Dual Input Microinverter for Tandem Cells

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Abstract

For every solar panel, there is an inverter which transforms the harvested DC electricity into AC electricity so that it can connect to the grid and power household appliances. In this project, we examined a tandem solar cell being designed by Iris Photovoltaics which has two layers with two distinct outputs, and we explored several solutions to create a microinverter which can handle dual inputs from the tandem PV and combine them into a single AC output. To examine the viability of such a microinverter, we designed and simulated the DC-DC combination portion of the specialized dual input microinverter, resulting in a working circuit simulation using flyback transformers which can take two DC inputs at different voltage and current levels and combine them together into a single high voltage on the DC bus, ready to be transformed into AC. We also purchased an already existing dual input microinverter and tested it by connecting it with two different solar panels and measuring its performance, however we could not obtain useful results because it did not function as intended. Overall the dual input microinverter is an interesting technology involving maximum power point tracking, DC combination, and power electronics. It has a multitude of applications, and it fits perfectly with the 4-terminal tandem solar module being developed by Iris Photovoltaics.

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Chapter 1: Introduction

Renewable energy generation is a growing industry as scientists and engineers innovate to improve technology and as solar facilities are being build out. Although much discussed, solar electricity generation accounted for only 0.6% of the total energy generation in the U.S. in 2016 [1]. Despite producing relatively little energy at this point, there is significant room for improving solar technologies and increasing its contribution to the nation's energy mix.

Table 1 - 1: Energy Generation in the U.S. by Source

Energy Source	Percent of Total Energy Generation
Coal	33%
Natural Gas	33%
Nuclear	20%
Hydropower	6%
Biomass	1.6%
Geothermal	0.4%
Solar	0.6%
Wind	4.7%
Petroleum	1%
Other Gases	<1%

Data found from [1].

A major area for improvement of solar technology is the efficiency of the module itself. The efficiency of "hero cells" (1 cm^2 solar cells made in research laboratories) of different technologies range from approximately 15% to almost 50% [2]. Cost-effective, commercially manufactured modules, however, have efficiencies that range from 15 to 22% and are usually made from single absorber silicon cells. The higher efficiency hero cells are made from multi-junctions meaning that they utilize more than one absorber material. Despite having higher efficiencies, they are considerable more expensive because of the complex structure and materials required.

The efficiency of the system is further effected by the power electron devices downstream. In grid-tied applications, the solar panels connect to a maximum power point tracker (MPPT), a DC-DC converter and a DC-AC inverter. The MPPT forces the panels to operate at a voltage and current so the panel generates the most power. Following the MPPT is the DC-DC converter that steps-up the voltage to the required input voltage for the inverter. The inverter takes the stepped-up DC voltage and inverts it into a 60 Hz AC voltage to be sent to the grid.

Scientists and engineers are presently researching modules for terrestrial application based on tandem solar cell concepts. Tandem solar cells have two different absorber materials stacked on each other in which each material converts a given portion of the solar spectrum to achieve a higher total efficiency. These will require power electronics specially designed for the new modules.

Chapter 2: Background

Solar Panels

To achieve their rated efficiencies throughout the day, several conditions must be met. The first condition requires a sunny location. Without sun, the panel cannot work which limits the possible locations slightly. The second condition requires a location without shading which has drastic effects on solar panels. Any cell under shading can cause a significant decrease in power output of the panel. The third condition involves energy storage. Without it, the solar panel only can effectively generate power during the day while there is sun. With storage, the unused energy can be stored so it can be used even during the night.

Tandem Solar Cells

Currently, the terrestrial market consists of 99% single absorber solar cells with 1% based on amorphous Si cells that have efficiencies of less than 10%. However, the current single layer solar cells only achieve efficiency's up to 20%. To achieve higher efficiencies, the industry began creating multi-junction solar cells which can achieve much higher total efficiencies up to 46% as shown in **Figure 2 - 1**.

