ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Network Power for Automobiles

Team #26

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Abstract

This report covers the design, manufacturing, and testing of a software-controlled DC/DC converter aimed for EV applications. Our project allows for control of up to 4 independent buck-boost converters over CAN, providing energy usage feedback and including automatic safety shutoff systems in the event of unsafe operation (eg:- overcurrent, overvoltage, overtemperature). The project accepts an input voltage range of 11-15V, and can produce 3.3V to 25V with a load current of up to 2A. It also includes the design of a custom GUI to control the converters and view data. Our project was unsuccessful in achieving a usable voltage conversion due to the limited testing time available during the semester. However, all communication and data platforms performed as expected, priming us for success with future revisions.

Contents

1 Introduction

Modern EVs contain a host of sensors, actuators, temperature control devices etc. that all require specific input voltages. Typical vehicles will have a single low-voltage battery that goes through two stages of conversion: once to distribute through the vehicle, and again to step down to the actual device requirement. Our project aims to simplify this system by moving all control and conversion local to the components that use them. The theory behind this is the desire of automotive companies to move to a "one power one communication" arrangement.

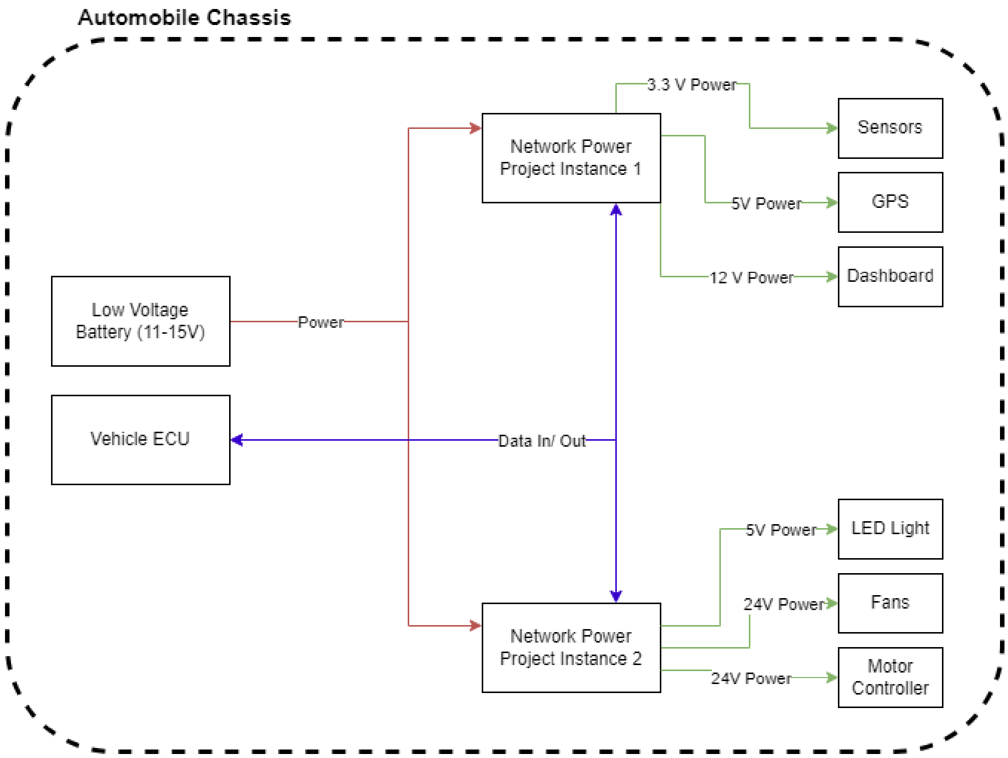

Figure 1.1: Status quo for power distribution/wire harness on moderns EVs

Applying our project onto such a vehicle produces three main improvements:

1. Simplified harnessing leads to easier manufacturing and fewer transmission losses
2. Switched converters for voltage step-downs lead to efficiency gains over linear regulators
3. Improved data feedback allows better duty cycle analysis and system optimization

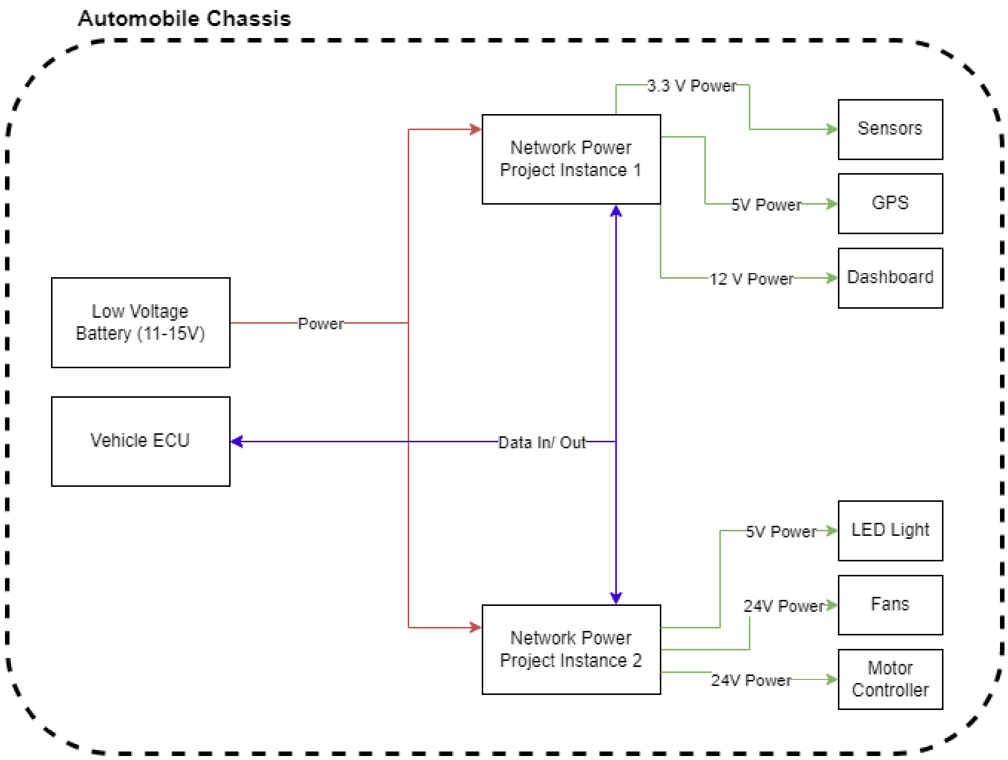

Figure 1.2: Theoretical application of our project into the same vehicle as the previous image

Our long-term hope was to create a software-configurable device that could be applied in a broad area for many automotive families. In doing so, we would be able to create a cost effective solution by taking advantage of the inherent economies of scale already prevalent in the industry.

We made no changes to the high level structure of the project through the semester.

