ECE 445

Design Document

Custom MPPTs for Illini Solar Car

Team #25

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1. Introduction

Problem

Illini Solar Car is manufacturing their 3rd generation vehicle to race at the American Solar Challenge this coming summer. The team has recently installed their array and is looking for easy-to-use, configurable, and efficient solar maximum power point trackers (MPPTs). MPPTs are used to control power output of a solar array. In this case, it will precisely control power into the vehicle's battery pack to charge the battery. Off-the-shelf models are very expensive and will take time to integrate into the vehicle's architecture. Also with off-the-shelf components if a part fails, we will not have access to the schematics to replace the component.

Solution

The idea is to create custom, efficient, and low cost boost MPPTs built for the team's electrical system. These MPPTs will function by utilizing a boost converter to step the voltage of the array in order to charge the battery. It will use an algorithm to vary the switching duty ratio of the boost converter in order to control the power output. For context, as the battery charges the voltage will increase and therefore the requested duty ratio will vary as a result.

For some background, the vehicle has the array wired in three separate sections. The goal behind the 3 sections is better resilience to shading and redundancy built into the system. We would make an easy to move enclosure with three MPPTs inside that can be mounted in the vehicle. If one of the MPPTs fails we would still have 2/3 of the solar array producing power.

By making the MPPTs in house lots of problems could be solved. We could drastically reduce the cost, make it plug-and-play with our vehicle's electrical systems, and be able to debug issues quickly.

Visual Aid

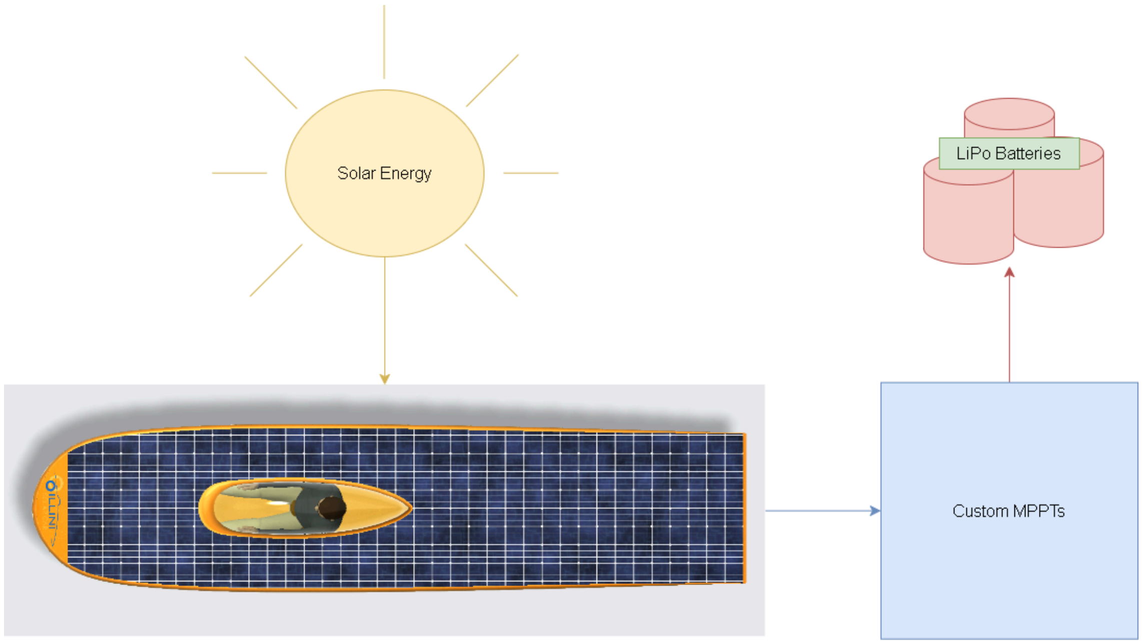

Figure 1: Visual Aid for MPPTs

High-Level Requirements

1. Logic Board is able to send information via CAN and control the power board using a perturb & observe algorithm
2. The power board is able to successfully boost input voltage from 20V - 90V to a range of to a range of 77V-120V. It should have a tolerance of +/-1.5%.
3. The size of a single power board should be less that 272mm x 164mm in order to fit in the space allotted for the MPPTs in the vehicle.

