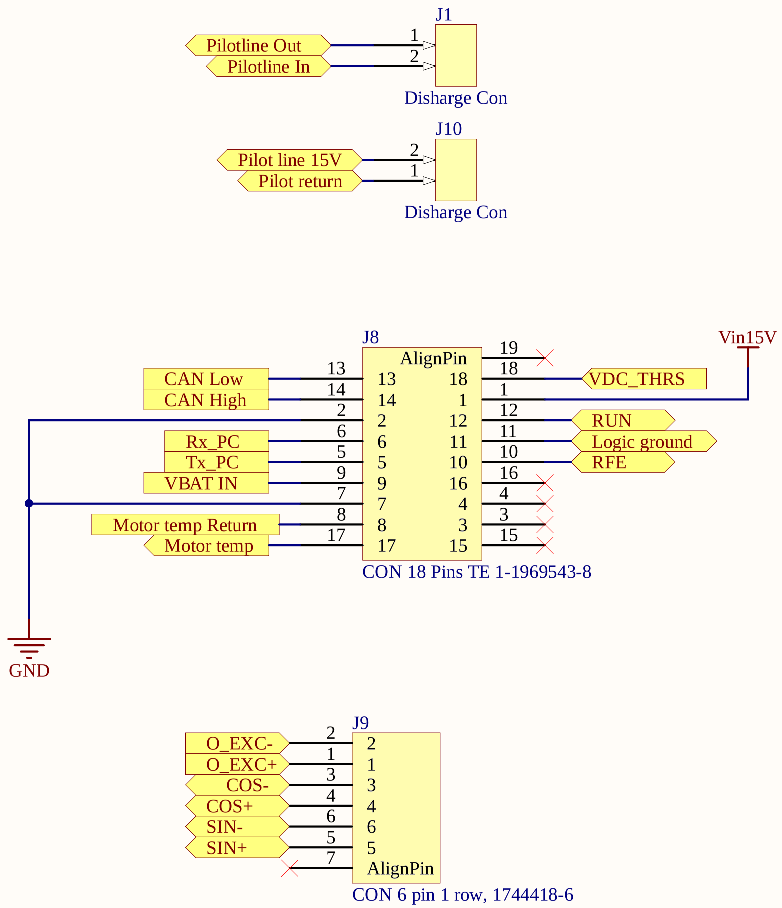

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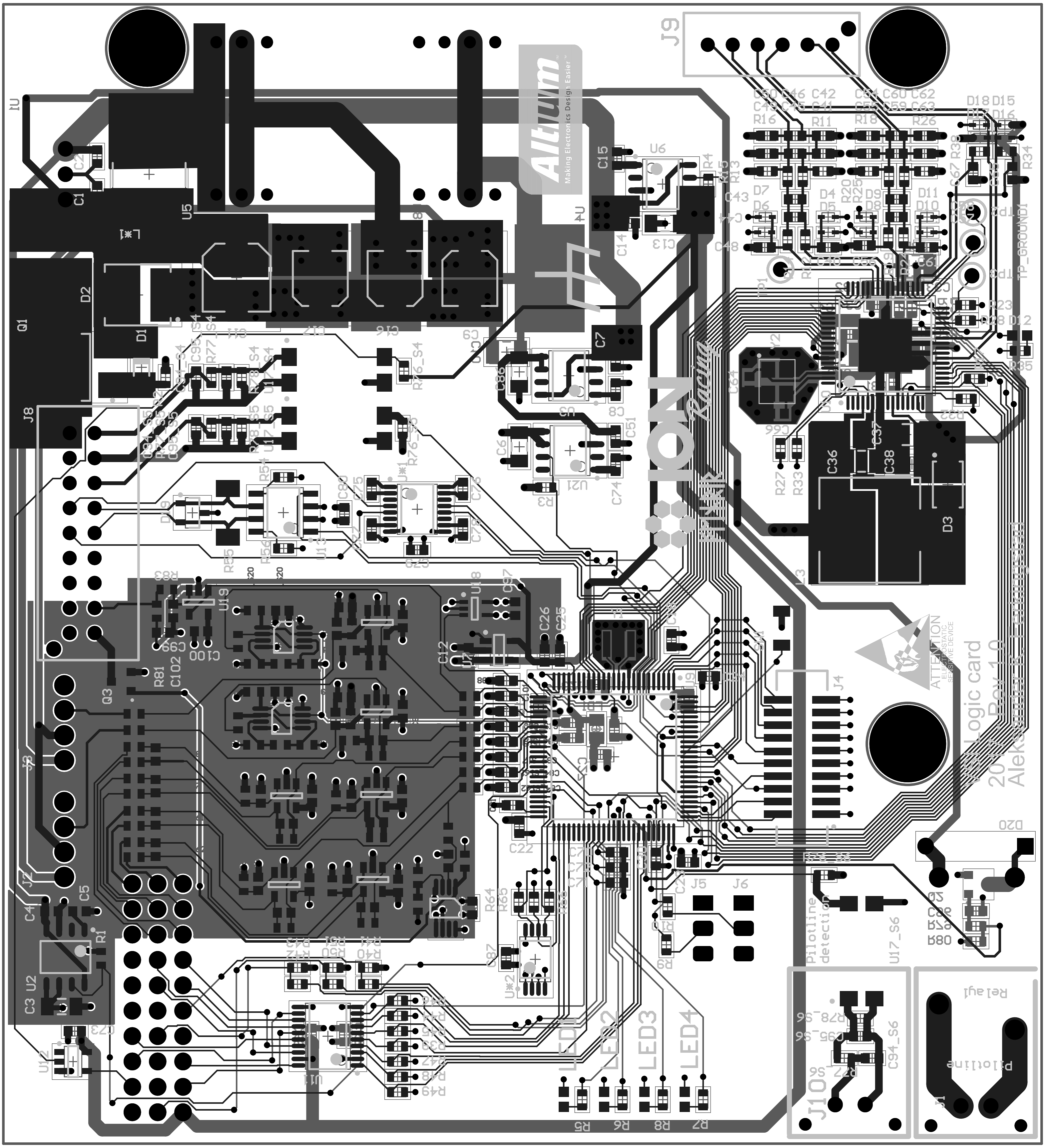

Appendix D

Electrical safety form, England

22.03.17

Electrical System Form FS2017
University of Stavanger
ION Racing
Car number: E39

Team ESF contact: Helge Vassbakk, h.vassbakk@ionracing.no

Table of Contents

I List of Figures

II List of Tables

III List of Abbreviations

AIR
Accumulator Isolation Relay;15; 17; 20; 33; 45; 46; 47; 52; 66
BMS
Battery Management System;15; 16; 19; 21; 26; 42; 44; 46; 47; 50; 60; 63; 64; 65; 66; 67; 80
BOTS
Brake Over Travel Switch;15; 16
BSPD
Brake System Plausibility Device;15; 23; 24; 25; 26
CAD
Computer Aided Design;40; 58; 59
CPU
Central Processing Unit;65; 66; 67
ECU
Engine Control Unit;39; 40; 53; 58; 60; 61; 62; 89
FET
Field Effect Transistor;66
FSG
Formula Student Germany;29
GLV
Ground Low Voltage;19; 20; 26; 29; 31; 47; 63; 64; 65; 66; 67; 68
GLVMS
Ground Low Voltage Master Switch;15; 23; 46; 52; 67
HV
High Voltage;20; 33; 38; 46; 52; 54; 65
HVD
High Voltage Disconnect;27; 28; 38; 39; 49; 53
IC
Intergrated Circuit;46; 47
IMD
Insulation Monitoring Device;15; 16; 19; 20; 21; 26; 50; 71
LED
Light Emitter Diode;15; 19; 23; 29; 47; 60
NC
Normal Close;22; 36
NO
Normal Open;22; 44; 45; 60
NTC
Negative Temperature Coefficient;44; 65; 91
PCB
Printed Circuit Board;26; 29; 33; 35; 36; 43; 46; 47; 48; 64
RTDS
Ready To Drive Sound;39; 40; 41; 60; 78
SOC
State Of Charge;66
TSAL
Tractive System Active Light;29; 30; 31
TSMP
Tractive System Measuring Points;31; 32
TSMS
Tractive System Master Switch;15; 16

1 System Overview

The concept is an electric formula student vehicle with a carbon-fibre monocoque. A high performance electric motor connected to the rear wheels through a parallel gearbox and a differential. The electric motor is regulated with a custom designed inverter which are compatible with the Bamocar D3-400-200/400. This system is driven by a 7.46 KWh lithium based accumulator which are located behind the driver to power the engine.

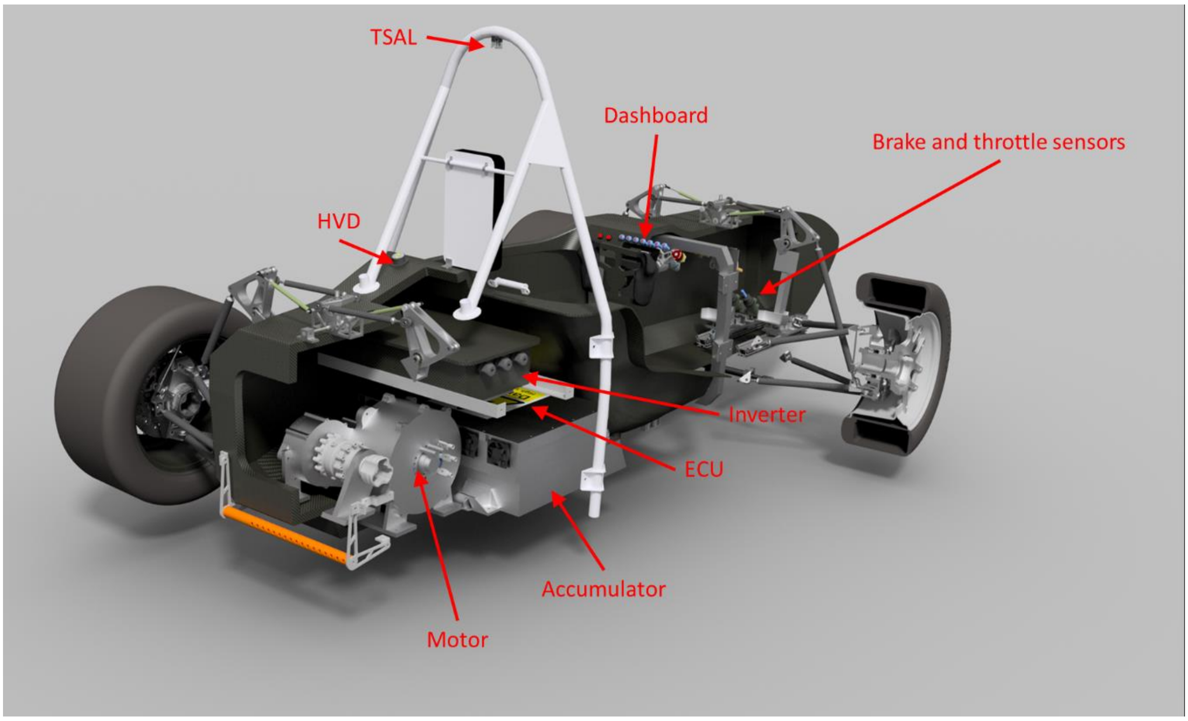

Figure 1.1 System overview

Maximum Tractive-system voltage:	403,2VDC
Nominal Tractive-system voltage:	355,2VDC
Control-system voltage:	12VDC
Accumulator configuration:	96s3p
Total Accumulator capacity:	21Ah
Motor type:	Permanent Magnet Synchronous Motor
Number of motors:	One, on rear wheels
Maximum combined motor power in kW	100

Table 1.1 General parameters

2 Electrical Systems

2.1 Shutdown Circuit

2.1.1 Description/concept

The shutdown circuit is a separated circuit consisting of relays and switches that control the Accumulator Isolation Relay (AIR) in the accumulator enclosure. AIRs are relays that normally are open, but will remain closed as long there is 12V presented at the inputs. In the accumulator there are two AIRs. One relay for each of the mains of the accumulator.

In the shutdown circuit, there are two master switches: Grounded Low Voltage Master switch (GLVMS) and Tractive System Master Switch (TSMS). The function of these are to enable the 12V battery, its applications and system, and the tractive system, respectively.

Connected in series with the shutdown buttons, there is a Brake Over Travel Switch (BOTS) which is an emergency switch in a normally closed position. The BOTS is positioned at the brake pedal's maximum travel position. The brake pedal will only reach its maximum travel position in the event if the brake system is being faulty, i.e. if the brake fluid pressure has dropped because of a leakage. The BOTS must be manually reset for the shutdown circuit to be closed again.

Every shutdown button, relay and interlock, and the inertia switch are connected in series with the shutdown circuit. This is so that in the event of any of them are to be tripped or deenergized, the AIRs will be opened.

Powering the shutdown circuit and all the low voltage applications is a secondary 12V accumulator. In the event of the voltage levels dropping below the relay threshold, they will open the circuit, causing the AIRs to open in the accumulator enclosure, resulting in the high voltage being isolated from the tractive system.

A custom relay circuit connected to the Battery Management System (BMS), Insulation Monitoring Device (IMD) and Brake System Plausibility Device (BSPD) outputs, require a manual reset. To reset the system, the GLVMS must be turned off an on again. In the event of a fault, a Light Emitter Diode (LED) will light up on the dashboard, indicating whether it is related to IMD, BMS or BSPD. These LEDs are all clearly marked.

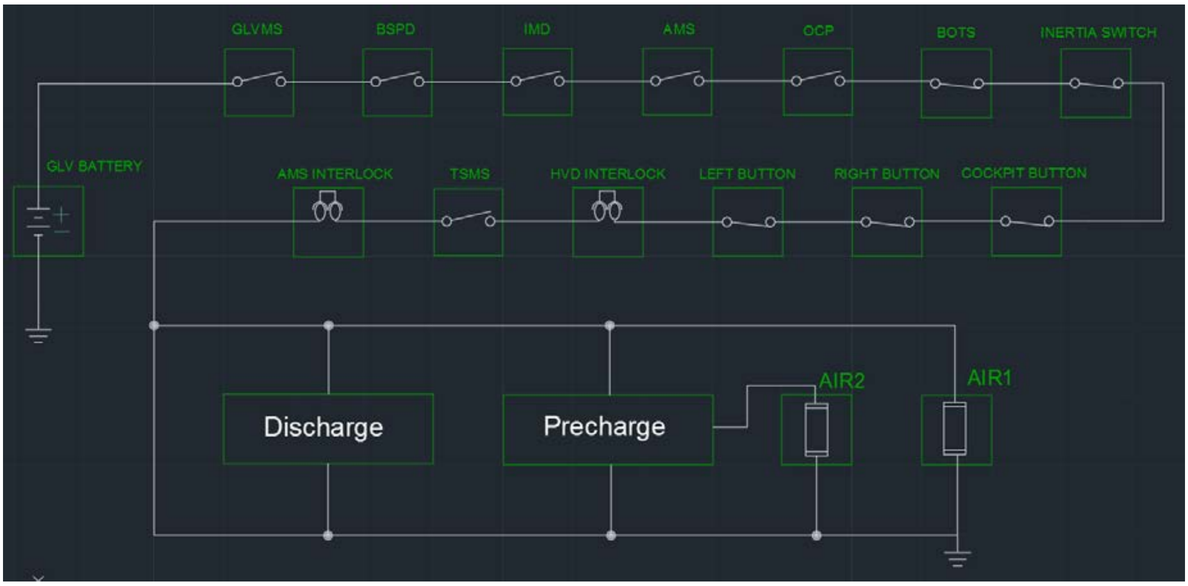

Figure 2.1 Shutdown circuit switches - Schematic

Part	Function
Main Switch (for control and tractive-system; CSMS, TSMS)	Normally open
Brake over travel switch (BOTS)	Normally closed
Shutdown buttons (SDB)	Normally closed
Insulation Monitoring Device (IMD)	Normally open
Battery Management System (BMS)	Normally open
Inertia Switch	Normally closed
Interlocks	Closed when circuits are connected
Brake System Plausibility Device	Normally open

Table 2.1 List of switches in the shutdown circuit

2.1.2 Wiring / additional circuitry

All the switches and relays in the Shutdown Circuit are connected in series with a single core wire. Any triggering of a relay or switch will break the connection and open the Shutdown Circuit and with it the AIRs.

Total Number of AIRs:	2
Current per AIR:	0.23A (3.9A Inrush)
Additional parts consumption within the shutdown circuit:	0.3A
Total current:	0.759A
Cross sectional area of the wiring used:	0.32 mm²

Table 2.2 Wiring – Shutdown circuit

2.1.3 Position in car

Figure 2.2 Shutdown circuit buttons outside group1 - Position

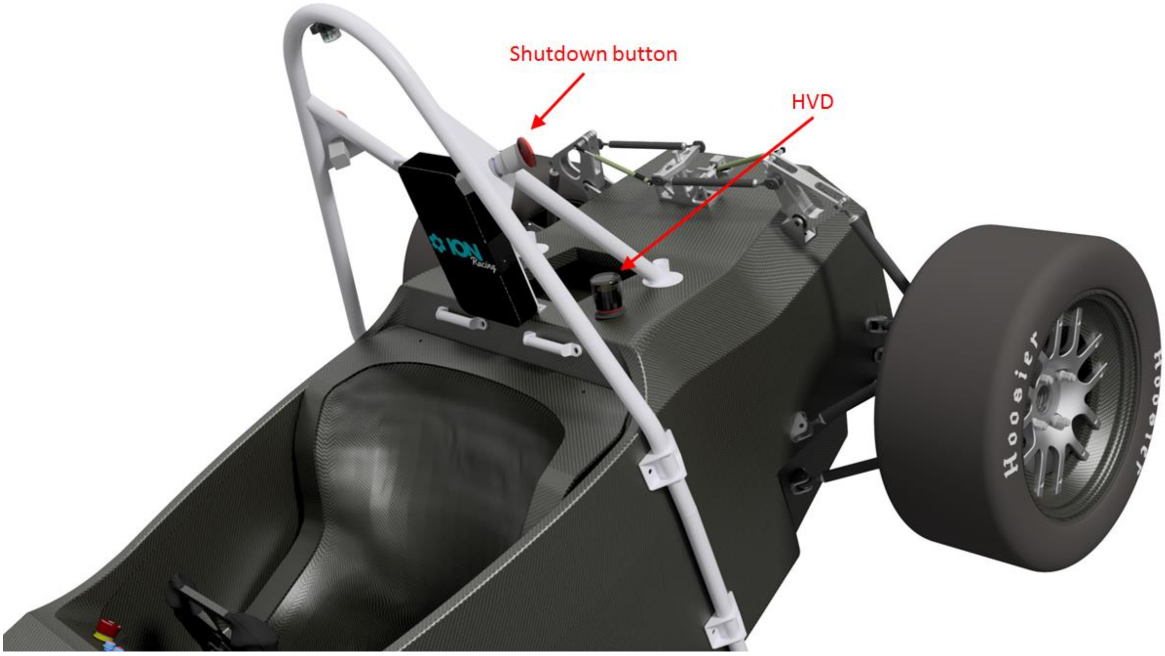

Figure 2.3 Shutdown circuit buttons outside group2 - Position

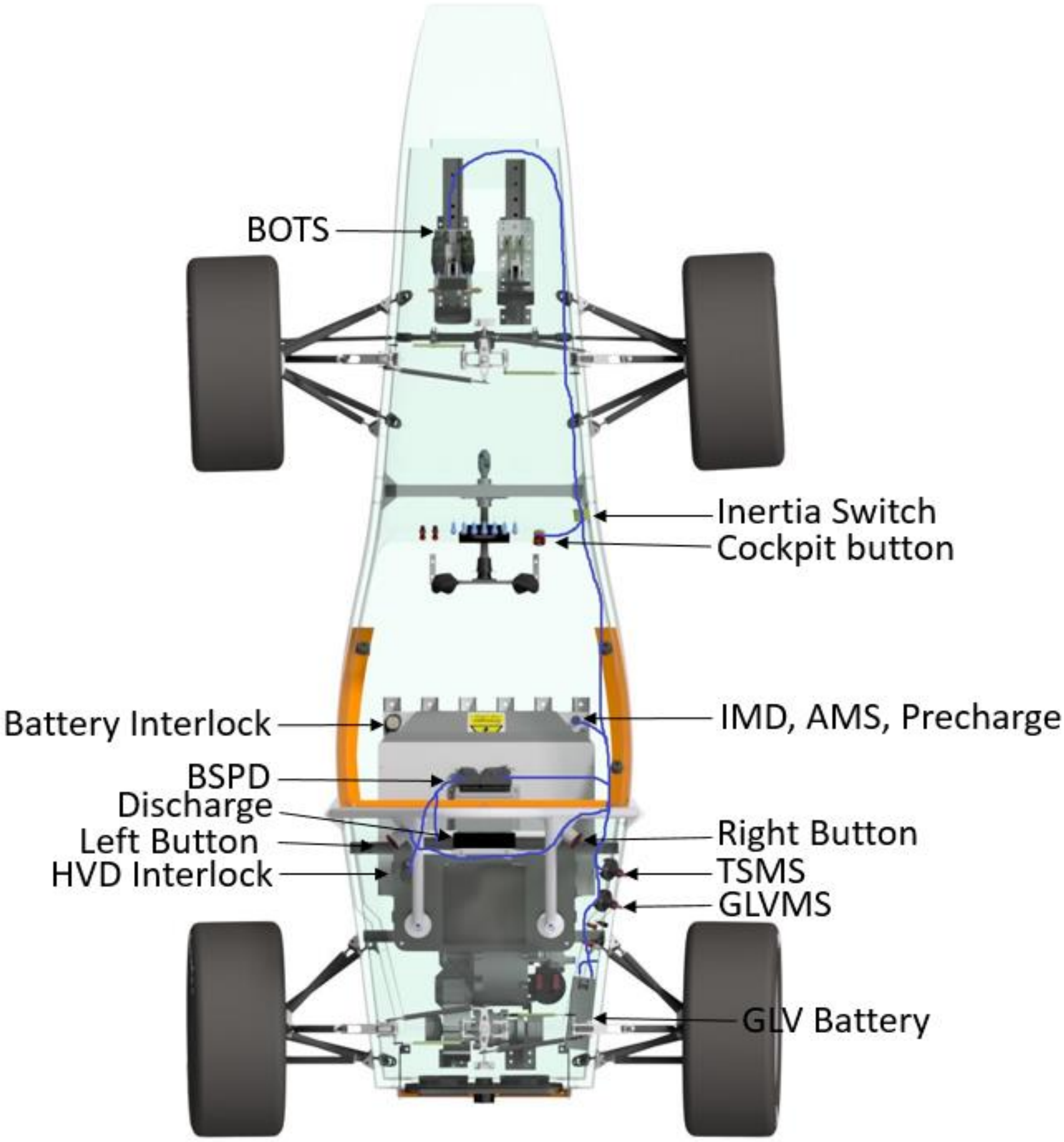

Figure 2.4 Shutdown circuit buttons overview - Position

2.2 IMD

2.2.1 Description (type, operation parameters)

The IMD used is a Bender IR155-3204. A failure mode output on the IMD is connected to a dedicated circuit on the BMS master. The OKHS signal is a logic high when there is no fault, this will give a fault if the IMD loses it's power The circuit Inverts the OKHS signal from the IMD which activates the latching stage if the IMD detects an insulation fault. This will activate a circuit which light up the IMD LED in the dashboard. The fault or an Ground Low Voltage (GLV) de-energized state will open up the shutdown circuit.

Supply voltage range:	10..36VDC
Supply voltage	12VDC
Environmental temperature range:	-40..105°C
Selftest interval:	Always at startup, then every 5 minutes
High voltage range:	DC 0..1000V
Set response value:	202kΩ (500Ω/Volt)
Max. operation current:	150mA
Approximate time to shut down at 50% of the response value:	20s

Table 2.3 Parameters of the IMD

2.2.2 Wiring/cables/connectors/

Connectors are used according to recommendation from datasheet for the IMD. Cables chosen is TE Connectivity M22759 22AWG for the IMD and rated for 600V and temperatures up to 150°C. For High Voltage (HV)+ and HV- the cables are chosen to be orange to separate HV and GLV. The IMD is connected to the terminals of the AIR’s on the battery side.

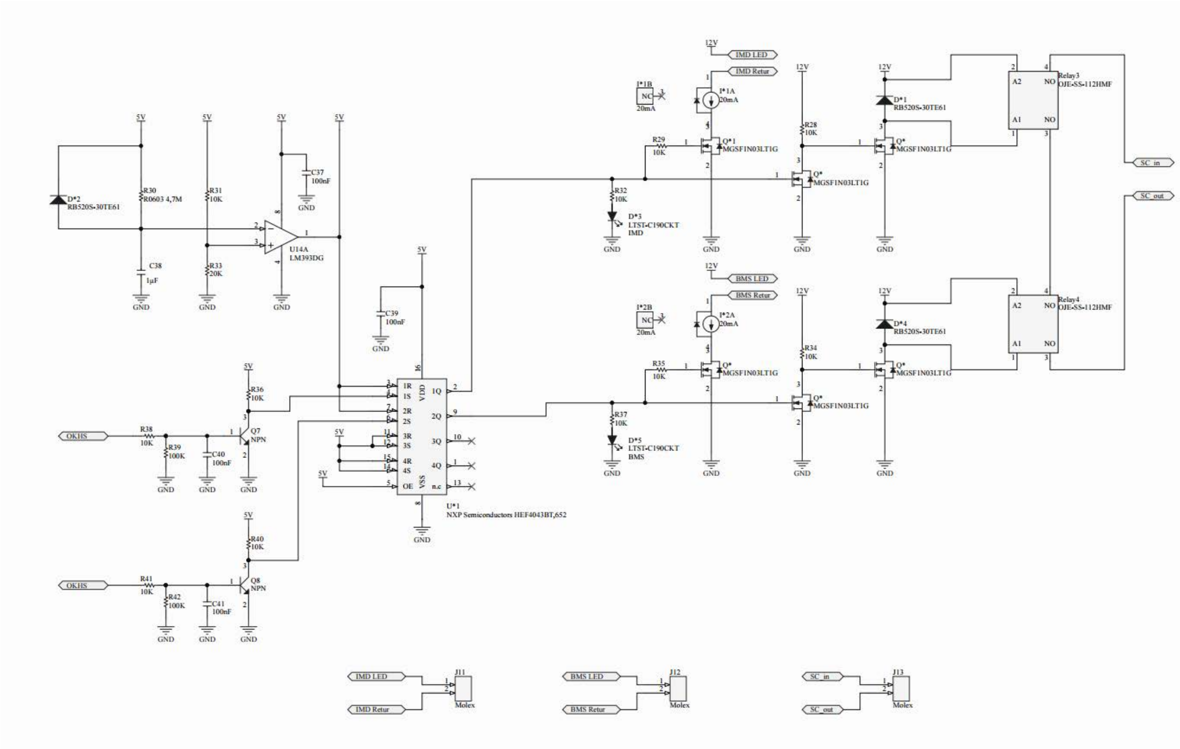

Figure 2.5 Schematic latching circuit for IMD and BMS

2.2.3 Position in car

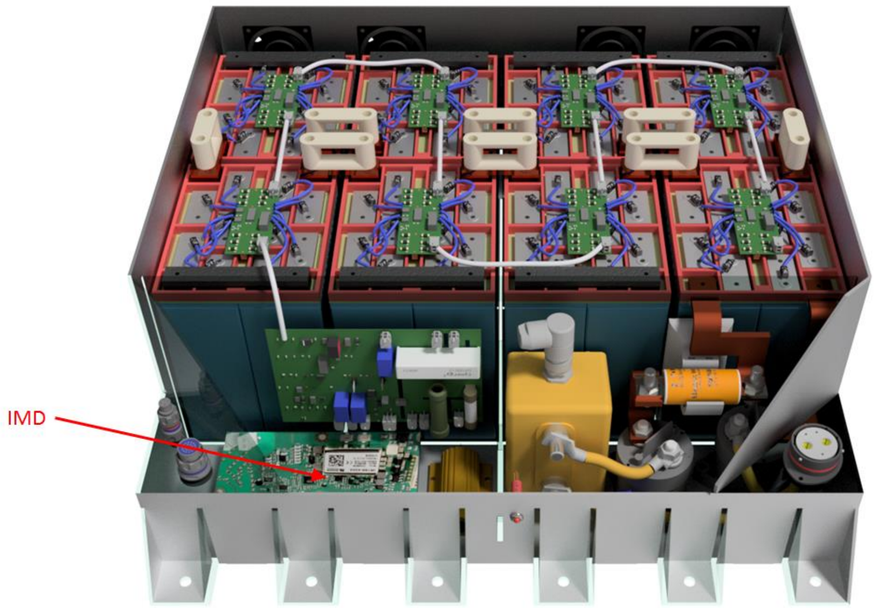

Figure 2.6 IMD - Position

2.3 Inertia Switch

2.3.1 Description (type, operation parameters)

The inertia switch used in the vehicle is a sensata resettable crash sensor. It is mounted in the driver compartment to allow the operator to reset it while remaining in the vehicle, in case of a mistrigger

Inertia Switch type:	Sensata 505
Supply voltage range:	10..36VDC
Supply voltage:	12VDC
Environmental temperature range:	-40..105°C
Max. operation current:	20A DC for max. 30s 10A DC continious
Trigger characteristics:	6g for 60ms / 12g for 60ms

Table 2.4 Parameters of the Inertia Switch

2.3.2 Wiring/cables/connectors/

The Inertia Switch has a Normal Close (NC) and a Normal Open (NO) option. We are using the NC option which is directly connected in series with the shutdown circuit. Forces above 6g will trigger the switch and opening the circuit. The connector used are a 3 way Econoseal III from TE Connectivity.

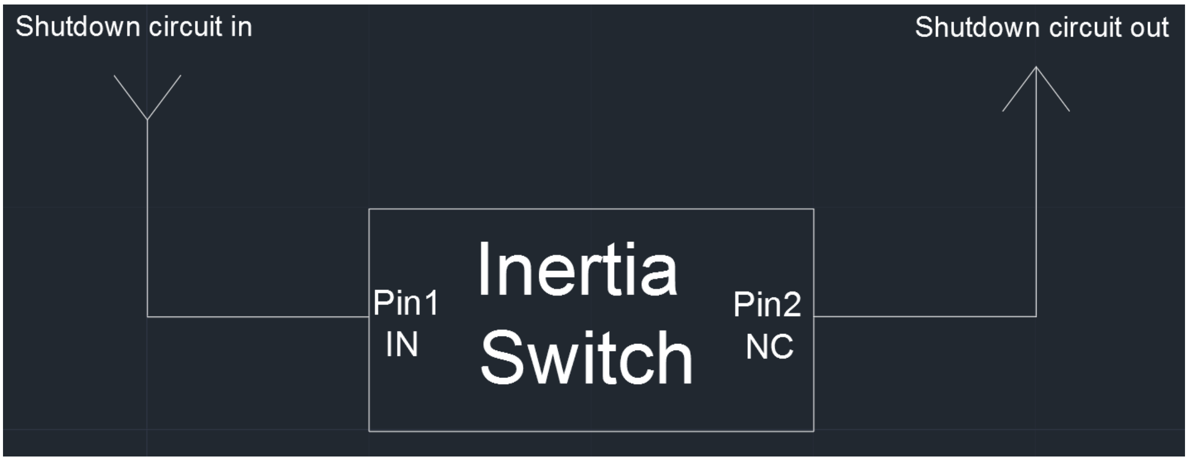

Figure 2.7 Inertia switch- Schematic

2.3.3 Position in car

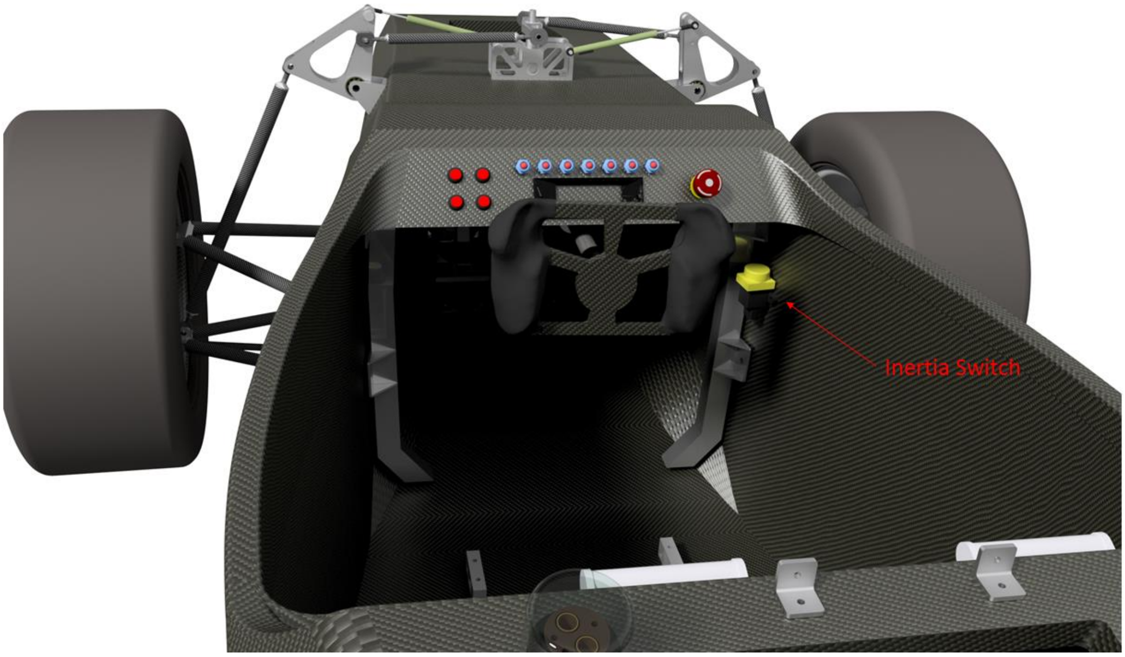

Figure 2.8 Inertia switch - Position

2.4 Brake System Plausibility Device

2.4.1 Description/additional circuitry

The BSPD, is an non-programmable circuit connected via three stages. The circuit located inside the accumulator monitors whether or not the operator is braking hard. Inside the accumulator enclosure a open loop hall effect current transducer measures current drawn from the accumulator. Both the brake sensor circuit and the output from the current sensor is fed into a third stage, which checks for if the operator brakes hard while a positive current of more than 5kW is delivered of the motors for more than 0.5 seconds. When such an implausibility occurs, the latching circuit will keep the onboard relay open, which keeps the AIRs and the LED labeled BSPD in the dashboard illuminated. The latching circuit keeps the AIRs open until the GLVMS is manually reset.