1.1 High Level Requirements

The success of this project is measured against the following criteria:

1. Communication with the solution over Controller Area Network (CAN)
   (a) Independent control over each voltage output
   (b) Voltage/current usage data received at 20Hz
   (c) Visualization of voltage/current usage data by the user within the accuracy provided by the E-meter chip
2. Supply up to 2A of current on all active rails simultaneously. Outputs should have less than ±5% voltage ripple and ±5% current ripple on the load compared to software setpoint
3. Stay below 60° Celsius while providing 2A on all active rails for 60 minutes

2 Design

There are two PCBs in the project, the control board that houses the microcontroller and the power stages that house the DC/DC controller ICs.

2.1 Control Board

2.1.1 MCU

The microcontroller we chose is the STM32F103, since it was easily available at the ECE supply store and was sufficient for our purposes. The members of this team also had prior experience working with this chip, which gave us confidence in creating a successful PCB with it.

2.1.2 Filter

The Filter subsystem is used to help stabilize and filter the thermistor readings. This is accomplished by a double buffer op-amp system with a RC filter. Below is the schematic of a single filter. There are 4 of these, one for each powerstage.

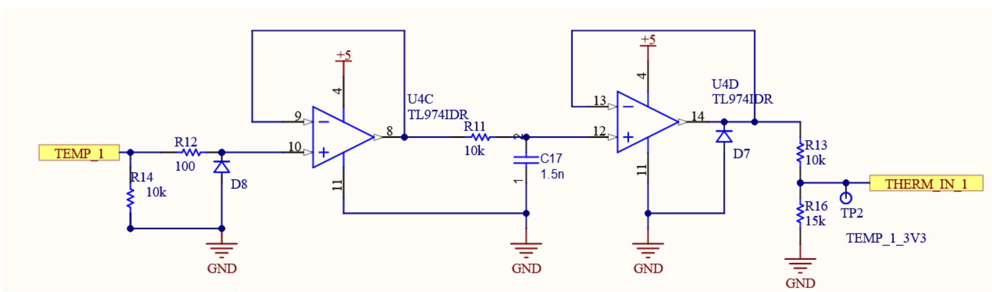

Figure 2.1.2.1: Double Op-Amp filter with an RC filter

Each of the thermistors are pulled up to 5V. To do the automatic powerstage detection, there are pulldown resistors (R14) on each line. This also sets the range of the thermistor values, since it forms a voltage divider. D8 and R12 are used to cap the voltage at 5V and to avoid shorting out the 5V supply if the diode does turn on. The first op-amp buffers the voltage from the thermistor voltage divider to ensure we don't run into non-linearities on the RC filter. R11 and C17 form a RC filter with a -3dB cutoff at 10.6 kHz based on the equation 1 [1].

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(10k\Omega)(1.5nF)} = 10.601kHz \qquad (1)$$

The second op-amp allows us to buffer the filtered voltage so we can use a resistor divider to convert the 5V signal into a 3.3V signal for the ADCs on the STM. D7 is used to cap the voltage of this op-amp to under 5V so the 3.3V ADC on the STM is kept safe from an overvoltage event. We chose to pull the thermistors up to 5V instead of 3.3V since the Emeter chip needs a 5V supply to operate and they are both on the powerstage.

2.1.3 MCU Power

The MCU power system powers all the circuits on the control board and the thermistors on the power stages. To keep the design simple, we chose to use linear regulators for this application. There is a 12V to 5V regulator and a 12V to 3.3V regulator on the PCB. There are diodes to help indicate power on the 5V and 3.3V rails. Below are tables that show the large loads on both power rails. We can see that we see a total of 301.2 mA is pulled from the 5V LDO and 153.9 mA on the 3.3V LDO.

We chose to use the 5V, 1A LDO from the supply shop for budget concerns and for the extra thermal headroom provided by the bigger package and TO252-3 footprint. The use of the 3.3V, 800mA was driven by my previous experience with the LDO.

Component	**Maximum Power Draw (mA)**	**Number**	**Total Draw (mA)**
PSN74LV4T125 [2]	100	1	100
TL974IDR [3]	5.6	2	11.2
TCAN1044A-Q1 [4]	130	1	130
INA219BIDR [5]	15	4	60

Table 2.1.3.1: 5V Power Rail Calculations

Component	**Maximum Power Draw (mA)**	**Number**	**Total Draw (mA)**
TCAN1044A-Q1 [4]	*0.3*	*1*	*0.3*
STM32F103 [6]	*150*	*1*	*150*
CPC1004NTR [7]	*1.8*	*2*	*3.6*