2. Design

Block Diagram

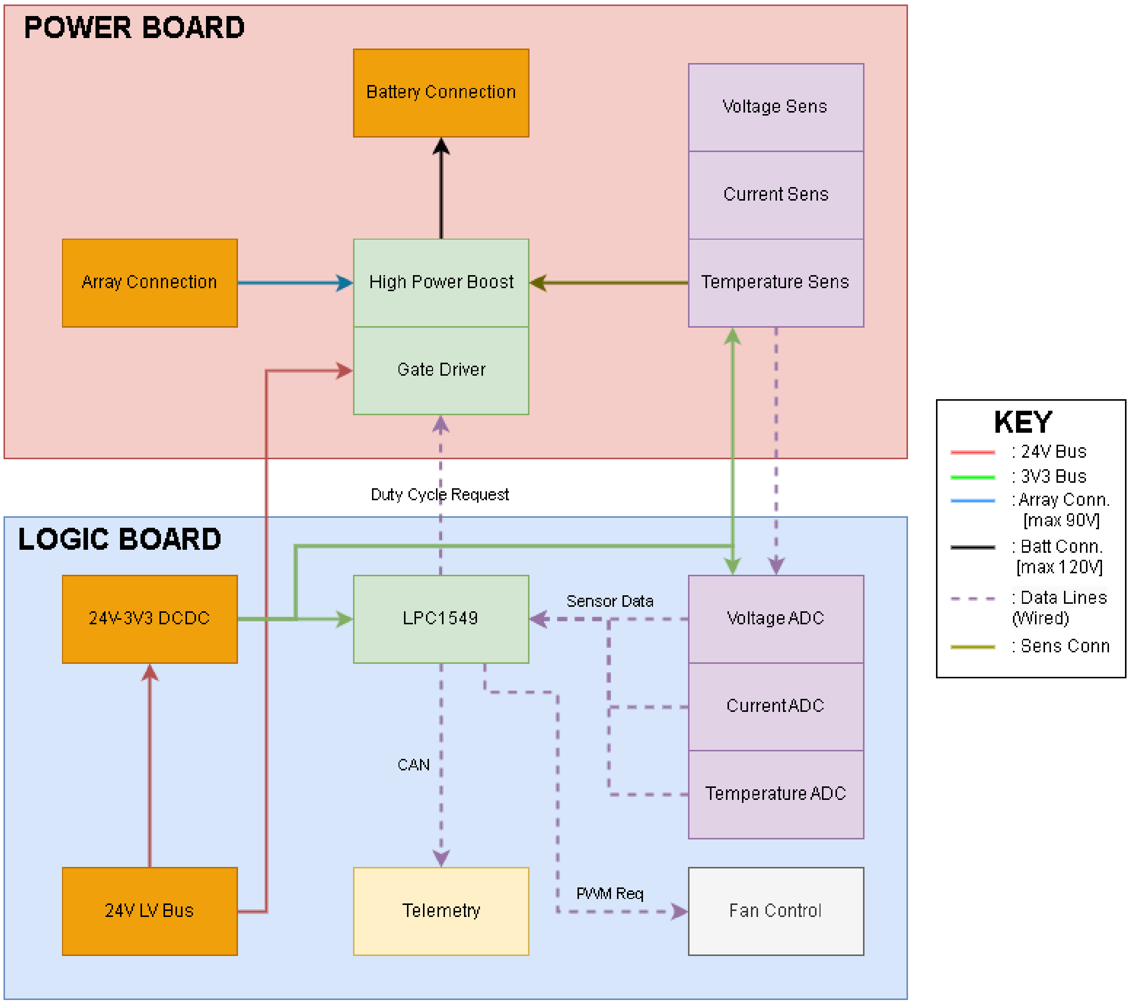

Figure 2: Block diagram of MPPTs

Subsystem Overview

1. Subsystem 1: Logic Board

The logic board will be the main control board for our system. The logic board will collect I-V characteristics from the power board. Using this information It will be tasked with running a perturb and observe algorithm to vary the switching signals to a separate power board. The board will send data over a CAN bus to communicate with the rest of the car. The plan is to have the switching frequency at 200kHz.

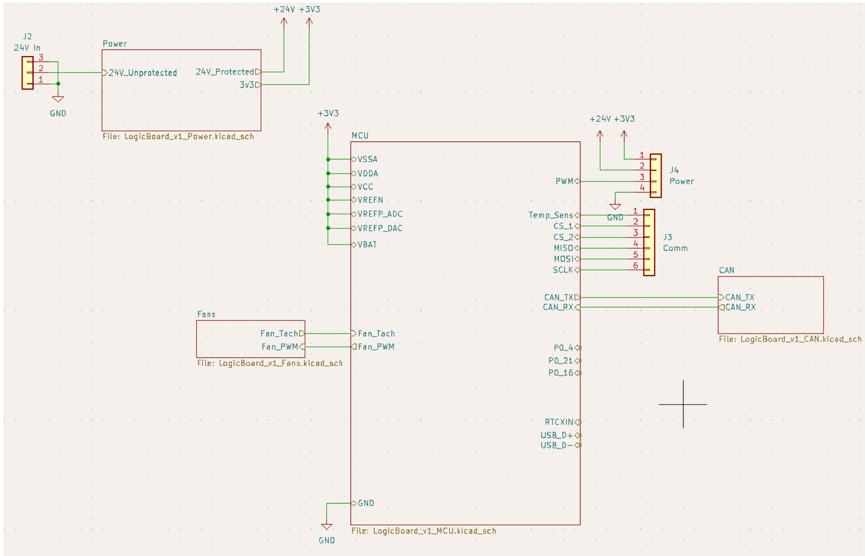

Figure 3: Main Sheet of Logic Board

The main things of note for the high-level design is how the subcircuits connect to each other and the power board. The first thing to note is that the low voltage power for the logic board is received from a connection to the car's 24V bus, and then the 24V along with a stepped down 3.3V is sent to the power board. The PWM signal from the microcontroller is also included along with the power.

The sensor communications also come in from the power board. It can be seen that there are two connections, one for SPI communication and another for ADC communication. This is due to us being uncertain about the sensor choice for the power board at the time the logic board was designed. Eventually we decided upon using the ADC sensors, but the SPI connections are left there as they can be repurposed into spare MCU pins if needed.

To provide the low voltage power from the LV bus to the rest of the logic board and to the power board, it is run through a power protection circuit along with a DCDC converter to provide 3v3 logic power for the MCU. This subcircuit is shown in Figure 4.

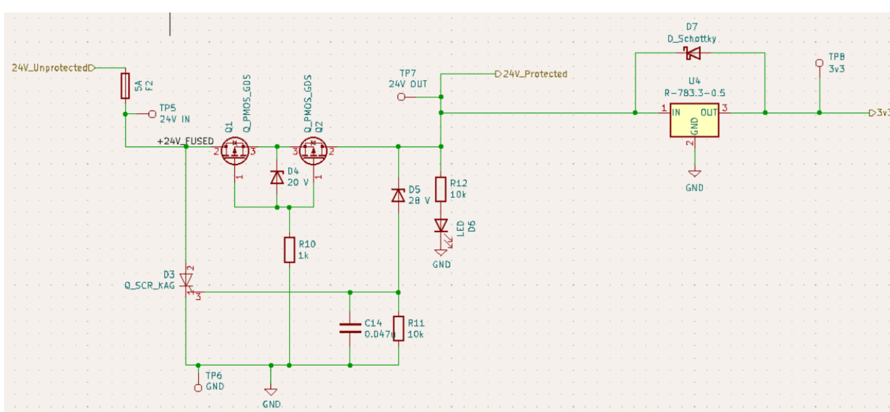

Figure 4: Power Protection of Logic Board

The design for the power circuit is mostly taken from the general power protection circuit used on all solar car boards that provides over and under volt, reverse polarity, and over current protection. The 3.3V DCDC is simply an off the shelf RECOM DCDC.