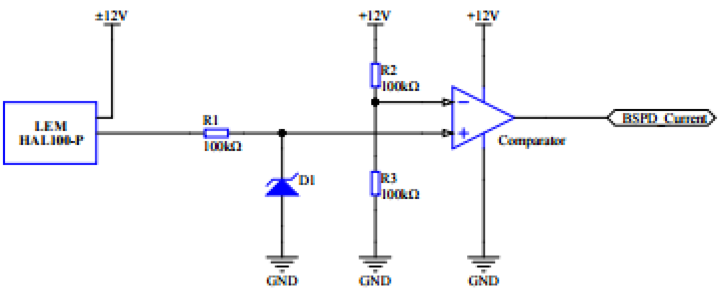

Figure 2.9 BSPD schematic - current measurement

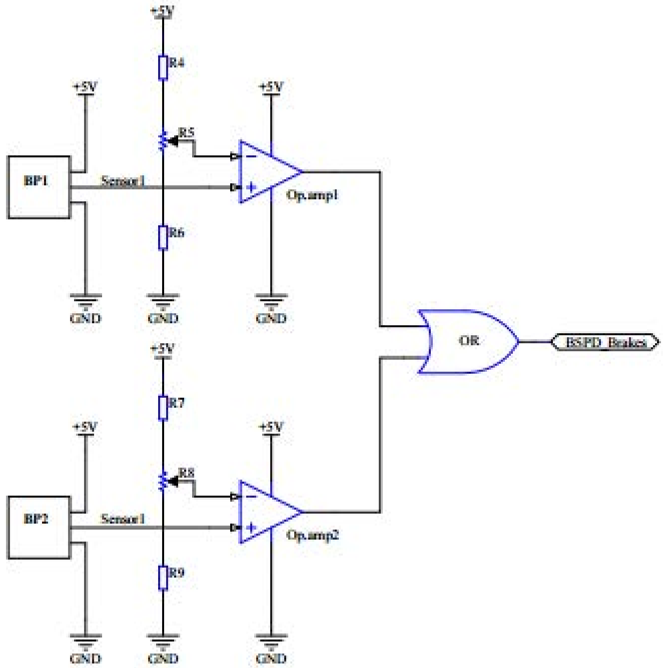

Figure 2.10 BSPD schematic - Brake detection

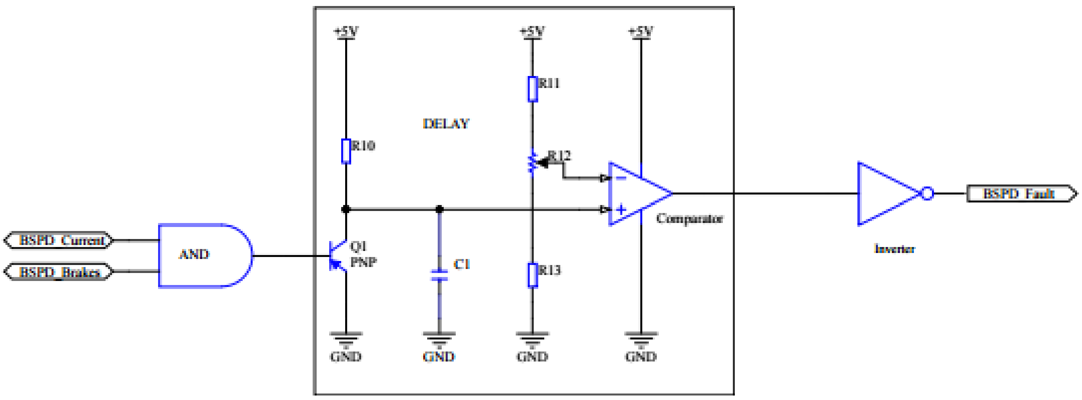

Figure 2.11 BSPD schematic - fault test

Brake sensor used:	TE Connectivity M3031-000005-100PG
Torque encoder used:	potentiometer
DC Current measurement used:	LEM HAL 200-P
Supply voltages:	±15V
Maximum supply currents:	80mA
Operating temperature:	-20..180 °C
Output used to control AIRs:	Open a relay

Table 2.5 Parameters of the BSPD

2.4.2 Wiring

Both the brake sensor circuit output and a LEM open loop current transducer is wired into the BSPD input stage. The current transducer gives out a 28mV when 5kW is drawn from the accumulator at nominal voltage.

2.4.3 Position in car/mechanical fastening/mechanical connection

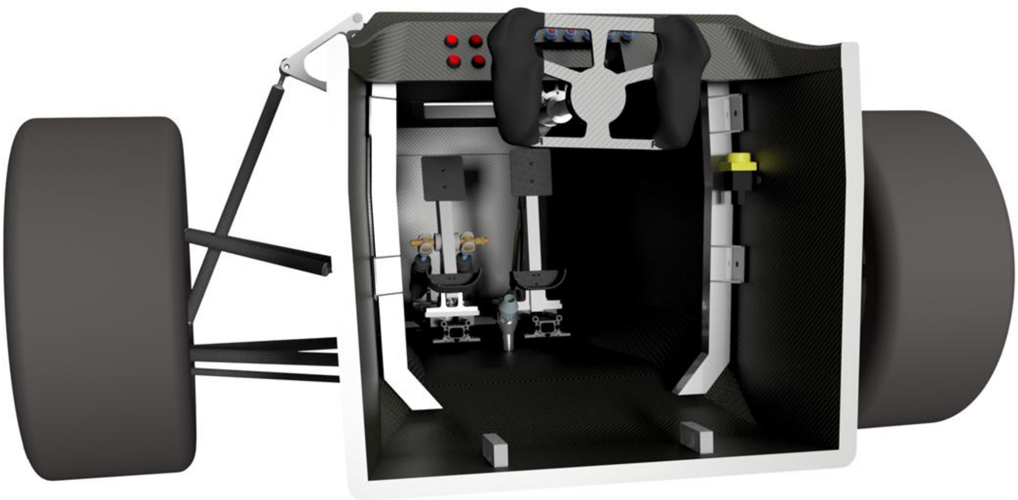

Figure 2.12 Brakes - Position

2.4.4 Wiring/cables/connectors/

Describe wiring, show schematics, describe connectors and cables used and show useful data regarding the wiring.

2.4.5 Position in car

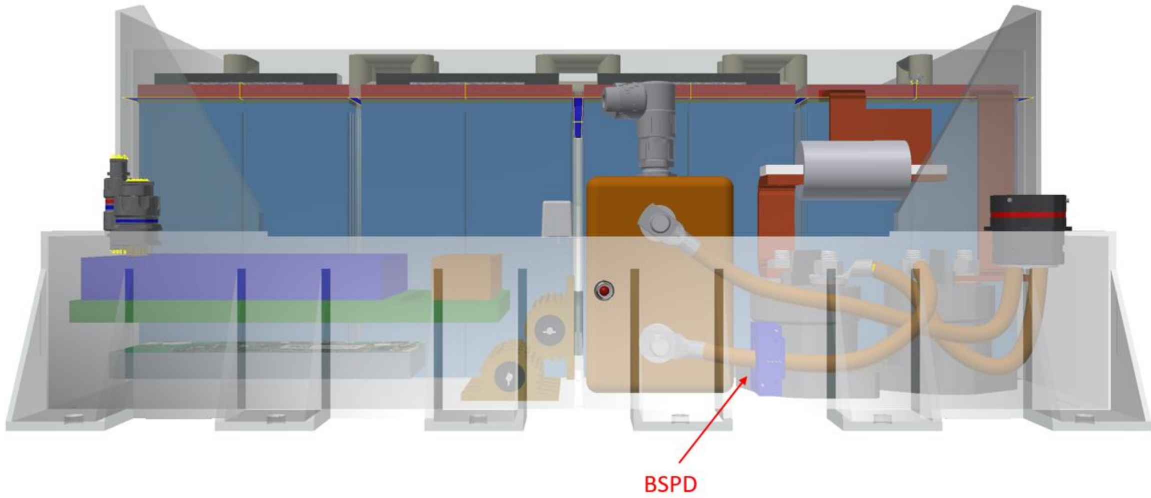

Figure 2.13 BSPD - Position

2.4.6 Testing Method

A self-constructed test circuit will simulate the current delivered from the closed loop Hall effect sensor when 5kW or more is being drawn from the accumulator. The test circuit will be mounted in a standalone enclosure, which will be connected to the BSPD input stage and controlled by a multimeter. At the scrutineering the test circuit will deliver a 28mV signal, which simulates when 5kW is drawn from the accumulator while operator press the brake pedal hard for lessthan half a second demonstrating that the device works properly.

2.5 Reset / Latching for IMD and BMS

2.5.1 Description/circuitry

Any fault detected by the IMD and BMS or a de-energized state on the GLV system will cause a relay to open the shutdown circuitry. To reset the latch the GLV system needs to be de-energized and re-energized again. This will start a delayed circuit which resets the BMS and IMD latch until the IMD is ready.

2.5.2 Wiring/cables/connectors

Wires for the circuit are Printed Circuit Board (PCB) traces, The only wires connected to the board are powersupply for the circuit, IMD, BMS and shutdown wires.

2.5.3 Position in car

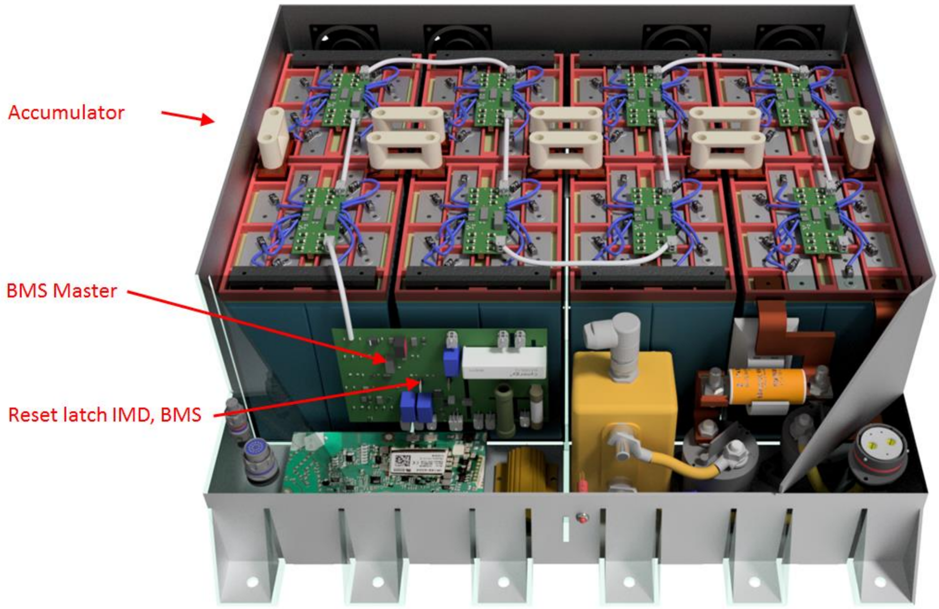

Figure 2.14 Reset latch - Position

2.6 Shutdown System Interlocks

2.6.1 Description/circuitry

There are two interlocks installed on the vehicle. One on the connector to the battery, and one on the High Voltage Disconnect (HVD). The interlocks are both connected in series with the shutdown circuit. In the event of one of the interlocks disconnecting, the shutdown circuit will open, as well as the AIRs. There are two control cables on each connector, used as interlocks.

2.6.2 Wiring/cables/connectors

The shutdown system interlocks uses the same wire as the rest of the shutdown circuit.

Figure 2.15 Interlock - HVD

2.6.3 Position in car

Figure 2.16 Interlock - Accumulator

2.7 Tractive system active light

2.7.1 Description/circuitry

The Tractive System Active Light (TSAL) will be mounted on the underside of the roll hoop, the control electronics will be inside the accumulator. The TSAL circuit receives a logical high when high voltage is present. When only GLV is present the TSAL will flash green to comply with Formula Student Germany (FSG) rules

Supply voltage:	12VDC
Max. operational current:	600mA
Lamp type	LED
Power consumption:	3.6W
Brightness	200 Lumen
Frequency:	3.14Hz
Size (length x height x width):	27mm x 16mm x 27mm

Table 2.6 Parameters of the TSAL

2.7.2 Wiring/cables/connectors

The wires used to the TSAL are of the type TE Connectivity M22759 rated for 600V and made for harsh environments. The wires are soldered onto the TSAL PCB and are sealed off with potting material.

Connector Accumulator	Deutsch group DTS24W15-35PN
Continuous current rating connector	5A
Continuous current rating cable	7A
Cross-sectional area	0.32mm2
Temperature rating cable	-65°C...150°C
Temperature rating connector	-65°C...200°C

Table 2.7 Parameters of the TSAL wire

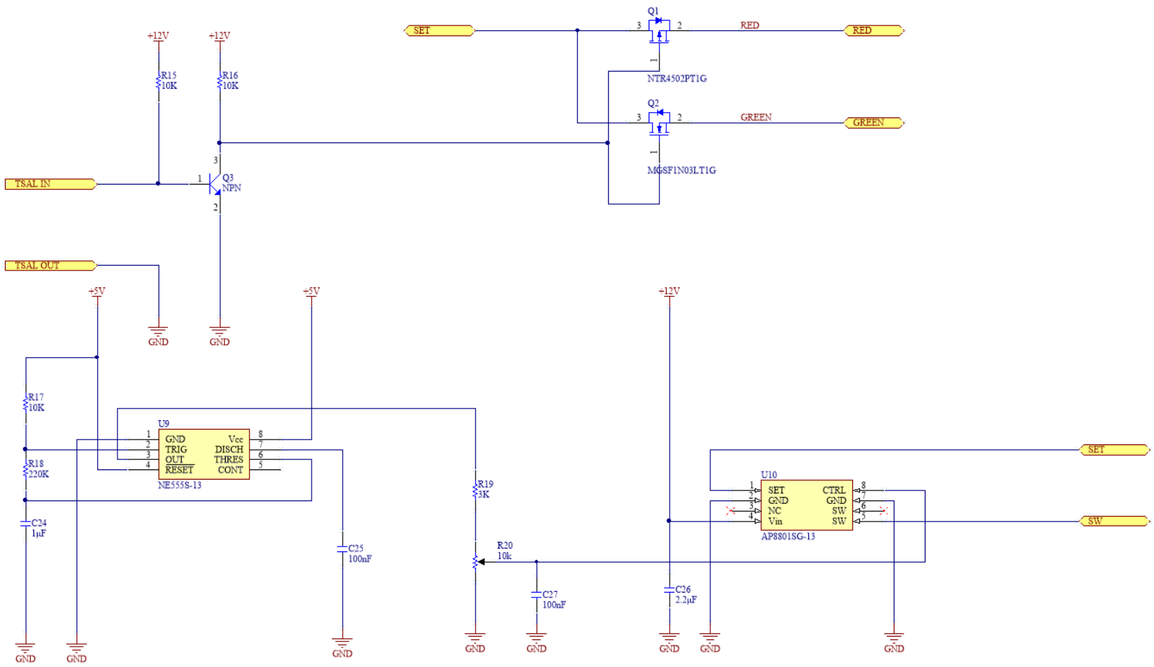

Figure 2.17 TSAL - Schematic

2.7.3 Position in car

Figure 2.18 TSAL - Position

2.8 Measurement points

2.8.1 Description

Four shrouded 4mm banana jacks are located behind the master switches on the right side of the car. They are marked with Tractive System Measuring Points (TSMP)+, TSMP-, GLV+ and GLV-. The positive sockets are red, the negative GLV is black and the TSMP- is blue. When not in use the holes are plugged by plastic inserts for waterproofing, easily removed without tools when measuring is required. The cable connections to the banana jacks are securely inside glued heat shrink tubing and mounted deep in the frame of the car sealed by non-conductive potting material. Touching any live component with bare hands is impossible from outside or inside of the car.

2.8.2 Wiring, connectors, cables

From the back of the banana plugs the TSMP wires leads to the motor-controller box, where they are lead through a cable gland. On the inside of the box two current limiting 15kOhm resistors are mounted and secured to the positive and negative terminal of the capacitor bank. The GLV+ is connected directly to the positive terminal of the low voltage battery, and the GLV- to nearby ground.

2.8.3 Position in car

Figure 2.19 Measurement points - Position

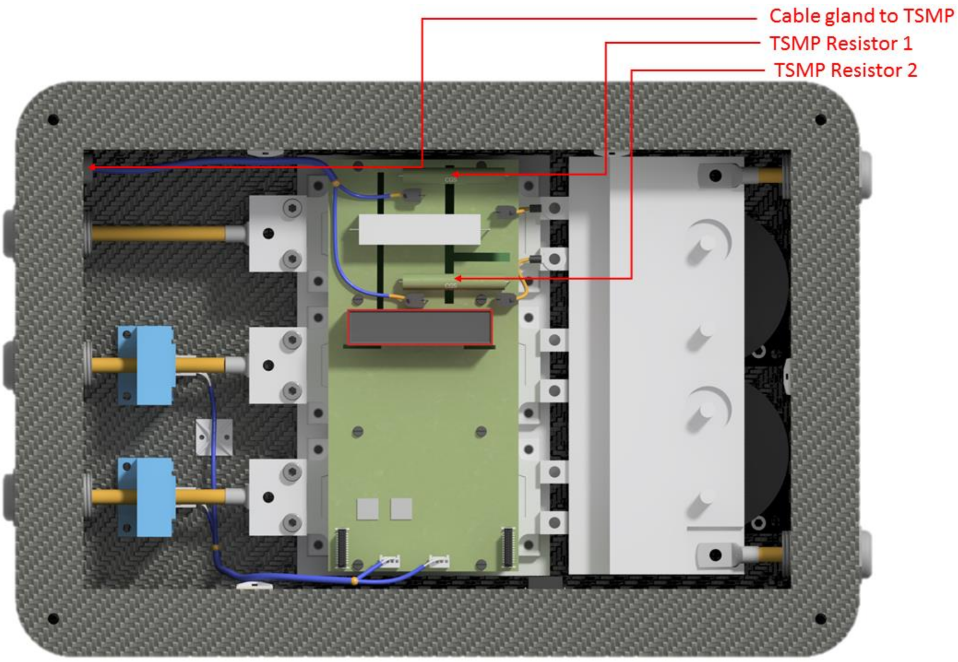

Figure 2.20 TSMP - Position

2.9 Pre-Charge circuitry

2.9.1 Description

The pre-charge circuit is allowed to charge the intermediate circuit to at least 90% of the current accumulator voltage before closing the second AIR. The circuitry controls a single relay bypassing one of the AIRs with a resistor limiting the maximum current possible drawn from the accumulator container. The circuitry is connected to the shutdown circuit, and can only be activated by enabling the shutdown circuit, i.e an open shutdown circuit will always result in the pre-charge and the AIRs to be disconnected.

2.9.2 Wiring, cables, current calculations, connectors

The pre-charge relay and pre-charge resistors are connected in series and just bypass one of the AIRs for 3,6 seconds. The intermediate circuit are pre-charged to 90% of the current accumulator voltage in 1,8 seconds.

The pre-charge circuit are powered in parallel with AIR. The pre-charge relay are PCB mounted. Connectors will be PCB mounted. HV cable to pre-charge will be soldered to the PCB. The pre-charge resistor used are WELWYN WH100-1K0JI.

C-input = 800µF

Vmax = 403.2V

The formula used to plot "Percentage of maximum voltage vs time" are standard voltage in capacitor formula:

$$\mathrm{Vc} = (1\text{-}e^{\frac{-t}{RC}}) * 100$$

Figure 2.21 Pre-Charge – Formula for presentage of maximum voltage vs time

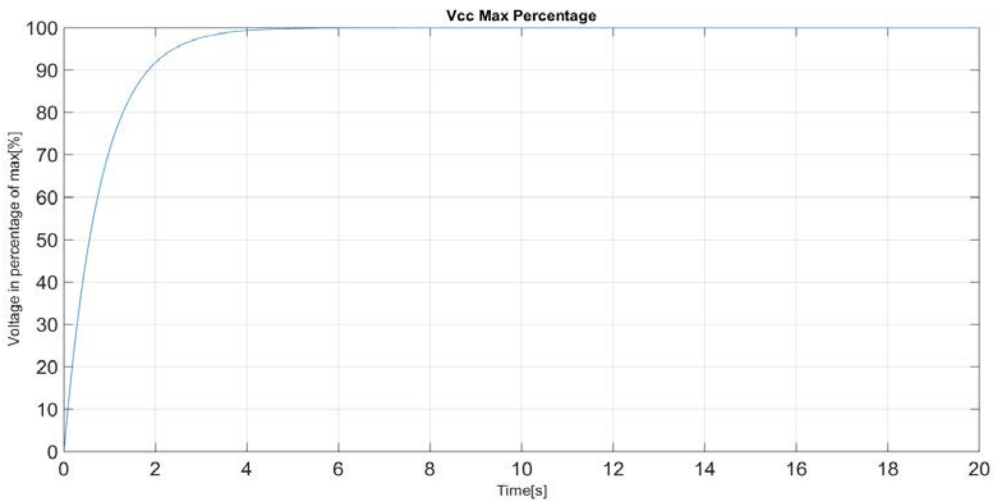

Figure 2.22 Pre-Charge – Graph for Presentage of maximum voltage vs time

The formula used to plot “Current vs time” are based on ohm’s law

$$I = \frac{Vmax - Vc}{R}$$

Figure 2.23 Pre-Charge – Formula for Current vs time

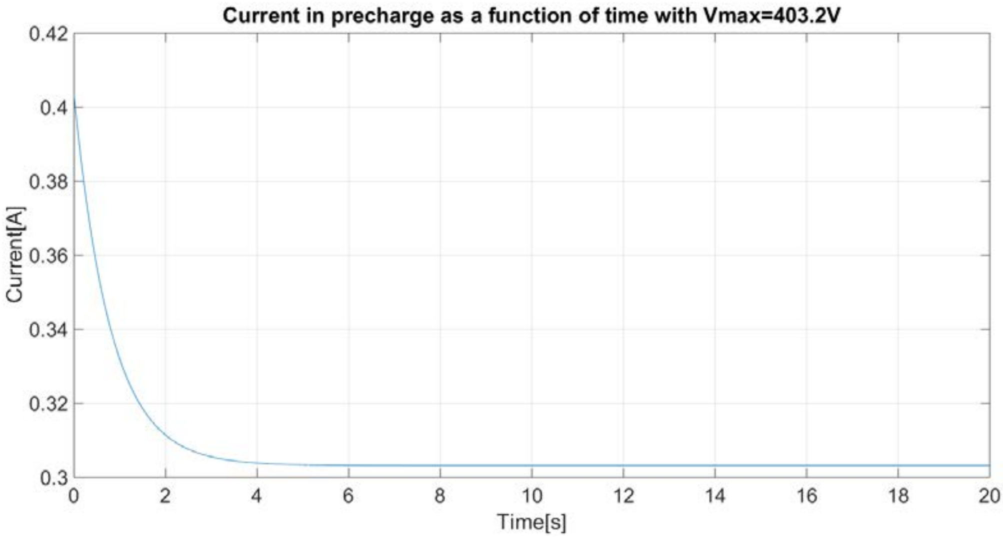

Figure 2.24 Pre-Charge – graph for Current vs time

Resistor Type:	WELWYN WH100-1K0JI
Resistance:	1kΩ
Continuous power rating:	100W
Overload power rating:	200W for 30 sec
Voltage rating:	1900V
Cross-sectional area of the wire used:	0,52 mm^2

Table 2.8 General data of the pre-charge resistor

Relay Type:	Cynergy 3 D200 Series
Contact arrangment:	SPNO
Continuous DC current:	3A
Voltage rating	2500VDC
Cross-sectional area of the wire used:	PCB Mounted

Table 2.9 General data of the pre-charge relay

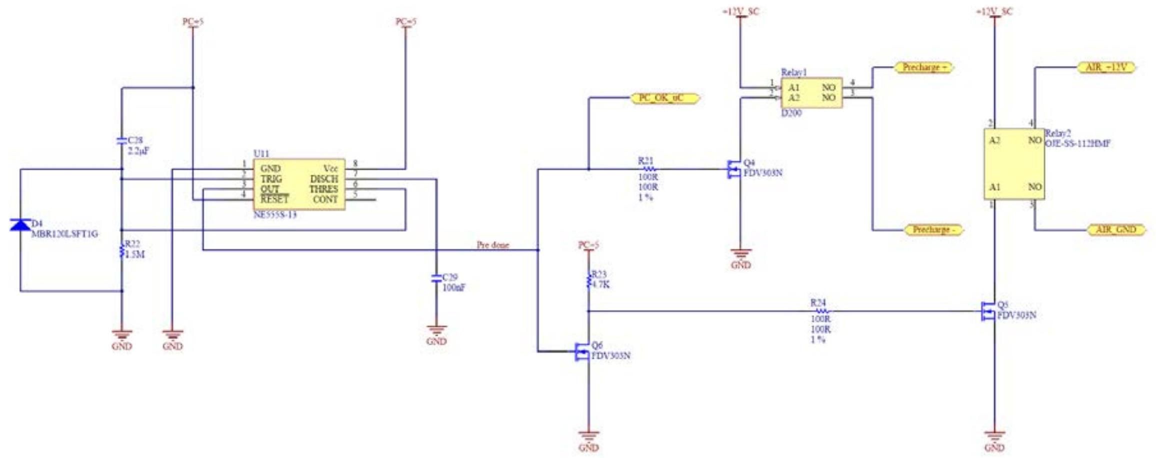

Figure 2.25 Pre-charge relay - Schematic

2.9.3 Position in car

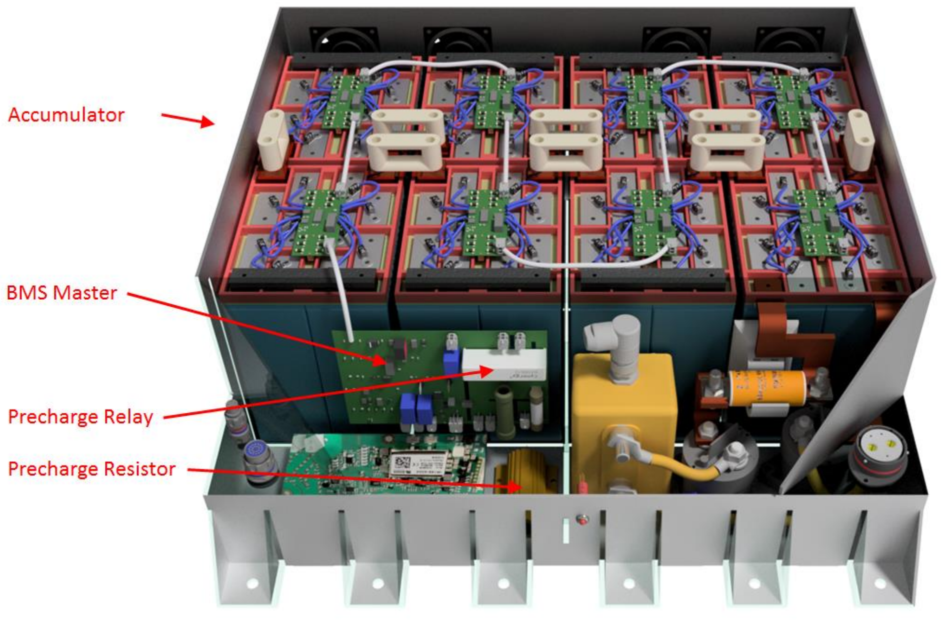

Figure 2.26 Precharge - Position

2.10 Discharge circuitry

2.10.1 Description

The discharge consists of a NC-relay connected in series with a fireproof-fusible resistor which discharges the capacitor bank in the inverter. The discharge circuitry is placed inside the inverter casing. The NC-relay is controlled by the shutdown circuit (connected in parallel with the precharge) so that the car discharges the capacitor bank if the shutdown-circuit is opened.

The resistor must handle the peak current for 15 seconds which results in a instantaneous power of 53.79W. For pulsed operation Vishay recommends to derate the power with a factor of equal to the square root of the duty ratio. Given that the discharging does not happen more often than every fifth minute and a discharge time of 15 seconds the derating factor, k, is equal to sqrt(0.25/5) = 0.2236. Which results in a needed power rating of 12W. A wirewound resistor is chosen to be able to handle the peak energy of the discharge. Further a fireproof-fusible resistor is chosen so that in a faulty case of permanent discharging it will open instead of short circuiting the battery. A 20W resistor were chosen to give some overhead.

2.10.2 Wiring, cables, current calculations, connectors

The discharge-relay/resistor is connected via a PCB and is further connected to the capacitor bank through orange colored 600V rated wires

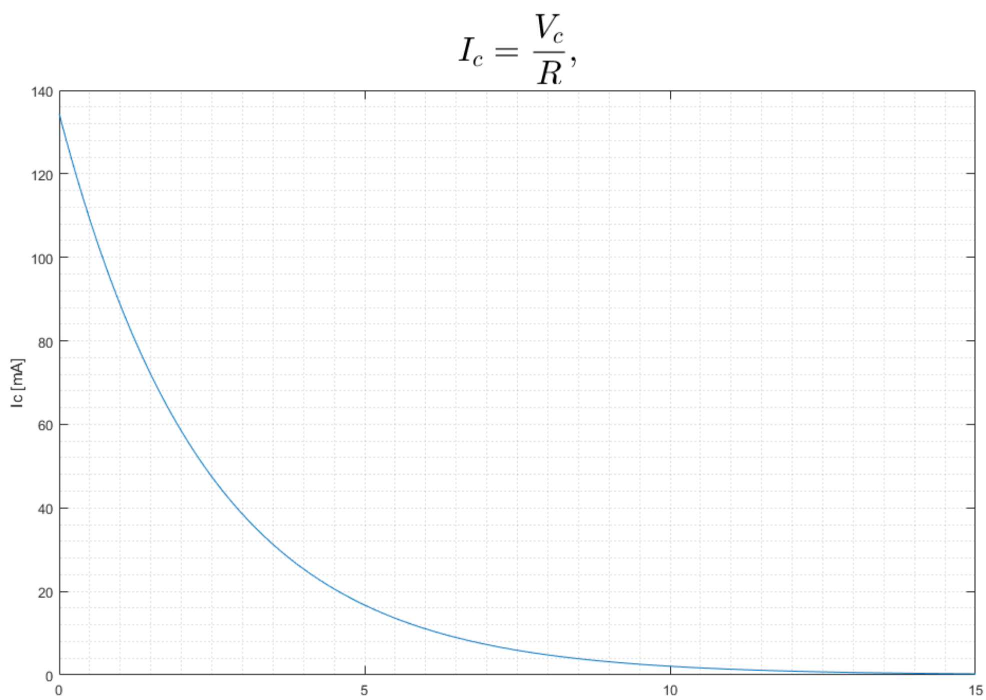

Figure 2.27 Discharge – Current over time

$$V_c = V \cdot e^{\frac{-t}{R \cdot C}},$$

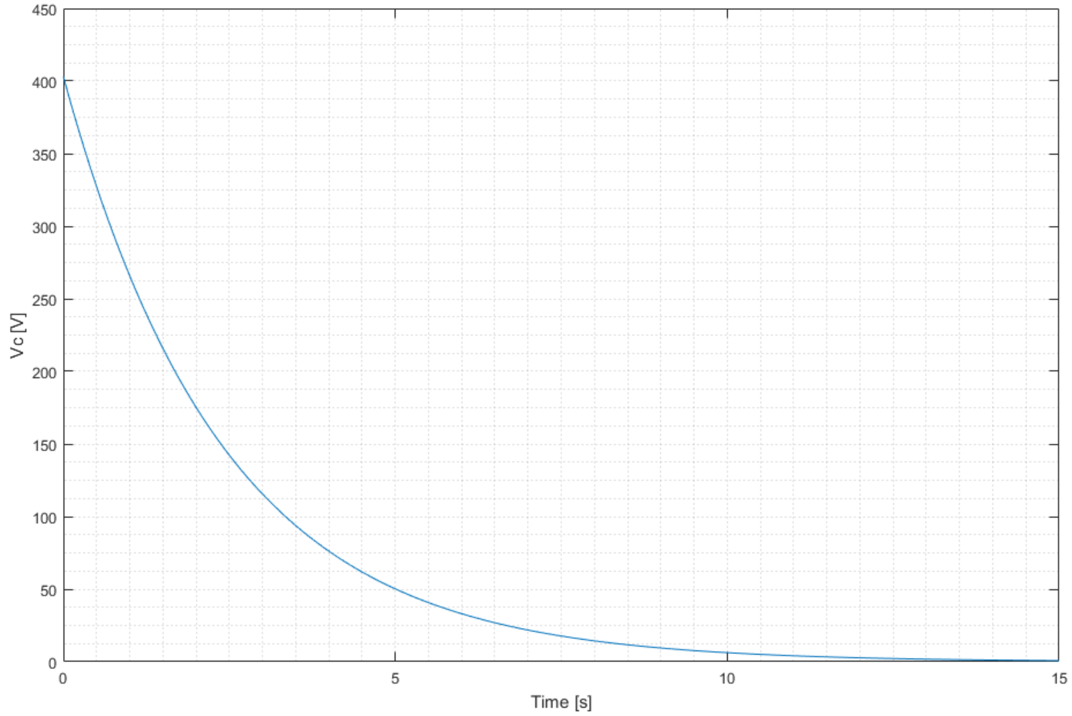

Figure 2.28 Discharge - Voltage over time

Resistor Type:	Vishay CP00253K000KE14-ND
Resistance:	3kΩ
Continuous power rating:	25W
Overload power rating:	125W for 5 sec
Voltage rating:	1000V
Maximum expected current:	133.4mA
Average current:	21.5084 mA (15 seconds)
Cross-sectional area of the wire used:	0.32 mm²

Table 2.10 General data of the discharge circuit

2.10.3 Position in car

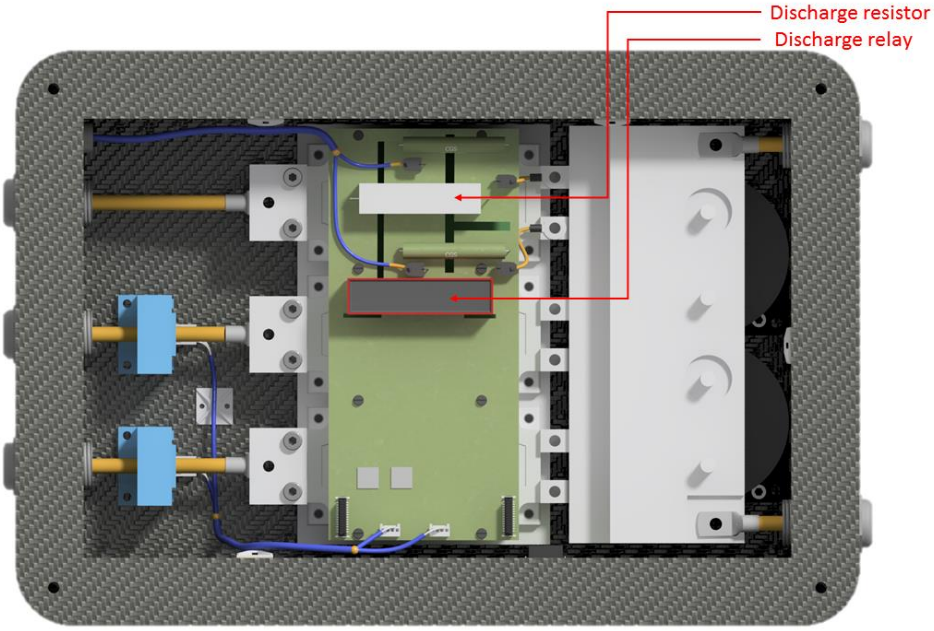

Figure 2.29 Discharge system – Position in Inverter

2.11 HV Disconnect (HVD)

2.11.1 Description

The High Voltage Disconnect is a Deutsch Autosport ASHD high current connector with interlock. The connector is clearly marked with instructions to disconnect so any untrained person can operate it quickly. The connector and internal circuitry is protected by a black POM casing glued permanently in place, to prevent any shocking hazard.