Table 2.1.3.2: 3.3V Power Rail Calculations

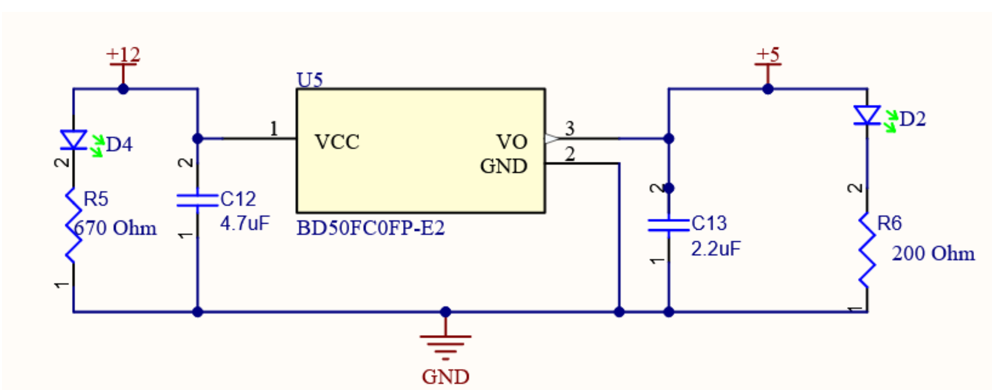

Figure 2.1.3.3: 5V LDO schematic

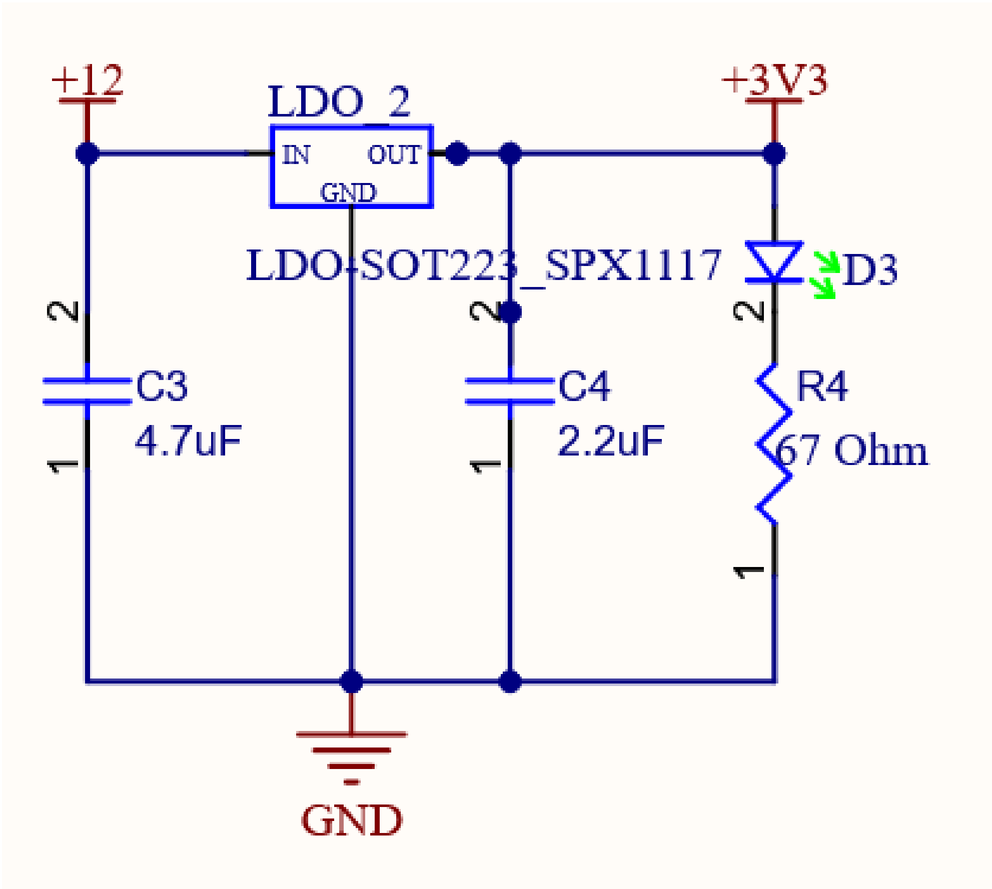

Figure 2.1.3.4: 3.3V LDO schematic

2.2 Power Stage

2.2.1 4 Switch Buck Boost & Relay

We used a MPQ4214GU 4 switch buck-boost controller for the DCDC controller. It would communicate over I2C with the STM. We used the I2C interface to set the output voltage level. The original design was made using a TI DC/DC controller, but we couldn't use the IC due to supply chain issues. The switches chosen were 40 V, 40 A NMOS. We chose a 15 uH inductor based on the design provided by TI for their DC/DC controller. The schematic for the DCDC is provided in appendix C, figure C.1.

2.2.2 E-Meter IC

We used a TI power monitor chip to report the power usage of each supply over I2C. We chose the shunt resistor side to fit within the range of the DC/DC controller and the power meter. Appendix C, figure C.2 shows the schematic for the power meter IC.

2.3 Software

2.3.1 Embedded Code

The embedded code in this project was responsible for a few key tasks. Firstly, it had to communicate over a CAN bus to receive output commands and transmit information about the current status of each output (voltage, power, temperature, possible errors), as well as automatically turn off each output when a CAN communication error was detected. Secondly, it was responsible for communicating over I2C to each of the e-meter and buck boost controller chips, to write configuration parameters to them, as well as read information, and act on any interrupts generated, using the EXTI (EXTernal Interrupt) pins. Thirdly, we used the ADCs on the STM32 to read the temperatures of the powerstage PCBs, and utilized DMA (Direct Memory Access) to enable frequent and fast reading of the temperatures without taking up precious clock cycles. Finally, the ALARM_Output pin was used as a digital output to indicate when an error has occurred. This can be used to notify of errors even if the CAN communication has failed, and is therefore an important safety feature. Whenever this pin is set high, all the powerstage outputs are also disabled.

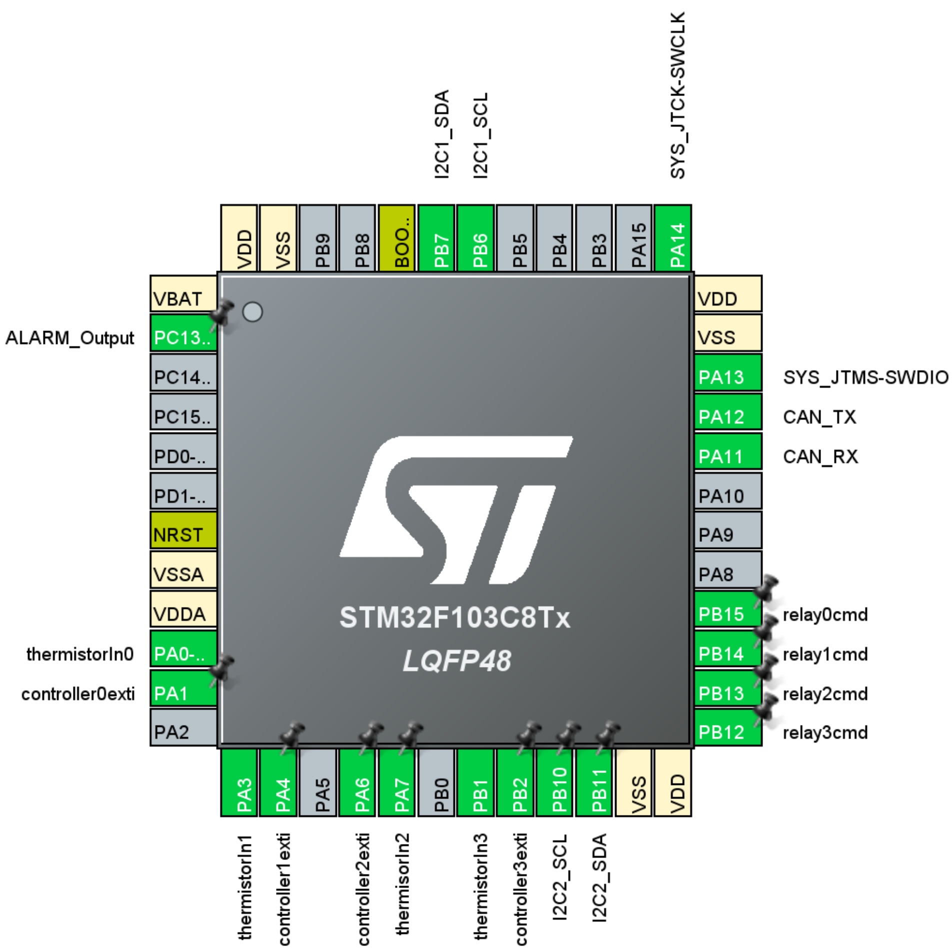

Figure 2.3.1.1: STM32 Microcontroller pinout configuration

2.3.2 Testing GUI

To facilitate testing, we decided to write a custom power controller GUI in Python, using the Flet library. This library uses the Flutter UI framework, and allows us to use well known Python libraries with a good looking UI framework. This GUI emulated the CAN signals that would normally come from a Vehicle Control Unit (VCU). It lets the user view which powerstage boards are connected, control individual output parameters for each board, as well as plot the information transmitted by the STM32. The appbar is used to select the CAN communication parameters used to connect to the Control board, and currently supports USB to CAN adapters by PEAK-System and Kvaser, using their respective Python CAN libraries.