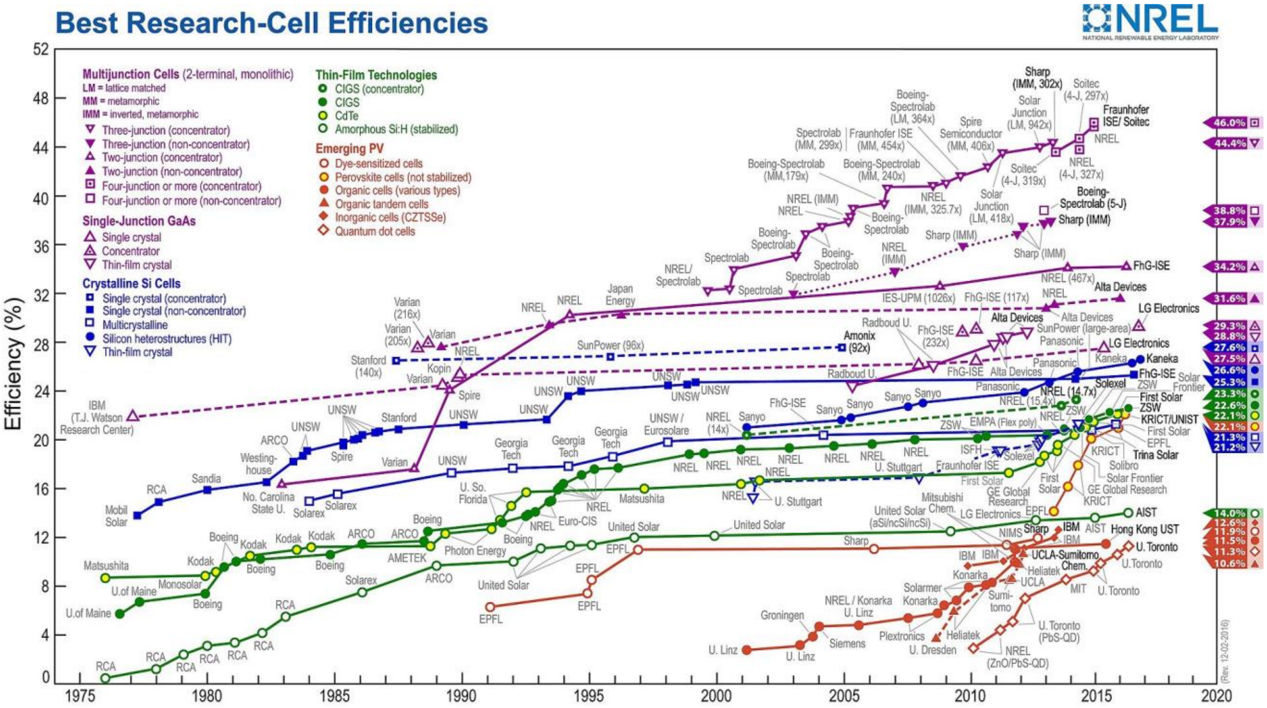

Figure 2 - 1: Solar Cell Efficiencies [3]

Tandem solar cells utilize more than one photovoltaic layer that absorb different spectrums of light shown in **Figure 2 - 2**. The top layer absorbs the high-energy photons while the lower cells absorb the lower energy photons. However, this causes some losses in efficiency because the solar cells do not receive the entire spectrum of light like it would as a single layer cell. Despite lower efficiencies per layer, combining the layers overcome these efficiencies losses with a higher total efficiency of the entire system by minimizing the thermal relaxation loss [4].

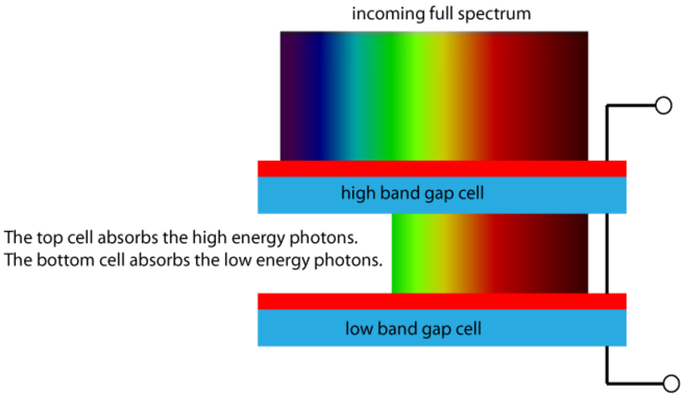

Figure 2 - 2: Tandem Solar Cell [5]

Power Optimization

Optimizing a solar cell's power output requires understanding of typical silicon I-V curves shown in **Figure 2 - 3**. Most current solar cells are made of silicon which follow typical PN junction I-V relations. Optimal power is achieved by operating at a specific voltage and current shown in **Figure 2 – 3**. Without ideal components, the solar cells need optimization. Most power optimizers utilize Maximum Power Point Tracking (MPPT) and DC-DC conversion. However, these methods only work if the cell follow typical I-V curves. Tandem solar cells utilize both silicon and perovskite layers [6].