2.11.2 Wiring, cables, current calculations, connectors

The HVD is connected in series with the negative cable coming from the energy meter in the accumulator container. It continues to the motor controller where it is led through a gland and terminated with a cable shoe on the negative side of the capacitor bank. The female side is connected by cable crimps and the male side is terminated by a bus bar with screws.

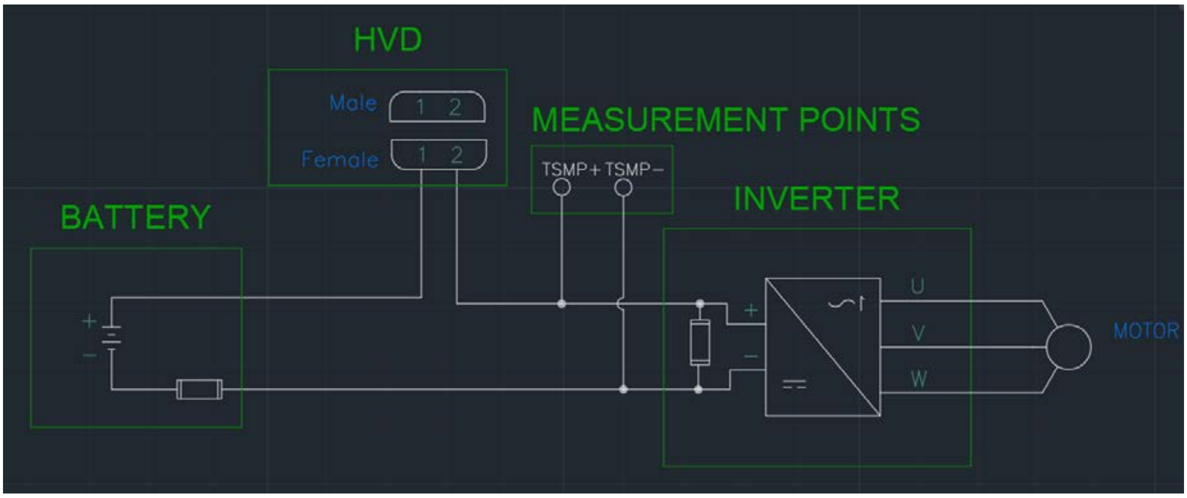

Figure 2.30 HVD connection - Schematic

2.11.3 Position in car

The HVD is located behind the left shoulder of the driver within the frame of the main hoop.

Figure 2.31 HVD - Position

2.12 Ready-To-Drive-Sound (RTDS)

2.12.1 Description

The Ready To Drive Sound (RTDS) is produced by a piezo buzzer (AE20M-12). Once the required start-up routine has been performed, the Engine Control Unit (ECU) will set a GPIO-pin high for two consecutive seconds. This enables the MOSFET driving the piezo buzzer.

The sound level is measured to be above 80 dBA, fast weighting in a radius of 2 meters at a 2.9kHz frequency.

2.12.2 Wiring, cables, current calculations, connectors

The piezo buzzer is connected to the RTDS control unit on the ECU by two wires. The wires are connected to the piezo buzzer by screw termination lugs at its terminals and fed through a common backplate connector for ease of removal during maintenance or inspection. At the ECU end, the wires are connected by crimp termination. Heat shrink tubing is used to prevent water intrusion. Wire used are TE Connectivity M22759.

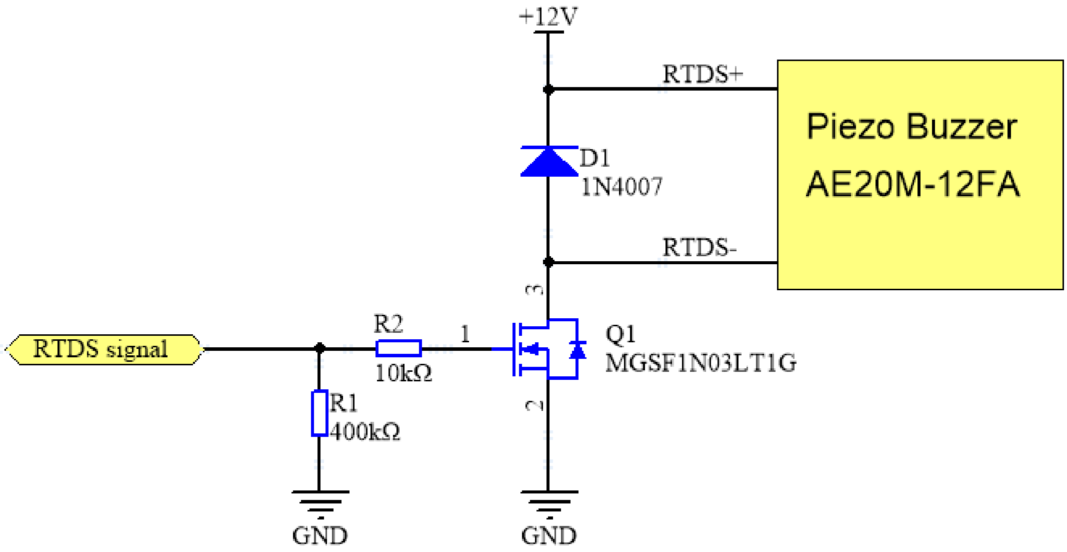

Figure 2.32 RTDS - Schematic

2.12.3 Position in car

The RTDS piezo buzzer is mounted on the back plate at the rear end of the vehicle. Its position is highlighted by a red arrow in the Computer Aided Design (CAD) render below.

Figure 2.33 RTDS - Position

3 Accumulator

3.1 Accumulator pack 1

3.1.1 Overview/description/parameters

The accumulator pack are mainly build to be the energy source for the electric motors. The accumulators energy source consist of 288 lithium cobalt oxide battery cells, which gives the accumulator high capacity according to size.

The accumulator is divided into two main segments. The relay- and monitor- systems for the accumulator is located in the front and the cells and the coupling are located in the back. The cells are divided into 8 new segments to reduce the amount of energy and voltage below 120VDC and 6MJ from rule EV3.3.3. Each segment has a 12s3p configuration 44.4VDC nominal, 21Ah and 5.2Kg. The accumulator container is cooled by 4 fans controlled by the BMS.

The accumulator is fastened to the vehicle's floor with 6 M8 bolts in the front, and two brackets at the rear of the battery casing. The fasteners will be accessible from drivers location.

Maximum Voltage:	403.2VDC
Nominal Voltage:	355VDC
Minimum Voltage:	288VDC
Maximum output current:	420A for 2s
Maximum nominal current:	315A
Maximum charging current:	14A
Total numbers of cells:	288
Cell configuration:	96s3p
Total Capacity:	30.48 MJ
Number of cell stacks < 120VDC	8

Table 3.1 Main accumulator parameters

3.1.2 Cell description

The cells used in the accumulator are Melasta SLPB7858150 pouch cells.

Cell Manufacturer and Type	Melasta
Cell nominal capacity:	7 Ah
Maximum Voltage:	4.2 V
Nominal Voltage:	3.7V
Minimum Voltage:	3.0V
Maximum output current:	20C for 2s
Maximum nominal output current:	15C
Maximum charging current:	2C
Maximum Cell Temperature (discharging)	60°C
Maximum Cell Temperature (charging)	45°C
Cell chemistry:	$LiCoO_2$

Table 3.2 Main cell specification

3.1.3 Cell configuration

Cell configuration The battery pack consist of 36 cells connected as 12S3P with a maximum Voltage at 4.2 V * 12 = 50.4 V.

$$\text{Energy pr. segment} = \frac{4.2V * 7Ah * 36cells}{1000Wh} * 3.6 = 3.81MJ$$

Figure 3.1 Battery segment – Formula for energy per segment

The celltab are guided through an PCB sheet, then they are bent over and connected with Aluminium bar on top of the celltab, and a PCB trace on the bottom. They are fastened together with screws.

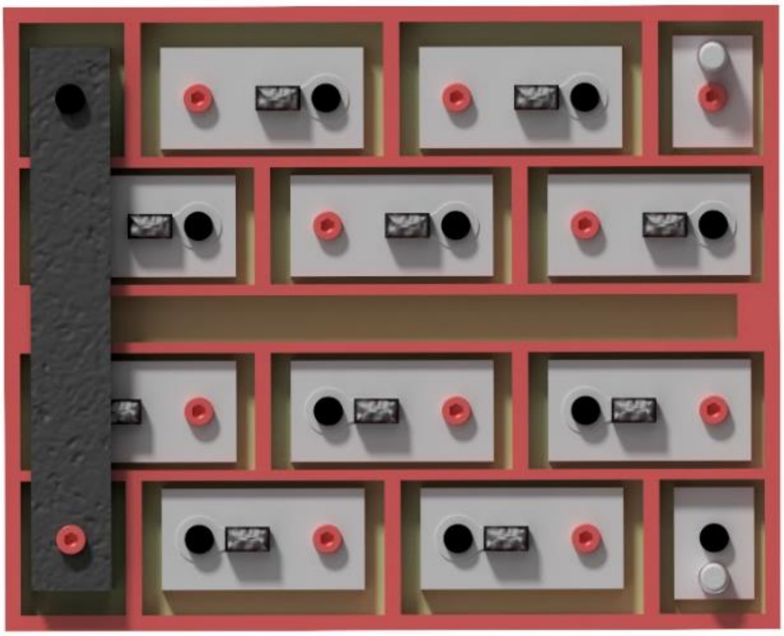

Figure 3.2 Battery cell – Visual configuration

3.1.4 Cell temperature monitoring

The BMS slave board monitors the cell temperature on each negative terminal through 12 Negative Temperature Coefficient (NTC) thermistors. The thermistor is placed on the aluminium bar 5.5mm from the celltab. The BMS slave board reads the thermistors and transfers the information to the BMS master.

3.1.5 Accumulator insulation relays

We use two normally open AIRs of the type GIGAVAC GV200BAB-1, one on each pole. They are capable of switching 500 + amps at a maximum of 800VDC. As according to EV3.5.4 in the FSAE-Rules, both of the AIRs are NO type.

Relay Type:	GIGAVAC GV200BAB-1
Contact arragment:	SPST-NO
Continous DC current rating:	350A
Overload DC current rating:	2000A for 25sec
Maximum operation voltage:	800VDC
Nominal coil voltage:	12VDC.
Normal Load switching:	Make and break up to 350A
Maximum Load switching	2 times at 1860A

Table 3.3 Basic AIR data

3.1.6 Fusing

The fuse used is the EV25 from EATON Bussman. This fuse will be mounted behind the AIR on the negative pole as shown on the figure below.

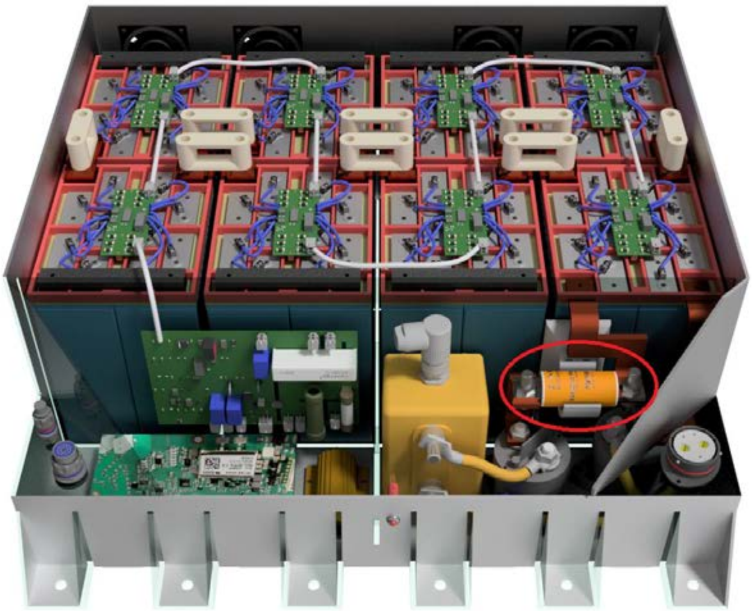

Figure 3.3 Fuse - Position

Fuse type:	EATON Bussmann EV25-125
Continous current rating:	125A
Maximum operating voltage	500VDC
Type of fuse:	Electric Vehicle
I2t rating:	3620A2s at 500VDC
Interrupt Current (maximum current at which the fuse can interrupt the current)	20 000A

Table 3.4 Basic fuse data

Location	Wire Size	Wire Ampacity	Fuse type	Fuse rating
Cells to AIRs	3/0 AWG	200A @ 75C	EATON Bussman EV25	125A
AIR to Motor controller	4 AWG	274A	EATON Bussman EV25	125A

Table 3.5 Fused HV wires - Spesification

3.1.7 Battery management system

We use Linear Technology's LTC6804-2 multicell battery monitor Intergrated Circuit (IC). Each battery segment is fitted with one BMS slave board, providing over-/ under voltage protection, cell balancing and temperature sensing at every parallel cell coupling. The BMS slave boards connected to a BMS master located in the front of the accumulator. The BMS master monitors the system and interfaces with the vehicle control unit via CAN-bus.

Each PCB trace used for voltage sensing is protected by a fuse from Schurter (USF 0603 0.75A).

If any cell voltage reaches 4.1V the BMS will enable cell voltage balancing to get all the cell voltages to the same set value. If a cell voltage below 3.2V is detected the BMS will open the shutdown circuit to avoid permanent cell damage.

If the cell temperature on one cell exceed 50°C the BMS master will give a fault. A failure mode output on the BMS is connected to a dedicated circuit, if a failure is detected by the BMS a relay will open and break the shutdown circuit. In case of a trigger, the relay will need to be manually reset, by turn off and on the GLVMS

BMS Slave IC	LTC6804-2
Support number of voltage measurements	12
Supply voltage	75V
Maximum current drain	13,3mA
Maximum Measuring error	1,2mV
Communication	isoSPI

Table 3.6 BMS Slave - Spesification

BMS master IC	STM32F407VGT
Maximum input voltage	6-36V
Maximum operating temperature	90°C

Table 3.7 BMS Master - Spesification

A BMS board senses each parallel cells in one pack, resulting in 12 measuring points for each board. Each PCB track used for sensing is protected by a fuse. Communication wires between each BMS board between the BMS master is galvanically isolated by a 1:1 transformer.

The BMS will send out a logic high as long as the system is ok. If a fault is detected or the GLV power to the BMS is lost, it will give a logic low. The dedicated circuit will open the shutdown circuit which opens the AIR's.

The galvanic isolation for the BMS is located on each slave board. This galvanic isolation is located just before the connector for the communication lines between each slaves and to the master.

3.1.8 Accumulator indicator

The accumulator indicator is put together by a resistor in series with a LED. This is connected outside the AIRs on the main output. The resistor value is chosen to limit the current to 20mA when the battery is fully charged. The power dissipation over the resistor is 8W, the resistor is of the type wire wound 20W.

$$R = \frac{403.2V}{20mA} \approx 20kOhm$$

Figure 3.4 Formula - Accumulator indicator dropdown resistor

If any voltage above the LEDs forward voltage is present at the main output, the LED will light up. The LED is placed in front of the container and is the first thing you see when removing the firewall. The accumulator still work when the Accumulator is removed from the car. All high voltage PCB traces have more than 4mm spacing to comply EV4.1.7.

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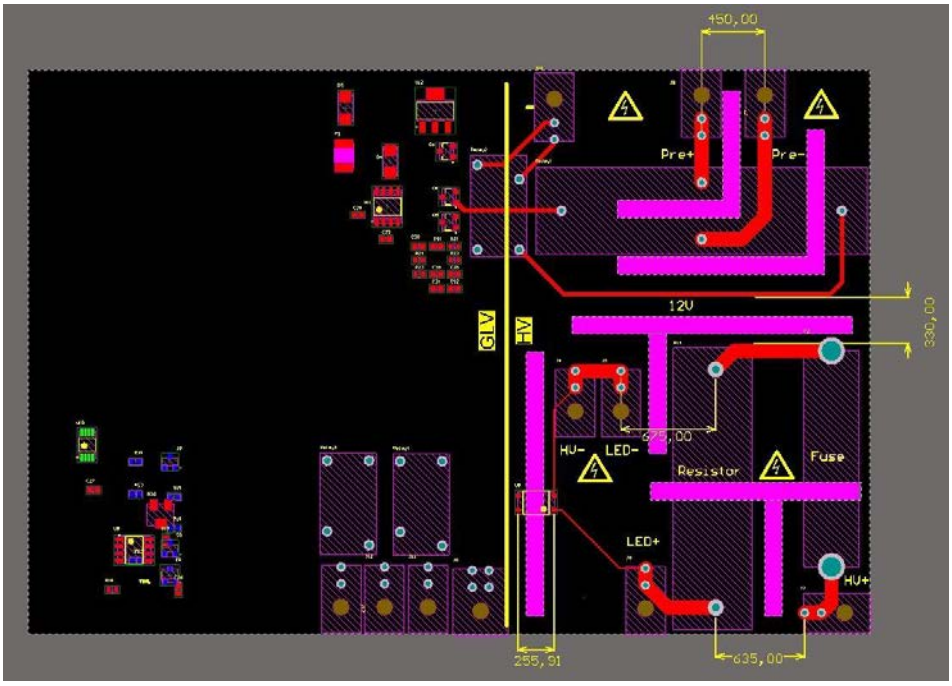


Figure 3.5 Accumulator indicator - High voltage PCB spacing

3.1.9 Wiring, cables, current calculations, connectors

Cells are connected 96s3p as shown (refferer til celle konfirurasjon bilde). Each cell pack will be connencted togheter with maintenece plugs. The accumulator lid works as a locking mechanism keeping the maintenance plugs in place. The lid is fastened on every side of the casing, keeping the maintenance plugs securely in place. The top of the maintenance plugs are made of a nonconductive material, the conductive part is of aluminium.

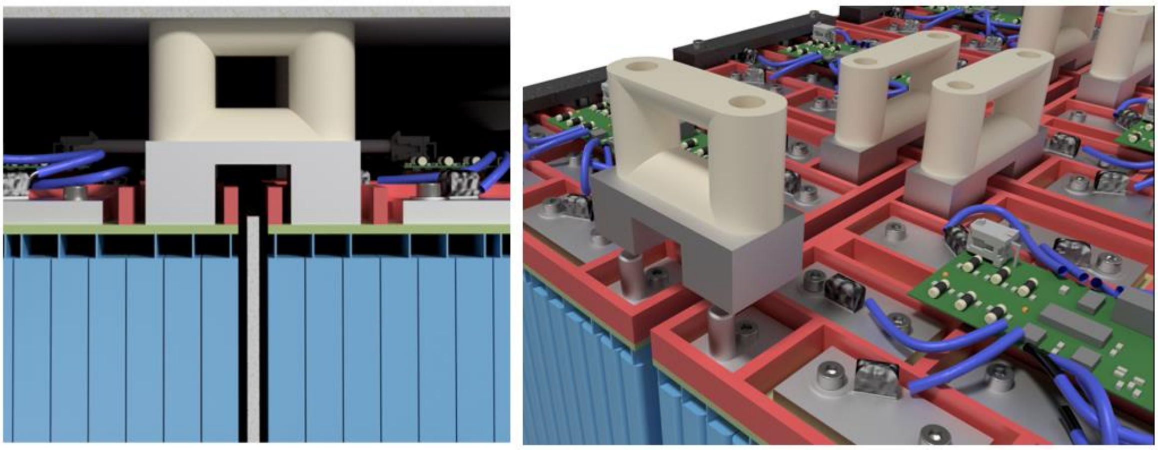


Figure 3.6 Maintainance plugs

Absolute DC pack current will be:

$$A = \frac{80kW}{325V} = 246A$$

Figure 3.7 Formula - Peak current

The max continuous current the battery is rated for is 315A. Nominal current drain is about 50-60A.

At low speed the AC-output voltage will be low so the maximum peak current (340A) that the motor is rated for will be reached. The output power will not excceed 80kW at any time.

Wire type	Coroplast High voltage cable
Continuous current rating:	216 A
Cross-sectional area	25 mm²
Maximum operating voltage:	600VDC
Temperature rating:	180 °C
Wire connects the following components:	Accumulator, Energy meter, HVD and Motor controller

Table 3.8 Wire data of Coroplast, 25 mm²

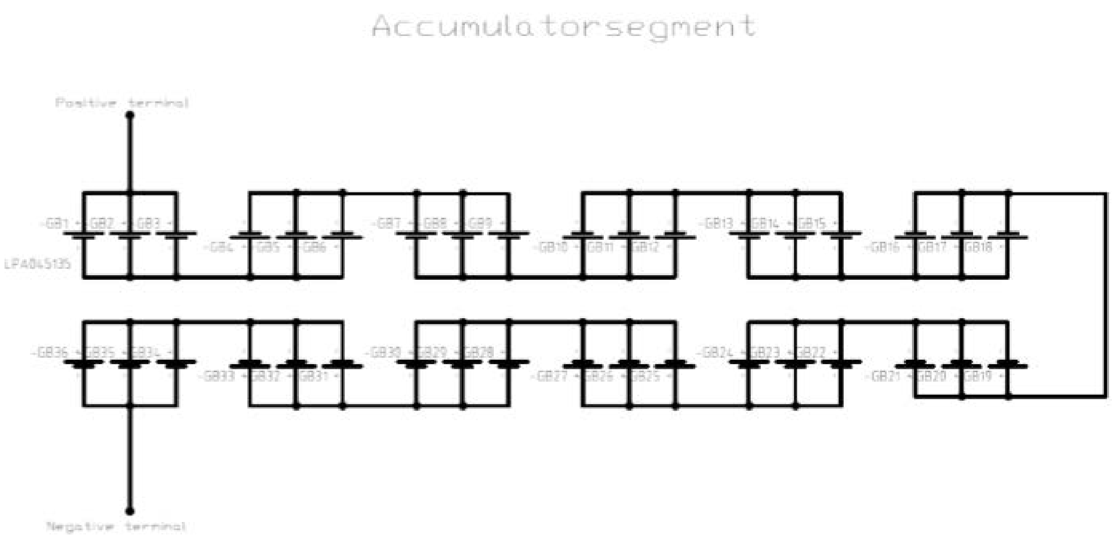


Figure 3.8 Battery cell – Schematic configuration

3.1.10 Charging / Chargers

The charger is a Brusa NLG513, which is placed in our battery charger hand cart. The charger communicates with the BMS over CAN-Bus, and will stop the charging process and open AIRs if any failure is detected. An emergency stop button (S1) will be mounted outside our hand cart to disable charging immediately. IMD is connected inside the accumulator container and open the AIRs through the shutdown circuit if any fault is detected. The charger will be connected to the accumulator with a connector from Deutsch Autosport

Charger Type:	Brusa NLG513
Maximum charging power:	3.7kW
Maximum charging voltage:	520V
Maximum charging current:	12.5A
Interface with accumulator	CAN-Bus.
Input voltage:	230 VAC
Input current:	16A

Table 3.9 General charger data

3.1.11 Mechanical Configuration/materials

The container is made of 4mm aluminium in bottom and 2.5mm aluminium on the sides and top. All cells are mounted with the tabs pointing up in eight separate banks.

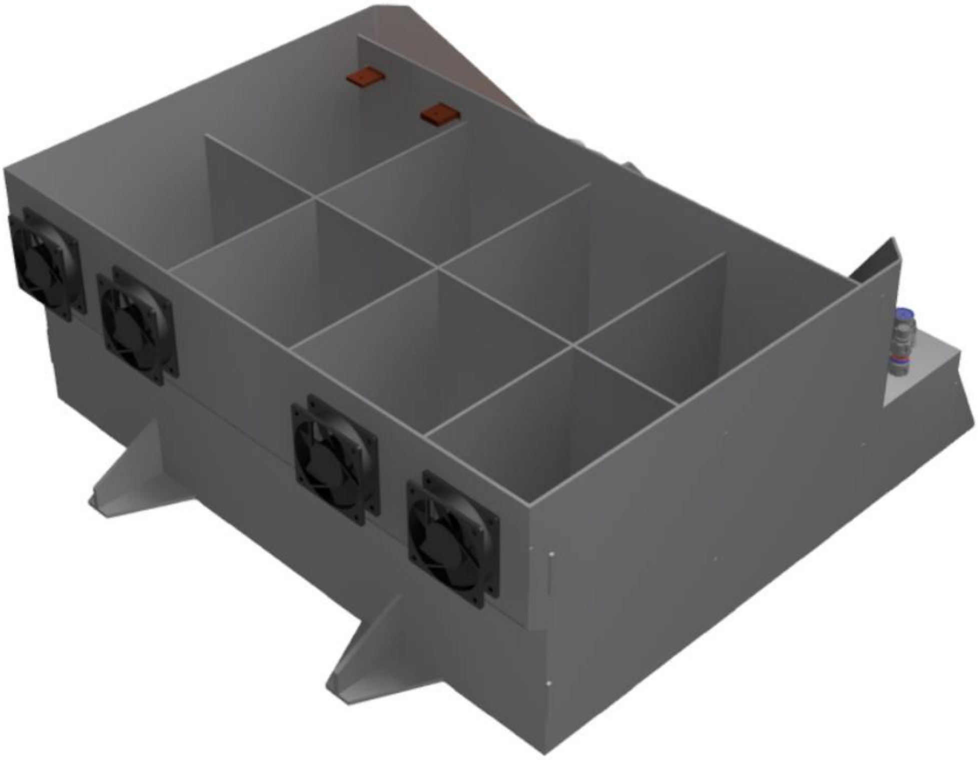


Figure 3.9 Accumulator - Casing

3.1.12 Position in car

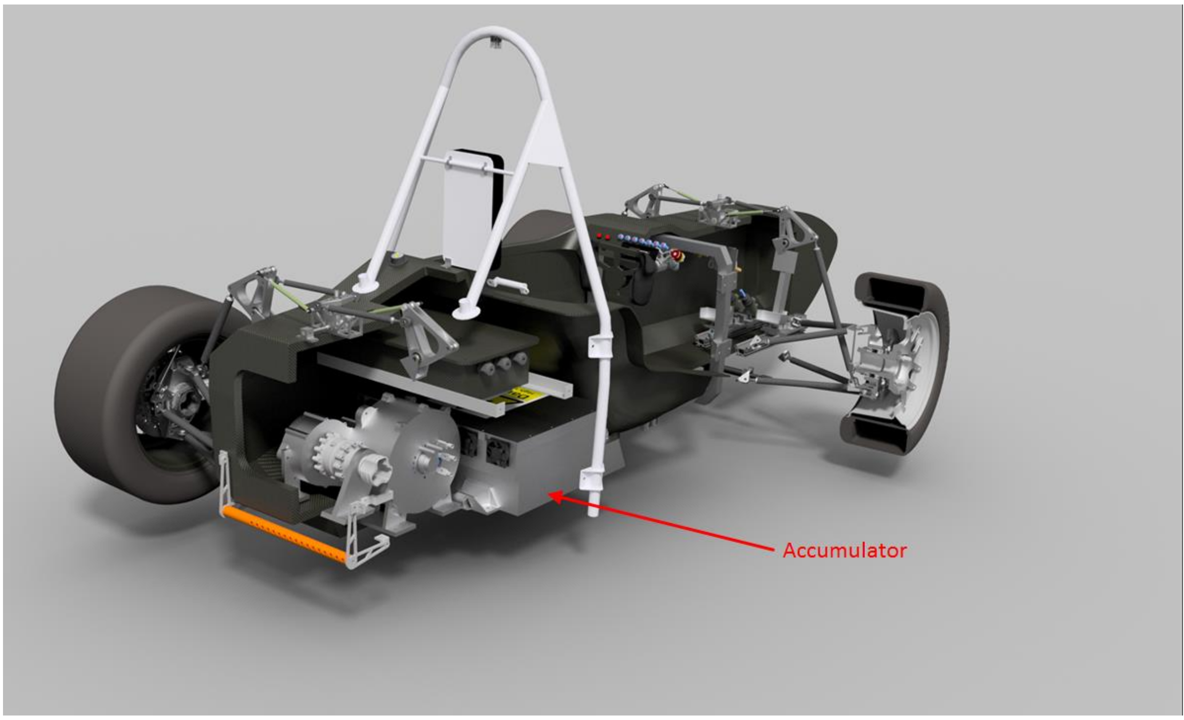


Figure 3.10 Accumulator - Position

4 Energy meter mounting

4.1 Description

The energy meter is mounted inside of the accumulator case between the main power connector of the battery and to one of the AIR's.

4.2 Wiring, cables, current calculations, connectors

The main power from the negative potential AIR is connected to the HV- #1 terminal of the Energy meter and the HV- #2 terminal connects to the main power output terminal of the battery. The HV+ connection is connected to the positive potential AIR and the 12V supply is directly connected to the GLVMS through the low-voltage connector of the battery.

4.3 Position in car

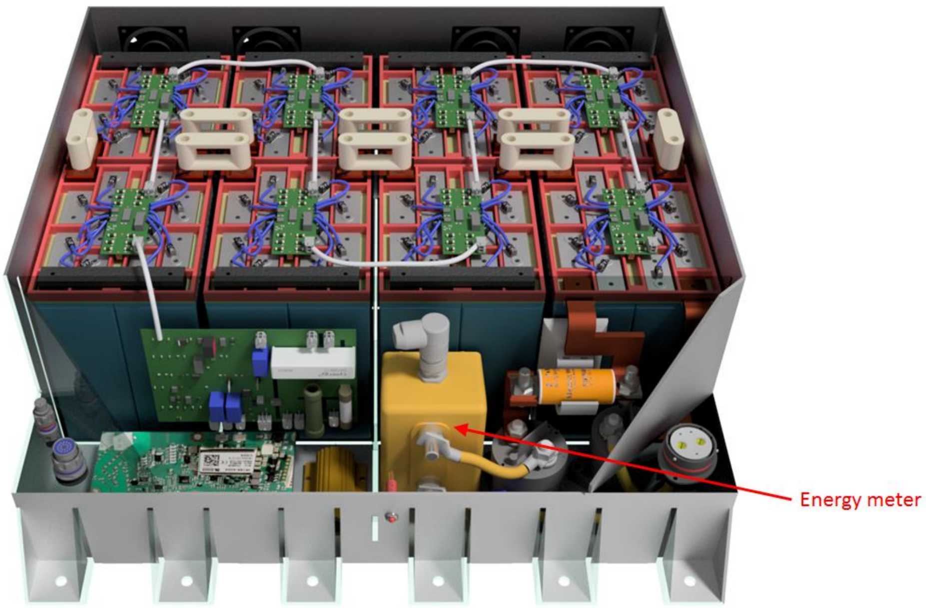


Figure 4.1 Energy meter - Position

5 Motor controller

5.1 Motor controller 1

5.1.1 Description, type, operation parameters

The motor-controller is a Bamocar D3 400-400 that inverts the DC current from the battery and simulates 3-phase AC on the output. The motor is controlled with a torque input from the pedal through the ECU that controls a current regulator in the motor-controller

Motor controller type:	UniTek BAMOCAR D3-400-400
Maximum continous power:	80kW
Maximum peak power:	140kW for 10s
Maximum Input voltage:	400VDC
Output voltage:	3x260VAC
Maximum continuous output current:	200A
Maximum peak current:	400A for 5s
Control method:	CAN-bus
Cooling method:	Water
Auxiliary supply voltage:	12VDC

Table 5.1 General motor controller data

5.1.2 Wiring, cables, current calculations, connectors

From the accumulator container, the positive wire connects with a cable shoe on the positive terminal of the capacitor bank in the motor-control box, through a cable gland in the wall. The negative wire connects to the HVD in series before going through a cable gland and fastened with a cable shoe to the negative terminal of the capacitor bank in the motor-controller box.