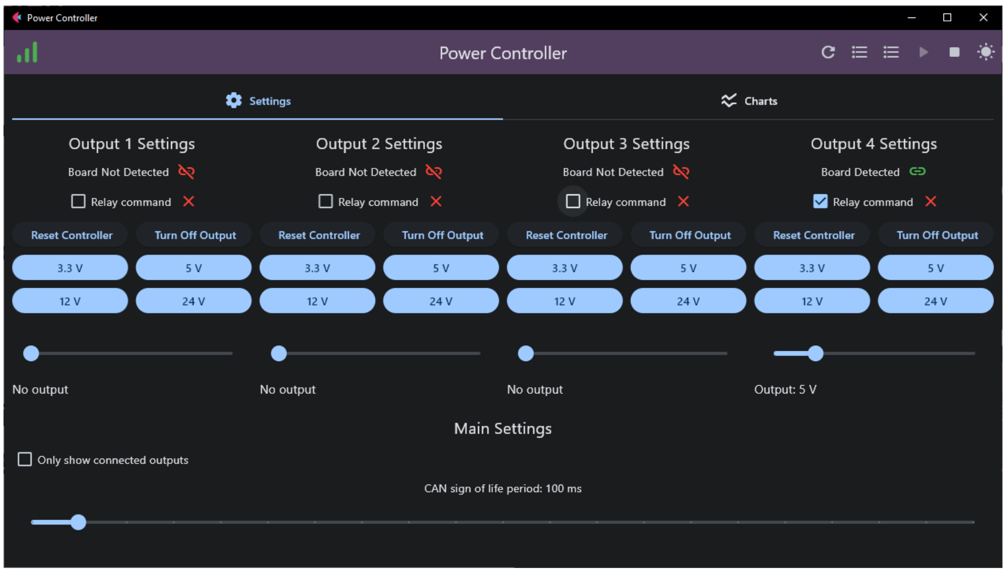

Figure 2.3.2.1: Settings page of the custom Power Controller GUI

Figure 2.3.2.2: Charts page of the custom Power Controller GUI

3 Design Verification

Design verification was primarily conducted using the requirements and validation tables generated during the design phase. In this section, we will cover the verification steps taken to validate our boards through manufacturing and testing. An in-depth check list of all requirements is included in Appendix A.

3.1 Control Board

Once our PCB and components were received, we sped into manufacturing the Control board. We did not have a stencil for our PCB, so we hand-soldered all our components. Validation of our soldering included measuring isolation between the various voltage nets on the PCB and GND. Once satisfied, we supplied 12V to the board using a lab power supply, and inspected it with an IR camera to find hotpots (indicative of short circuits).

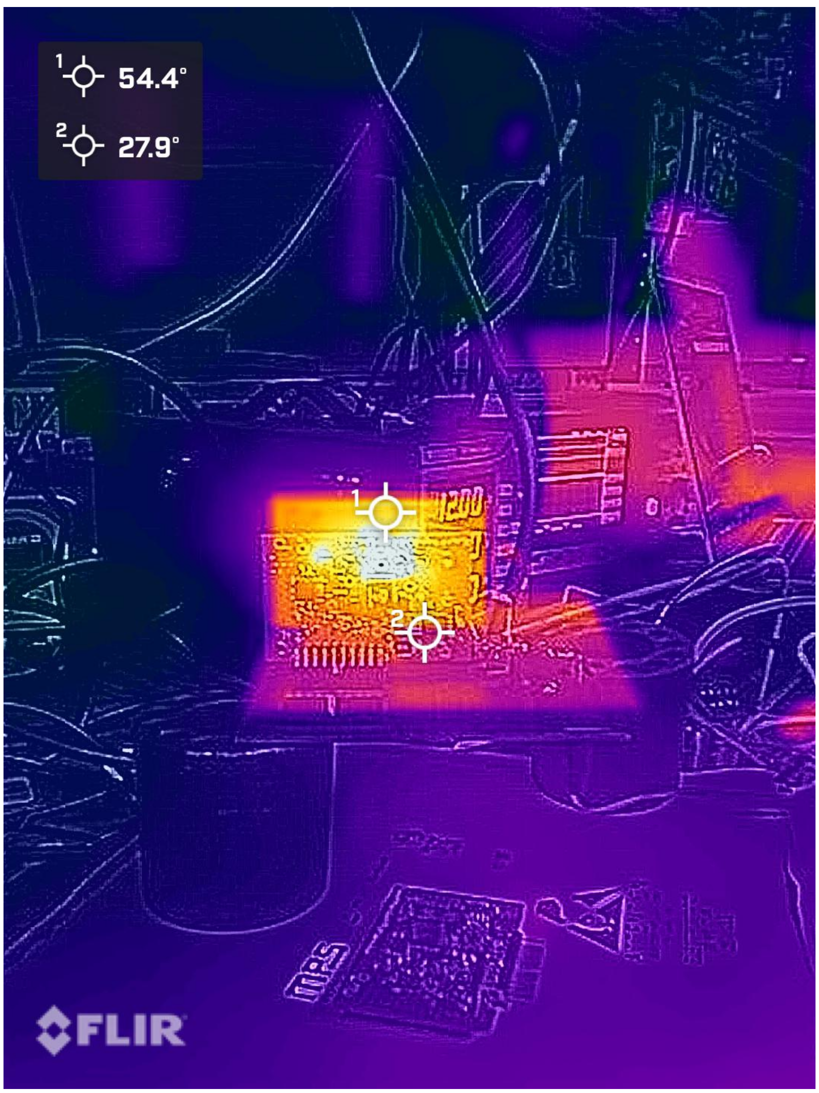

Image 3.1.1: Thermal camera image captured during testing

3.2 Power Stage Board

To test the power stage, we used the working control board to communicate with the DC/DC controller IC and E-meter IC. We had noise issues on the I2C line when the DC/DCs were enabled. To solve this issue, we swapped the 1 kOhm pull ups to 100 Ohm pull ups. Our DC output was a sinusoidal waveform. This was likely caused by our controller gain being set too low due to a misinterpretation in the application note for the DC/DC controller.