The MCU used on this board is the LPC1549 from NXP, specifically the 48-pin version. This controller was chosen as the LPC1549 series is used on the rest of the solar car boards, and so therefore there are already common libraries written for standard functions like CAN, PWM, and so on. This subcircuit also contains the JTAG header for the debugger, and an ISP and reset button for programming and resetting. Capacitors were also added to the power input pins of the MCU as requested by the datasheet [5].

The rest of the pin assignments were determined by their purpose. The datasheet requested specific pins for CAN, and the ADC sensors from the power board had to go to the pins that had ADC functionality. The temperature sense and fan tachometer also needed ADC pins. A 12MHz crystal was used for the MCU clock, this is a much higher frequency than we are taking our measurements and running the boost converter at, so it should be more than enough for this board.

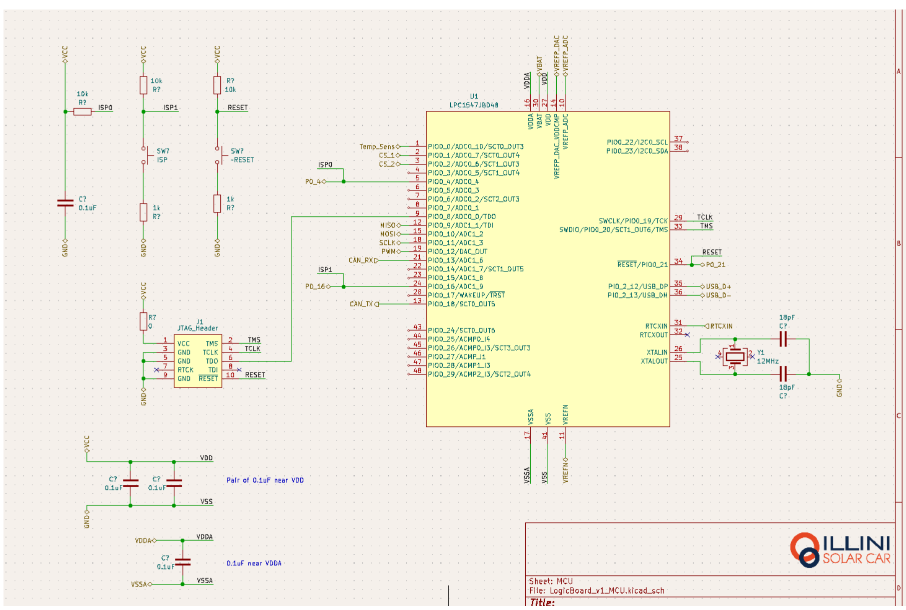

Figure 4: MCU Sheet of Logic Board

Requirements	Verification
MCU sends PWM gate signal requests to the power board.	Scope the PWM gate signal output to verify its voltage range(0V-3V3) and frequency(200kHz).
MCU receives temperature data and is within Actual Temperature ± 10°C.	We will use an infrared digital thermometer to verify the actual temperature and compare with our sensor readout using CAN telemetry application.
MCU receives voltage data from solar array and boost output. The reading is within Actual Voltage ± 10%.	We will use a multimeter to verify the actual voltage and compare with our sensor readout using CAN telemetry application.
MCU receives current data from solar array and boost output. The reading is within Actual Current ± 10%.	We will use a current sense probe to verify the actual current and compare with our sensor readout using CAN telemetry application.
MCU sends a fan request rpm message and spins the fan.	The fan spins and a noticeable RPM change will be felt. Also scoping the PWM input to the fan can verify the speed request.
Can send and receive CAN data at 500kHz	Using the brain battery management system we are able to receive CAN information. By scoping the CANH and CANL signal, we view the frequency of data. Using the telemetry application made by Illini Solar Car we can verify the message integrity.
The bus voltage(24V) is stepped down to 3V3 ± 5%	We will use a multimeter to verify the actual voltage from a test point on the board and compare with 3V3 ± 5%.

2. **Subsystem 2: Power Board**

The power board will be a high power boost circuit controlled by the logic board to take in the input power and vary the output power to charge the battery. Each module should handle power up to 400W. MPPTs should be able to output in the range of 77V-125V. Max charge current is ~25A.

The idea behind the circuit design is to keep the low voltage and high voltage separate for safety and functionality purposes. The main sheet can be seen in Figure 5 below.