Wire type:	Coroplast High Voltage, 25mm^2
Current rating:	274A
Maximum operating voltage:	600V
Temperature rating:	180 °C

Table 5.2 HV wire - Spesification

5.1.3 Position in car

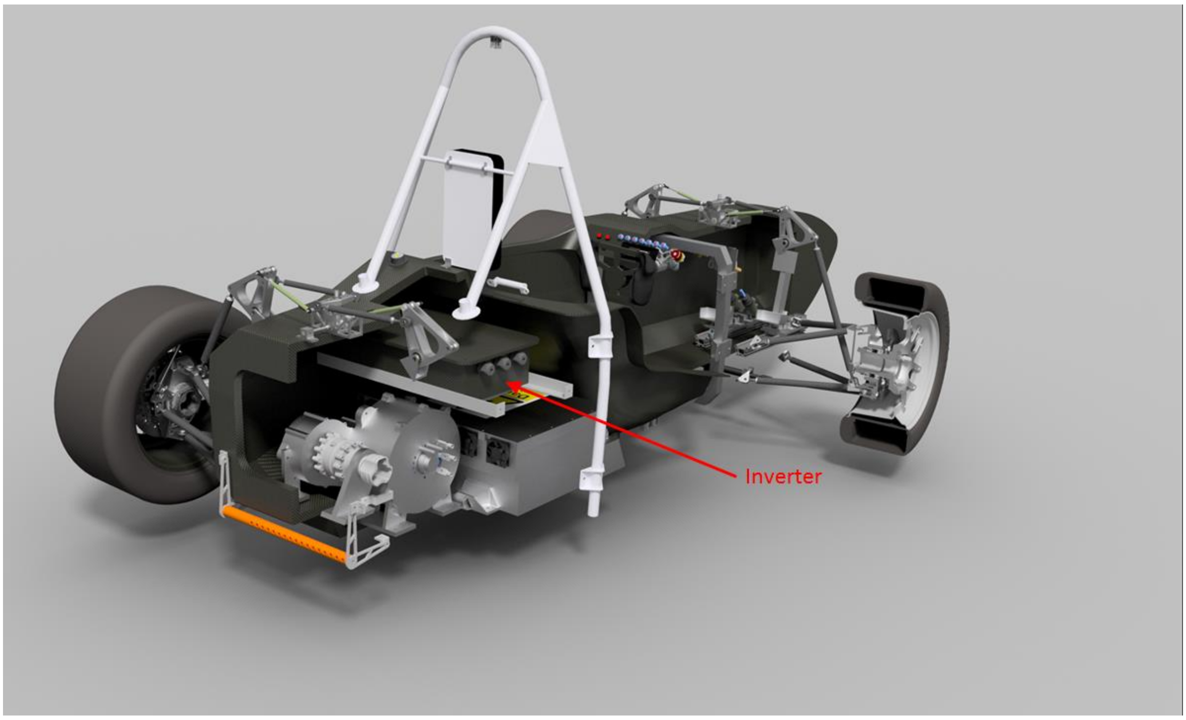


Figure 5.1 Inverter – Position in car

6 Motors

6.1 Motor 1

6.1.1 Description, type, operating parameters

The motor is manufactured by Enstroj, type EMRAX 228 Medium voltage with liquid cooling. It is mounted inside an aluminum casing on a gear and differential that powers both rear wheels

Motor Manufacturer and Type:	Enstroj EMRAX 228
Motor principle	Permanent Magnet Synchronous Motor
Maximum continuous power:	28-42kW (depends on motor RPM)
Peak power:	100kW
Input voltage:	250VAC
Nominal current:	160A
Peak current:	340A
Maximum torque:	240Nm
Nominal torque:	125Nm
Cooling method:	Water

Table 6.1 General motor data

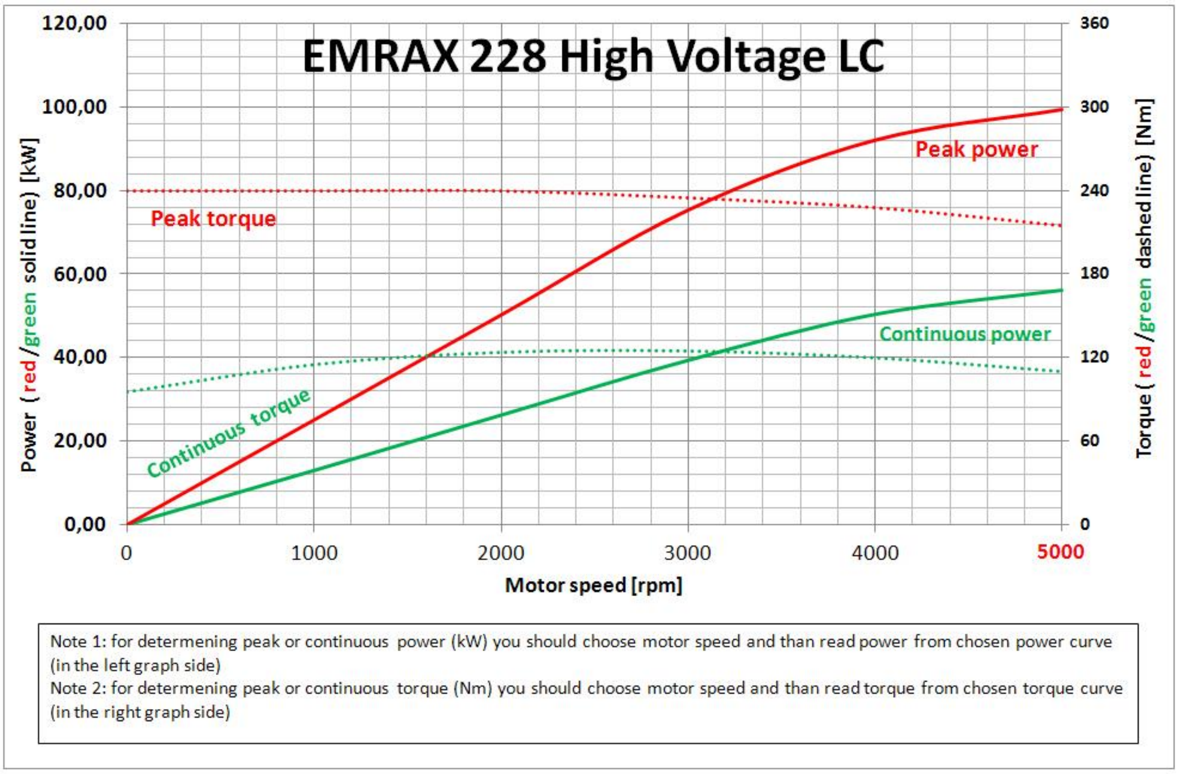


Figure 6.1 Inverter - Power and Torque graph

6.1.2 Wiring, cables, current calculations, connectors

Describe the wiring, show schematics, provide calculations for currents and voltages and show data regarding the cables and connectors used.

6.1.3 Position in car

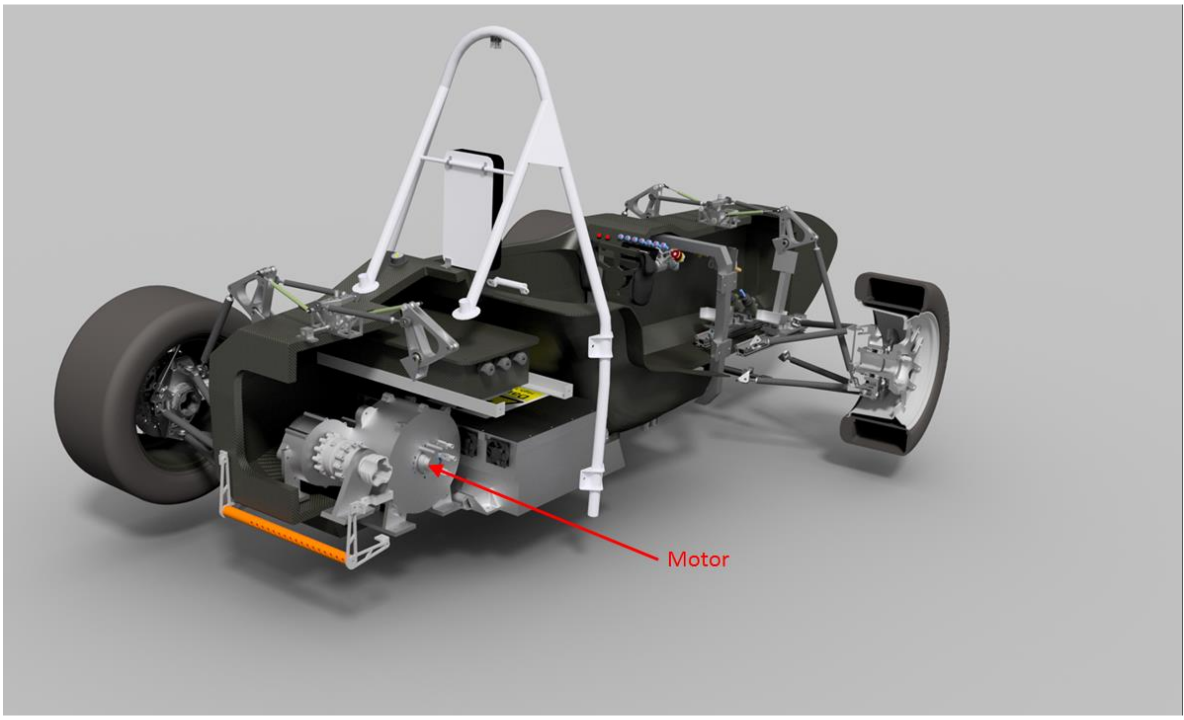


Figure 6.2 Motor – Position in car

7 Torque encoder

7.1 Description/additional circuitry

Two separate linear potentiometers are used as torque encoders. They are mounted with a slight offset relative to each so that they will have their own positively sloped transfer functions. They also be mounted in a manner such that the linear travel is never fully extended or retracted. This is done both to ensure the sensors are not damaged by mechanical distress, but also to ensure that the sensors only can return ground voltage or overvoltage when a sensor fault is present.

Torque encoder manufacturer and type:	Active Sensors MLS1322-050 V1
Torque encoder principle:	Potentiometer
Supply voltage:	5V
Maximum supply current:	2.5mA
Operating temperature:	-30 to +125 °C
Used output:	0-5V

Table 7.1 Torque encoder data

7.2 Torque Encoder Plausibility Check

The ECU buffers the sensor outputs before the signal is digitized by the internal 12-bit ADC's in a STM32F407 microcontroller. In software the ECU calibrates the pedal position based on the accelerator pedals fully retracted and extracted position. Since the torque encoders are mounted in a position which prevents them from output 0 or 5 volts, the out of range signals will be interpreted as sensor faults. The software also checks the torque encoders position relative to each other. If the deviation is greater than 10% the ECU will disable the motor controller until the deviation is less than 10%. This way the driver is unable to provide torque to the motor while the implausibility occurs regardless of throttle position.

7.3 Wiring

The torque encoders are wired directly to the ECU with separate 3-pin Deutsch DTM-series connectors at the sensor end (MPN: DTM063S-E007, MPN: DTM043P-E003). This way it is easy to unplug any of the sensors at the scrutineering to demonstrate that torque encoder plausibility check works. The wire used is an isolated 3 core 24AWG Alpha Wire (MPN: B953033).

7.4 Position in car/mechanical fastening/mechanical connection

The torque encoders are mounted in parallel with the accelerator pedal return springs. They are bolted to the pedal and base via the sensors rod ends as illustrated by the CAD-renders below.

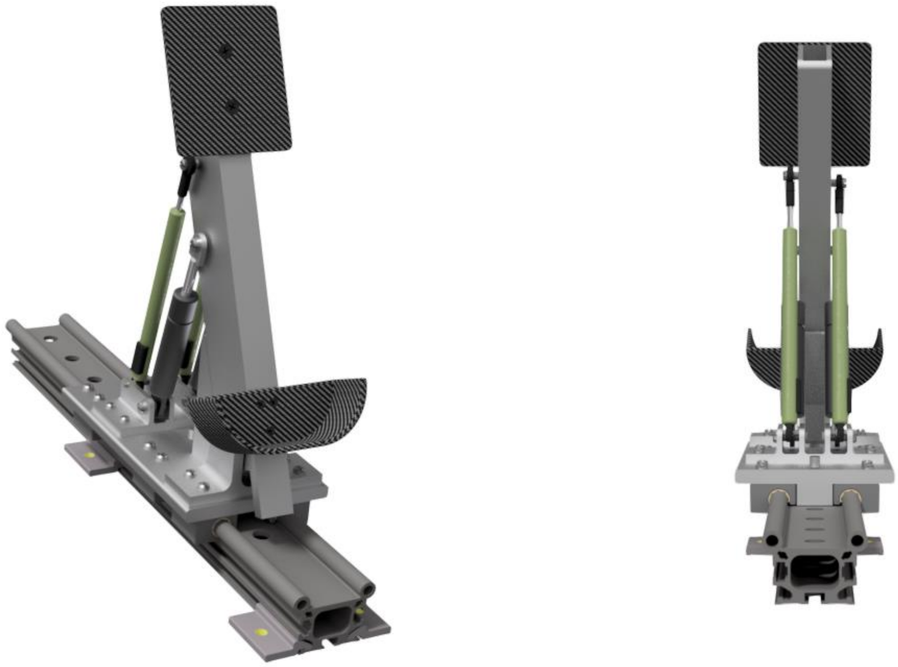


Figure 7.1 Torque encoder - Position on pedal

CAD render of the torque encoders position on the accelerator pedal.

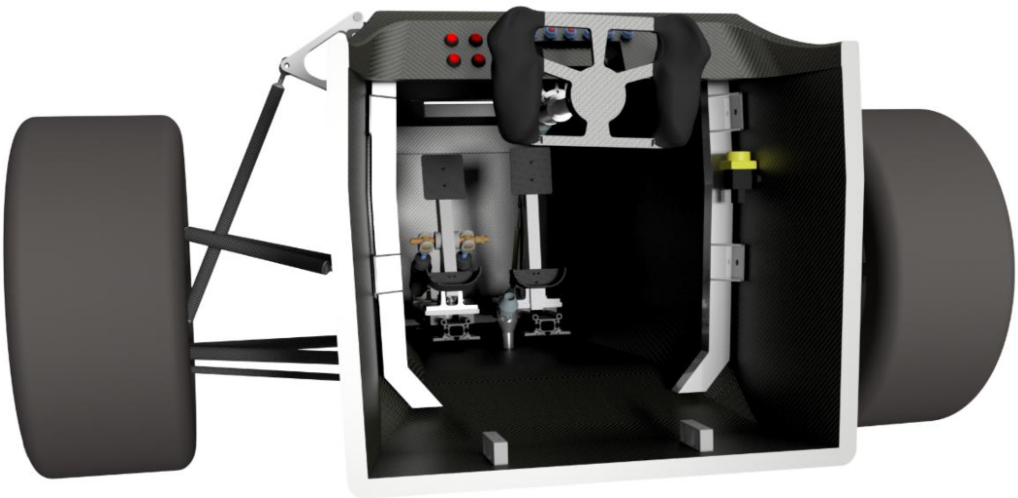


Figure 7.2 Torque encoder - Position in car

8 Additional LV-parts interfering with the tractive system

8.1 Engine control unit (ECU)

8.1.1 Description

The ECU is a self designed control module consisting of multiple STM32F407 microcontrollers. The module collects and processes signals from several sensors throughout the vehicle. It communicates with the other modules in the vehicle via CAN-bus. The main task of the ECU is send torque requests to the motor controller, while ensuring safe operation. This includes different modes of operation, sensor failure checks, a start-up routine, plausibility checks etc.

The ECU includes two features for extra redundancy in the safety systems. A NO relay is connected in series with the shutdown circuit, which will isolate the tractive system if certain safety parameters or critical fail checks are exceeded. It also has the possibility to disable the run signal to the motor controller, which makes the user unable to provide torque to the motor regardless of the throttle position

ECU functions include:

- Provide signal for the RTDS piezo buzzer.
- Provide the brake light signal
- Regulating backplate fans.
- Regulating the radiator fan.
- Regulating torque request.
- Torque encoder plausibility check
- Brake pedal plausibility check
- Able to open the shutdown circuit
- Able to disable the motor controller
- Illuminate fault LED in the dashboard.

8.1.2 Wiring, cables,

The ECU use three different types of wires to connect with the different parts in the car. The CAN-bus line is connected to the Motor controller, the Dashboard module, the BMS module and the Logger circuit with a 1 pair Raychem spec 44 twisted cable (MPN: 44A1121-22-2/6-9). The sensors are wired with a 3 core cable described in the Torque encoder wiring chapter. The Shutdown Circuit, backplate, buttons and the LEDs are connected to the ECU with a stranded single core 22AWG Raychem spec 55 wire (MPN: M22759/32-22-9).

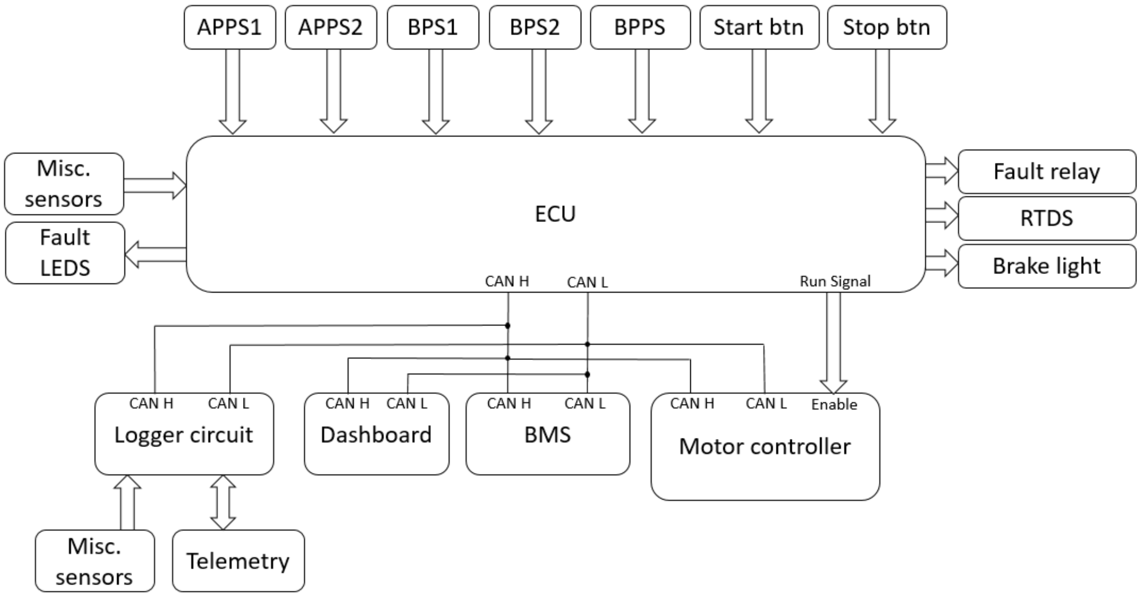


Figure 8.1 ECU - Connection overview

8.1.3 Position in car

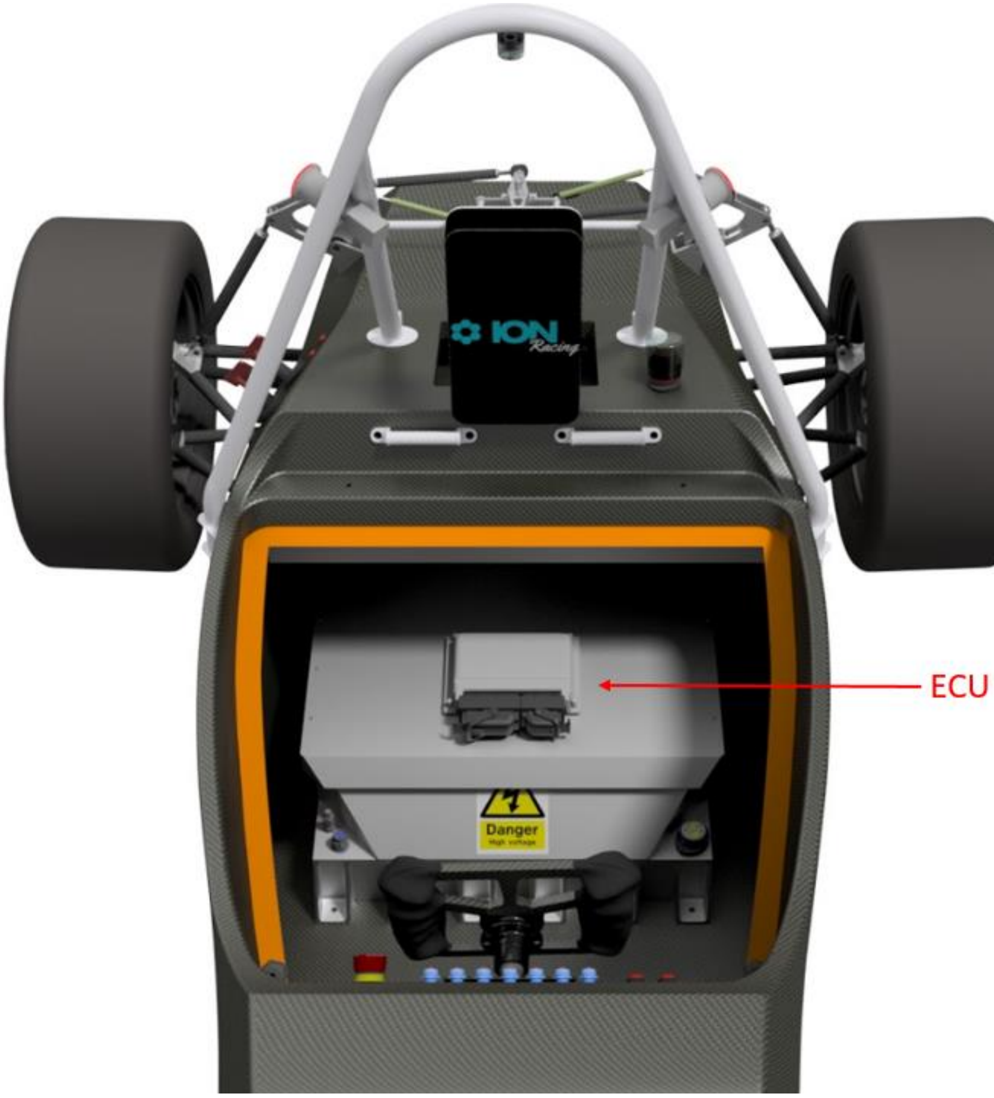


Figure 8.2 ECU – Position in car

8.2 GLV 12V battery

8.2.1 Overview

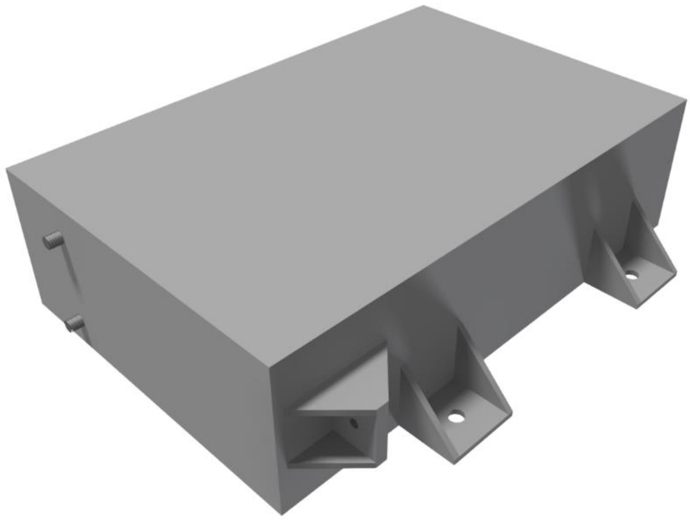


Figure 8.3 GLV battery - Casing

Accumulator pack 2 are mainly used to supply power to all low voltage devices on the car. The accumulator pack is made up by eight Polymer Li-ion battery-cells in 4S2P configuration. The pack are divided in two parts: the battery-cells and the BMS.

Max Voltage	16.8VDC
Nominal Voltage	14VDC
Minimum Voltage	12VDC
Maximum nominal discharge current	112A
Peak discharge current	154A @ 2sec
Maximum charging current	14A
Peak charge current	56A @ 1sec
Total number of cells	8
Total capacity	14Ah

Table 8.1 GLV battery - Spesification

8.2.2 Cell Description

The cells we are using are Melasta LPB042126. The chemistry is made of Lithium-Polymer (LIP).

Cell manufacturer and type	Melasta LPB042126
Nominal cell capacity	7Ah
Maximum voltage	4.2V (+/- 0.03V)
Nominal voltage	3.7V
Minimum voltage	3.0V
Peak output current	77A for 2 seconds
Nominal output current	56A
Nominal charge current	14A
Maximum cell temperature charge	45℃
Maximum cell temperature discharge	60℃
Cell chemistry	LiPo

Table 8.2 GLV battery - Cells

8.2.3 Cell configuration

The accumulator pack consists of eight cells in the 4S2P configuration, with a maximum voltage of 3.7V*4 = 14.8V

$$Energy\ per\ segment = \frac{4{,}2V * 7aAh * 8celler}{1000Wh} * 3{,}6 \approx 0.847MJ$$

The celltabs are bent and soldered on a PCB, which are connected to the BMS.

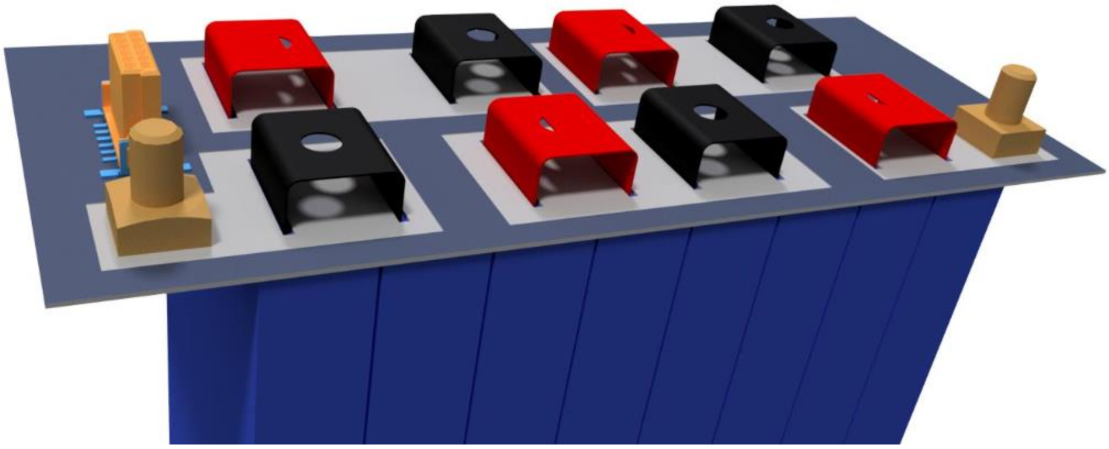


Figure 8.4 GLV battery - Cell configuration

8.2.4 Cell temperature monitoring

We monitor the temperature using thermistors of type AVX 10kΩ 1206 Control Protection NTC Thermistor. They will be placed next to the negative terminal of each parallel-connection.

8.2.5 Battery protection circuit

The charge/discharge of the battery is controlled by two relays of the type Willow Durakool DG20-series and diodes of the type Vishay VBT3045BP-E3/4W. A HV logic signal is sent from the Central Processing Unit (CPU) to the relay to switch it. If the battery gets heavily discharged, the charge- and discharge-relays are disabled and a precharge-MOSFET is enabled. The mosfet is a Single P-channel MOSFET of type BSS84L. The BMS CPU detects when the cells are charged to a level to which it won't take damage by the *surge* currents. Then the battery charges as normal.

Relay type	Willow Durakool DG20-7021-35-1012
Contact configuration	SPNO
Maximum continuous current	30A
Maximum switching voltage	16VDC
Maximum switching current	30A
Coil power	0.55W
Coil resistance	254 ohm

Table 8.3 GLV battery – Air Relay

MOSFET type	BSS84L Power MOSFET Single P-Channel
Drain-source-voltage	50VDC
Gate-source-voltage	+/- 20VDC
Continuous Drain current	130mA
Total power dissipation	225mW
Operating temperature range	-40..150°C

Table 8.4 GLV battery - AIR mosfet

8.2.6 Fuse

The fuse-type is Schurter 0090.0025

Fuse type	Schurter 0090.0025
Current rating	25A
Fuse speed	Fast
Breaking capacity at max voltage	20kA
Operating temperature range	-40..85°C
Voltage rating	1000VDC

Table 8.5 GLV battery - Fuse

8.2.7 Battery Management System

We make the BMS ourself, and for the CPU we use an ATmega406 AVR. This CPU is made especially for battery purposes, and have a built-in voltage regulator. It can monitor up to four battery-cells from 4-25V.

From the CPU we can gather information and state of the battery pack via SMBus to a *STM32* microcontroller which is used to send the information via CAN-bus to our own analysis-software. Through this, we can monitor temperature, State Of Charge (SOC), current etc. in real time.

The ATmega406 has an internal cell-balancing Field Effect Transistor (FET) for each of the four cells in the battery pack.

BMS CPU	ATmega406 AVR
Operating voltage range	4..25VDC
Maximum supply current (active)	1.2mA
Maximum output current	5mA
Regulated output voltage range	3.25..3.35VDC
Cell balancing current	2mA (typical)

Table 8.6 GLV battery - Battery management system

8.2.8 Position in car

The 12V battery is placed in the rear right of the car, relative to the driver, in close proximity to the GLVMS. It is mounted on the inside wall of the monocoque, highlighted in red in the picture below.

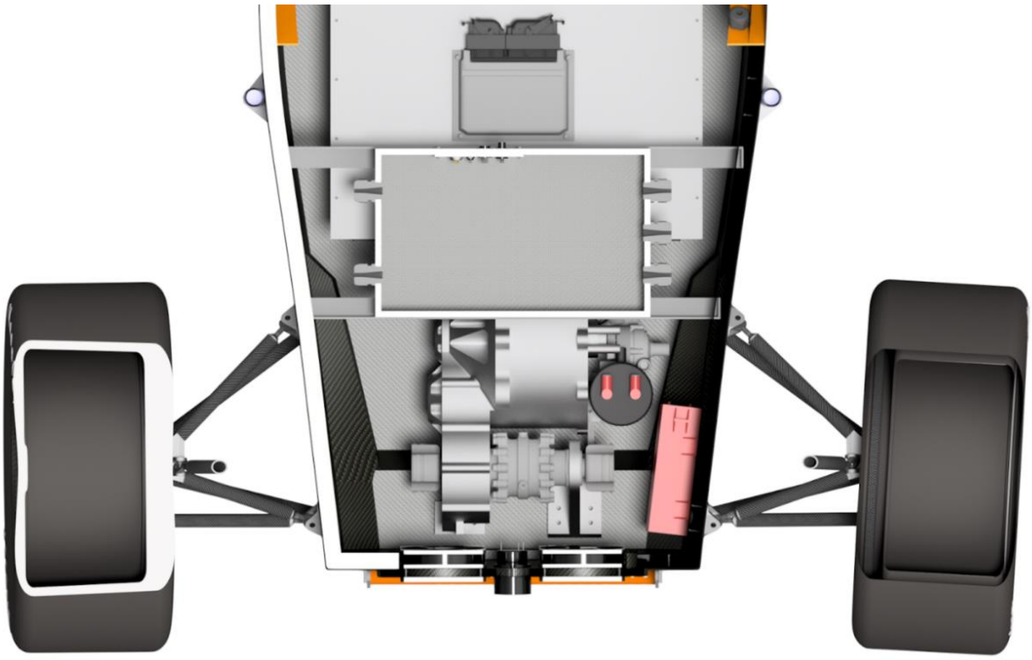


Table 8.7 GLV battery – Position in car

9 Overall Grounding Concept

9.1 Description of the Grounding Concept

All electrically conductive parts will be connected to GLV system ground with a resistance below 300 mOhm. The carbon fibre monocoque will have built in copper mesh around the places where tractive system or GLV components are mounted to reduce the resistance to system ground below 5 Ohm.

9.2 Grounding Measurements

Grounding Measurements To measure the connection to GLV system ground we will use a Megger DLRO10X Digital low Ohm meter with adjustable measurement current from 0-10 Amp. We will check the area around the component within 100mm to make sure the resistance around is able to comply with EV4.3

10 Firewall(s)

10.1 Firewall 1

10.1.1 Description/materials

Firewall 1 consist of a 0.5-0.7 mm aluminium plate, facing the tractive system, and several layers of kapton tape, facing the driver. The layer consisting of kapton tape is approximately 0.4 mm, a thickness sufficient enough to prevent penetration with a 4mm wide screwdriver and 250 N of force, and acts as the electrical insulation and heat resistant layer.

Firewall 1 is attached to the monocoque by sliding the top of the firewall in between the monocoque shoulder flange and firewall 2. The firewall is then attached to each side of the flange (firewall 2) and the monocoque floor using quarter-turn screws and blind nuts. The firewall is sealed with gaskets at the edges around the firewall. Three grommets are used to seal the pass-through for wiring, cables, etc.