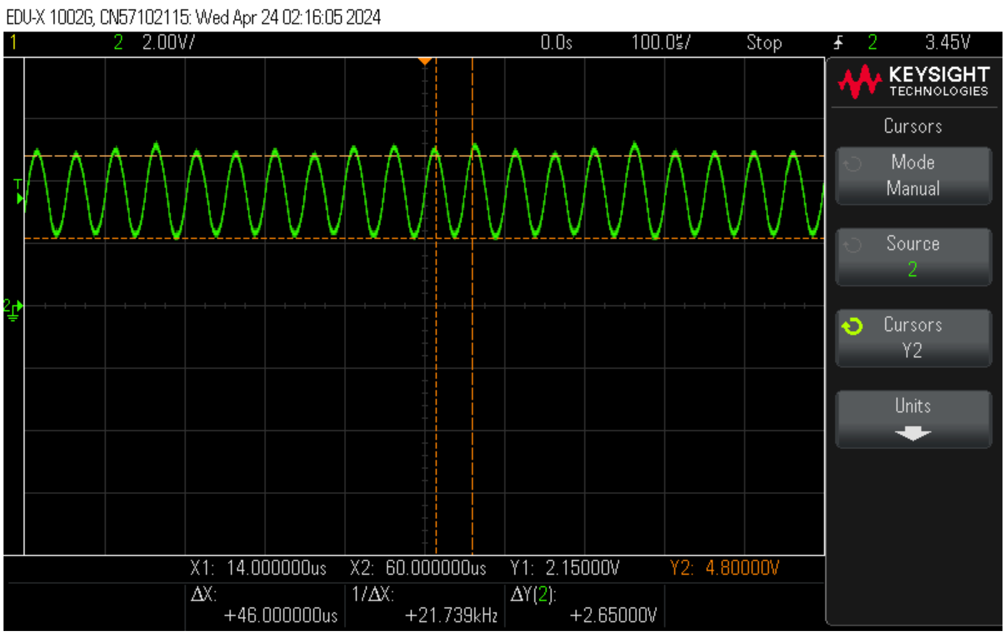

Figure 3.2.1: DC output of the DC/DC controller

4 Costs

We were given a $150 budget to complete this project, which we adhered to. Our projected costs during the design phase were much lower than this figure, mostly due to us creating a very rough estimate before the system was fully fleshed out. Once smaller components such as SMD capacitors and resistors were included, our costs quickly inflated.

4.1 Parts

Part	**Component Cost ($)**	**Quantity**	**Actual Cost ($)**
Control PCB	33.81	1	33.81
Power Stage PCB	27.25	4	109
Total			**142.81**

Table 4.1.1: Overall PCB costs

Complete BOMs for each PCB are included in Appendix B.

4.2 Labor

Our estimates during design season of 3 junior engineers working for 15 hrs/week over 12 weeks was roughly in line with the actual work put into the project. With an average salary of $40 per hour, this would come out to a man-hour cost of 540 hours, or $21,600, before any benefits or taxes that have to be paid by the employer. This also represents the cost if the engineers are employed by the company needing the product, and the man-hour cost would likely be much higher if a company contracted another company to design such a product.

5 Conclusion

5.1 Accomplishments

While we technically did not accomplish our final goal during this project, we did still manage to complete a lot of the sub goals we set out for ourselves. Notably, we were always able to communicate reliably with the STM32 microcontroller over CAN, and the I2C communication with the E-Meters was very stable when the DC/DC were not enabled. Furthermore, while the power output wasn't particularly stable, we were still able to command a voltage output over CAN, and have the STM32 relay that command to the DC/DC controller to output the correct voltage, albeit with significant ripple. The safety aspects of the project were also functional, which provided greater confidence during testing, as we knew that the board would automatically shut down if anything catastrophic were to happen.

5.2 Uncertainties

The main uncertainties of this project are both noise related: the first is the noise in the I2C clock and signal lines when the DC/DC is enabled, and the other is the noise in the DC/DC's output. We believe that, given more time to work on this project, we would be able to solve both of these issues, and would then get a reliable and noise-free system.

5.3 Future Work

The main potential future work of this project would be redesigning the PCBs to reduce noise. A good first step would be switching to a 4 layer PCB, and separating power and signal traces into different planes. Another aspect of the project that could be improved is the external packaging, which is something we somewhat neglected in the final push to complete the project.

References

[1] RC and RL Passive Filter Calculator. “Low Pass/High Pass Filter Calculator.” (2024), [Online]. Available: https://www.digikey.com/en/resources/conversion-calculators/conversion-calculator-low-pass-and-high-pass-filter.

[2] Texas Instruments. “SN74LV4T125 Single Power Supply Quadruple Buffer.” (2022), [Online]. Available: https://www.ti.com/lit/ds/symlink/sn74lv4t125.pdf.

[3] Texas Instruments. “TL97x Output Rail-To-Rail Very-Low-Noise Operational Amplifiers.” (2015), [Online]. Available: https://www.ti.com/lit/ds/symlink/tl974.pdf.

[4] Texas Instruments. “TCAN1044A-Q1 Automotive Fault-Protected CAN FD Transceiver.” (2021), [Online]. Available: https://www.ti.com/lit/ds/symlink/tcan1044a-q1.pdf.

[5] Texas Instruments. “INA219 Zerø-Drift, Bidirectional Current/Power Monitor.” (2019), [Online]. Available: https://www.ti.com/lit/ds/symlink/ina219.pdf.

[6] STMicroelectronics. “STM32F103C6.” (2019), [Online]. Available: https://www.st.com/resource/en/datasheet/stm32f103c6.pdf.

[7] IXYS. “CPC1004N Single-Pole Normally Open Relay.” (2019), [Online]. Available: https://www.mouser.com/datasheet/2/240/media-3320037.pdf.

Appendix A Requirement and Verification Tables

The following section will cover the results of our R&V tables created during the design phase. Items are marked either as "achieved" or are given reasoning for failure.

Table 1: MCU System Requirements

Requirements	Verification	Result
Use I2C to communicate with the E-meters and DC/DC Controller ICs on each Powerstage board	• Demonstrate voltage control over DC/DC output by sending I2C data in STM's software debug mode • Receive data from E-meter over I2C by viewing received data in STM's software debug mode	Achieved
Send and receive CAN messages	• Create a test CAN bus, sending and receiving signals using a laptop and custom viewing and controlling software with an off the shelf CAN to USB adapter • Configure a custom CAN message with a specific message ID and decode format for data received from the E-meter module	Achieved

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Table 1 – continued from previous page

Requirements	Verification	Result
Read analog temperatures	• Receive analog voltage from thermistors, viewing received voltage on laptop in remote debug mode, or on custom viewing software • Convert STM's ADC reading into a temperature value in Celsius • Measure error between system's reading and an external temperature reading (thermal camera) less than 10%	Achieved
Open/close the relays using the digital GPIO pins on the MCU	Measure continuity of the circuit using probe points and a portable voltmeter while actuating the relay	N.A. Relay functionality was replaced via an ”enable” pin on the DC/DC converters
Send digital signals out of the device (alarm signal)	• View the alarm signal on an oscilloscope as it is set high/low by the STM • Verify the alarm signal is automatically set by the STM when reading temperature greater than 60°C. Temperature reading can be spoofed using a potentiometer instead of the thermistor	Achieved