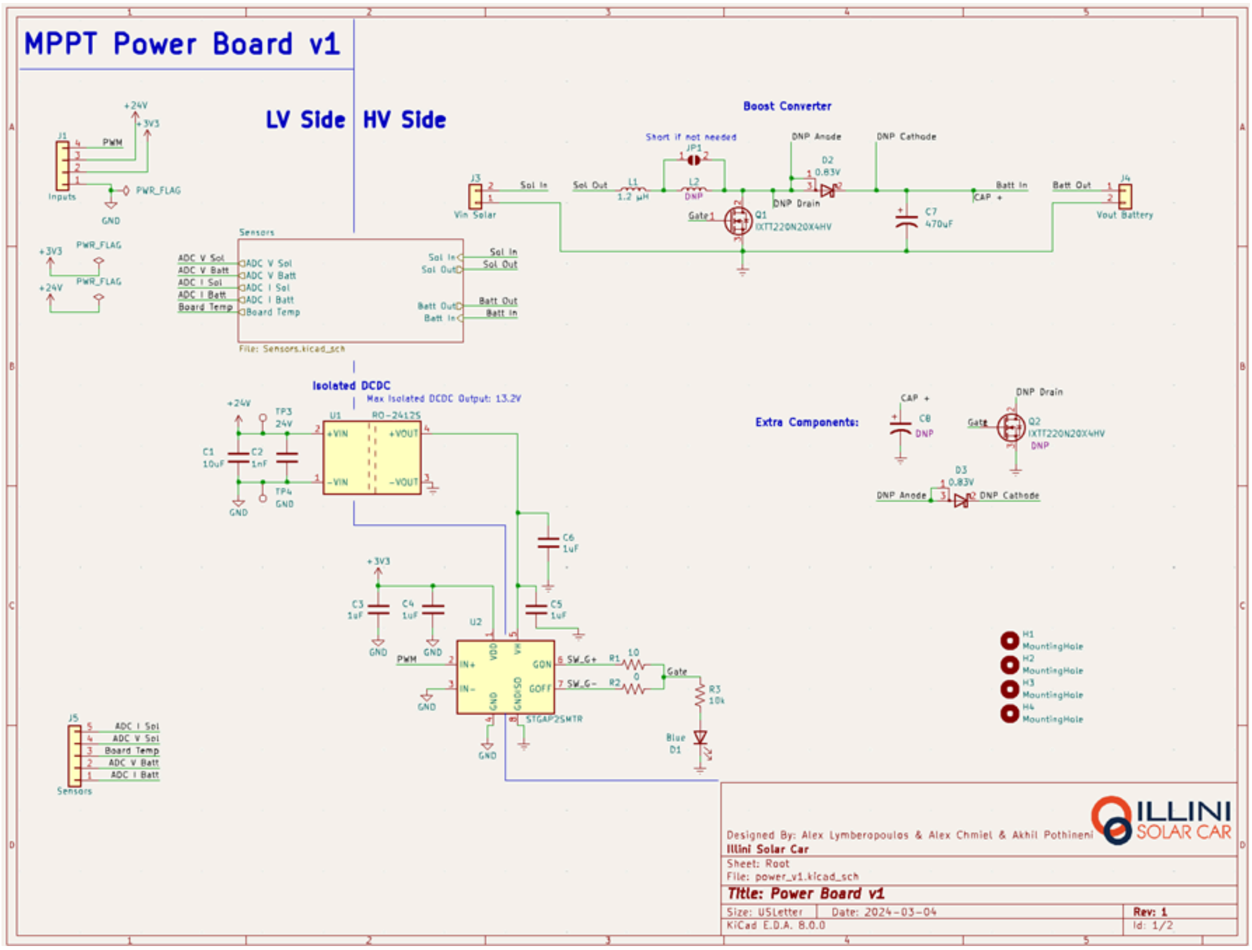

Figure 5: Main Sheet of Power Board

The main sheet shows connectors to and from the logic board, facilitating communication. Five sensors send signals to the logic board, along with 3.3V and 24V lines. As there's no power protection on this board, reliance is on the logic board for voltage regulation.

Here, the boost converter is visible on the high voltage side of the schematic. Additionally, an isolated DCDC feeds into a gate driver, regulating MOSFET switching. The presence of extra components caters to fault or errors during simulation.

The below sheet shows the sensors utilized in the power board. The sensor sheet can be seen in Figure 6 below.