To ensure that the firewall is grounded, it is attached to the copper mesh that covers the roof inside the monocoque

10.1.2 Position in car

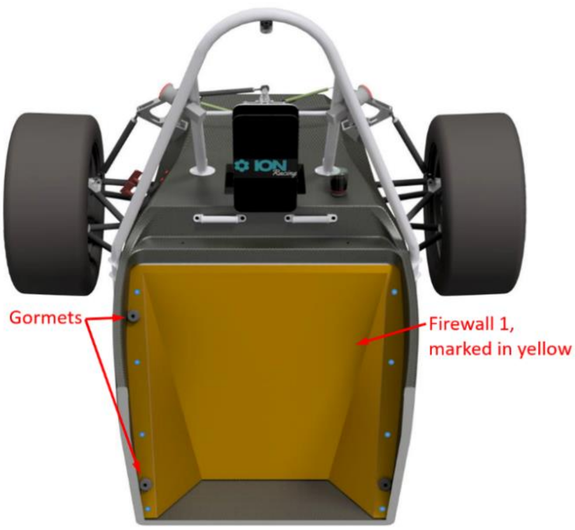


Table 10.1 Firewall – Position in car

10.2 Firewall 2

Firewall 2 consist of a 2 mm thick aluminium flange covered with several layers of Kapton tape, the Kapton tape act as the electrically insulating and heat resistant layer. The flange is a permanent installation that is mounted to the monocoque with pop-rivets, and sealed with gaskets located between the monocoque and the flange edge. The flange edge is covered with Tech7 to ensure a proper seal. The flange is attached to a copper mesh covering the inside of the roof of the monocoque, this is to ensure that the flange is grounded.

11 Appendix

11.2.1 - Bender IR155-3204 IMD ratings

Referred from 2.2

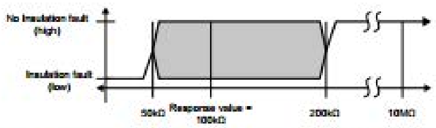
Technical data

Insulation coordination acc. to IEC 60664-1	
Protective separation (reinforced insulation)	between (L+/L-) – (Kl. 31, Kl. 15, E, KE, M_{HS}, M_{LS}, OK_{HS})
Voltage test	AC 3500 V/1 min

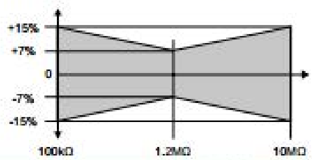
Supply/IT system being monitored	
Supply voltage U_S	DC 10…36 V
Max. operating current I_S	150 mA
Max. current I_k	2 A
	6 A/2 ms inrush current
HV voltage range (L+/L-) U_n	AC 0…1000 V (peak value)
	0…660 V r.m.s. (10 Hz…1 kHz)
	DC 0…1000 V
Power consumption	< 2 W

Response values	
Response value hysteresis (DCP)	25 %
Response value R_{an}	100 kΩ…1 MΩ
Undervoltage detection	0…500 V

Measuring range	
Measuring range	0…10 MΩ
Undervoltage detection	0…500 V default setting: 0 V (inactive)
Relative uncertainty	
SST (≤ 2 s)	good > 2* R_{an}; bad < 0.5* R_{an}
Relative uncertainty DCP	0…85 kΩ ▸ ±20 kΩ
(default setting 100 kΩ)	100 kΩ…10 MΩ ▸ ±15%
Relative uncertainty output M (fundamental frequency)	±5 % at each frequency
	(10 Hz; 20 Hz; 30 Hz; 40 Hz; 50 Hz)
Relative uncertainty undervoltage detection	U_n ≥ 100 V ▸ ±10 %; at U_n ≥300 V ▸ ±5 %
Relative uncertainty (SST)	"Good condition" ≥ 2* R_{an}
	"Bad condition" ≤ 0.5* R_{an}



Relative uncertainty DCP	100 kΩ…10 MΩ ±15 %
	100 kΩ…1.2 MΩ ▸ ±15 % to ±7 %
	1.2 MΩ ▸ ±7 %
	1.2…10 MΩ ▸ ±7 % to ±15 %
	10 MΩ ▸ ±15 %



Time response	
Response time t_{an} (OK_{HS}; SST)	t_{an} ≤ 2 s (typ. < 1 s at U_n > 100 V)
Response time t_{an} (OK_{HS}; DCP) (when changing over from R_F = 10 MΩ to R_{an}/2; at C_e = 1 µF; U_n = DC 1000 V)	t_{an} ≤ 20 s (at F_{ave} = 10*)
	t_{an} ≤ 17.5 s (at F_{ave} = 9)
	t_{an} ≤ 17.5 s (at F_{ave} = 8)
	t_{an} ≤ 15 s (at F_{ave} = 7)
	t_{an} ≤ 12.5 s (at F_{ave} = 6)
	t_{an} ≤ 12.5 s (at F_{ave} = 5)
	t_{an} ≤ 10 s (at F_{ave} = 4)
	t_{an} ≤ 7.5 s (at F_{ave} = 3)
	t_{an} ≤ 7.5 s (at F_{ave} = 2)
	t_{an} ≤ 5 s (at F_{ave} = 1)
	during the self test t_{an} + 10 s
Switch-off time t_{ab} (OK_{HS}; DCP) (when changing over from R_F = 10 MΩ to R_{an}/2; at C_e = 1 µF; U_n = DC 1000 V	t_{ab} ≤ 40 s (at F_{ave} = 10)
	t_{ab} ≤ 40 s (at F_{ave} = 9)
	t_{ab} ≤ 33 s (at F_{ave} = 8)
	t_{ab} ≤ 33 s (at F_{ave} = 7)
	t_{ab} ≤ 33 s (at F_{ave} = 6)
	t_{ab} ≤ 26 s (at F_{ave} = 5)
	t_{ab} ≤ 26 s (at F_{ave} = 4)
	t_{ab} ≤ 26 s (at F_{ave} = 3)
	t_{ab} ≤ 20 s (at F_{ave} = 2)
	t_{ab} ≤ 20 s (at F_{ave} = 1)
	during a self test t_{ab} + 10 s
Duration of the self test	10 s
	(every five minutes; should be added to t_{an}/t_{ab})

Measuring circuit	
System leakage capacitance C_e	≤ 1 µF
Smaller measurement range and increased measuring time at C_e	> 1 µF
	(e.g. max. range 1 MΩ @ 3 µF, t_{an} = 68 s when changing over from R_F 1 MΩ to R_{an}/2)
Measuring voltage U_M	±40 V
Measuring current I_M at R_F = 0	±33 µA
Impedance Z_i at 50 Hz	≥ 1.2 MΩ
Internal DC resistance R_i	≥ 1.2 MΩ

* F_{ave} = 10 is recommended for electric and hybrid vehicles

Complete datasheet located at:

http://www.bender-es.com/fileadmin/products/doc/IR155-32xx-V004_D00115_D_XXEN.pdf

11.2.2 - Inertia Switch Senasta 505.

Referred 2.3:

6. Operational Specification

All parameters apply at 15°C - 28°C ambient unless otherwise stated.

6.1 Horizontal Impact performance (response to shock)
When subjected to a ½ sine shaped pulse the switch will perform as foll
Low Range: Sensata partnumber 500FCS01-01 (20769/12)
6.1.3 Operate above 12 'g' peak, 60ms duration.
6.1.4 Not operate below 6 'g' peak, 60ms duration.

6.4 Maximum load current
6.4.1 N.C. circuit: 20A DC for max. duration 30s (resistive loac
10A DC continuous (resistive load).
6.4.2 N.O. circuit: 16A DC for max. duration 10s (resistive load
0.7A DC continuous (resistive load).

6.5 Minimum load current
6.5.1 N.O. circuit: 0.01A DC (resistive load).
6.5.2 N.C. circuit: 0.1A.

6.6 Initial Contact resistance
6.6.1 N.C. circuit : 16 mOhm max. (reset condition).

11.2.3 - TE Connectivity M3031-000005-100PG

Referred from 2.4

PERFORMANCE SPECIFICATIONS (ANALOG)

Supply Voltage: 5.0V, Ambient Temperature: 25°C (unless otherwise specified)

PARAMETERS	MIN	TYP	MAX	UNITS	NOTES
Pressure Accuracy (RSS combined Non Linearity, Hysteresis & Repeatability)	-1		1	%Span	BFSL @ 25°C
Pressure Cycles	1.00E+6			0~F.S. Cycles	
Proof Pressure	2X			Rated	
Burst Pressure	5X			Rated	
Isolation, Body to Any Lead	50			MΩ	@ 250Vdc
Long Term Stability (1 year)	-0.25		0.25	%Span	
Zero Thermal Error	-2.0		2.0	%Span	Over comp. temp
Span Thermal Error	-2.0		2.0	%Span	Over comp. temp
Zero Offset (mV Output)	-3.0		3.0	%Span	@ 25°C
Zero Offset (V Output)	-2.0		2.0	%Span	@ 25°C
Span Tolerance	-2.0		2.0	%Span	@ 25°C
Compensated Temperature	0		55	°C	
Operating Temperature	-20		+85	°C	
Storage Temperature	-40		+85	°C	
Load Resistance (R_L, mV Output)	1			MΩ	
Load Resistance (R_L, V Output)	5			KΩ	
Response Time		1		ms	
Bandwidth	DC to 1KHz (typical)				
Shock	50g, 11 msec Half Sine Shock per MIL-STD-202G, Method 213B, Condition A				
Vibration	±20g, MIL-STD-810C, Procedure 514.2-2, Curve L				
Wetted Material (except elastomer seal)	17-4PH or 316L Stainless Steel				

For custom configurations, consult factory.

Complete datasheet can be located at:

http://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=MSP300&DocType=Data+Sheet&DocLang=English

11.2.4 - TE-Connectivity M22759

Referred from 2.7

Part Number	Size (AWG)	Conductor Stranding (No. x AWG)	Diameter of Stranded Conductor (inch)	Finished Wire		
			Nominal	Max. Resistance at 20°C (Ω/1000 ft.)	Diameter (inch)	Max. Weight (lbs/1000 ft)
M22759/32-30-*	30	7 x 38	0.011	108.4	.024 ± .002	0.66
M22759/32-28-*	28	7 x 36	0.014	68.6	.027 ± .002	0.91
M22759/32-26-*	26	19 x 38	0.018	41.3	.032 ± .002	1.40
M22759/32-24-*	24	19 x 36	0.023	26.2	.037 ± .002	2.00
M22759/32-22-*	22	19 x 34	0.029	16.2	.043 ± .002	2.80
M22759/32-20-*	20	19 x 32	0.037	9.88	.050 ± .002	4.30
M22759/32-18-*	18	19 x 30	0.046	6.23	.060 ± .002	6.50
M22759/32-16-*	16	19 x 29	0.052	4.81	.068 ± .002	8.30
M22759/32-14-*	14	19 x 27	0.065	3.06	.085 ± .006	13.00
M22759/32-12-*	12	37 x 28	0.084	2.02	.103 ± .006	19.70

Note: This wire was formerly listed under MIL-W-22759 and is supplied in full compliance with SAE AS22759™ specification requirements, including those for product identification (wire mark), labelling and testing.

Complete datasheet located at:

http://docs-europe.electrocomponents.com/webdocs/14dd/0900766b814ddd7a.pdf

11.2.5- WELWYN WH100-1K0JI

Referred from 2.9

Aluminium Housed Wirewound Resistors

WH Series

TT Electronics

Terminations

WH5-100	
Material	Pb-free solder dipped, copper clad steel
Strength	The terminations meet the requirements of IEC 68.2.21
Solderability	The terminations meet the requirements of IEC 115-1, clause 4.17.3.2
WH25T & 50T	6.35mm (¼") spade terminal
WH200 & 300	
Material	M6 threaded steel terminal with a set of four nuts and washers
Strength	Termination robustness 50N max Tightening torque 5Nm max

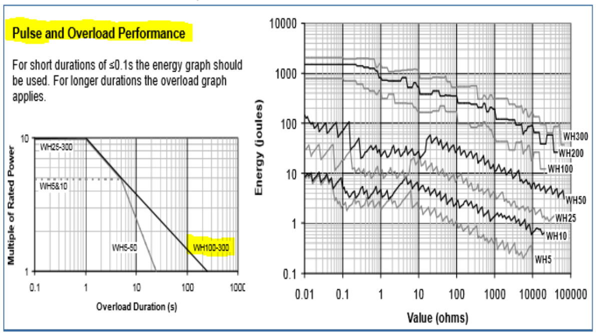
Performance Data

		WH5, 10, 25 & 50			WH100, 200 & 300
		CECC 40203-006 Requirements	Actual Maximum	Actual Typical	Maximum
Load at commercial rating: 1000hrs at 25°C	ΔR%	1	1	0.4	2
Load at CECC rating: 1000hrs at 25°C	ΔR%	1	1	0.4	N/A
Dry heat: 1000hrs at 200°C	ΔR%	1	1	0.4	2
Derating from 25°C		Zero at 200°C, see derating graph			
Short-term overload	ΔR%	1	1	0.2	
Climatic sequence	ΔR%	1	1	0.4	
Climatic category		55/200/56			
Long-term damp heat	ΔR%	1	0.5	0.2	
Temperature rapid change	ΔR%	0.25	0.25	0.1	0.25
Resistance to solder heat	ΔR%	0.25	0.25	0.05	WH100: 0.5
Vibration and bump	ΔR%	0.25	0.25	0.025	
Noise (in decade of frequency)	µV/V	Not specified	0	0	0
Insulation resistance	ohms	1G min	10G min		
Pulse and overload performance		Not specified	See graphs		

Note: A 0.05 ohm addition is to be added to the performance of all resistors < 10 ohms.

Pulse and Overload Performance

For short durations of ≤0.1s the energy graph should be used. For longer durations the overload graph applies.

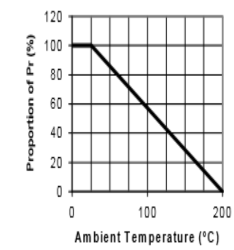


The standard aluminium heatsinks are defined in the table below. If smaller heatsinks are used then derating should be applied as indicated in the graph below. If no heatsink is employed, use the ratings for 1cm².

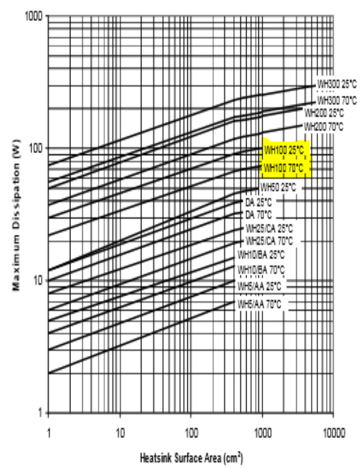
Reference heatsink dimensions

Type (CECC)	Thickness (mm)	Area (cm²)
WH5 (AA)	1	410
WH10 (BA)	1	410
WH25 (CA)	1	544
WH50 (DA)	1	544
WH50 @ 50W	1.5	930
WH100	3	1000
WH200	3	3800
WH300	3	5800

Derating for ambient temperature



Derating for reduced heatsink dimensions



Complete datasheet located at:

http://www.farnell.com/datasheets/1851673.pdf?_ga=1.107758594.1848611837.1479745318

11.2.6 - Cynergy 3 D200 Series

Referred from 2.9

D200 Series

High Power 200W reed relay with 7kV isolation

- *200W switching power*
- *7kV Isolation across contacts*
- *Low Contact Resistance*
- *PCB Mount*
- *Excellent AC characteristics*

The D200 series combines a high power 200W switching capacity with isolation of 7kV across the contacts.

This switching performance is achieved through the use of high vacuum reed switches with Tungsten contacts and make these relays suitable for high reliability applications, such as test equipment and high voltage power supplies.

These are PCB Mount relays, though custom options may be available on request.

Contact Specification	Unit		Condition		
Switch Action			SPNO		
Contact Material			Tungsten		
Isolation across contacts	kV	DC or AC peak	7		
Switching Power Max.	W	resistive	200		
Switching Voltage Max.	V	DC or AC peak	2500		
Switching Current Max.	A	DC or AC peak	3		
Carry Current Max	A	DC or AC peak	5		
Capacitance across contacts	pF	coil to screen grounded	0.8 typ		
Lifetime operations		dry switching	10^9		
		50W switching	10^6		
Contact Resistance	mΩ	max (typical)	600		
Insulation Resistance	Ωmin	(typical)	(10^{13})		
Coil Specification			**5V**	**12V**	**24V**
Must Operate Voltage	V	DC	3.75	9	20
Must Release Voltage	V	DC	0.5	1.25	4
Operate Time	ms	diode fitted	6.0	6.0	6.0
Release Time	ms	diode fitted	1.0	1.0	1.0
Resistance	Ω		28	150	780
Relay Specification					
Isolation contact/coil	kV		17		
Insulation resistance contact to all terminals	Ωmin	(typical)	10^{10} (10^{13})		
Environmental					
Operating Temp range	°C		20 to +70		
Standard Parts			**Coil Voltage Vdc**		
DAT200-05			5		
DAT200-12			12		
DAT200-24			24		

Please refer to this document for circuit design notes:-
http://www.cynergy3.com/blog/application-notes-reed-relays-0

Complete datasheet located at:

http://www.cynergy3.com/sites/default/files/D200%20series%202016.pdf

11.2.7-Vishay CP00253K000KE14-ND

Referred from 2.10

Available

STANDARD ELECTRICAL SPECIFICATIONS

GLOBAL MODEL	POWER RATING $P_{40\,°C}$ W	RESISTANCE RANGE Ω WIREWOUND [(1)]	RESISTANCE RANGE Ω METAL OXIDE [(1)]	TOLERANCE ± %	WEIGHT (typical) g
CP0002	2	0.1 to 1K	100 to 30K	5, 10	2.0
CP0002...3	2	0.1 to 1K	100 to 30K	5, 10	2.2
CP0003	3	0.1 to 2K	150 to 33K	5, 10	3.4
CP0003...3	3	0.1 to 2K	150 to 33K	5, 10	3.6
CP0005	5	0.1 to 2.4K	150 to 50K	5, 10	4.8
CP0005...3	5	0.1 to 2.4K	150 to 50K	5, 10	5.0
CP0007	7	0.1 to 7K	-	5, 10	6.8
CP0007...3	7	0.1 to 7K	-	5, 10	7.0
CP0010	10	0.1 to 11K	-	5, 10	9.5
CP0010...3	10	0.1 to 11K	-	5, 10	9.9
CP0015	15	0.1 to 11K	-	5, 10	16.8
CP0015...3	15	0.1 to 11K	-	5, 10	17.4
CP0020	20	0.1 to 16K	-	5, 10	22.8
CP0020...3	20	0.1 to 16K	-	5, 10	23.6
CP0022	22	0.1 to 16K	-	5, 10	24.5
CP0022...3	22	0.1 to 16K	-	5, 10	25.3
CP0025	25	0.1 to 16K	-	5, 10	37.0

Note

[(1)] To specifically order a Wirewound sub-assembly for resistance values that overlap between the Wirewound and Metal Oxide technologies, the model will be a CPxxxx...85 for standard body and CPxxxx...91 for body with stand-offs. To specifically order a Metal Oxide sub-assembly for resistance values that overlap between the Wirewound and Metal Oxide technologies, the model will be a CPxxxx...100 for a standard body and CPxxxx...101 for body with stand-offs. If no dash type is specified, either technology may be supplied.

TECHNICAL SPECIFICATIONS

PARAMETER	UNIT	WIREWOUND CHARACTERISTICS	METAL OXIDE CHARACTERISTICS
Temperature Coefficient	ppm/°C	± 300 1 Ω and above; ± 600 below 1 Ω	± 300 (CP0002 to CP0005)
Short Time Overload	-	5 x rated power for 5 s	5 x rated power for 5 s
Terminal Strength	lb	10 minimum	10 minimum
Operating Temperature Range	°C	-65 to +275	-65 to +225
Dielectric Withstanding Voltage	V_{AC}	1000	1000
Maximum Working Voltage	V	$(P \times R)^{1/2}$	$(P \times R)^{1/2}$

Note

- Wirewound CP resistors can reliably function as a fuse and as a resistor. Such components involve compromise between fusing and resistive functions; therefore, each design should be tailored to the application to ensure optimum performance. Contact factory by using the e-mail address at the bottom of this page for design assistance.

GLOBAL PART NUMBER INFORMATION

Global Part Numbering example: CP000515R00JE143

C	P	0	0	0	5	1	5	R	0	0	J	E	1	4	3		

GLOBAL MODEL	VALUE	TOLERANCE	PACKAGING	SPECIAL
(See Standard Electrical Specifications Global Model column for options)	**R** = Decimal **K** = Thousand **R1500** = 0.15 Ω **1K500** = 1500 Ω	**J** = ± 5.0 % **K** = ± 10.0 %	**E14** = Lead (Pb)-free bulk pack **E31** = Lead (Pb)-free four layer bulk pack **B14** = Bulk pack **B31** = Four layer bulk pack	(Dash Number) (up to 3 digits) From **1 to 999** as applicable

Historical Part Numbering example: CP-5-3 15 Ω 5 % B14

CP-5-3	15 Ω	5 %	B14
HISTORICAL MODEL	RESISTANCE VALUE	TOLERANCE CODE	PACKAGING

Complete datasheet located:

https://www.vishay.com/docs/30213/cp.pdf

11.2.8 - RTDS-AE20M-12
Referred from 2.12

Acoustic Signals Piezo Buzzers >
AE20M Series

Product overview

The AE20M piezo miniature buzzer range is a compact, low cost audible signalling solution for local indication where very low current consumption may be a requirement. A threaded locking ring allows for easy installation for all panel mount installations.

The unit offers a single stage alarm, either a fast pulsed or continuous tone selectable by a three pin connection combination.

AE20M Series > Ordering Information

Code No:	Voltage:	Frequency:	Current:	dB:
AE20M-12	10-20v Dc ⎓	2900 Hz	25 mA	90
AE20M-24	10-28v Dc ⎓	2900 Hz	25 mA	85
AE20M-48	6-48v Dc ⎓	2900 Hz	35 mA	82
AE20M-115	60-120v Ac ~	2900 Hz	25 mA	90
AE20M-230	130-240v Ac ~	2900 Hz	25 mA	90

Frequency +/- 500 dB at prime voltage +/- 3dB

Complete datasheet located at:

http://docs-europe.electrocomponents.com/webdocs/0f08/0900766b80f08d21.pdf

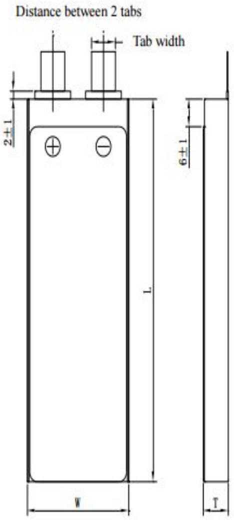
11.3.1 - MELASTA SLPB7858150 7000mAh 15C 3.7V

2. 型号 MODEL

SLPB7858150 7000mAh 15C 3.7V

3. 产品规格 SPECIFICATION

单颗电池规格 Specifications of single cell



◆标称容量 Typical Capacity①		7.0Ah
◆标称电压 Nominal Voltage		3.7V
◆ 充电条件 Charge Condition	最大电流 Max. Continuous charge Current	14A
	峰值充电 Peak charge current	28A(≤1sec)
	电压 Voltage	4.2V±0.03V
◆ 放电条件 Discharge Condition	Max Continuous Discharge Current	105A
	Peak Discharge Current	140A
	Cut-off Voltage	3.0V
◆交流内阻 AC Impedance(mOHM)		<2.0
◆循环寿命【充电:1.0C,放电:15C】 Cycle Life【CHA:1.0C,DCH:15C】		>100cycles
◆使用温度 Operating Temp.	充电 Charge	0℃~45℃
	放电 Discharge	-20℃~60℃
◆ 电芯尺寸 Cell Dimensions	厚度 Thickness(T)	7.5±0.3mm
	宽度 Width(W)	58±0.5mm
	长度 Length(L)	152±0.5mm
	极耳间距 Distance between 2 tabs	24±1mm
◆ 极耳尺寸 Dimensions of Cell tabs	极耳宽度 Tab Width	15mm
	极耳厚度 Tab Thickness	0.2mm
	极耳长度 Tab Length	Max 30mm
◆重量 Weight(g)		149±3.0
①标称容量：0.5CmA,4.2V~3.0V@23℃±2℃ Typical Capacity:0.5CmA,4.2V~3.0V@23℃±2℃		

11.3.2- BMS- Master and Slave.

Referred from 3.1.5

- **Measures Up to 12 Battery Cells in Series**
- **Stackable Architecture Supports 100s of Cells**
- **Built-In isoSPI™ Interface:**
  - **1Mbps Isolated Serial Communications**
  - **Uses a Single Twisted Pair, Up to 100 Meters**
  - **Low EMI Susceptibility and Emissions**
- **1.2mV Maximum Total Measurement Error**
- **290µs to Measure All Cells in a System**
- Synchronized Voltage and Current Measurement
- 16-Bit Delta-Sigma ADC with Frequency Programmable 3rd Order Noise Filter
- Engineered for ISO26262 Compliant Systems
- Passive Cell Balancing with Programmable Timer
- 5 General Purpose Digital I/O or Analog Inputs:
  - Temperature or other Sensor Inputs
  - Configurable as an I^2C or SPI Master
- 4µA Sleep Mode Supply Current
- 48-Lead SSOP Package

APPLICATIONS

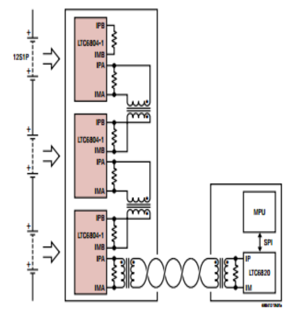
- Electric and Hybrid Electric Vehicles
- Backup Battery Systems
- Grid Energy Storage
- High Power Portable Equipment

The LTC®6804 is a 3rd generation multicell battery stack monitor that measures up to 12 series connected battery cells with a total measurement error of less than 1.2mV. The cell measurement range of 0V to 5V makes the LTC6804 suitable for most battery chemistries. All 12 cell voltages can be captured in 290µs, and lower data acquisition rates can be selected for high noise reduction.

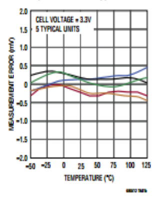
Multiple LTC6804 devices can be connected in series, permitting simultaneous cell monitoring of long, high voltage battery strings. Each LTC6804 has an isoSPI interface for high speed, RF-immune, local area communications. Using the LTC6804-1, multiple devices are connected in a daisy-chain with one host processor connection for all devices. Using the LTC6804-2, multiple devices are connected in parallel to the host processor, with each device individually addressed.

Additional features include passive balancing for each cell, an onboard 5V regulator, and 5 general purpose I/O lines. In sleep mode, current consumption is reduced to 4µA. The LTC6804 can be powered directly from the battery, or from an isolated supply.

TYPICAL APPLICATION



Total Measurement Error vs Temperature of 5 Typical Units

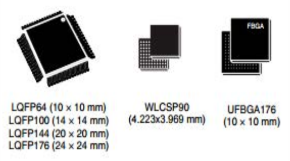


680412fc

Datasheet - production data

Features

- Core: ARM® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator™) allowing 0-wait state execution from Flash memory, frequency up to 168 MHz, memory protection unit, 210 DMIPS/ 1.25 DMIPS/MHz (Dhrystone 2.1), and DSP instructions
- Memories
- Up to 1 Mbyte of Flash memory
- Up to 192+4 Kbytes of SRAM including 64-Kbyte of CCM (core coupled memory) data RAM
- Flexible static memory controller supporting Compact Flash, SRAM, PSRAM, NOR and NAND memories
- LCD parallel interface, 8080/6800 modes
- Clock, reset and supply management
  - 1.8 V to 3.6 V application supply and I/Os
  - POR, PDR, PVD and BOR
  - 4-to-26 MHz crystal oscillator
  - Internal 16 MHz factory-trimmed RC (1% accuracy)
  - 32 kHz oscillator for RTC with calibration
  - Internal 32 kHz RC with calibration
- Low-power operation
  - Sleep, Stop and Standby modes
  - V_{BAT} supply for RTC, 20×32 bit backup registers + optional 4 KB backup SRAM
- 3×12-bit, 2.4 MSPS A/D converters: up to 24 channels and 7.2 MSPS in triple interleaved mode
- 2×12-bit D/A converters
- General-purpose DMA: 16-stream DMA controller with FIFOs and burst support



- Up to 17 timers: up to twelve 16-bit and two 32-bit timers up to 168 MHz, each with up to 4 IC/OC/PWM or pulse counter and quadrature (incremental) encoder input
- Debug mode
  - Serial wire debug (SWD) & JTAG interfaces
  - Cortex-M4 Embedded Trace Macrocell™
- Up to 140 I/O ports with interrupt capability
  - Up to 136 fast I/Os up to 84 MHz
  - Up to 138 5 V-tolerant I/Os
- Up to 15 communication interfaces
  - Up to 3 × I^2C interfaces (SMBus/PMBus)
  - Up to 4 USARTs/2 UARTs (10.5 Mbit/s, ISO 7816 interface, LIN, IrDA, modem control)
  - Up to 3 SPIs (42 Mbits/s), 2 with muxed full-duplex I^2S to achieve audio class accuracy via internal audio PLL or external clock
  - 2 × CAN interfaces (2.0B Active)
  - SDIO interface
- Advanced connectivity
  - USB 2.0 full-speed device/host/OTG controller with on-chip PHY
  - USB 2.0 high-speed/full-speed device/host/OTG controller with dedicated DMA, on-chip full-speed PHY and ULPI
  - 10/100 Ethernet MAC with dedicated DMA: supports IEEE 1588v2 hardware, MII/RMII

Complete datasheet located at:

Slave: http://cds.linear.com/docs/en/datasheet/680412fc.pdf

Master : http://www.st.com/content/ccc/resource/technical/document/datasheet/ef/92/76/6d/bb/c2/4f/f7/DM00037051.pdf/files/DM00037051.pdf/jcr:content/translations/en.DM00037051.pdf

11.3.3 - Coroplast EV 25mm^2

Referred from 3.1.7

Silicone-insulated single-core high voltage automotive cables

Application: Connection of HV batteries and electric motors

Cable construction according to LV 216-2, ISO 6722 and ISO 14572
Construction of HV wiring systems for hybrid and electric vehicles

High voltage cable, single-core, shielded FLR2GCB2G, 4 mm²

Single-core, shielded automotive cables for high voltage cable sets

After several years of development work, it was possible to develop insulation materials which on the one hand can withstand high voltage loads and on the other hand correspond to the high automotive requirements in terms of flexibility and EMC shielding. Operational voltages of up to 600 volts are possible with the Coroplast silicone high voltage cables.

Prototype cables for testing the future voltage class of 1000 volts are available. The normative recognition of this voltage class is proactively supported by our company. The very good flexibility of Coroplast high voltage cables is obtained through the simultaneously fine wired and compact cable constructions. Double shieldings with braided wires and metal foils are used because of the high EMC requirements. The current standards and specifications of the OEM (inter alia LV 216) are the basis for this design.

Furthermore, customer-specific details such as extruded vertical stripes can be installed. A detailed overview of the construction data of Coroplast HV cables can be found on the internet at: www.coroplast.de.

Optimised dimensioning of the cable cross sections

Coroplast HV cables are able to permanently withstand temperatures of up to 180°C. This enables an optimisation of the conductor cross section in contrast to other inferior insulation material.

The increased conductor heating through a permanent current load can be realised through silicone materials. Coroplast is capable of calculating the conductor heating depending on the operational environment temperatures and the current loads for an optimised dimensioning of the nominal conductor cross sections. So-called Derating-Simulations are used for selection of the optimal cross section. This results in the saving of costs, weight and construction room.

By means of the current heating table shown below as an example, the maximum current load can be identified depending on the ambient temperature and the cable cross section. Further graphics for deviating ambient temperatures can be derived from our website at: www.coroplast.de.