Table 2: MCU Power System Requirements

Requirements	Verification	Result
Provide 5V ±10% at a 500 mA load while keeping the LDO under 60°C	• Connect the net to an electronic load and then produce a 500mA current draw. Let the load run for an hour and measure temperature with an IR camera • Use an oscilloscope to verify voltage output is within tolerance	Achieved
Provide 3.3V ±10% at a 300 mA load while keeping the LDO under 60°C	• Connect the net to an electronic load and then produce a 300mA current draw. Let the load run for an hour and measure temperature with an IR camera • Use an oscilloscope to verify voltage output is within tolerance	Achieved

Table 3: Filter System Requirements

Requirements	Verification	Result
Detects when the Powerstage is not plugged in with a pull up resistor on the input	Unplug the Powerstage and view that the alarm signal is raised on an oscilloscope	Achieved

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Table 3 – continued from previous page

Requirements	Verification	Result
Scale down the 5V signal to a 3.3V signal	• Measure the voltage out of the 'Buffering Op-Amp' and the 'Amplifying Op-Amp' on an oscilloscope • Verify that the measured voltage is scaled correctly based on the measurement	Achieved
Read in analog temperatures	See MCU Subsystem	Achieved

Table 4: Powerstage Subsystem Requirements

Requirements	Verification	Result
Use I2C to communicate with the E-meters and DC/DC Controller ICs on the powerstage	See MCU subsystem	Achieved
Outputs should have less than ±5% voltage ripple compared to software setpoint	• Send a CAN message to MCU to command one output to turn on at voltage X, where X can be 3.3V, 5V, 12V or 24V • Measure open circuit voltage using an oscilloscope • Connect output to a resistive load and measure voltage using an oscilloscope	Failed. DC/DC control gains were not configured for our application. Missing buffering capacitors on the input and outputs led to instability and high ripple

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Table 4 – continued from previous page

Requirements	Verification	Result
Supply up to 2A of current on all active rails simultaneously. $\pm5\%$ current ripple on the load	Send a CAN message to MCU to supply 4 resistive loads with 2A	Failed. Same as above
Temperature of all components must stay below 60° Celsius while providing 2A on all active rails for 60 minutes	Set up 4 resistive loads, and supply each with 2A for 60 minutes. Measure temperature of the board with an IR camera	Failed. Due to the high amount of output ripple, our converters were not operating at the efficiencies predicted during our simulations, thus our cooling solution was insufficient

Table 5: Relay System Requirements

Requirements	Verification	Result
Relays can be actuated via CAN commands	Individual outputs can be toggled from the CAN based viewing and controlling tool	N.A.
Relays are automatically opened in the event of a failure / alarm condition	Measure the voltage output from the device when temperature rises above 60°C. Temperature reading can be spoofed using a potentiometer instead of the thermistor	Achieved using enable pin

Appendix B BOMs

Table 6: MCU Controller board BOM

Name	Description	Quantity	Link	Price	Total
CMP-010-000011-1	ESD for CAN	1	Link	$0.37	$0.37
CMP-009-000195-1	LEDs	4	Link	$0.15	$0.60
DIODE-SOD123	5V zeners	8	Link	$0.15	$1.20
BCS-110-F-D-TE		4	Link	$3.81	$15.24
FTSH-105-01-L-DV-K	Connector Header Surface Mount 10 position 0.050″ (1.27mm)	1	Link	$1.95	$1.95
744235900	CAN Choke	1	Link	$1.80	$1.80
LDO-SOT223_SPX1117	3.3V LDO	1	Link	$0.40	$0.40
NMOS-SOT23	NMOS for the ALARM system	1	Link	$0.32	$0.32
CPC1004NTR	CAN Termination controller	2	Link	$1.87	$3.74
1kOhms		10	Link	$0.15	$1.5
100Ohms		4	Link	$0.15	$0.60
2.5kOhms		1	Link	$0.25	$0.25
CMP-009-000205-1	CAN IC	1	Link	$1.64	$1.64
IC-LQFP48 STM32F103C8T6		1	FROM ECEB SUPPLY SHOP		$-
REF2033 QDDCRQ1*	3.3V Analog referance	1	Link	$3.69	$3.69

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Table 6 – continued from previous page

Name	Description	Quantity	Link	Price	Total
TL974IDR	Output Rail-To-Rail Very-Low-Noise Operational Amplifier, 2.7 to 12 V, -40 to 125 degC, 14-pin SOIC (D14), Green (RoHS & no Sb/Br)	2	Link	$1.00	$2.00
BD50FC0FP-E2	5V LDO	1	FROM ECEB SUPPLY SHOP		$-
PSN74LV4T 125QPWRQ1	3.3V to 5V level shifter	1	Link	$0.86	$0.86

Table 7: Powerstage board BOM

Name	Description	Quantity	Link	Price	Total
CPDUR5V0HE-HF	ESD Suppressors / TVS Diodes Bidir,12V	6	Link	$0.45	$2.70
INA219AID	No Description Available	1	Link	$2.70	$2.70
TSW-110-08-F-D-RA	No Description Available	1	Link	$2.43	$2.43
XAL7070-153	No Description Available	1	Link	$3.25	$3.25
10Ohms		6	Link	$0.10	$0.60
1kOhms		3	Link	$0.15	$0.45
100Ohms		4	Link	$0.15	$0.60
2.5kOhms		1	Link	$0.25	$0.25
5mOhms		1	Link	$0.45	$0.45

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Table 7 – continued from previous page

Name	Description	Quantity	Link	Price	Total
82kOhms		1	Link	$0.21	$0.21
10kOhms		1	Link	$0.17	$0.17
WSL2512R0150FEA		1	Link	$0.97	$0.97
IPZ40N04S5L-4R8	Insulated-Gate Field-Effect Transistor (IGFET), N-Channel, Enhancement, Body Diode, Pin 1 Source, 2 Source, 3 Source, 4 Gate, 5 Drain, 6 Drain, 7 Drain, 8 Drain, 8 Pins	4	Link	$0.94	$3.76
NCU15XV 103E60RC	NTC Thermistor, 100000ohm, Surface Mount	1	Link	$0.39	$0.39
5000	Test Point Miniature THM H .300 Nylon 46 Insulated Red PhosBronze/Silver	14	Link	$0.38	$5.32
MPQ4214GU-AEC1-P		1	Link	$5.67	$5.67