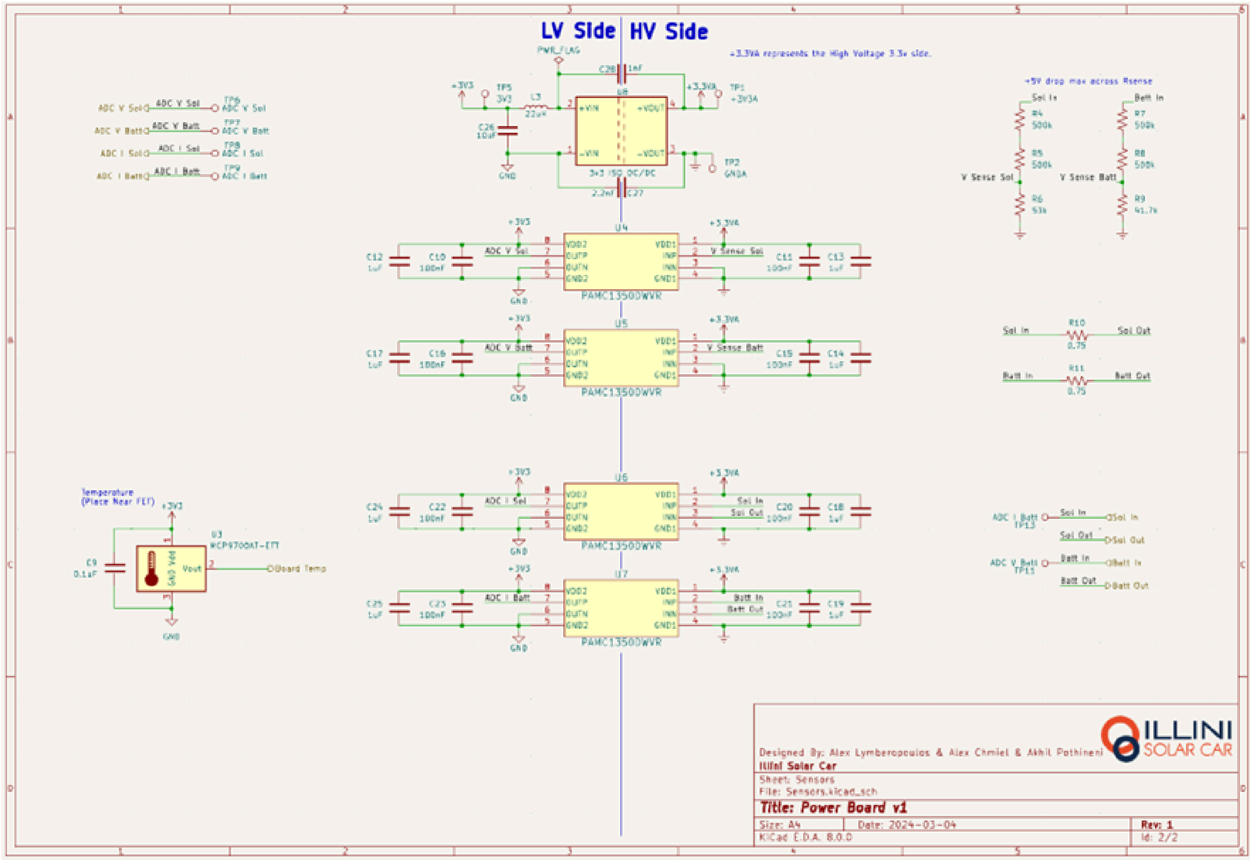

Figure 6: Sensor Sheet of Power Board

To preserve isolation, isolated amplifiers were used to sense voltage and current. Resistor dividers were used to create a voltage reference for the amplifiers to send to the logic board. The resistors were sized according to the equations below. Equation 1 was used to size the voltage sense resistor. Equation 2 was used to size the current sense resistor. These were found from references [2] and [3].

$$R_{VOLT} = \frac{V_{IN} R_{TOP}}{V_{source} - V_{IN}} \quad [1]$$

$$R_{CURR} = \frac{V_{sens,MAX}}{I_{MAX}} \quad [2]$$

Temperature sensing was added to verify conditions and regulate fan speeds for cooling the power board, ensuring correct performance.

Requirement	Verification
The boost converter handles inputs up to 90V at 400W, and is able to boost the voltage to an output range of 77-125V	We will make sure to test the converter at maximum and minimum inputs, and verify that the output is boosted correctly when tested with a load.
The duty cycle input adjusts output voltage of the boost converter.	We will test the MCU control loop with inputs from the sensors. We will test the PWM duty cycle output and make sure it is logical for the desired output

The layout design is shown below in Figure 7. The notable feature is the isolation between the low voltage and high voltage sides on the right side of the board.

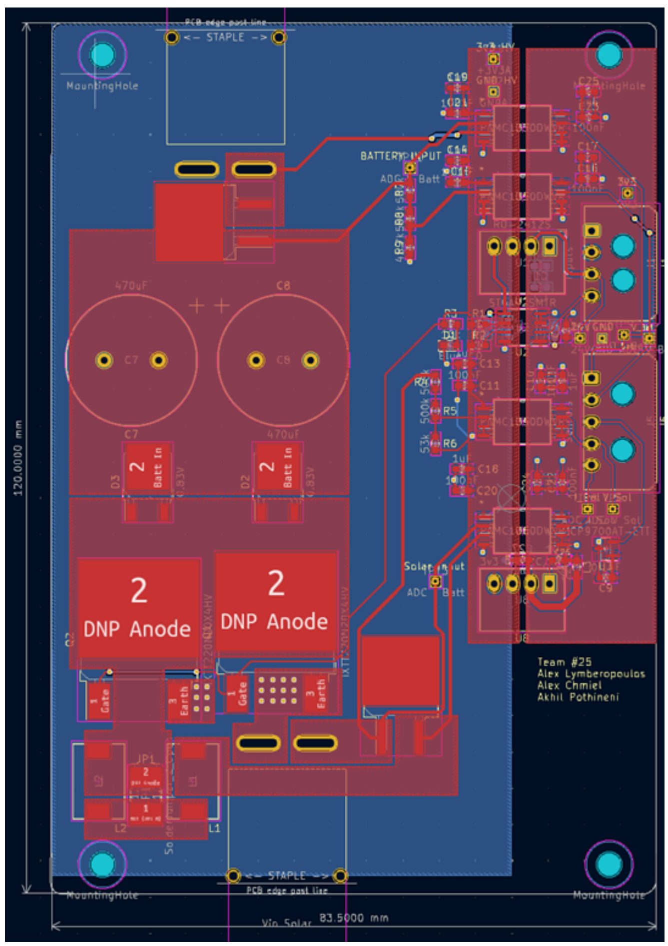

Figure 7: Layout of the Power Board

Tolerance Analysis

High power MPPTs can have a few different tolerance challenges. To verify our design would meet specifications, we used a simulation to validate the operating conditions. The first simulation that was run was using our nominal case. If we vary the duty cycle, we are able to get the current down to an acceptable value. This simulation doesn't take into account the real characteristics of solar cells, which have an Isc of 6.46A. In this case, we are modeling the solar cells as a voltage source.

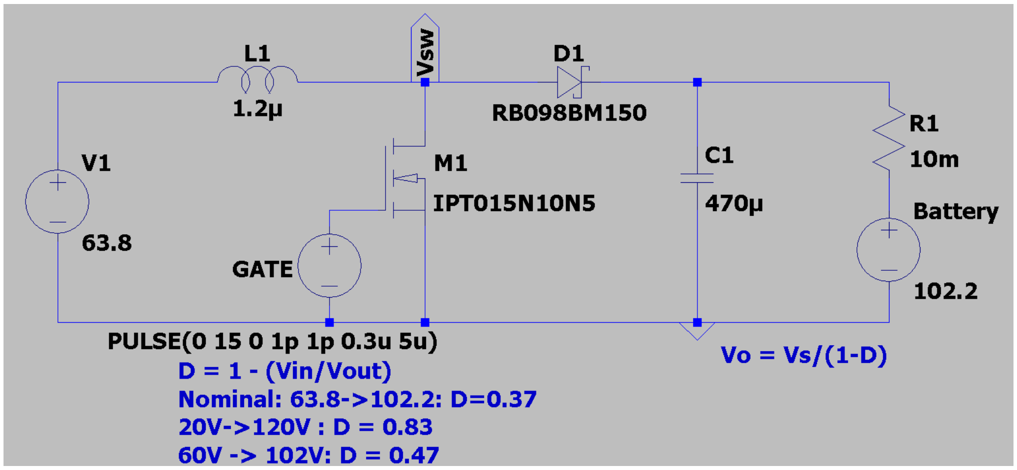

Figure 6: Nominal Power Board Operating Condition

With the nominal simulation complete, we simulated the worst case. This included the tolerance present in the inductor(±20%) and capacitor(±5%). With this addition, the current ripple and voltage ripple increases. This is still within the specifications.