High voltage cable, single-core, shielded FLR2GCB2G, 25 mm² and 35 mm²

High voltage cable, single-core, shielded HV-2GCB2G, 70 mm²

Maximum current load per cross section according to the ambient temperature

ambient temperature	+20 °C	+85 °C	+105 °C	+125 °C
nom. cross section	max. current load up to conductor temperature of +180 °C			
10 mm²	154 A	121 A	108 A	92 A
16 mm²	206 A	162 A	144 A	123 A
20 mm²	232 A	182 A	163 A	139 A
25 mm²	274 A	216 A	192 A	164 A
30 mm²	300 A	236 A	210 A	180 A
35 mm²	343 A	270 A	241 A	206 A
40 mm²	378 A	298 A	266 A	227 A
50 mm²	432 A	340 A	304 A	260 A
70 mm²	538 A	425 A	380 A	325 A

Coroplast 2 Coroplast 3

Complete Datasheet located at:

http://www.coroplast.de/fileadmin/user_upload/images/kabel-leitungen/coroplast_kabel_und_leitungen_en.pdf

11.3.4 GIGAVAC GV200

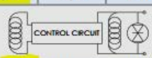
Referred from 3.1.8

PRODUCT SPECIFICATIONS

Specifications	Units	Data
Contact Arrangement (main)	Form X	SPST-NO
Contact Arrangement (Auxilary) 1/	Form A	SPST-NO
	Form C	SPST-NC
Mechanical Life	cycles	1,000,000
Contact Resistance		
Max @ rated carry current	mohms	.4
Typical @ rated carry current	mohms	.15 to .3
Operate time, 25˚C		
Close (includes bounce) Max	ms	20
Close (includes bounce) Typical	ms	13
Bounce on close, Max	ms	7
Release time (includes arc time at max. break current)	ms	12
Insulation Resistance	Mohms	100 2/
Dielectric at sea level (leakage < 1mA)	VRMS	2,200
Shock, sawtooth 11msec, 1/2 sine 11msec	G's peak	25
Vibration, Sinusoidal (10-2000 Hz peak)	G's	25
Operating ambient Temp Range	˚C	-55 to +85 3/
Storage ambient Temp Range	˚C	-70 to +150
Weight, typical without nuts and washers	Kg (Lb)	0.38 (0.84)

POWER SWITCHING

COIL RATINGS at 25˚C

Coil P/N Designation	B 10/	C 10/	F 10/	M	N	P 4/	Q 4/
Coil Voltage, Nominal	12 VDC	24 VDC	48 VDC	12/24 VDC	48 VDC	12/24 VDC	48 VDC
Coil Type	Dual	Dual	Dual	PWM	PWM	External PWM 4/	External PWM 4/
Coil Voltage, Max 5/	16 VDC	32 VDC	64 VDC	36 VDC	95 VDC		
Pick-Up Voltage, Max 6/ 8/ 9/	8 VDC	16 VDC	40 VDC	8.5 VDC	32 VDC		
Drop-Out Voltage 9/	0.5 VDC	2 VDC	4 VDC	6.5 VDC	20 VDC		
Pick-Up Current, Max (75 ms) 6/ 7/	3.9 A	1.6 A	0.97 A	3.6 A	0.9 A		
Coil Current 7/	0.23 A	0.097 A	0.042 A	0.13 A @12 VDC 0.07 A @24 VDC	0.04 A @48 VDC		
Coil Power 7/	2.8 W	2.3 W	2 W	1.7 W	1.9 W		
Internal Coil Suppression	 CONTROL CIRCUIT			N/A			
Coil Back EMF	55 V	55 V	125 V	0 V	0 V		
Transients, Max (13 ms)	±50 V	±50 V	±75 V	±60 V	±100 V		
Reverse Polarity	16 V	32 V	64 V	100 V	100 V		

Complete datasheet located at

: http://www.gigavac.com/sites/default/files/catalog/spec_sheet/gv200.pdf

11.3.5 EATON EV Fuse

Referred from 3.1.9

Technical Data 10563
Effective February 2017

Electric vehicle power fuses

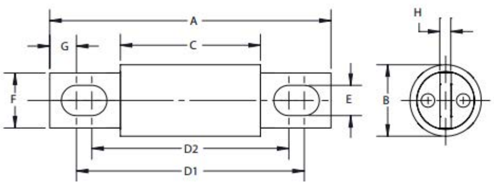
Catalog numbers:

Catalog no.	Amp	Average @ 20 kA/500 Vdc* Melting I^2t	Clearing I^2t	Power loss (W) @ 50%**
20 mm diameter case				
EV20-50	50	368	746	1.19
EV20-60	60	529	1074	1.43
EV20-70	70	720	1462	1.67
EV20-80	80	910	2200	1.90
EV20-100	100	1470	2983	2.38
EV20-125	125	1384	4114	3.12
EV20-150	150	1993	5924	3.75
25 mm diameter case				
EV25-100	100	1043	2317	3.00
EV25-125	125	1630	3620	3.75
EV25-150	150	1618	5499	4.50
EV25-175	175	2202	7485	5.25
EV25-200	200	3398	10,220	6.00
EV25-225	225	4300	12,934	6.97
EV25-250	250	5309	15,968	7.75
30 mm diameter case				
EV30-200	200	3211	8665	6.74
EV30-225	225	4064	10,967	7.58
EV30-250	250	5017	13,539	8.42
EV30-300	300	7224	19,496	10.11
EV30-350	350	9833	26,536	11.79
EV30-400	400	12,843	34,660	13.47

* For system parameters below 500 Vdc and 20 kA, see clearing I^2t correction factors on page 9.

** 50 percent of fuse label amp rating tested at 23°C ± 2°C.

Dimensions† — mm:



Complete datasheet located at:
http://www.cooperindustries.com/content/dam/public/bussmann/Electrical/Resources/product-datasheets-b/bus-ele-ds-10563-ev-power.pdf

11.3.7 - Brusa NLG513

Referred from 3.1.10

Specifications NLG513

AC Input	NLG513 air	NLG513 water	
Min. input voltage	100	100	V
Max. input voltage	264	264	V
Min. input frequency	48	48	Hz
Max. input frequency	62	62	Hz
Max. input current^{eff}	16	16	A
Max. input power (by input current^{eff} = 16 A)	3'680	3'680	W
Powerfactor	> 0.99	> 0.99	---
DC Output	**NLG513 air**	**NLG513 water**	
Max. charging power	3'300	3'300	W
Voltage range	200 - 520	200 - 520	V
Charging voltage accuracy	± 1	± 1	%
Max. charging current	12.5	12.5	A
Charging current accuracy	± 2	± 2	%
Max. charging current - ripple (100 %, fr = 2 fn (100 / 120 Hz)	12.5	12.5	A
Efficiency ($P = Pal_{max}$)	93	93	%
Mechanical data and cooling system	**NLG513 air**	**NLG513 water**	
Weight (without coolant)	6.3	6.2	kg
Coolant quantity in device	---	- 0.3	l
Coolant flow rate	---	4 - 6	l / min
Pressure drop @ 5l/min, $T_{coolant}$ = 25°C	---	50	mbar
Ambient temperature range (storage)	- 40 to + 85	- 40 to + 85	°C
Ambient temperature range (operation)	- 25 to + 70	- 25 to + 70	°C
Coolant temperature range for full power	- 20 to + 40	- 20 to + 60	°C
IP - protection	IP54	IP65	---
Safety - and protection features	**NLG513 air**	**NLG513 water**	
Insulation testing (AC input / DC output)	2	2	kV
Mains input overvoltage protection	264	264	V
Insulation resistance (initial) min.	2	2	> GΩ

Complete datasheet located at:
http://www.brusa.biz/_files/drive/05_Sales/Datasheets/BRUSA_DB_EN_NLG513.pdf

11.5.1- UniTek BAMOCAR D3-400 400

Referred from 5.1

For three-phase current motors

Auxiliary voltage connection	12V= to 700V=
Auxiliary voltage connection	12V= or 24V= ±10% / 4A (2A) residual ripple <10%, regenerating fuse

Data BAMOCAR D3-400-(700)	Dim.	125/250	200/400	125/250	200/400
Supply voltage, rated value	V=	24 up to max. 400		24 up to max. 700	
Max. output voltage, rated value	V~eff	up to 3x260		up to 3x450	
Continuous current	A_{eff}	125	200	125	200
Max. peak current	A_{lo}	250	400	250	400
Max. power loss	kW	2	3	2.6	4
Pulse frequency	kHz	8-24		8-16	
Over-voltage switching threshold	V=	440		800	
Input fuse	A	160	250	160	250
Weight	kg	8.5			
Dimensions h x w x d	mm	403x250x145			
Size		2			

Control signals		V	A	Function	Connector
Analogue inputs		± 10	0.005	Differential input	X1
Digital inputs	ON OFF	10-30 <6	0.010 0	Logic IO	X1
Digital outputs		+24	1	Transitor output open emitter	X1
Resolver / TTL / SINCOS				Differential input	X7
CAN interface				Logic IO	X9
RS232 interface				Logic IO	X10

Complete datasheet located at:

http://www.unitek-online.de/pdf/download/Antriebe-Drive/BAMOCAR/E-BAMOCAR-D3.pdf

11.6.1 - Enstroj EMRAX228

Referred from 6.1

EMRAX 228 Technical Data Table

Technical data / Type	EMRAX 228 High Voltage			EMRAX 228 Medium Voltage			EMRAX 228 Low Voltage		
Air cooling = AC Liquid cooling = LC Combined cooling = Air + Liquid cooling = CC	AC	LC	CC	AC	LC	CC	AC	LC	CC
Ingress protection	IP21	IP65	IP21	IP21	IP65	IP21	IP21	IP65	IP21
Cooling medium specification (Air Flow = AF; Water Flow = WF – if inlet water temperature and/or ambient temperature are lower, then continuous power is higher)	AF speed 25 m/s; 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C	AF speed 25 m/s; 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C	AF speed 25 m/s; 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C	inlet WF 8 l/min - 40°C; ambient air 25°C
Weight [kg]	12,0	12,3	12,3	12,0	12,3	12,3	12,0	12,3	12,3
Diameter ø / width [mm]	228 / 86								
Battery voltage range [Vdc]	50 – 600 (*700 – to get 6500 RPMp)			50 – 450 (*540 – to get 6500 RPMp)			24 – 150 (*180 – to get 6500 RPMp)		
Peak motor power (few min at cold start / few seconds at hot start) [kW]	**100**								
Continuous motor power (depends on the motor RPM 3000 - 5000) [kW]	28 - 42	28 - 42	35 - 55	28 - 42	28 - 42	35 - 55	28 - 42	28 - 42	35 - 55
Maximal rotation speed [RPM]	5500 (*6500 RPM peak)								
Maximal motor current (for 2 min if cooled as described in Manual for EMRAX) [Arms]	240			340			900		
Continuous motor current [Arms]	115			160			450		
Maximal motor torque (for a few seconds) [Nm]	240								
Continuous motor torque [Nm]	125								
Torque / motor current [Nm/1Aph rms]	**1,1**			**0,75**			**0,27**		
Maximal temperature of the copper windings in the stator and also max. temp. of the magnets [°C]	120								
Motor efficiency [%]	93 – 98								
Internal phase resistance at 25 °C [mΩ]	18			8,0			1,12		
Input phase wire cross-section [mm²]	10,2			15,2			38		
Induction in Ld/Lq [µH]	175/180			75/80			10,6/11,2		
Controller / motor signal	sine wave								
Specific idle speed (no load RPM) [RPM/1Vdc]	9,8			14			40		
Specific load speed (depends on the controller settings) [RPM/1Vdc]	8 – 9,8			11 – 14			34 – 40		
Magnetic field weakening (for higher RPM at low torque) [%]	up to 100								
Magnetic flux – axial [Vs]	0,0542			0,0355			0,0131		
Temperature sensor in the motor	kty 81/210								
Number of pole pairs	10								
Rotor inertia (mass dia=175mm, m=5,5kg) [kg*cm²]	421								
Bearings SKF _ FAG	R/R 6206/6206 or R/AR 6206/7206 or AR/AR 7206/7206 (»O« orientation)								

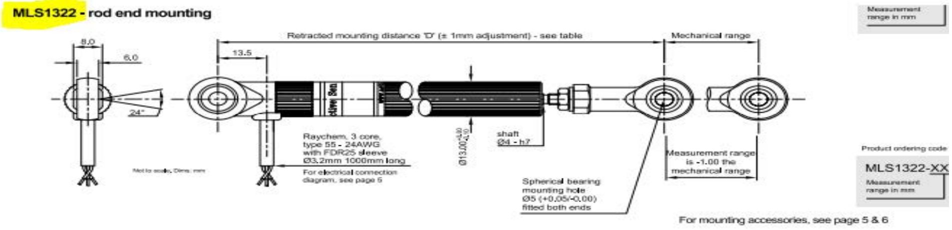
*For a few seconds.
Maximal battery voltage is 700 Vdc (EMRAX 228 High Voltage). Maximal RPM must not be exceeded.
It is possible to weaken the magnetic field (up to 100%) to get higher RPM at existing battery voltage. Maximal RPM must not be exceeded.
These data are valid for the motors, which were sold after January 2014.
EMRAX motors that had been made before May 2012 have 30% lower power/torque and RPM than new generation of EMRAX motors.

Complete datasheet located at:
http://www.enstroj.si/images/stories/emrax_228_tech_data_table_dec_2014.pdf

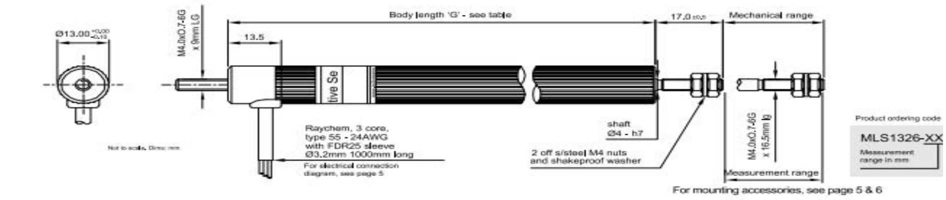
11.7.1 -Active Sensors MLS1322-050 V1

Referred from 7.1

MLS1322 - rod end mounting



MLS1326 - threaded mounting



Doc. Ref: WS-MLS-4 Page 3/6

sales@activesensors.com Europe: +44 (0) 1202 480620 North America: +1 317 713 2973

Electrical & mechanical information for MLS1320 range

Measurement range (±0.5mm)	25	50	75	100	125	150	175	200	225	250	300	350	mm
Retracted mounting distance (D)	123	148	173	198	223	248	273	298	323	348	398	448	mm
Body length (G)	85	110	135	160	185	210	235	260	285	310	360	410	mm
Body length (C)	81	106	131	156	181	206	231	256	281	306	356	406	mm
Resistance (Typical)	1	2	3	4	5	6	7	8	9	10	12	14	kohms
Non-linearity	<±0.25		<±0.15										%
Applied voltage	<22	<44	<66	<88	<110	<130							Volts
Wiper load	>500					>600	>700	>800	>900	>1000	>1200	>1400	kohms
Mechanical range	Measurement range +1												mm
Shaft velocity	<10												m/sec
Insulation resistance (at 500V dc.)	>100												Mohms
Operating temp. range	-30° to +125°												°C
Sealing	IP66												
Shaft operating force	200 (typical)												grams
Weight (approx.)	60	66	73	78	85	90	96	102	108	114	120	126	grams
Materials	Case - Aluminium 6063 - Sulphuric acid anodised Shaft - Stainless steel - 303 series Rod end bearing - Aluminium 6262 housing & BS970 230M07, electroless nickel plate												

Complete datasheet located at: http://www.activesensors.com/datasheet/mls.pdf

11.7.2 DTM-Connector-Data and AlphaWire3Wire

Referred from 7.3

DT Series **Boot Adaptors**

To meet the application requirements where wires are to be protected, the DT Series maybe supplied with boot adaptors. These will accept shaped boots / sleeves or shrink tubing. Parts for standard or thin wall wire are available.

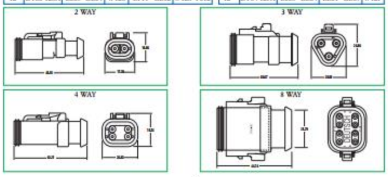
Wire Sealing Range Standard - 2.24mm - 3.68mm wire insulation diameter Thin wall - 1.35mm - 3.05mm wire insulation diameter

Part Nos. - Plugs

No. of Ways	Basic Part No.	Grey Std.	Grey Thin wall	Orange Wedge	Black Std.	Black Thin wall	Green Wedge	
2	DT06-2S	-E008	-CE04	W2S	-EP11	-CE13	W2S	-P012
3	DT06-3S	-E008	-CE04	W3S	-EP11	-CE13	W3S	-P012
4	DT06-4S	-E008	-CE04	W4S	-EP11	-CE13	W4S	-P012
8	DT06-8SA	-E008	-CE04	W8S	-EP11	-CE12	W8S	-P012
12	DT06-12SA	-E008	-CE04	W12S	-EP11	-CE12	W12S	-P012

Part Nos. - Receptacles

No. of Ways	Basic Part No.	Grey Std.	Grey Thin wall	Black Std.	Black Thin wall	Wedges
2	DT04-2P	-E008	-CE04	-EE01	-CE09	W2P
3	DT04-3P	-E008	-CE04	-EE01	-CE09	W3P
4	DT04-4P	-E008	-CE04	-EE01	-CE09	W4P
8	DT04-8PA	-E008	-CE04	-EE01	-CE09	W8P
12	DT04-12PA	-E008	-CE04	-EE01	-CE09	W12P



5

ALPHA WIRE
CUSTOMER PRODUCT SPECIFICATION

Part Number: B953033	Issue: 1
Page 1 of 2 Pages	Issue Date: 8/19/2010
	Effective Date: 10/14/2010

A. Construction — Diameters (mm)
1) Component 1 — 3 X 1 COND
   a) Conductor — 24 (7/32) AWG TC — 0.61
   b) Insulation — 0.25 Wall, Nom. PVC, Semi Rigid — 1.12
      (1) Color Code — Alpha Wire Color Code E
2) Cable Assembly — 3 Components Cabled
   a) Twists: — 39.4 Twists/meter (min)
   b) Core Wrap — Clear Mylar Tape, 25% Overlap, Min.
3) Shield — TC BRAID Shield,85% Coverage, Min.
   a) Drain Wire — 24 (7/32) AWG TC
4) Jacket — 0.81 Wall, Nom.,PVC — 4.67 (4.93 Max.)
   a) Color(s) — GREY
   b) Ripcord — 1 End 810 Denier Nylon
   c) Print — ALPHA WIRE-* P/N B953033 0.23MM2 (24AWG) (UL) TYPE CM 105C OR AWM 2464 VW-1 CE ROHS (SEQ METERS)
   * = Factory Code

B. Applicable Specifications
1) UL
   a) Component 1 — AWM/STYLE 10002 — 105°C / 300 V_{RMS}
   b) Overall — AWM/STYLE 2464 — 80°C / 300 V_{RMS}; CM — 105°C; VW-1
2) IEC — EN 60332-1 Flame Behavior; EN 60332-2 Flame Behavior
3) CE: — LVD 73/23/EEC Amendment 93/68/EEC

C. Environmental Compliance
1) EU Directive 2002/95/EC(RoHS): All materials used in the manufacture of this part are in compliance with EU Directive 2002/95/EU regarding the restriction of use of certain hazardous substances in electrical and electronic equipment. Consult Alpha Wire's web site for compliance Date of Manufacture.
2) REACH Regulation (EC 1907/2006): This product does not contain any of the substances listed on the European Union REACH Substance of Very High Concern (SVHC) candidate list, dated 30 March 2010, in excess of a concentration of 0.1% weight/weight.

D. Physical & Mechanical Properties
1) Temperature Range — -30 to 105°C
2) Bend Radius — 10X Cable Diameter
3) Pull Tension — 16.7 Lbs, Maximum
4) Sunlight Resistance — Yes

E. Electrical Properties (For Engineering purposes only)
1) Voltage Rating — 300 V_{RMS}
2) Capacitance — 104.96 pf/m @1 kHz, Nominal Conductor to Conductor
3) Ground Capacitance — 190.24 pf/m @1 kHz, Nominal
4) Inductance — 0.6232 µH/m, Nominal
5) Conductor DCR — 85.28 Ω/Km @20°C, Nominal
6) OA Shield DCR — 21.648 Ω/Km @20°C, Nominal

F. Other
1) Packaging — Flange x Traverse x Barrel (inches)

711 Lidgerwood Ave Elizabeth, NJ 07207-0711
Toll Free 1-800-52 ALPHA • T: 1-908-925-8000 • F: 908-925-5411 • Email: info@alphawire.com
www.alphawire.com

11.8.1- ECU Cables

Referred from 8.1.2

SPECIFICATION CONTROL DRAWING — **55A0111**

TITLE: WIRE, RADIATION-CROSSLINKED, MODIFIED, ETFE-INSULATED, TIN-COATED COPPER, LIGHTWEIGHT — Date: 24MAR11 — Revision: R

This specification sheet forms a part of the latest issue of Raychem Specification 55A.

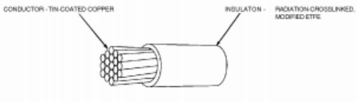


TABLE I. CONSTRUCTION DETAILS

PART NUMBER 1/	WIRE SIZE (AWG)	CONDUCTOR STRANDING (number x AWG)	DIAMETER OF STRANDED CONDUCTOR (in.)		FINISHED WIRE		
			MINIMUM	MAXIMUM	MAXIMUM RESISTANCE AT 20°C (ohms/1000 ft.)	DIAMETER (in.)	MAXIMUM WEIGHT (lbs/1000 ft.)
55A0111-30-*	30	7 x 38	.011	.013	108.4	.024 ± .002	.66
55A0111-28-*	28	7 x 36	.014	.016	68.6	.027 ± .002	.91
55A0111-26-*	26	19 x 38	.018	.020	41.3	.032 ± .002	1.4
55A0111-24-*	24	19 x 36	.023	.025	26.2	.037 ± .002	2.0
55A0111-22-*	22	19 x 34	.029	.031	16.2	.043 ± .002	2.8
55A0111-20-*	20	19 x 32	.037	.039	9.88	.050 ± .002	4.3
55A0111-18-*	18	19 x 30	.046	.049	6.23	.060 ± .002	6.5
55A0111-16-*	16	19 x 29	.052	.055	4.81	.068 ± .002	8.3
55A0111-14-*	14	19 x 27	.065	.069	3.06	.085 ± .003	13.0
55A0111-12-*	12	37 x 28	.084	.089	2.02	.103 ± .003	19.7
55A0111-10-*	10	37 x 26	.106	.113	1.26	.128 ± .006	31.8
55A0111- 8-*	8	133 x 29	.158	.173	.701	.188 ± .008	58.8

TABLE II. PERFORMANCE DETAILS

PART NUMBER 1/	BEND TESTING			
	MANDREL DIAMETER (inch) (± 3%)		WEIGHT (lb) (± 3%)	
	IMMERSION, LIFE CYCLE AND ACCELERATED AGING	COLD BEND	IMMERSION, LIFE CYCLE AND ACCELERATED AGING	COLD BEND
55A0111-30-*	.250	.375	.125	.500
55A0111-28-*	.250	.375	.125	.500
55A0111-26-*	.375	.500	.125	.500
55A0111-24-*	.375	.500	.250	1.00
55A0111-22-*	.500	.750	.375	1.00
55A0111-20-*	.500	.750	.500	1.00
55A0111-18-*	.500	1.00	.500	1.00
55A0111-16-*	.750	1.00	.750	1.00
55A0111-14-*	1.00	1.50	1.00	3.00
55A0111-12-*	1.50	2.00	1.50	3.00
55A0111-10-*	2.00	3.00	1.50	3.00
55A0111- 8-*	3.00	4.00	4.00	6.00

TE Connectivity. Users should evaluate the suitability of this product for their application. Specifications are subject to change without notice.

DIMENSIONS ARE IN INCHES, AND UNLESS OTHERWISE DESIGNATED ARE NOMINAL.

THIS SPECIFICATION SHEET TAKES PRECEDENCE OVER DOCUMENTS REFERENCED HEREIN. REFERENCED DOCUMENTS SHALL BE OF THE ISSUE IN EFFECT ON DATE OF INVITATION FOR BID.

Page 1 of 2 — TE Connectivity

SPECIFICATION CONTROL DRAWING — **44A112X**

TITLE: TWO CONDUCTOR CABLE, SHIELDED, JACKETED, GENERAL PURPOSE, 600 VOLT — Date: 28MAR11 — Revision: G1

This specification sheet forms a part of the latest issue of Raychem Specification 44.

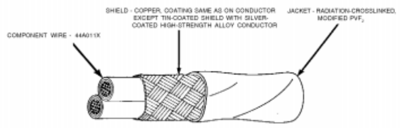


TABLE I. CABLE CONSTRUCTION DETAILS

PART NUMBER 1/	CONDUCTOR SIZE (AWG)	SHIELD SIZE (AWG)	JACKET THICKNESS (in.)		OUTSIDE DIAMETER (in.)		MAXIMUM WEIGHT (lb/1000 ft)
			MINIMUM	NOMINAL	NOMINAL	MAXIMUM	
44A112X-26-*	26	38	.006	.008	.102	.107	8.1
44A112X-24-*	24	36	.006	.008	.118	.123	11.2
44A112X-22-*	22	36	.006	.008	.132	.137	14.5
44A112X-20-*	20	36	.006	.008	.148	.153	18.8
44A112X-18-*	18	36	.007	.009	.170	.175	25.7
44A112X-16-*	16	36	.007	.009	.184	.189	30.2
44A112X-14-*	14	36	.007	.009	.218	.225	43.2
44A112X-12-*	12	36	.007	.009	.256	.265	61.5
44A112X-10-*	10	36	.008	.010	.299	.314	86.3

TABLE II. CABLE PERFORMANCE DETAILS

PART NUMBER 1/	BEND TESTING			
	MANDREL DIAMETER (inch) (± 3%)		WEIGHT (lb) (± 3%)	
	LIFE CYCLE, IMMERSION AND ACCELERATED AGING	COLD BEND	LIFE CYCLE, IMMERSION AND ACCELERATED AGING	COLD BEND
44A112X-26-*	3.00	3.00	.250	1.50
44A112X-24-*	3.00	3.00	.375	1.50
44A112X-22-*	6.00	6.00	.375	3.00
44A112X-20-*	6.00	6.00	.375	3.00
44A112X-18-*	6.00	6.00	.500	3.00
44A112X-16-*	6.00	6.00	.500	3.00
44A112X-14-*	6.00	6.00	1.00	9.00
44A112X-12-*	10.0	10.0	1.00	9.00
44A112X-10-*	10.0	10.0	1.00	9.00

NOTE: Nominal values are for information only. Nominal values are not requirements.

Users should evaluate the suitability of this product for their application. Specifications are subject to change without notice.

DIMENSIONS ARE IN INCHES, AND UNLESS OTHERWISE DESIGNATED ARE NOMINAL.

THIS SPECIFICATION SHEET TAKES PRECEDENCE OVER DOCUMENTS REFERENCED HEREIN. REFERENCED DOCUMENTS SHALL BE OF THE ISSUE IN EFFECT ON DATE OF INVITATION FOR BID.

Page 1 of 2 — TE Connectivity

11.8.2-Melasta LPB042126

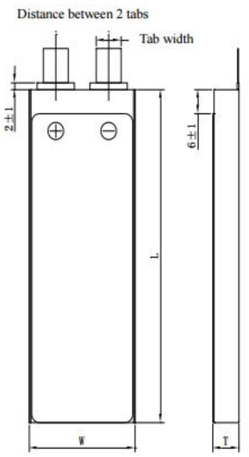
Referred from 8.2.2

2. 型号 MODEL

LPB042126 7000mAh 8C 3.7V

3. 产品规格 SPECIFICATION

单颗电池规格 Specifications of single cell



◆标称容量 Typical Capacity①		7.0Ah
◆标称电压 Nominal Voltage		3.7V
◆充电条件 Charge Condition	最大电流 Max. Continuous charge Current	14.0A
	峰值充电 Peak Charge current	28A(≤1 sec)
	电压 Voltage	4.2V±0.03V
◆ 放电条件 Discharge Condition	Max Continuous discharge Current	56A
	Peak Discharge Current	77A(≤2 secs)
	Cut-off Voltage	3.0V
◆交流内阻 AC Impedance(mOHM)		<2.0
◆循环寿命【充电:1.0C,放电:8C】 Cycle Life【CHA:1.0C,DCH:8C】		>100cycles
◆使用温度 Operating Temp.	充电 Charge	0℃~45℃
	放电 Discharge	-20℃~60℃
◆ 电芯尺寸 Cell Dimensions	厚度 Thickness(T)	10.7±0.3mm
	宽度 Width(W)	42.0±0.5mm
	长度 Length(L)	127.5±0.5mm
	极耳间距 Distance between 2 tabs	21±1mm
◆ 极耳尺寸 Dimensions of Cell tabs	极耳宽度 Tab Width	12mm
	极耳厚度 Tab Thickness	0.2mm
	极耳长度 Tab Length	30mm
◆重量 Weight(g)		135.5±2.5
①标称容量：0.5CmA,4.2V~3.0V@23℃±2℃ Typical Capacity:0.5CmA,4.2V~3.0V@23℃±2℃		

11.8.3- AVX 10kΩ 1206 Control Protection NTC Thermistor.

Referred from 8.2.4

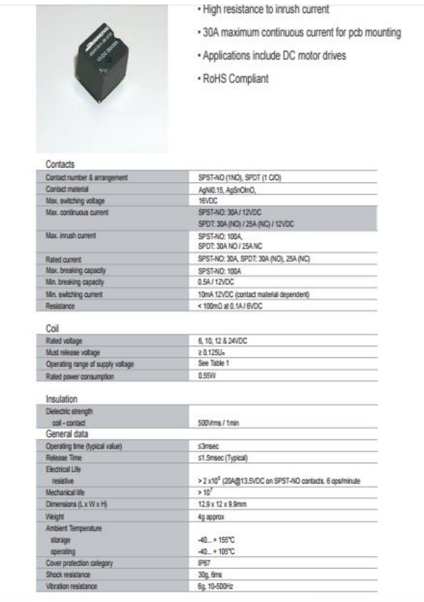
TABLE OF VALUES

NB 12 IEC SIZE : 0805				
Types	Rn at 25°C (Ω)	Material Code	B (K) (ΔB/B (1) ± 5% (2) ± 3%)	α at 25°C (%/°C)
NB 12 KC 0 180	18	KC	3470 ± 5%	− 3.9
NB 12 KC 0 220	22			
NB 12 KC 0 270	27			
NB 12 KC 0 330	33			
NB 12 KC 0 390	39			
NB 12 KC 0 470	47			
NB 12 KC 0 560	56			
NB 12 KC 0 680	68			
NB 12 KC 0 820	82			
NB 12 KC 0 101	100			
NB 12 MC 0 121	120	MC	3910 ± 3%	− 4.4
NB 12 MC 0 151	150			
NB 12 MC 0 181	180			
NB 12 MC 0 221	220			
NB 12 MC 0 271	270			
NB 12 MC 0 331	330			
NB 12 MC 0 391	390			
NB 12 MC 0 471	470			
NB 12 MC 0 561	560			
NB 12 MC 0 681	680			
NB 12 MC 0 821	820			
NB 12 MC 0 102	1,000			
NB 12 MC 0 122	1,200			
NB 12 MC 0 152	1,500			
NB 12 MC 0 182	1,800			
NB 12 MC 0 222	2,200			
NB 12 MC 0 272	2,700			
NB 12 MC 0 332	3,300			
NB 12 J 0 0332	3,300	J	3480 ± 3%	− 3.9
NB 12 J 0 0392	3,900			
NB 12 J 0 0472	4,700			
NB 12 J 0 0562	5,600			
NB 12 K 0 0682	6,800	K	3630 ± 3%	− 4.0
NB 12 K 0 0822	8,200			
NB 12 K 0 0103	10,000			

NB 20 IEC SIZE : 1206				
Types	Rn at 25°C (Ω)	Material Code	B (K) (ΔB/B (1) ± 5% (2) ± 3%)	α at 25°C (%/°C)
NB 20 MC 0 221	220	MC	3910 ± 3%	− 4.4
NB 20 MC 0 102	1,000	MC	3910 ± 3%	− 4.4
NB 20 J 0 0472	4,700	J	3480 ± 3%	− 3.9
NB 20 J 0 0562	5,600			
NB 20 J 0 0682	6,800			
NB 20 J 5 0822	8,200	J5	3480 ± 3%	− 3.9
NB 20 K 0 0103	10,000	K	3630 ± 3%	− 4.0
NB 20 K 0 0123	12,000			
NB 20 L 0 0153	15,000	L	3790 ± 3%	− 4.2
NB 20 L 0 0183	18,000			
NB 20 L 0 0223	22,000			
NB 20 M 0 0273	27,000	M	3950 ± 3%	− 4.4
NB 20 M 0 0333	33,000			
NB 20 M 0 0393	39,000			
NB 20 M 0 0473	47,000			
NB 20 N 0 0563	56,000	N	4080 ± 3%	− 4.6
NB 20 N 0 0683	68,000			
NB 20 N 0 0823	82,000			
NB 20 N 5 0104	100,000	N5	4160 ± 3%	− 4.7
NB 20 P 0 0124	120,000	P	4220 ± 3%	− 4.7
NB 20 P 0 0154	150,000			
NB 20 P 0 0184	180,000			
NB 20 P 0 0224	220,000			
NB 20 Q 0 0274	270,000	Q	4300 ± 3%	− 4.7
NB 20 Q 0 0334	330,000			
NB 20 Q 0 0394	390,000			
NB 20 Q 0 0474	470,000			
NB 20 Q 0 0564	560,000			
NB 20 R 0 0684	680,000	R	4400 ± 3%	− 4.8
NB 20 R 0 0824	820,000			
NB 20 R 0 0105	1,000,000			

11.8.4- Willow Durakool DG20-series, - Single P-channel MOSFET Type BSS84L, - Vishay VBT3045BP

Referred from 8.2.5



- High resistance to inrush current
- 30A maximum continuous current for pcb mounting
- Applications include DC motor drives
- RoHS Compliant

Contacts

Contact number & arrangement	SPST-NO (1NO), SPDT (1 C/O)
Contact material	AgNi0.15, AgSnOInO,
Max. switching voltage	16VDC
Max. continuous current	SPST-NO: 30A / 12VDC SPDT: 30A (NO) / 25A (NC) / 12VDC
Max. inrush current	SPST-NO: 100A, SPDT: 30A NO / 25A NC
Rated current	SPST-NO: 30A, SPDT: 30A (NO), 25A (NC)
Max. breaking capacity	SPST-NO: 100A
Min. breaking capacity	0.5A / 12VDC
Min. switching current	10mA 12VDC (contact material dependent)
Resistance	< 100mΩ at 0.1A / 6VDC

Coil

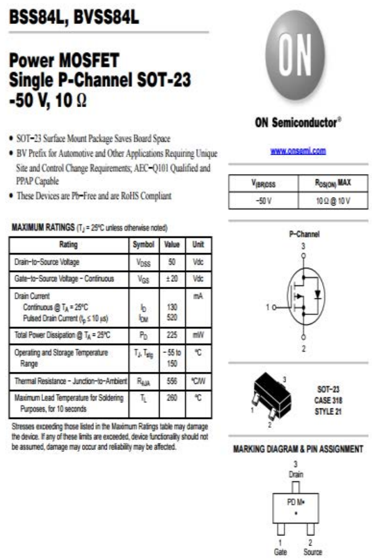
Rated voltage	6, 10, 12 & 24VDC
Must release voltage	≥ 0.125U
Operating range of supply voltage	See Table 1
Rated power consumption	0.55W

Insulation

Dielectric strength coil - contact	500Vrms / 1min

General data

Operating time (typical value)	≤3msec
Release Time	≤1.5msec (Typical)
Electrical Life resistive	> 2 x10⁵ (20A@13.5VDC on SPST-NO contacts. 6 ops/minute
Mechanical life	> 10⁷
Dimensions (L x W x H)	12.9 x 12 x 9.9mm
Weight	4g approx
Ambient Temperature storage operating	 -40... + 155°C -40... + 105°C
Cover protection category	IP67
Shock resistance	30g, 6ms
Vibration resistance	6g, 10-500Hz



BSS84L, BVSS84L

Power MOSFET
Single P-Channel SOT-23
-50 V, 10 Ω

- SOT−23 Surface Mount Package Saves Board Space
- BV Prefix for Automotive and Other Applications Requiring Unique Site and Control Change Requirements; AEC−Q101 Qualified and PPAP Capable
- These Devices are Pb−Free and are RoHS Compliant

MAXIMUM RATINGS (T_J = 25°C unless otherwise noted)

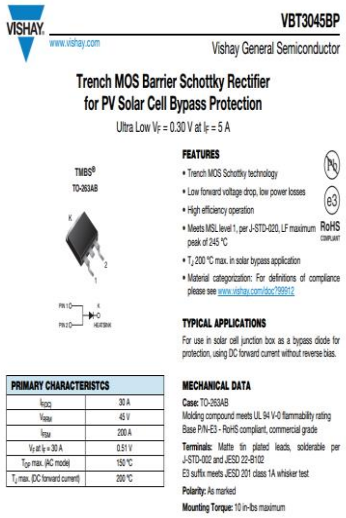
Rating	Symbol	Value	Unit
Drain−to−Source Voltage	V_{DSS}	50	Vdc
Gate−to−Source Voltage − Continuous	V_{GS}	± 20	Vdc
Drain Current Continuous @ T_A = 25°C Pulsed Drain Current (t_p ≤ 10 μs)	 I_D I_{DM}	 130 520	mA
Total Power Dissipation @ T_A = 25°C	P_D	225	mW
Operating and Storage Temperature Range	T_J, T_{stg}	− 55 to 150	°C
Thermal Resistance − Junction−to−Ambient	$R_{θJA}$	556	°C/W
Maximum Lead Temperature for Soldering Purposes, for 10 seconds	T_L	260	°C

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.