Appendix C Schematics

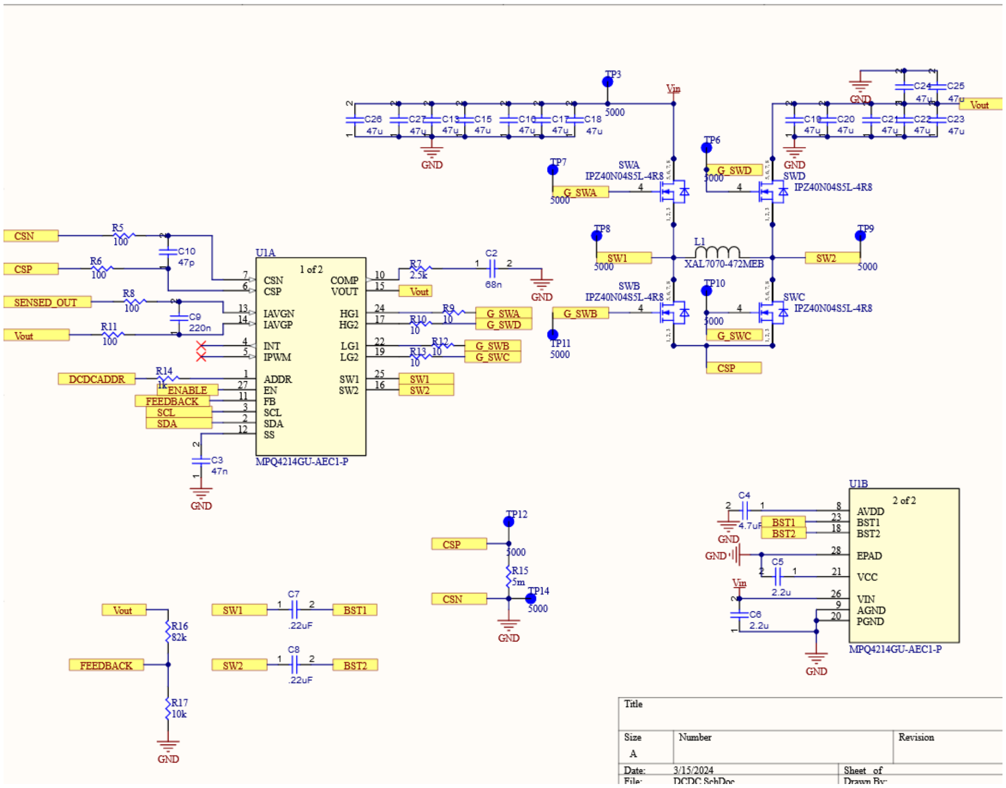

Figure C.1: 4 switch buck boost IC schematic

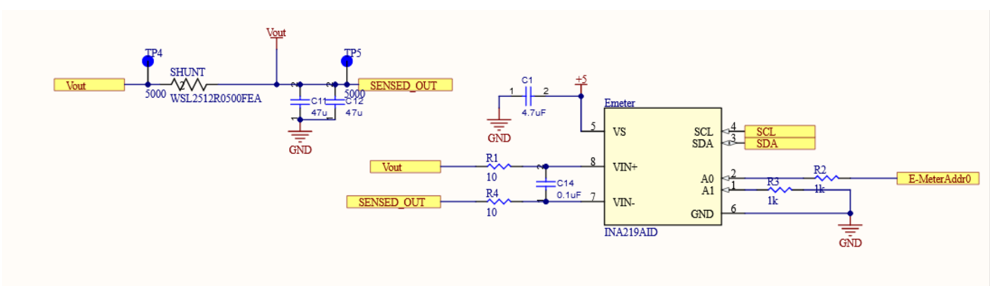

Figure C.2: Power meter schematic

Appendix D PCB Layouts

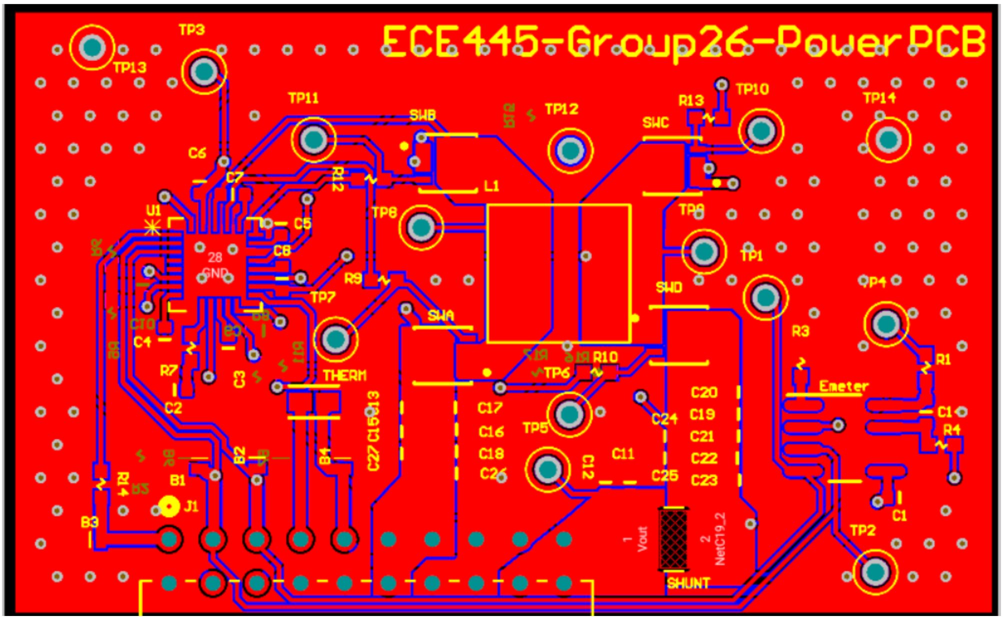