$$L_{worst,case} = 1.2\mu H * 0.8 = 0.96\mu H$$
$$C_{worst,case} = 470\mu F * 0.95 = 446.5\mu F$$

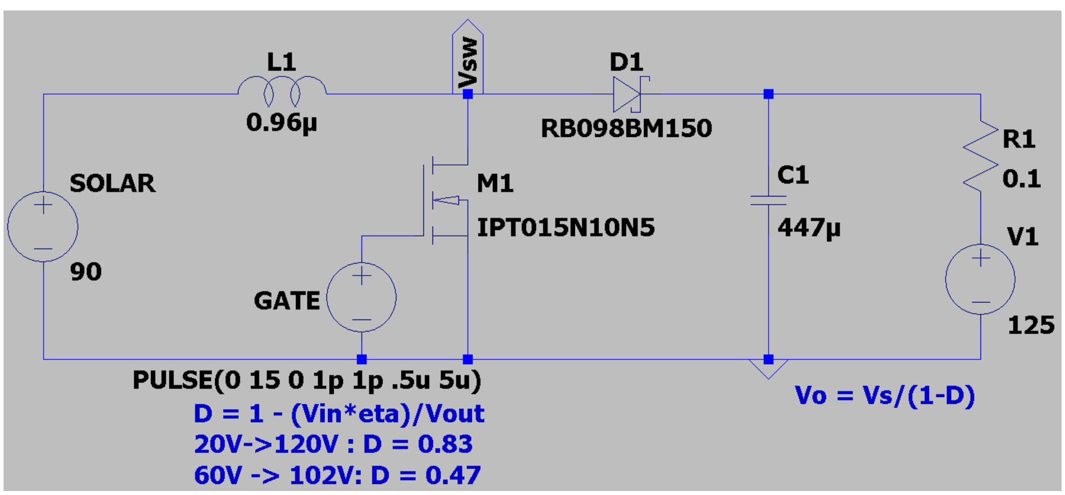

Figure 7: Worst Case Power Board Usage Operating Condition

With the nominal simulation complete, we simulated the worst case. This included the tolerance present in the inductor(±20%) and capacitor(±5%). With this addition, the current ripple and voltage ripple increases. This is still within the specifications.

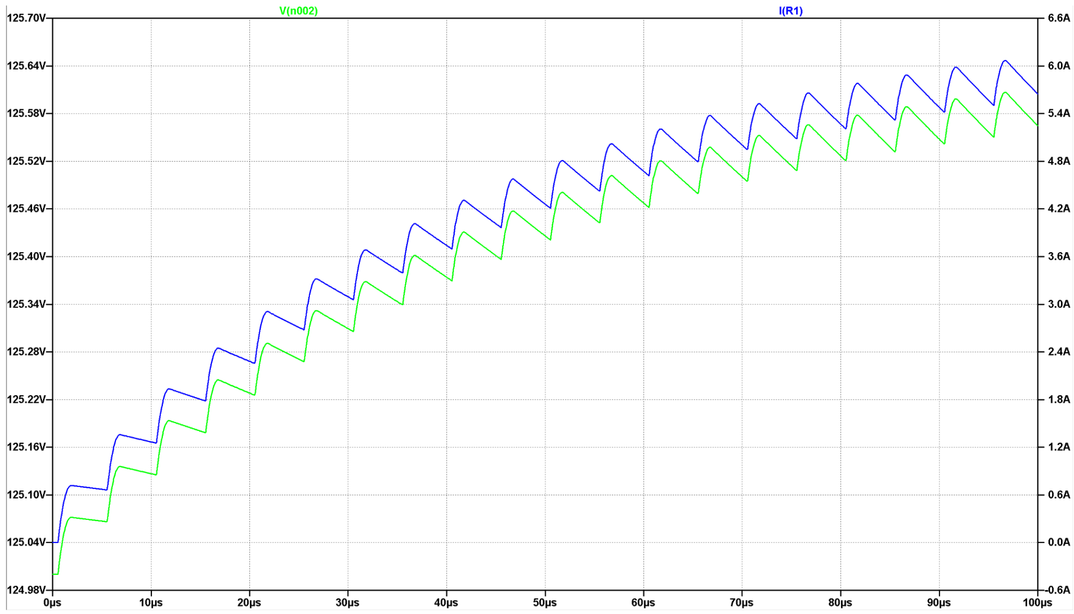

Figure 8: Output Voltage and Current at Worst Case (Blue: Output Current | Green: Output Voltage)

As shown above in Figure 8, the ripple voltage and ripple current still stay within acceptable ranges even in the worst case scenario.