ON Semiconductor®

www.onsemi.com

$V_{(BR)DSS}$	$R_{DS(ON)}$ MAX
−50 V	10 Ω @ 10 V



VISHAY. www.vishay.com

VBT3045BP

Vishay General Semiconductor

Trench MOS Barrier Schottky Rectifier for PV Solar Cell Bypass Protection

Ultra Low V_F = 0.30 V at I_F = 5 A

FEATURES

- Trench MOS Schottky technology
- Low forward voltage drop, low power losses
- High efficiency operation
- Meets MSL level 1, per J-STD-020, LF maximum peak of 245 °C
- T_J 200 °C max. in solar bypass application
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

TYPICAL APPLICATIONS

For use in solar cell junction box as a bypass diode for protection, using DC forward current without reverse bias.

PRIMARY CHARACTERISTCS	
$I_{F(DC)}$	30 A
V_{RRM}	45 V
I_{FSM}	200 A
V_F at I_F = 30 A	0.51 V
T_{OP} max. (AC mode)	150 °C
T_J max. (DC forward current)	200 °C

MECHANICAL DATA

Case: TO-263AB
Molding compound meets UL 94 V-0 flammability rating
Base P/N-E3 - RoHS compliant, commercial grade

Terminals: Matte tin plated leads, solderable per J-STD-002 and JESD 22-B102
E3 suffix meets JESD 201 class 1A whisker test

Polarity: As marked

Mounting Torque: 10 in-lbs maximum

Complete datasheet located at:

Willow: http://docs-europe.electrocomponents.com/webdocs/14ac/0900766b814ac371.pdf

MOSFET: https://www.onsemi.com/pub/Collateral/BSS84LT1-D.PDF

Vishay: http://docs-europe.electrocomponents.com/webdocs/112b/0900766b8112bbd2.pdf

11.8.4- Schurter 0090.0025

Referred from 8.2.6

Variants

Rated Current [A]	Mounting	Rated Voltage [VDC]	Breaking Capacity	Power Dissipation 1.0 I_n typ. [mW]	Melting I^2t 20 kA typ. [A^2s]	VDE	UL	Order Number
1	Standard	1000	1)	602	0.554	•	•	0090.0001
2	Standard	1000	1)	1586	4.755	•	•	0090.0002
3	Standard	1000	1)	1504	7.882	•	•	0090.0003
4	Standard	1000	1)	1491	23.03	•	•	0090.0004
5	Standard	1000	1)	1465	42.6	•	•	0090.0005
6	Standard	1000	1)	1348	80.25	•	•	0090.0006
8	Standard	1000	1)	1610	199	•	•	0090.0008
10	Standard	1000	1)	1760	401	•	•	0090.0010
12	Standard	1000	1)	1965	642	•	•	0090.0012
15	Standard	1000	1)	1914	505	•	•	0090.0015
20	Standard	1000	1)	2810	1313	•	•	0090.0020
25	Standard	1000	1)	2981	2371	•	•	0090.0025
30	Standard	1000	1)	3923	2679		•	0090.0030
1	PCB	1000	1)	602	0.554	•	•	0090.1001
2	PCB	1000	1)	1586	4.755	•	•	0090.1002
3	PCB	1000	1)	1504	7.882	•	•	0090.1003
4	PCB	1000	1)	1491	23.03	•	•	0090.1004
5	PCB	1000	1)	1465	42.6	•	•	0090.1005
6	PCB	1000	1)	1348	80.25	•	•	0090.1006
8	PCB	1000	1)	1610	199	•	•	0090.1008
10	PCB	1000	1)	1760	401	•	•	0090.1010
12	PCB	1000	1)	1965	642	•	•	0090.1012
15	PCB	1000	1)	1914	505	•	•	0090.1015
20	PCB	1000	1)	2810	1313	•	•	0090.1020
25	PCB	1000	1)	2981	2371	•	•	0090.1025
30	PCB	1000	1)	3923	2679		•	0090.1030

1) 20 kA @ 1000 VDC, L/R < 2ms

Complete datasheet located at:

https://www.elfadistrelec.no/Web/Downloads/_t/ds/ASO_eng_tds.pdf?mime=application%2Fpdf

11.8.5- ATmega406 AVR

Referred from 8.2.7

Features

- High Performance, Low Power AVR® 8-bit Microcontroller
- Advanced RISC Architecture
  - 124 Powerful Instructions - Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 1 MIPS Throughput at 1 MHz
- Nonvolatile Program and Data Memories
  - 40K Bytes of In-System Self-Programmable Flash, Endurance: 10,000 Write/Erase Cycles
  - Optional Boot Code Section with Independent Lock Bits
    In-System Programming by On-chip Boot Program
    True Read-While-Write Operation
  - 512 bytes EEPROM, Endurance: 100,000 Write/Erase Cycles
  - 2K Bytes Internal SRAM
  - Programming Lock for Software Security
- On-chip Debugging
  - Extensive On-chip Debug Support
  - Available through JTAG interface
- Battery Management Features
  - Two, Three, or Four Cells in Series
  - Deep Under-voltage Protection
  - Over-current Protection (Charge and Discharge)
  - Short-circuit Protection (Discharge)
  - Integrated Cell Balancing FETs
  - High Voltage Outputs to Drive Charge/Precharge/Discharge FETs
- Peripheral Features
  - One 8-bit Timer/Counter with Separate Prescaler, Compare Mode, and PWM
  - One 16-bit Timer/Counter with Separate Prescaler and Compare Mode
  - 12-bit Voltage ADC, Eight External and Two Internal ADC Inputs
  - High Resolution Coulomb Counter ADC for Current Measurements
  - TWI Serial Interface for SM-Bus
  - Programmable Wake-up Timer
  - Programmable Watchdog Timer
- Special Microcontroller Features
  - Power-on Reset
  - On-chip Voltage Regulator
  - External and Internal Interrupt Sources
  - Four Sleep Modes: Idle, Power-save, Power-down, and Power-off
- Packages
  - 48-pin LQFP
- Operating Voltage: 4.0 - 25V
- Maximum Withstand Voltage (High-voltage pins): 28V
- Temperature Range: -30°C to 85°C
  - Speed Grade: 1 MHz

30. Electrical Characteristics

30.1 Absolute Maximum Ratings*

Operating Temperature....................................-30·C to +85·C

Storage Temperature .... -65°C to +150°C

Voltage on PA0 - PA7, PB0 - PB7, PD0 - PD1,
VCC, PI, PPI, NI, NNI, XTAL1, and XTAL2
with respect to Ground .... -0.5V to V_{REG} +0.5V

Voltage on SCL, SDA, NV, PV1 and $\overline{RESET}$
with respect to Ground ....-0.5V to + 6.0V

Voltage on PVT and VFET
with respect to Ground ....-0.5V to + 35V

Voltage on PC0, OPC, OC and BATT
with respect to Ground ....-0.5V to VFET + 0.5V

Voltage on OD, PV2 - PV4
with respect to Ground ....-0.5V to PVT + 0.5V

Maximum Operating Voltage 25V

*NOTICE: Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at these or other conditions beyond those indicated in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

30.2 DC Characteristics

DC Characteristics, TA = -30·C to 85·C, V_{CC} = 3.3V

	Parameter	Condition	Min	Typ	Max	Unit
Supply Current	Power Supply Current	Active		1.2		mA
		Idle		270		µA
		ADC Noise Reduction		220		µA
		Power-save		35		µA
		Power-down		20		µA
		Power-off		1.5		µA
Voltage Regulator(1)	Regulated Output Voltage(2)	I_{OUT} = 5 mA	3.25	3.3	3.35	V
	Temperature Stability(2)	I_{OUT} = 5 mA T_A = 0 - 60 ·C		± 5	± 15	mV
		I_{OUT} = 5 mA T_A = -30 – 85 ·C		± 20	± 70	mV
	Load Regulation	0.1 mA < I_{OUT} < 5 mA		± 20	± 60	mV
	Line Regulation	4V < V_{FET} < 25V, I_{OUT} = 1 mA		± 2	± 10	mV

Complete datasheet located at:

http://www.atmel.com/Images/Atmel-2548-8-bit-AVR-Microcontroller-Battery-Management-ATmega406_Datasheet-Summary.pdf

Appendix E

Matlab code

E.1 DC link ripple

```
pf =linspace(0,1,500);
Irms = 240;
m = linspace(0,1,500); %(8/sqrt(3)/(9*pi))*(1 + 1/(4*cos(phi).^2));
[PF, M] = meshgrid(pf,m);
phi = acos(PF);
Icrms = 1 .* sqrt( (2.*M.* ( (sqrt(3)./(4.*pi)) + cos(phi).^2.*( ...
  (sqrt(3)./pi) - (9./16).*M ) ) ) );
mesh(PF, M, Icrms);
xlabel('Power factor')
ylabel('Modulation index m')
zlabel('Normalized capacitor RMS-current')

\section{Power loss IGBT}
```

```
clc, clear, close
syms wt
% Variables ----------------------------------------------------------------
Vm = 0:0.01:1; % modulation index
% 1st order approximation of Vce
% calculated from datasheet graphs of Vce and Vd vs current.
Rc = 1.65/300; % Transistor resistance
Rd = 0.65/300; % Diode resistance
vceo = 0.75; % Zero state voltage transistor
vdeo = 0.75; % Zero state voltage diode
io = 166; % Peak output current
cosPhi = 0.9; % Current lag
fsw = 15; % Switching speed of inverter [kHz]

% Compute conduction losses ------------------------------------------------
% Losses computed for one leg of the inverter.
```

```
Phi = acos(cosPhi);
ir = io*sin(wt - Phi);
dr = 0.5 + 0.5*Vm*sin(wt);
vce = vceo + ir * Rc;
vd  = vdeo + ir * Rd;
% Transistor conduction loss
Ptcond = (1/pi) * int((dr*vce*ir),wt,Phi,pi+Phi);
% Diode conduction loss
Pdcond = (1/pi) * int(((1-dr)*vd*ir),wt,Phi,pi+Phi);

% Compute Switching losses ------------------------------------------------
% First order approximation for Eon and Eoff
Vbat = 400; % used for scaling the Eon/Eoff
Vnom = 600; % Used in the datasheet for Eon/Eoff variables.
Eon = (3 + 7*ir/150)*fsw * (Vbat/Vnom);
Eoff = (4 + 16*ir/300)*fsw * (Vbat/Vnom);
Ptsw = (1/pi) * int(Eon + Eoff,wt,Phi,pi+Phi);
% Switching loss for diode
% Switch off power is neglected
% Switch on power is equal to Eond*Fsw
Erec = (1.5 + 2*ir/125) * (Vbat/Vnom) * fsw;
Pdsw = (1/pi) * int(Erec,wt,Phi,pi+Phi);
% Display power losses ----------------------------------------------------
totalLoss = Ptcond + Pdcond;
disp('IGBT losses: ')
disp(['Conduction Transistor: ',+num2str(double(Ptcond(end))/2)]);
disp(['Conduction diode: ',+num2str(double(Pdcond(end))/2)]);
disp(['Switching Transistor: ',+num2str(double(Ptsw(end)))]);
disp(['Switching Diode: ', + num2str(double(Pdsw(end)))]);
disp(['Total loss: ', + num2str( double(Ptcond(end))/2 + ...
    double(Pdcond(end))/2 + double(Ptsw(end)) + double(Pdsw(end)) )]);
```