Figure D.1: Top layer of Powerstage PCB

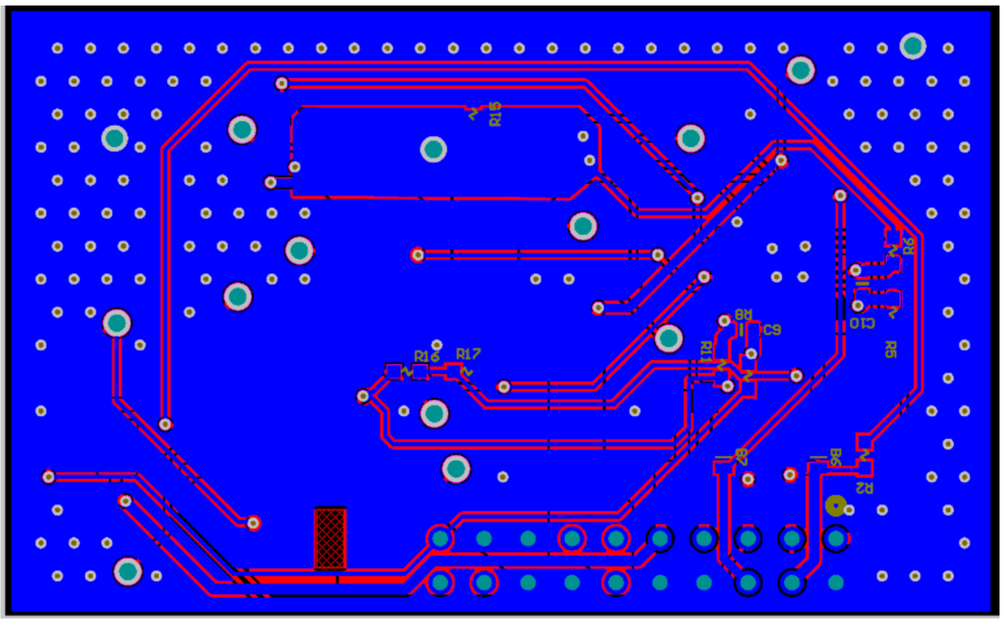

Figure D.2: Bottom layer of Powerstage PCB

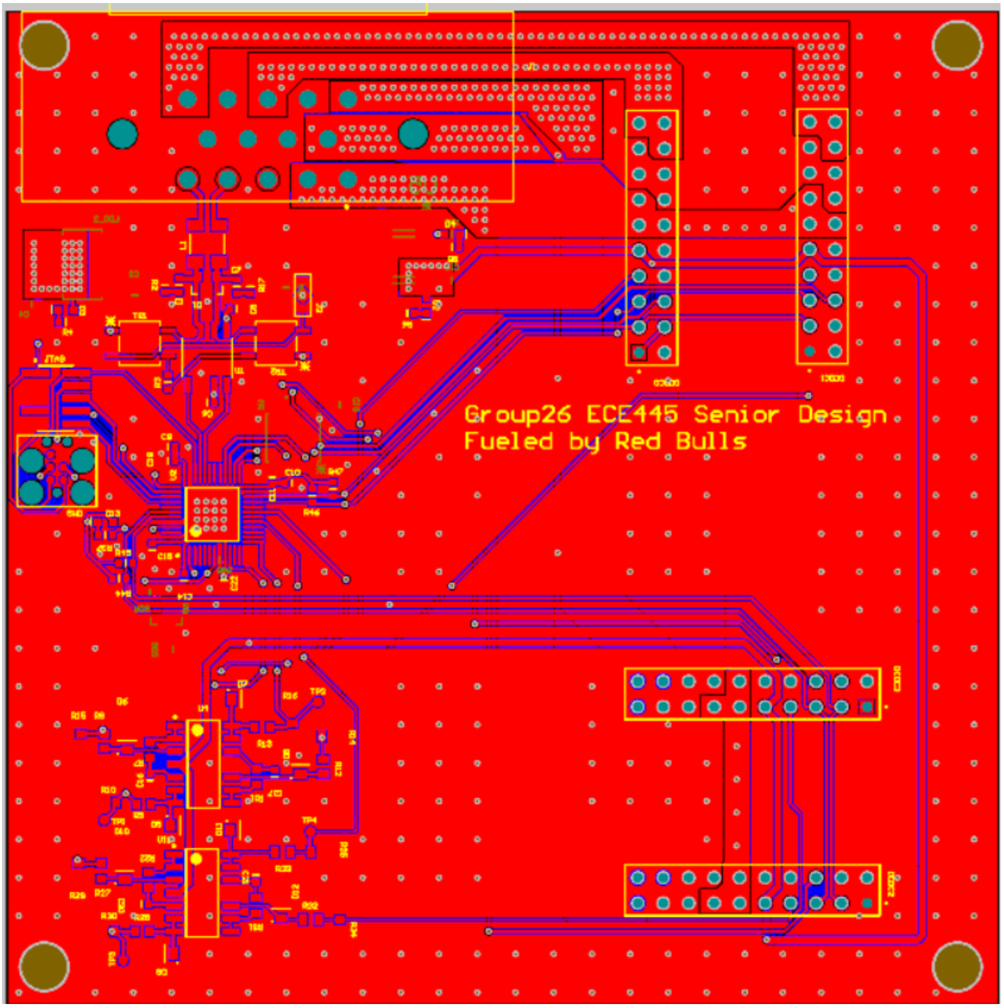

Figure D.3: Top layer of Controller PCB

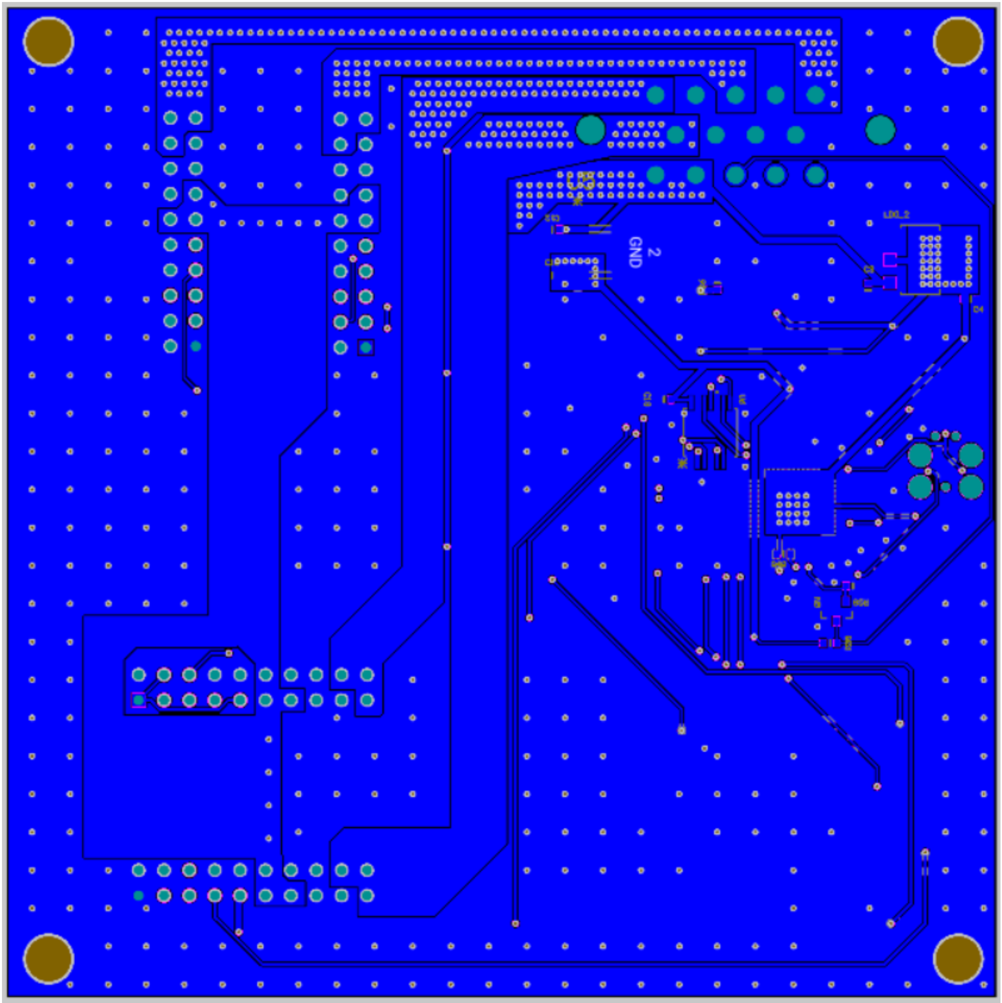

Figure D.4: Bottom layer of Controller PCB