3. Cost and Schedule

Cost Analysis

Reference	Value	Footprint	Datasheet	DNP	MPN	Note	Qty	Unit Price	Total Price
C1	10uF	Capacitor_SMD	~		CAP CER 10uF 50V X5R 0603		1	$ 0.24	$ 0.24
C2	1nF	Capacitor_SMD	~		CAP CER 1nF 50V X5R 0603		1	$ 0.10	$ 0.10
C3-C6	1uF	Capacitor_SMD	~		-- mixed values --		4	$ 0.10	$ 0.40
C7, C8	470uF	Capacitor_THT:	https://www.chemi-con.co.jp/products/relatedfiles	-- mixed va	EKXJ201ELL471MM40S		2	$ 3.76	$ 7.52
C9	0.1uF	Capacitor_SMD	~		CAP CER 0.1UF 10V X5R 0603		1	$ 0.27	$ 0.27
C10, C13	1nF		~			Place Ne	2	$ 0.10	$ 0.20
C11, C14	100nF		~			Place bet	2	$ 0.24	$ 0.48
C12, C15	1uF		~				2	$ 0.10	$ 0.20
D1	Blue	LED_SMD:LED_	~		LED BLUE CLEAR 0603		1	$ 0.55	$ 0.55
D2, D3	0.83V	Package_TO_S(	https://www.rohm.com/datasheet?p=RB098BM150	-- mixed va	RB098BM150TL		2	$ 1.19	$ 2.38
J1	Inputs	Connector_Mol	~		43650-0400		1	$ 1.66	$ 1.66
J2	Sensors	Connector_Mol	~		43650-0800		1	$ 2.49	$ 2.49
J3	Vin Solar	layout:Anderso	https://www.andersonpower.com/content/dam/app/ecommer		3-5912P1		1	$ 0.91	$ 0.91
J4	Vout Battery	layout:Anderso	https://www.andersonpower.com/content/dam/app/ecommer		3-5912P1		1	$ 0.91	$ 0.91
JP1	SolderJumper_2_Open	Resistor_SMD:F	~				1	$ 0.10	$ 0.10
L1, L2	1.2 Î¼H	Inductor_SMD:I	https://www.we-online.com/components/products/	-- mixed va	744325120		2	$ 4.27	$ 8.54
Q1, Q2	IXTT220N20X4HV	Package_TO_S(	https://www.mouser.com/datasheet/2/240/Littelfus	-- mixed va	IXTT220N20X4HV		2	$ 18.54	$ 37.08
R1	10	Resistor_SMD:F	~		RES SMD 10 OHM 5% 1/10W 0603		1	$ 0.44	$ 0.44
R2	0	Resistor_SMD:F	~		RES SMD 0 OHM 5% 1/10W 0603		1	$ 0.44	$ 0.44
R3	10k	Resistor_SMD:F	~		RES SMD 10K OHM 5% 1/10W 0603		1	$ 0.44	$ 0.44
U1	RO-2412S	Converter_DCD	https://www.mouser.com/datasheet/2/468/RO-1711124.pdf		RO-2412S		1	$ 8.11	$ 8.11
U2	STGAP2SMTR	Package_SO:S(	https://www.st.com/resource/en/datasheet/stgap2s.pdf		STGAP2SMTR		1	$ 2.26	$ 2.26
U3	MCP9700AT-ETT	Package_TO_S(	http://ww1.microchip.com/downloads/en/DeviceDoc/21942e.		MCP9700AT-ETT		1	$ 0.36	$ 0.36
U4, U5	AMC130M02DFMR	SOIC20_DFM_T	https://www.ti.com/lit/ds/symlink/amc130m02.pdf?ts=1708614190529&ref_url=https%253A%252F%252Fwv				2	$ 8.27	$ 16.54
			Total Power Board Component Cost						$ 92.62

Figure 9: Power Board BOM

Reference	Value	Footprint	Datasheet	DNP	MPN	Note		Quantity	Unit Price	Total Cost
C1	0.047u	Capacitor_SMD:C_0603_	...		CAP CER 0.047UF 50V X7R 0603			1	$ 0.28	$ 0.28
> C2-C5	0.1uF	Capacitor_SMD:C_0603_	~		CAP CER 0.1uF 10V X7R	10V X5R 0603 20%		4	$ 0.31	$ 1.24
> C6, C7	18pF	Capacitor_SMD:C_0603_	~		CAP CER 18pF 10V X7R	10V X5R 0603 20%		2	$ 1.88	$ 3.76
D1	Q_SCR_KAG	Package_TO_SOT_SMD:S	https://www.littelfuse		S602TSRP			1	$ 0.86	$ 0.86
D2	20 V	Diode_SMD:D_SOD-123F			DIODE ZENER 20V 500MW SOD123F			1	$ 0.20	$ 0.20
D3	28 V	Diode_SMD:D_SOD-123F			DIODE ZENER 28V 500mW SOD123F			1	$ 0.39	$ 0.39
> D4, D5	LED	LED_SMD:LED_0603_160	~		-- mixed values --			2	$ 0.55	$ 1.10
F1	5A	layout:Littelfuse_154_4.2	~		FUSE BOARD MNT 5A 125VAC/VDC		32V 125°C	1	$ 2.95	$ 2.95
J1	JTAG_Header	layout:IDC-Header_2x05_Pitch1.27mm_Straigh			3220-10-0100-00	JTAG_header		1	$ 0.61	$ 0.61
J2	24V In		~					1	$ 0.61	$ 0.61
J3	Comm		~					1	$ 0.61	$ 0.61
J4	Power		~					1	$ 0.61	$ 0.61
> Q1, Q2	Q_PMOS_GDS	Package_TO_SOT_SMD:T	https://www.mouser.		FQD11P06		30Vgs 9.4A	2	$ 1.09	$ 2.18
R1	1k	Resistor_SMD:R_0603_16	~		RES SMD 1K OHM 5% 0.1W 0603		0.1W 1% 0	1	$ 0.10	$ 0.10
> R2-R4	10k	Resistor_SMD:R_0603_16	~		RES SMD 10K OHM 5% 0.1W 0603		0.1W 1% 0	3	$ 0.20	$ 0.60
> R5, R6, R9	10k	Resistor_SMD:R_0603_16	~		RES SMD 10K OHM 1% 1	0.1W 5% 0603		3	$ 0.20	$ 0.60
> R7, R10	1k	Resistor_SMD:R_0603_16	~		RES SMD 1K OHM 5% 1/	0.1W 5% 0603		2	$ 0.20	$ 0.40
R8	0	Resistor_SMD:R_0603_16	~	DNP	RES SMD 0 OHM 5% 1/4	0.1W 5% 0603		1	$ 0.20	$ 0.20
SW1	ISP	layout:RST_STM_PTS_820	https://www.mouser.		ADTSM31NV			1	$ 0.59	$ 0.59
SW2	~RESET	layout:RST_STM_PTS_820	https://www.mouser.		ADTSM31NV			1	$ 0.59	$ 0.59
TP1	24V IN	TestPoint:TestPoint_THT	~					1		$ -
TP2	24V OUT	TestPoint:TestPoint_THT	~					1		$ -
TP3	GND	TestPoint:TestPoint_THT	~					1		$ -
TP4	VGS Threshold	TestPoint:TestPoint_THT	~					1		$ -
U1	LPC1547JBD48	Housings_QFP:LQFP-48_	https://www.mouser.		LPC1547JBD48			1	$ 10.37	$ 10.37
Y1	12MHz	layout:Crystal_SMD_TXC_	http://www.mouser.c		7V-12.000MAAE-T			1	$ 0.79	$ 0.79
Total Logic Board Cost										$ 29.64