Appendix F

C code

```
#include "hal_pga411.h"
/* Macros ----------------------------------------------------------------*/

/* Typedefs --------------------------------------------------------------*/
typedef union ordMapping
{
    struct
    {
        uint16_t ord0:1;
        uint16_t ord1:1;
        uint16_t ord2:1;
        uint16_t ord3:1;
        uint16_t ord4:1;
        uint16_t ord5:1;
        uint16_t ord6:1;
        uint16_t ord7:1;
        uint16_t ord8:1;
        uint16_t ord9:1;
        uint16_t ord10:1;
        uint16_t ord11:1;
    }bit;

    struct
    {
        uint16_t ord;
    }val;
}ord_t;


ord_t ordStruct;

/* Public functions ------------------------------------------------------*/
uint16_t hal_pga411ReadORD(void)
```

```
{
    ordStruct.bit.ord0  = IO_READ_BIT(PGA411_pxx[ord0]);
    ordStruct.bit.ord1  = IO_READ_BIT(PGA411_pxx[ord1]);
    ordStruct.bit.ord2  = IO_READ_BIT(PGA411_pxx[ord2]);
    ordStruct.bit.ord3  = IO_READ_BIT(PGA411_pxx[ord3]);
    ordStruct.bit.ord4  = IO_READ_BIT(PGA411_pxx[ord4]);
    ordStruct.bit.ord5  = IO_READ_BIT(PGA411_pxx[ord5]);
    ordStruct.bit.ord6  = IO_READ_BIT(PGA411_pxx[ord6]);
    ordStruct.bit.ord7  = IO_READ_BIT(PGA411_pxx[ord7]);
    ordStruct.bit.ord8  = IO_READ_BIT(PGA411_pxx[ord8]);
    ordStruct.bit.ord9  = IO_READ_BIT(PGA411_pxx[ord9]);
    ordStruct.bit.ord10 = IO_READ_BIT(PGA411_pxx[ord10]);
    ordStruct.bit.ord11 = IO_READ_BIT(PGA411_pxx[ord11]);
    return ordStruct.val.ord;
}


void hal_pga411initGPIO(void)
{
    const uint16_t nbrOfInputs = 15;
    const uint16_t nbrOfOutputsOD = 6;

    portPin_t inputs[nbrOfInputs] =
    {
        PGA411_pxx[ord0],
        PGA411_pxx[ord1],
        PGA411_pxx[ord2],
        PGA411_pxx[ord3],
        PGA411_pxx[ord4],
        PGA411_pxx[ord5],
        PGA411_pxx[ord6],
        PGA411_pxx[ord7],
        PGA411_pxx[ord8],
        PGA411_pxx[ord9],
        PGA411_pxx[ord10],
        PGA411_pxx[ord11],
        PGA411_pxx[ordCLK],
        PGA411_pxx[prd],
    };
    /*TODO : should any of the ouputs be configured as push pull ? */
    portPin_t outputsOD[nbrOfOutputsOD] =
    {
        PGA411_pxx[va0],
        PGA411_pxx[va1],
        PGA411_pxx[amode],
        PGA411_pxx[inhb],
        PGA411_pxx[faultres],
        PGA411_pxx[nRes],
    };
```

```
    /* Configure inputs */
    for(int k = 0; k<nbrOfInputs; k++)
    {
        HAL_gpioEnableClock(inputs[k].port);
        GPIO_InitTypeDef GPIO_initStruct;
        GPIO_initStruct.GPIO_Mode    = GPIO_Mode_IN;
        GPIO_initStruct.GPIO_PuPd    = GPIO_PuPd_NOPULL; /*hiz*/
        GPIO_initStruct.GPIO_OType   = GPIO_OType_OD;
        GPIO_initStruct.GPIO_Speed   = GPIO_Speed_100MHz;
        GPIO_initStruct.GPIO_Pin     = inputs[k].pin;
        GPIO_Init(inputs[k].port, &GPIO_initStruct);
    }

    /* Configure ouputs */
        for(int k = 0; k<nbrOfOutputsOD; k++)
    {
        HAL_gpioEnableClock(outputsOD[k].port);
        GPIO_InitTypeDef GPIO_initStruct;
        GPIO_initStruct.GPIO_Mode    = GPIO_Mode_OUT;
        GPIO_initStruct.GPIO_PuPd    = GPIO_PuPd_NOPULL; /* should there be a pull-up/
        GPIO_initStruct.GPIO_OType   = GPIO_OType_OD;
        GPIO_initStruct.GPIO_Speed   = GPIO_Speed_100MHz;
        GPIO_initStruct.GPIO_Pin     = outputsOD[k].pin;
        GPIO_Init(outputsOD[k].port, &GPIO_initStruct);
    }
}

/* TODO: finish the PGA init function - see code for BMS */
void hal_PGAspiInit(void)
{
    SPI_InitTypeDef SPI_initStruct;
}

/* TODO: write the code :) */
uint16_t hal_PGAspiXmit4B(uint16_t frame)
{
}

/*
* Module containing all the hardware specific code for the PGA411.
* note - hardware dependent.
*/

#ifndef _HAL_PGA411_H
#define _HAL_PGA411_H

/* Dependencies --------------------------------------------------------------*/
#include "hal_gpio.h" /* GPIO functions */
```

```
#include "stdint.h"
#include "stm32f4xx_spi.h"
#include "hardware.h" /* Pin and port mapping, common for all GPIOs*/

/* Macros ------------------------------------------------------------------*/
#define HAL_VA0_LOW IO_LOW(PGA411_pxx[va0])
#define HAL_VA0_HIGH IO_HIGH(PGA411_pxx[va0])

#define HAL_VA1_LOW IO_LOW(PGA411_pxx[va1])
#define HAL_VA1_HIGH IO_HIGH(PGA411_pxx[va1])

#define HAL_INHB_LOW IO_LOW(PGA411_pxx[inhb])
#define HAL_INHB_HIGH IO_HIGH(PGA411_pxx[inhb])

#define HAL_PGA_FAULTRES_LOW IO_LOW(PGA411_pxx[faultres])
#define HAL_PGA_FAULTRES_HIGZ IO_HIGH(PGA411_pxx[faultres])

#define HAL_PGA_RESET_N_LOW IO_LOW(PGA411_pxx[nRes])
#define HAL_PGA_RESET_N_HIGH IO_HIGH(PGA411_pxx[nRes])

#define HAL_IS_ORDCLK_HIGH (IO_READ_BIT(PGA411_pxx[ordCLK]))

/* Public functions --------------------------------------------------------*/

/* GPIO functions */

/**
* @brief     Reads the paralell interface of the PGA411.
* @input     none.
* @output    uint16_t - returns the paralell interface data. 12 bits.
*/
uint16_t hal_pga411ReadORD(void);

/**
* @brief     Initializes all the hardware pins for the PGA411.
* @note      hardware.h contains structures with the pin and
*            port mappings used by this function.
* @input     none.
* @output    none.
*/
void hal_pga411initGPIO(void);

/* SPI functions */

/**
* @brief     Initializes the SPI module with the settings used for
*            the PGA411.
* @note      Hardware.h contains the pin and port mapping structure for
*            the SPI.
```

```
*/

void hal_PGAspiInit(void);
/**
* @brief    For transmitting a frame consisting of 4 bytes.
* @input    frame: the frame to be sent.
* @output   uint16_t : Return frame from the SPI.
*/
uint16_t hal_PGAspiXmit4B(uint16_t frame);

#endif

#include "stdint.h"
/* Paralell interface*/

typedef union
{
        struct
        {
                uint16_t ord0:1;
                uint16_t ord1:1;
                uint16_t ord2:1;
                uint16_t ord3:1;
                uint16_t ord4:1;
                uint16_t ord5:1;
                uint16_t ord6:1;
                uint16_t ord7:1;
                uint16_t ord8:1;
                uint16_t ord9:1;
                uint16_t ord10:1;
                uint16_t ord11:1;
        };
        struct
        {
                uint16_t ord:12;
        };

}ord_t;

uint16_t hal_pgaReadGPIO(uint16_t data[13])
{
        ord_t val;
        val.ord0 =
        val.ord1 =
        val.ord2 =
        val.ord3 =
        val.ord4 =
        val.ord5 =
        val.ord6 =
```

```
        val.ord7 =
        val.ord8 =
        val.ord9 =
        val.ord10 =
        val.ord11 =
        return val.ord;
}

/*
Or this solution could be used :) A bit harder to understand, but does just the same.
*/

#define SET_BIT_N_TO_X(number,n,x) number ^= (-x ^ number) & (1 << n)
uint16_t hal_pgaReadGPIO(uint16_t data[13])
{
        ord_t val;
        for(int k = 0; k<12; k++)
        {
                SET_BIT_N_TO_X(val.ord, k, data[k]);
        }
        return val.ord;
}

#include "hal_gpio.h"

void HAL_gpioEnableClock(GPIO_TypeDef* GPIOx)
{
    if(GPIOx == GPIOA)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOA, ENABLE);
    }else if(GPIOx == GPIOB)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOB, ENABLE);
    }else if(GPIOx == GPIOC)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOC, ENABLE);
    }else if(GPIOx == GPIOD)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOD, ENABLE);
    }else if(GPIOx == GPIOE)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOE, ENABLE);
    }else if(GPIOx == GPIOF)
    {
        RCC_AHB1PeriphClockCmd(RCC_AHB1Periph_GPIOF, ENABLE);
    }
}

uint16_t gpio_pins[16] = {1,2,4,8,16,32,64, 128, 256,512,1024,2048,4096,8192,16384,32
```

```
uint8_t HAL_gpioPin2pinSource(uint16_t gpioPin)
{
    for(uint8_t k = 0; k<16; k++)
    {
        if(gpio_pins[k] == gpioPin)
        {
            return k;
        }
    }
    return 16; /* GPIO_pins does not go as higher than 15. */
}

/*
* Just some extra functions for simplifying usage of the
* stm32f4xx_gpio.h abstraction layer from the STM
* standard peripheral library.
*/

#ifndef HAL_GPIO_H
#define HAL_GPIO_H
/* Dependencies ---------------------------------------------------------------*
#include "stm32f4xx_gpio.h"

/* Typedefs -------------------------------------------------------------------*

/*      Used for mapping ports and pins together.
        Not currently used by any functions in this module
        since SPL does not map them together, but added here since
        it's still useful for modules dependent on this module.
*/
typedef struct
{
        GPIO_TypeDef* port;
        uint16_t pin;
}portPin_t;

/* Macros ---------------------------------------------------------------------*
#define IO_HIGH(portPin)(portPin.port->BSRRL = portPin.pin)
#define IO_LOW(portPin)(portPin.port->BSRRH = portPin.pin)
#define IO_READ_BIT(portPin) (portPin.port->IDR & portPin.pin)

/* Functions ------------------------------------------------------------------*
/*
* @brief: Enables the clock for a specific PORT.
* input : GPIO_TypeDef*, Port.
* output : none.
*/
void HAL_gpioEnableClock(GPIO_TypeDef* GPIOx);
```

```
/*
* @brief :       Translates the gpio pin number to the pinsource number
*                         used by STM's Standard Peripheral library.
*/
uint8_t HAL_gpioPin2pinSource(uint16_t gpioPin);

#endif

/* TODO:          calculate period time values
*                         Calculate dead time values
*                         Write Overvoltage shutdown function
*/

#include "HALPWM.h"
/* Private typedefs ------------------------------------------------------------

/* Private constants -----------------------------------------------------------

#define deadtime 0x0A

const uint32_t periodList[5] =
{
        5000,   /*  5kHz,*/
        5000,   /*      8kHz */
        5000,   /*  10kHz */
        5000,   /*      15Khz */
        5000,   /*      20kHz */
};

/*Private variables ------------------------------------------------------------
uint8_t isPwm6ChannelConfigured = 0;
uint32_t period;
PWM_state_t irqState_f = disable;
PWM_state_t overvoltageProtection_f = disable;
uint16_t maxDr = 90; /* Maximum duty ratio in percentage */
uint16_t minDr = 10; /* Minimum duty ratio in percentage */

void HAL_pwm6channelInitTim1(const portPin_t portPin[6], const PWM_state_t irqState,
{
    /* PWM Init */
    GPIO_InitTypeDef GPIO_initStruct;
    TIM_TimeBaseInitTypeDef TIM_baseInitStruct;
    TIM_OCInitTypeDef TIM_ocInitStruct;
    TIM_BDTRInitTypeDef TIM_bdtrInitStruct;

    /*Enable clocks*/
    RCC_APB2PeriphClockCmd(RCC_APB2Periph_TIM1, ENABLE);
```

```
/* Configure GPIO */
/* Alternate function mapping */
    for(int k = 0; k<6; k++)
    {
            /* Enable GPIO Clock */
            HAL_gpioEnableClock(portPin[k].port);
            /* Configure Alternate function for the gpio */
            GPIO_PinAFConfig(portPin[k].port, HAL_gpioPin2pinSource(portPin[k].pi
            /* Configure GPIO's as alternate function pins */
            GPIO_initStruct.GPIO_Mode       = GPIO_Mode_AF;
            GPIO_initStruct.GPIO_OType      = GPIO_OType_PP;
            GPIO_initStruct.GPIO_Pin        = portPin[k].pin;
            GPIO_initStruct.GPIO_PuPd       = GPIO_PuPd_NOPULL;
            GPIO_initStruct.GPIO_Speed      = GPIO_Speed_100MHz;
            GPIO_Init(portPin[k].port, &GPIO_initStruct);
    }
    /*Calculate the period for given frequency */
    period = periodList[freq];
/* Timer 1 configuration for PWM */
TIM_baseInitStruct.TIM_Period                   = period;
TIM_baseInitStruct.TIM_Prescaler        = 0;
TIM_baseInitStruct.TIM_CounterMode      = TIM_CounterMode_CenterAligned1;
TIM_baseInitStruct.TIM_ClockDivision = TIM_CKD_DIV1;
TIM_TimeBaseInit(TIM1, &TIM_baseInitStruct);
TIM_Cmd(TIM1, ENABLE);

/* PWM Config */
TIM_ocInitStruct.TIM_OCMode                     = TIM_OCMode_PWM1;
TIM_ocInitStruct.TIM_OCPolarity         = TIM_OCPolarity_High;
TIM_ocInitStruct.TIM_OutputNState       = TIM_OutputNState_Enable;
TIM_ocInitStruct.TIM_OutputState        = TIM_OutputState_Enable;
TIM_ocInitStruct.TIM_OCNPolarity        = TIM_OCNPolarity_High;
TIM_ocInitStruct.TIM_Pulse = 0;
TIM_OC1Init(TIM1, &TIM_ocInitStruct);
TIM_OC2Init(TIM1, &TIM_ocInitStruct);
    TIM_OC3Init(TIM1, &TIM_ocInitStruct);
    TIM_OC1PreloadConfig(TIM1, TIM_OCPreload_Enable);
    TIM_OC2PreloadConfig(TIM1, TIM_OCPreload_Enable);
    TIM_OC3PreloadConfig(TIM1, TIM_OCPreload_Enable);

    /* Configure the break functionality */
TIM_bdtrInitStruct.TIM_OSSRState        = TIM_OSSRState_Disable;
TIM_bdtrInitStruct.TIM_OSSIState        = TIM_OSSIState_Enable;
TIM_bdtrInitStruct.TIM_LOCKLevel        = TIM_LOCKLevel_OFF;
TIM_bdtrInitStruct.TIM_DeadTime                 = deadtime;
TIM_bdtrInitStruct.TIM_Break                    = TIM_Break_Enable;
TIM_bdtrInitStruct.TIM_BreakPolarity    = TIM_BreakPolarity_High;
TIM_bdtrInitStruct.TIM_AutomaticOutput  = TIM_AutomaticOutput_Disable;
TIM_BDTRConfig(TIM1, &TIM_bdtrInitStruct);
```

```
    TIM_SelectOCxM(TIM1, TIM_Channel_1, TIM_OCMode_PWM1);
    TIM_SelectOCxM(TIM1, TIM_Channel_2, TIM_OCMode_PWM1);
    TIM_SelectOCxM(TIM1, TIM_Channel_3, TIM_OCMode_PWM1);

        /* Enable the three PWM outputs*/
        TIM_CCxCmd(TIM1, TIM_Channel_1, TIM_CCx_Enable);
        TIM_CCxCmd(TIM1, TIM_Channel_2, TIM_CCx_Enable);
        TIM_CCxCmd(TIM1, TIM_Channel_3, TIM_CCx_Enable);
        /* Enable the three complementary PWM outputs*/
        TIM_CCxNCmd(TIM1, TIM_Channel_1, TIM_CCxN_Enable);
        TIM_CCxNCmd(TIM1, TIM_Channel_2, TIM_CCxN_Enable);
        TIM_CCxNCmd(TIM1, TIM_Channel_3, TIM_CCxN_Enable);

        TIM_SetCompare4(TIM1, (uint32_t)(TIM1->ARR));
        /* Configure interrupt on channel 4 */
        NVIC_InitTypeDef nvicStructure;
        nvicStructure.NVIC_IRQChannel = TIM1_CC_IRQn;
        nvicStructure.NVIC_IRQChannelPreemptionPriority = 0;
        nvicStructure.NVIC_IRQChannelSubPriority = 1;
        nvicStructure.NVIC_IRQChannelCmd = ENABLE;
        NVIC_Init(&nvicStructure);
        /* Enable the interrupt event */
        /* Set the configuration done flag */
        isPwm6ChannelConfigured = 1;
}


void HAL_PWM6channel_enableOutput(void)
{
        TIM_CtrlPWMOutputs(TIM1, ENABLE);
        TIM_ITConfig(TIM1, TIM_IT_CC4, ENABLE);
}


void HAL_PWM6channel_disableOutput(void)
{
        TIM_CtrlPWMOutputs(TIM1, DISABLE);
        TIM_ITConfig(TIM1, TIM_IT_CC4, DISABLE);
}

void HAL_PWM6channel_OvervoltageProtection(PWM_state_t state)
{
        if(state == enable)
        {
                overvoltageProtection_f = enable;
                TIM1->CCR1 = (period * 0)/100;
                TIM1->CCR2 = (period * 0)/100;
                TIM1->CCR3 = (period * 0)/100;
```

```
        }else if(state == disable)
        {
                overvoltageProtection_f = disable;
        }
}

void PWM_updateRefCh1(uint8_t dr)
{
        if(overvoltageProtection_f == disable)
        {
                if(dr > period){dr = maxDr;}
                else if(dr < 0){period = 0;}
                TIM1->CCR1 = (dr);
        }
}


void PWM_updateRefCh2(uint8_t dr)
{
        if(overvoltageProtection_f == disable)
        {
                if(dr > period){dr = maxDr;}
                else if(dr < 0){period = 0;}
                TIM1->CCR2 = (dr);
        }
}


void PWM_updateRefCh3(uint8_t dr)
{
        if(overvoltageProtection_f == disable)
        {
                if(dr > period){dr = maxDr;}
                else if(dr < 0){period = 0;}
                TIM1->CCR3 = (dr);
        }
}

/*Private functions ----------------------------------------------------------------

#ifndef HAL_PWM_H
#define HAL_PWM_H
/* Dependencies -------------------------------------------------------------*/
#include "HAL_GPIO.h"
#include "stm32f4xx_rcc.h"

/* Macros -------------------------------------------------------------------*/

/* Typedefs -----------------------------------------------------------------*/
```

```
typedef enum
{
        def,
        alt,
}PWM_pinSet_t;

typedef enum
{
        enable,
        disable,
}PWM_state_t;

typedef enum
{
        freq5kHz,
        freq8kHz,
        freq10kHz,
        freq15kHz,
        freq20kHz,
}PWM_freq_t;
#define IS_PWM_FREQ_T(freq) (freq == freq5kHz || freq == freq8kHz || freq == freq10kH

/*Structure containing the configuration for the six channel PWM */
typedef struct
{
        portPin_t portPin[6]; /* Pins used for PWM */
        uint16_t maxDutyRatio; /* Max Duty ratio, number between 0->100*/
        uint16_t minDutyRatio; /* Min duty Ration number between 0->100*/
        PWM_state_t irqState; /* Wether to configure a IRQ on ch4 or not*/
        PWM_freq_t freq; /* The PWM frequency*/
        uint16_t deadtime; /* Deadtime insertion value, number of ticks */
}pwm6ChannelConfig_t;

/* Public functions ----------------------------------------------------------*/
/**
* @brief:        initializes three PWM outputs and their complementary output for TIM
*                        the PWM module is hardware controlled. Use macros PWM_UPDATE
*                        to change the PWM reference.
* @note:         Uses center aligned PWM.
* @note:         The APB2 TIM1 clock should have a frequency of -- for the frequency s
*                        to be correct.
* @input:        pins - struct array containing the pins and ports used. Refer to the
*                        STM32f407 datasheet for compatible gpio to be used with TIM1.
*                        alternative pinSet : A = , nA = , B= , nB = , C = , nC =
* @input:        irqState : on - enables the a IRQ for the midpoint of the timer.
*                        off - disables the IRQ.
* @input:        freq - Sets the PWM frequency.
*/
void hal_pwm6channelInitTim1(const portPin_t portPin[6], const PWM_state_t irqState,
```

```
/**
* @brief:         Enables the PWM output (and IRQ if configured).
*                         HAL_pwm6channelInitTim1 must be called before this function.
*/
void hal_pwm6channel_enableOutput(void);

/**
* @brief:         Disables the PWM output (and IRQ if configured).
*                         HAL_pwm6channelInitTim1 must be called before this function.
*/
void hal_pwm6channel_disableOutput(void);
/**
* @brief          Called if overvoltage is detected. Turns all top
*                         transistor off and all bottom transistors. This
*                         prevents voltage build up in the capacitor bank.
* @note           Implements deadtime to not get shot through in phase legs.
* @input          state : enable if overvoltage is detected.
*                                   : disable if overvoltage is not detected.
* @note           if overvoltage protection have been enabled
*                         PWM_updateRefChx function are ignored. Overvoltage
*                         protection needs to be disabled to continue operation.
*/
void hal_pwm6channel_OvervoltageProtection(PWM_state_t state);
/**
* @brief:         Updates the reference signal for channel 1.
* @input:         dr - duty ratio, number between 0->100. Min and Max
*                         values are programmed by init function.
*/
void hal_pwmUpdateRefCh1(uint8_t dr);

/**
* @brief:         Updates the reference signal for channel 2.
* @input:         dr - duty ratio, number between 0->100. Min and Max
*                         values are programmed by init function.
*/
void hal_pwmUpdateRefCh2(uint8_t dr);

/**
* @brief:         Updates the reference signal for channel 3.
* @input:         dr - duty ratio, number between 0->100. Min and Max
*                         values are programmed by init function.
*/
void hal_pwmUpdateRefCh3(uint8_t dr);

#endif

/*
* Hardware mapping files. Contains pin/port functions and configuration settings.
```

```
* Uses SPL librarys from STM for definitions.
*/

#ifndef HARDWARE_H
#define HARDWARE_H

#if defined COMPILING_FOR_DEVBOARD
    #warning "compiling for development board!"
    #include "hardware_discovery.h"
#elif defined COMPILING_FOR_V1
    #include "hardwareV1.h"
#else
    #error "please specify which board you are compiling for."
#endif

#endif

#ifndef HARDWARE_DISCOVERY_H
#define HARDWARE_DISCOVERY_H
#endif

#include "hardware.h"

const portPin_t led[]=
{
[led1] = {GPIOE, GPIO_Pin_14},
[led2] = {GPIOC, GPIO_Pin_6},
[led3] = {GPIOC, GPIO_Pin_7},
[led4] = {GPIOE, GPIO_Pin_12},
};

const portPin_t PGA411_pxx[] =
{
    [ord0] = {GPIOD, GPIO_Pin_5},
    [ord1] = {GPIOD, GPIO_Pin_6},
    [ord2] = {GPIOD, GPIO_Pin_7},
    [ord3] = {GPIOB, GPIO_Pin_5},
    [ord4] = {GPIOB, GPIO_Pin_8},
    [ord5] = {GPIOE, GPIO_Pin_0},
    [ord6] = {GPIOE, GPIO_Pin_1},
    [ord7] = {GPIOC, GPIO_Pin_13},
    [ord8] = {GPIOC, GPIO_Pin_14},
    [ord9] = {GPIOC, GPIO_Pin_3},
    [ord10] = {GPIOC, GPIO_Pin_2},
    [ord11] = {GPIOC, GPIO_Pin_1},
    [ord12] = {GPIOC, GPIO_Pin_0},
    [prd] = {GPIOD, GPIO_Pin_4},
    [va0] = {GPIOC, GPIO_Pin_8},
    [va1] = {GPIOA, GPIO_Pin_12},
```

```
    [amode] = {GPIOD, GPIO_Pin_1},
    [inhb] = {GPIOD, GPIO_Pin_3},
    [faultres] = {GPIOB, GPIO_Pin_12},
    [nRes] = {GPIOD, GPIO_Pin_2},
    [pgaCs] = {GPIOD, GPIO_Pin_15},
    [pgaSclk] = {GPIOC, GPIO_Pin_10},
    [pgaSdi] = {GPIOC, GPIO_Pin_12},
    [pgaSdo] = {GPIOC, GPIO_Pin_11},
};

#ifndef HARDWAREV1_H
#define HARDWAREV1_H

#include "hal_gpio.h"

/* LEDs */
enum
{
        led1,
        led2,
        led3,
        led4,
};
extern const portPin_t led[]; /*Pin and port mapping*/

/* PGA411 CHIP */
enum
{
    ord0, /* ORD 0-> 11 parallel interface */
    ord1,
    ord2,
    ord3,
    ord4,
    ord5,
    ord6,
    ord7,
    ord8,
    ord9,
    ord10,
    ord11,
    ord12, /* unused */
    ordCLK, /* parallel interface clock */
    prd, /* Parallel interface parity check bit */
    va0, /* Configuration bit */
    va1, /* Configuration bit */
         /*Va0 = 0 & Va1 = 1 -> angle output
           Va0 = 1 & va1 = 0 -> velocity output */
    amode, /* Accleration mode on/off [1/0]*/
    inhb, /* 1 -> new update, 0-> keep last output */
```

```
    faultres, /* HIGH -> LOW -> HIGH -> reset faults in PGA */
    nRes, /* To set the whole chip in reset */
    pgaCs, /* SPI chip select */
    pgaSclk, /* SPI clock */
    pgaSdi, /* SPI, slave data in */
    pgaSdo, /* SPI, Slave data out */
};
extern const portPin_t PGA411_pxx[];

/* CAN BUS ---------------------------------------------------------------*/
#define PIN_CAN_TX GPIO_Pin_9
#define PORT_CAN_TX GPIOB
#define PIN_CAN_RX GPIO_Pin_0
#define PORT_CAN_RX GPIOD


/* Analog ----------------------------------------------------------------*/
/* Current measurement */
#define PIN_ADC_I1 GPIO_Pin_6
#define PORT_ADC_I1 GPIOA
#define CH_ADC_I1 ADC1
#define PIN_ADC_I2 GPIO_Pin_5
#define PORT_ADC_I2 GPIOA
#define CH_ADC_I2 ADC2

/* Voltage */
#define PIN_ADC_VDC GPIO_Pin_0
#define PORT_ADC_VDC GPIOB
#define CH_ADC_VDC ADC3

/* IGBT temperature */
#define PIN_ADC_IGBT_TEMP1 GPIO_Pin_5
#define PORT_ADC_IGBT_TEMP1 GPIOC
#define CH_ADC_IGBT_TEMP1 ADC3
#define PIN_ADC_IGBT_TEMP2 GPIO_Pin_4
#define PORT_ADC_IGBT_TEMP2 GPIOC
#define CH_ADC_IGBT_TEMP2 ADC3
#define PIN_ADC_IGBT_TEMP3 GPIO_Pin_7
#define PORT_ADC_IGBT_TEMP3 GPIOA
#define CH_ADC_IGBT_TEMP3 ADC3

/* Motor temperature */
#define PIN_ADC_MOTOR_TEMP GPIO_Pin_4
#define PORT_ADC_MOTOR_TEMP GPIOA
#define CH_ADC_MOTOR_TEMP ADC3

/* Ambient temperature */
#define PIN_ADC_AMB_TEMP GPIO_Pin_3
#define PORT_ADC_AMB_TEMP GPIOA
```

```
#define CH_ADC_AMB ADC3


/* Inputs --------------------------------------------------------*/
/* Supply status */
#define PIN_5V_ERROR GPIO_Pin_1
#define PORT_5V_ERROR GPIOA
#define PIN_3V3A_ERROR GPIO_Pin_13
#define PORT_3V3A_ERROR GPIOE
#define PIN_3V3_ERROR GPIO_Pin_0
#define PORT_3V3_ERROR GPIOA

/* Current overload detected */
#define PIN_OC GPIO_Pin_1
#define PORT_OC GPIOB

/* Pilotline present */
#define PIN_PL_PR GPIO_Pin_11
#define PORT_PL_PR GPIOA

/* Run signal from ECU */
#define PIN_RUN GPIO_Pin_2
#define PORT_RUN GPIOA

/* outputs -------------------------------------------------------*/
/* Pilotline enable/disable */
#define PIN_PL_CTRL GPIO_Pin_9
#define PORT_PL_CTRL GPIOC


/* Driver ---------------------------------------------------------*/
#define PIN_NTRIP GPIO_Pin_11
#define PORT_NTRIP GPIOD

/* PWM */
#define CH_PWM TIM1
#define PIN_PWM_U GPIO_Pin_8
#define PORT_PWM_U GPIOA
#define PIN_NPWM_U GPIO_Pin_13
#define PORT_NPWM_U GPIOB

#define PIN_PWM_V GPIO_Pin_9
#define PORT_PWM_V GPIOA
#define PIN_NPWM_V GPIO_Pin_14
#define PORT_NPWM_V GPIOB

#define PIN_PWM_W GPIO_Pin_10
#define PORT_PWM_W GPIOA
#define PIN_NPWM_W GPIO_Pin_15
```

```
#define PORT_NPWM_W GPIOB

/* EEPROM ---------------------------------------------------*/
#define PIN_EEP_WP GPIO_Pin_15
#define PORT_EEP_WP GPIOE
#define PIN_EEP_SCL GPIO_Pin_10
#define PORT_EEP_SCL GPIOB
#define PIN_EEP_SDA GPIO_Pin_11
#define PORT_EEP_SDA GPIOB



#endif

#include "parkClarke.h"

/* Constants ------------------------------------------------------------------------------*/
const float sqrt3Inv = 0.577350269189626; /* (1/sqrt(3))*/
const float sqrt3 = 1.732050807568877;

void inline parkClarke_forward(
        uint16_t theta,
        float ia,
        float ib,
        float* iq,
        float* id
){
        /* Clarke transformation */
        float ibeta;
        /* ialpha = ia; */
        ibeta = sqrt3Inv * (ia + 2*ibeta);

        /* Park transformation */
        *id = ia * LUT_COSINE(theta) + ibeta * LUT_SINE(theta);
        *iq = ibeta * LUT_COSINE(theta) - ia * LUT_SINE(theta);
}

void inline parkClarke_inverse(
        uint16_t theta,
        float vq,
        float vd,
        float* va,
        float* vb,
        float* vc
){
        float vAlpha, vBeta;

        /* Inverse Park transformation */
        vAlpha = vd * LUT_COSINE(theta) - vq*LUT_SINE(theta);
```

```
        vBeta = vq * LUT_COSINE(theta) + vd*LUT_SINE(theta);

        /* Inverse clarke transformation */
        *va = vAlpha;
        *vb = (-vAlpha + sqrt3 * vBeta )/2;
        *vc = (-vAlpha - sqrt3 * vBeta) /2;
}

#ifndef PARKCLARKE_H
#define PARKCLARKE_H

/* Dependencies --------------------------------------------------------*/
#include "stdint.h"
#include "sinLUT.h"
/* public functions ----------------------------------------------------*/
/**
* @brief        Performs the forward park and clarke transformations.
*                       Takes the three phase currents (ia, ib) and the current
*                       angle theta and calculates the rotating frame values
*                       (iq and id).
* @note         Assumes a balanced three phase load (ia + ib + ic = 0).
* @input        theta - The current angle. A value between 0->4095
*                       corresponding to 0->360 degrees.
* @note         Uses a 12-bit look up table for the sin and cosine
*                       functions.
* @input        ia - the current in phase A.
* @input        ib - the current in phase B.
* @output       iq - pointer to the output for the calculated q-axis current.
* @output       id - pointer to the output for the calculated d-axis current.
*/
void inline parkClarke_forward(
        uint16_t theta,
        float ia,
        float ib,
        float* iq,
        float* id
);

/**
* @brief        performs the inverse clarke and park transforms.
*                       Takes the rotating frame values (vq, vd and the
*                       angle theta) and calculates the three phase output
*                       (va, vb and vc).
* @input        theta - The current angle. A value between 0->4095
*                       corresponding to 0->360 degrees.
* @note         Uses a 12-bit look up table for the sin and cosine
*                       functions.
* @input        vq - the q-axis voltage.
* @input        vd - the d-axis voltage.
```

```
* @output        va - pointer to the output variable va.
* @output        vb - pointer to the output variable vb.
* @output   vc - pointer to the output variable vc.
*/
void inline parkClarke_inverse(
        uint16_t theta,
        float vq,
        float vd,
        float* va,
        float* vb,
        float* vc
);

#endif

/*
* For communication with the PGA411 chip.
* Based upon http://www.ti.com/lit/an/slaa708/slaa708.pdf
* TODO: Write HAL code.
*/
#include "pga411.h"

/* Private constants ----------------------------------------------*/
/* Register constants */
/* Constants used for calculating the angle*/
#define RES_ANGLE 4096 /* 2^12 */
/* Constants used for calculating velocity */
#define RES_VEL 33554432 /* 2^25 */
#define FCLK 20000000 /* Clock frequency typ 20Mhz */
/* SPI Dummy constant for reading data */
#define SPI_DUMMY 0x10

/* Private enums --------------------------------------------------*/
enum pga411_states{DIAG, NORM}; /* Selects pga411 state */
enum {READ, WRITE}; /* Selects SPI operation */

/* REGISTER LOCATIONS
* See PGA411 datasheet for register field descriptions.
*/
enum regLocation
{
        DEV_OVUV1, /* Diag state only */
        DEV_OVUV2, /* Diag state only */
        DEV_OVUV3, /* Diag state only */
        DEV_OVUV4, /* Diag state only */
        DEV_OVUV5, /* Diag state only */
        DEV_OVUV6, /* Diag state only */
        DEV_TLOOP_CFG, /* Diag state only */
        DEV_AFE_CFG, /* Diag state only */
```

```
        DEV_PHASE_CFG, /* Diag state only */
        DEV_CONFIG1, /* Diag state only */
        DEV_CONTROL1, /* Diag state only */
        DEV_CONTROL2, /* Diag state only */
        DEV_CONTROL3, /* All states */
        DEV_STAT1, /* Read only */
        DEV_STAT2, /* Read only */
        DEV_STAT3, /* Read only */
        DEV_STAT4, /* Read only */
        DEV_STAT5, /* Read only */
        DEV_STAT6, /* Read only */
        DEV_STAT7, /* Read only */
        DEV_CLCRC, /* Diag state only */
        DEV_CRC, /* Diag state only */
        CRCCALC, /* Read only */
        DEV_EE_CTRL1, /* Diag state only */
        DEV_CRC_CTRL1, /* Diag state only */
        DEV_EE_CTRL4, /* Diag state only */
        DEV_UNLK_CTRL1, /* Diag state only */
};
/* Structures ------------------------------------------------------------*/

/* SPI frame struct. Union trick allows the same struct to be used for
* for both outgoing and incoming frames.
*/
typedef union spiFrame
{
        /* Outgoing data frame */
        struct
        {
                uint32_t mcrc:6; /* Master's CRC for data, bits 0..5*/
                uint32_t reserved:2; /* Reserved, always 0, bits 6..7*/
                uint32_t dataout:16; /* data, MSB first, bits 8..23*/
                uint32_t addr:8; /* Register adress, bits 24..31*/
        }outMsg;
        /* Incoming messages */
        struct
        {
                uint32_t scrc:6; /* Slave's CRC for data, bits 0..5*/
                uint32_t stat:2; /* status of SPI communication, bits 6..7*/
                uint32_t datain:16; /* data, MSB first, bits 8..23 */
                uint32_t ecbk:8; /* register adress, bits 24..31 */
        }inMsg;
        /* The whole frame */
        struct
        {
                uint32_t frame;
        }wholeFrame;
```

```
}pga411_spi_frame_t;

/* Structure for spir write adress, read adress and default value.
 * Use the regLocation enum for accessing the structure.
 */
typedef struct
{
        const uint16_t read_add;
        const uint16_t write_add;
        const uint16_t def_val;
        uint16_t real_val; /* Realtime register content*/
}PGA411_reg_t;

/* Register structure init */
#define N_REGISTERS 27
PGA411_reg_t PGA411_regs[N_REGISTERS] =
{
        {0x53, 0x87, 0x8B40, 0}, /* DEV_OVUV1 */
        {0x68, 0x26, 0x00ED, 0}, /* DEV_OVUV2 */
        {0x65, 0x17, 0xFCFF, 0}, /* DEV_OVUV3 */
        {0xEC, 0x39, 0x07E2, 0}, /* DEV_OVUV4 */
        {0x52, 0x75, 0x1C00, 0}, /* DEV_OVUV5 */
        {0xE9, 0x83, 0x038F, 0}, /* DEV_OVUV6 */
        {0xA6, 0x42, 0x0514, 0}, /* DEV_TLOOP_CFG */
        {0xC2, 0x91, 0x0005, 0}, /*DEV_AFE_CFG*/
        {0x57, 0x85, 0x1400, 0}, /*DEV_PHASE_CFG*/
        {0xBE,0xEB,0x0002, 0}, /*DEV_CONFIG1*/
        {0x90,0x0D,0x0000, 0}, /*DEV_CONTROL1*/
        {0x63,0x38,0x0000, 0}, /*DEV_CONTROL2*/
        {0xDD,0xAE,0x0000, 0}, /*DEV_CONTROL3*/
        {0x81,0,0x0000, 0}, /*DEV_STAT1*/
        {0x4D,0,0x0000, 0}, /*DEV_STAT2*/
        {0x84,0,0x0000, 0}, /*DEV_STAT3*/
        {0x1F,0,0x0000, 0}, /*DEV_STAT4*/
        {0x41,0,0x0000, 0}, /*DEV_STAT5*/
        {0x64,0,0x0000, 0}, /*DEV_STAT6*/
        {0xE1,0,0x0000, 0}, /*DEV_STAT7*/
        {0x4F,0xFC,0x00CE, 0}, /*DEV_CLCRC*/
        {0x0F,0xE7,0x0000, 0}, /*DEV_CRC*/
        {0xD9,0,0x00FF, 0}, /*CRCCALC*/
        {0xE3,0x6E,0x0000, 0}, /*DEV_EE_CTRL1*/
        {0x7A,0xB6,0x0000, 0}, /*DEV_CRC_CTRL1*/
        {0xBA,0x56,0x0000, 0}, /*DEV_EE_CTRL4*/
        {0x64,0x95,0x0000, 0}, /*DEV_UNLK_CTRL1*/
};

/* Private function prototypes -----------------------------------------------*/
void pga411_reset(void);
void pga411_state(enum pga411_states states);
```

```
void pga411_deviceUnclock(void);
/* TODO: Write the function and the return frame definition */
pga411_spi_frame_t pga411_XmitSPI(uint16_t dir, uint16_t reg, uint16_t wdata);
void pga411_writeReg(uint16_t reg, uint16_t data);
uint16_t pga411_readReg(uint16_t reg);
uint16_t pga411_crc2 (uint32_t datain);

/* Public functions -----------------------------------------*/
void pga411_init(void)
{
        //gpio_pga411Init();
        //spi_init();
        pga411_reset();
}

void pga411_defaultConfig(void)
{
        int i;

        pga411_state(DIAG);
        pga411_deviceUnclock();
        for(i = 0; i < 12; i++)
        {
                pga411_XmitSPI(WRITE, i, PGA411_regs[i].def_val);
        }
        pga411_state(NORM);
}


float pga411_getAngle(void)
{
        float angle;
    uint16_t ORDx;
    ORDx = pga411_getAngleRaw();
        angle = 360 * ORDx / RES_ANGLE;
        return angle;
}

/*TODO : CRC CHECK */
uint16_t pga411_getAngleRaw(void)
{
    uint16_t ORDx;
        /* ORD[11:0] should be set to hiz */
        /* Set VA0 low */
        HAL_VA0_LOW;
        /* Set VA1 high */
        HAL_VA1_HIGH;
        /* Set inhb high, PGA will then start to update the angle*/
        HAL_INHB_HIGH;
```

```
        /* Wait for ORDCLK to go high */
    while(!HAL_IS_ORDCLK_HIGH);
        /* Read ORD[11:0] */
    ORDx = hal_pga411ReadORD();
    /* Disable output again */
        HAL_INHB_LOW;
    /* Return raw angle */
    return ORDx;
}

void pga411_faultReset()
{
//        HAL_PGA_FAULTRES_LOW; /* assert FAULTRES low - open collector */
//        HAL_DELAY_US(1000); /* Hold the state for 1ms */
//        HAL_PGA_FAULTRES_HIGZ; /* Return to high impedance state */
}


/* Private functions ------------------------------------------------*/

void pga411_reset(void)
{
        HAL_PGA_RESET_N_LOW; /* RESET_N low */
//        HAL_DELAY_US(500); /* hold it for 500us */
        HAL_PGA_RESET_N_HIGH; /* Release from reset */
//        HAL_DELAY_US(10000); /* Wait for atleast 10 ms */
}

/* Change the state of the of pga411 diagnostic/normal*/
void pga411_state(enum pga411_states state)
{
        uint16_t temp;
        if(state == DIAG) /* Enter diagnostic state */
        {
                temp = pga411_readReg(DEV_CONTROL3);
                temp |= 0x0004; /* Set bit SPIDIAG */
                pga411_writeReg(DEV_CONTROL3, temp);
        }
        else /* Return to normal state */
        {
                temp = pga411_readReg(DEV_CONTROL1);
                temp |= 0x0001; /*Set bit diagexit */
                pga411_writeReg(DEV_CONTROL1, temp);
        }
}

/*
* @brief : Unclocks the pga411. Must be in diagnostic state
* to unlcok it.
```

```
*/
void pga411_deviceUnclock(void)
{
        pga411_writeReg(DEV_UNLK_CTRL1, 0x000F);
        pga411_writeReg(DEV_UNLK_CTRL1, 0x0055);
        pga411_writeReg(DEV_UNLK_CTRL1, 0x00AA);
        pga411_writeReg(DEV_UNLK_CTRL1, 0x00F0);
}

/*
* brief: spi write wrapper for writing data to pga411 registers.
*/
void pga411_writeReg(uint16_t reg, uint16_t data)
{
        pga411_XmitSPI(WRITE, reg, data);
}

/*
* brief: spi read wrapper for reading data from pga411 registers.
*/
uint16_t pga411_readReg(uint16_t reg)
{
        /* First read returns garbage */
        pga411_XmitSPI(READ, reg, SPI_DUMMY);
        /* Second read returns requested data */
        return (pga411_XmitSPI(READ, reg, SPI_DUMMY).inMsg.datain);
}
/*
* SPI transmit/recieve function.
*/
pga411_spi_frame_t pga411_XmitSPI(uint16_t dir, uint16_t reg, uint16_t wdata)
{
        pga411_spi_frame_t out, in;
        /* Read data? */
        if(dir == READ) out.outMsg.addr = PGA411_regs[reg].read_add;
        /* if not the write data */
        else out.outMsg.addr = PGA411_regs[reg].write_add;
        /* Compose the rest of the frame */
        out.outMsg.dataout = wdata;
        out.outMsg.reserved = 0x00; /* Always zero */
        out.outMsg.mcrc = pga411_crc2(out.wholeFrame.frame); /* Calculate Tx crc*/
//      in.frame = hal_spiXmit4B(out.frame);

        /* Check RX CRC */
        if(pga411_crc2(in.wholeFrame.frame) != in.inMsg.scrc)
        {
//              hal_assert(); /* if error -> terminate */
        }
        return(in);
```

```
}

/*CRC6 calculation */
/*TODO:
        define CRC_INITSEED, CRC_BYTECOUNT.
*/
uint16_t pga411_crc2 (uint32_t datain)
{
//      uint16_t byte_idx, bit_idx, crc = (CRC_INITSEED << 2);

//      /* Byte for byte starting from MSB (3-2-1) */
//      for(byte_idx = CRC_BYTECOUNT; byte_idx >= 1; byte_idx--)
//      {
//              /* XOR-in new byte from left to right */
//              crc ^= ((datain << (byte_idx<<3)) & 0x000000FF);
//              /* bit by bit each byte */
//              for(bit_idx = 0; bit_idx < 8; bit_idx++)
//              {
//                      crc = crc << 1 ^ ( crc & 0x80 ? (CRC_POLYNOM << 2) : 0 );
//              }
//      }
//      return (crc >> 2 & CRC_INITSEED); /* Restore two bit offset */
return 0;
}

#ifndef PGA_411_H
#define PGA_411_H
/* Dependencies ---------------------------------*/
#include "stdint.h"
/* Must be initialized before using the module */
#include "hal_delay.h"
#include "hal_pga411.h"

/* Public variables/constants ----------------*/

/*
* @brief : Initializes the pga411 to be ready for configuration.
*/
void pga411_init(void);

/*
* @brief configures the pga411 to operate in normal condition:
* parallel interface, acceleration mode.
*/
void pga411_defaultConfig(void);

/**
* @brief     Polls the angle from the chip.
*            PGA411 writes a new angle every 100ns. The function starts a
```

```
*           new conversion and busy waits for the data. Expect > 100ns delay
*           from this function.
* @output   float : angle in degrees. A number between 0->360.
*/
float pga411_getAngle(void);

/**
* @brief    Polls the angle from the chip.
*           PGA411 writes a new angle every 100ns. The function starts a
*           new conversion and busy waits for the data. Expect > 100ns delay
*           from this function.
* @output   uint16_t : raw angle, a value between 0 -> 4095 corresponding to
*           a angle of 0->360 degrees.
*/
uint16_t pga411_getAngleRaw(void);

/*
* @brief : To continue operation if a fault has been detected
* it needs to be cleared. Use this function to clear the faults.
*/

void pga411_faultReset(void);
#endif

/*
* Series connected PI regulator with limited output and dynamic integrator
* anti-windup implementation.
*/

#include "pi.h"

/* Macros ------------------------------------------------------------------*/
#define MAX(val1,val2) (val1 > val2 ? val1 : val2)
#define MIN(val1, val2) (val1 < val2 ? val1 : val2)

/* Public functions --------------------------------------------------------*/
void PI_update(PIregulator_t *PI)
{
        float iMax, iMin; /* min and max values for integrator anti-windup */

        PI->error = PI->setPoint - PI->plantValue;
        PI->proportionalTerm = PI->error * PI->Ka;
        PI->integralSum += PI->Kb * PI->proportionalTerm;

        /* Integral Anti windup */
        iMax = MAX(PI->outputMax - PI->proportionalTerm, 0);
        iMin = MIN(PI->outputMin - PI->proportionalTerm, 0);
        if(PI->integralSum > iMax){ PI->integralSum = iMax;}
        else if(PI->integralSum < iMin){ PI->integralSum = iMin;}
```

```
        /* Calculate and limit output */
        PI->output = PI->proportionalTerm + PI->integralSum;
        if(PI->output > PI->outputMax){PI->output = PI->outputMax;}
        else if(PI->output < PI->outputMin){PI->output = PI->outputMin;}
}

#ifndef PI_H
#define PI_H
/* Series connected PI regulator using floating point operation */

/*  Dependencies ------------------------------------------------------------*/
#include "stdint.h"

/* Typedefs ------------------------------------------------------------------*/
typedef struct
{
        float setPoint; /* Desired set point */
        float plantValue; /* The current value */
        float error; /* Error term */
        float integralSum; /* Proportional term * Kb */
        float proportionalTerm; /* Error * proportional gain */
        float Ka; /* Proportional gain */
        float Kb; /* Integral gain */
        float outputMax; /* Max output of the regulator */
        float outputMin; /* Minimum output of the regulator */
        float output; /* The output of the regulator */
}PIregulator_t;

/* Public functions ----------------------------------------------------------*/

/**
* @brief          Updates the PI-regulator variables.
* @note           Series connected PI regulator.
* @note           Uses dynamic integral anti windup method.
*                         H = max(H-P,0) and L = min(L-P, 0). If the output is satured
*                         the integrator cannot do anything, so it is limited based upo
*                         how large the proportional output is  (P).
*/
void PI_update(PIregulator_t *PI);
#endif

#include "sinLUT.h"

/* 12-bit sinus look-up table */
const float LUT_sin[nbrOfPoints] =
        {
          0.00000000000000000000,
          0.00153435478432692495, 0.00306870595640525200, 0.00460304990399488731, 0.0
```

```
0.00920600227773685220, 0.01074028120543850558, 0.01227453484787620341, 0.0
0.01687710794384936208, 0.01841122432584920907, 0.01994529736329802086, 0.0
0.02454722029304650527, 0.02608108383758618240, 0.02761488598083881515, 0.0
0.03221588789417286630, 0.03374940832437495902, 0.03528284930016786086, 0.0
0.03988265940110490709, 0.04141574646028634704, 0.04294873601661275409, 0.0
0.04754708357931542589, 0.04907964703629951603, 0.05061209494772138384, 0.0
0.05520870933243125778, 0.05674065898685839299, 0.05827247505981664188, 0.0
0.06286708572878300927, 0.06439833141641947145, 0.06592942549454242074, 0.0
0.07052176202794499527, 0.07205221362598962509, 0.07358249559539925544, 0.0
0.07817228770726399045, 0.07970185513965247215, 0.08123123493426812058, 0.0
0.08581821248837512295, 0.08734680573108150048, 0.08887519333792077980, 0.0
0.09345908636370339750, 0.09498661545003850293, 0.09651392091451510558, 0.0
0.10109445962294930088, 0.10262083464885579653, 0.10414696808007385675, 0.1
0.10872388287955686570, 0.11024901400890062264, 0.11177388558494531778, 0.1
0.11634690709716269397, 0.11787070456702028465, 0.11939422454024434250, 0.1
0.12396308361602445536, 0.12548545774196609437, 0.12700753644427201228, 0.1
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  };

#ifndef __SINLUT_H
#define __SINLUT_H
/*---------------------- Dependencies ---------------------------------*/
#include <stdint.h>

/*---------------------- Constants ------------------------------------*/
#define nbrOfPoints 4096
#define nintyDeg 1024 /* (90/360) * 4096 */

/*---------------------- Macros ---------------------------------------*/
#define LUT_SINE(angle) (LUT_sin[ WRAP_ANGLE(angle) ])
#define LUT_COSINE(angle) (LUT_sin[ ( WRAP_ANGLE(angle + nintyDeg) ) ])
```

```
/* If the angle is larger than 4095 (360 degrees) it wraps to around.
* It skips zero when wrapping around (360 = 0).
* 4097 -> 1, 4098 ->2.. 4096 + 1024 = 1024.
*/
#define WRAP_ANGLE(angle)  (angle > nbrOfPoints ? angle-nbrOfPoints : angle)

/*------------------------ SINUS LUT -------------------------------------------*/
extern const float LUT_sin[nbrOfPoints];


#endif

/*
* Controller code for the VSI.
* Interrupt driven at 15kHz.
*/

#ifndef CONTROLLER_H
#define CONTROLLER_H

/* Dependencies ------------------------------------------------------------------*
#include "stdint.h"
#include "HAL_PWM.h"
#include "parkClarke.h"
#include "hal_gpio.h"

/* Typedefs ----------------------------------------------------------------------*
typedef struct
{
        uint16_t freq; /* Interrupt frequency in kHz */
        uint16_t motorTempThr;
        uint16_t igbtTempThr;
        uint16_t maxRPM;
        uint16_t maxCurrent; /* Max min current on the output */
        uint16_t maxVoltage;
        uint16_t minVoltage;
}ctrlConfig_t;

/* Function declerations ---------------------------------------------------------*

/*
* @brief:        initializes the controller. Call controller enable to start
*                        the PWM and interrupt function.
* input:         confic : struct containing the controller configuration.
* output:    uint8_t : 1 - succesfull, 0 - failure.
*/
uint8_t controller_init(ctrlConfig_t config);

/*
```

```
* @brief:        Enables the PWM output and interrupt function of the controller.
*/
void controller_enable(void);
/*
* @brief:        Disables the PWM output of the controller.
*/
void controller_disable(void);

uint16_t getMaxCurrent(void);


#endif

#include "controller.h"

/* Private function declerations ----------------------------------------------------*

/*Private Typedefs ----------------------------------------------------------------*
typedef union
{
        float iq;
        float id;
        float tempMotor;
        float tempIgbtA;
        float tempIgbtB; /* */
        float dcLinkVoltage; /* DC LINK VOLTAGE */
}controllerVar_t;

/* Private variables ---------------------------------------------------------------*
ctrlConfig_t configVar; /* Configurations variables, min/max values */
controllerVar_t ctrlVar; /* Variables used for the controller */


/* Public functions ----------------------------------------------------------------*
uint8_t controller_init(ctrlConfig_t config)
{
        return 1;
}
/* Private Functions ---------------------------------------------------------------*

/* Background task */
void TIM1_CC_IRQHandler()
{
        static volatile int k = 10;
        if (TIM_GetITStatus(TIM1, TIM_IT_CC4) != RESET)
                {
                        TIM_ClearITPendingBit(TIM1, TIM_IT_CC4);

                        /* TODO : Start Conversion of readings (currents, voltage, te
```

```
                /* TODO : Read Angle */
                /* TODO : Wait for current conversion complete */
                /* Park Clarke transformation */
                /* TODO: PI-calculations*/
                /* Inverse transformation */
                /* TODO: Scale output */
                /* Update PWM registers*/

                /*
                if current > max current -> disable output, turn on led.
                if voltage > max voltage -> overvoltage  protection enabled.
                if any temperature > max temperature -> disable output.
                */
        }
}
```