Figure 10: Logic Board BOM

In order to estimate the labor cost associated with this project we began by looking at the average salary for a UIUC Electrical/Computer Engineering graduate. The average yearly salary is $98,472, when combined with the fact that the average working hours per year is 2080, the result is an hourly rate of around $47. We anticipate that we will spend 10 hours a week for the duration of the project (10 weeks) resulting in the following calculation: $47 * 10 hrs * 10 weeks * 3 people = $14,100 in labor costs.

When combined with the component costs the total is: $14,222.26

Schedule

WEEK	Deadlines	Tasks
Week of 2/19	Design Review Sign-up: 2/21 Design Document: 2/22	Finalize Simulation/Design (Alex L) Finish Board Design(Alex L)
Week of 2/26	Design Review: 2/27 PCB Review: 2/30	Finish Layouts of Boards(Alex C)
Week of 3/4	First Round PCB Orders: 3/5 Teamwork Evaluation I: 3/6	Start FW with brain board (Akhil)

Week of 3/11	Spring Break	Break 🙂 (Everyone)
Week of 3/18	Second Round PCB Orders: 3/19	Test power board manually(Alex L)
Week of 3/25	Third Round PCB: 3/26 Individual Progress Reports: 3/27	Test power board with brain board (Alex C)
Week of 4/1	Fourth Round PCB: 4/2	Demo voltage ranges(Akhil)
Week of 4/8	Fifth Round PCB: 4/9	Verify Everything is Working (Alex L)
Week of 4/15	Mock Demo: 4/15-19 Team Contract Fulfillment: 4/19	**Alex C:** - Check functionality of project, prepare for mock demos
Week of 4/22	Final Demo 4/22-24 Mock Presentation: 4/25-26	**Akhil:** - Make adjustments for final demo - Work on presentation
Week of 4/29	Final Presentation: 4/29-30 Final Paper: 5/1 Lab Notebook: 5/2	**Alex C:** - Finalize presentation and report

4. Ethics and Safety

As MPPTs are high power devices, there are safety issues that may arise when working with high voltage electronics. For example when working with a solar array there will always be a voltage present, especially in strong light. This means that we should take caution when connecting the MPPTs to any solar array, or when handling solar array connections. When testing, we will also be using a high voltage power supply to test the power converter. When testing, care should be taken to ensure that there are no unwanted connections and everything is properly connected and covered so that there is no risk of accidental contact with the test setup. For safety for the LiPo battery that will be used, a battery management system that was previously manufactured will verify everything is in good operating conditions. Also, the team will take the high voltage training to make sure everyone is safe while working on the project.

The MPPTs should also have an enclosure that will prevent any accidental touches or any debris from getting inside and damaging the electronics or causing a short. Since these will be used inside our solar car, extra care will have to be taken with the construction of the enclosure to ensure there is no way for the driver or another person doing maintenance on the car to accidentally come into contact with the electronics. The enclosure should also be located in a safe place inside the car and built correctly so that any possible debris getting inside the car or other mechanical components becoming loose or damaged will not cause damage to the electronics. The enclosure should also comply with the American Solar Challenge regulations regarding labeling, mechanical structure, and wiring.

The MPPTs will be used to charge the car's batteries, which introduce additional safety concerns. We must ensure that the MPPTs are thoroughly tested with a load and power supply before actually connecting them to batteries to avoid any possible overvoltage or overcurrent issues. The battery itself already has a BMS with automatic monitoring and shut off, and the BMS should always be used and in working order whenever working with the batteries. Campus policy regarding batteries will be followed, which includes rules about battery storage, bringing batteries into buildings, and training for working with batteries. If any work is being done with batteries safety equipment such as fire extinguishers and sand will be present.

In terms of ethics, as this product is being built for a single specific application for our battery and solar array, there are minimal ethical issues with this product. This product will not be sold or used in any other situation and will remain with the team. There is little to no risk beyond the aforementioned high voltage safety concerns.

5. References

[1] B. Hauke, "Basic Calculation of a Boost Converter's Power Stage," Texas Instruments, https://www.ti.com/lit/an/slva372d/slva372d.pdf?ts=1709431024850&ref_url=https%253A%252F%252Fwww.google.com%252F (accessed Mar. 28, 2024).

[2] A. Smith, "Design considerations for isolated current sensing," TI.com, https://www.ti.com/technologies/current-sensing-solutions.html (accessed Mar. 27, 2024).

[3] D. Miller, "Isolated Voltage-Measurement Circuit With ±250-mV Input and Differential Output," TI.com, https://www.ti.com/lit/an/sbaa350a/sbaa350a.pdf?ts=1674027566594&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FAMC1301 (accessed Mar. 28, 2024).

[4] IEEE Code of Ethics

[5] LPC15XX, datasheet, NXP Semiconductors, 2015. Available at: https://www.nxp.com/docs/en/datasheet/LPC15XX