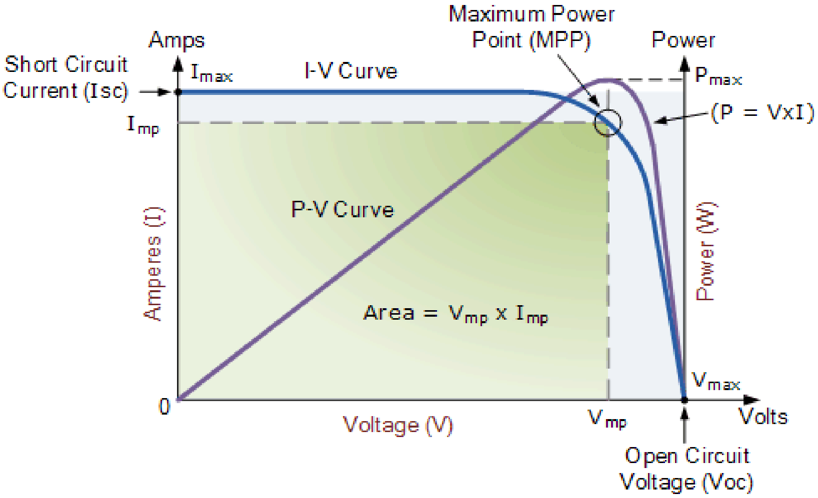

Figure 2 - 3: Solar I-V Curves [7]

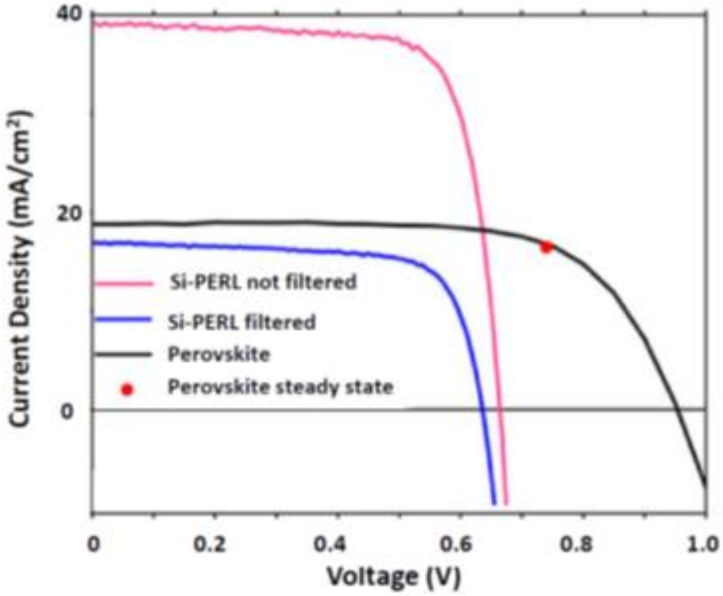

Figure 2 - 4: Perovskite I-V Curve [8]

The perovksite layer follows a slightly different I-V curve than standard silicon layers shown in **Figure 2 - 4**. Silicon cells have an open circuit voltage of approximately 0.7 V while the perovskite cells have an open circuit voltage of 1.2 V. Since the cells have different open circuit voltages, they also have different short circuit currents. Both the perovskite and silicon cells alone have short circuit currents of approximately 20 mA while the tandem cell has an short circuit current of 40 mA. MPPT becomes difficult since the voltage and currents are different. This may require two different power optimizers instead of a single module.

MPPT Algorithms

Tracking the Maximum Power Point can be implemented using multiple different algorithms. **Table 2 – 1** shows the basic characteristic of the algorithms. Hill-Climbing and Perturb & Observer (P&O) are the simplest form of tracking. Both involve perturbing a specific parameter of the circuit and checks the output of an increase or decrease in power. If an increased is sensed, the tracker continues to perturb in the same direction while a decrease will cause the tracker to perturb in the other direction. Hill-Climbing perturbs the duty cycle of the converter while P&O perturbs the operating voltage of the panel or array. Incremental Conductance is derived from the fact that the derivative of the panel's power curve is zero at the MPP. Using the instantaneous conductance and incremental conductance, an error signal is created that is driven to zero to forcing the panel to operate at the MPP. Fractional Open Circuit Voltage and Short Circuit current are similar methods. Both depend on knowing the precise I-V curves the connected panel. Using the Voc and Isc, the engineer can define an operating point using a predefined proportionality constant found using linear equations with the panel's power curve. Fuzzy Logic Control works in three stages: fuzzification, rule base table lookup and defuzzification. Fuzzification converts numerical input variables into linguistic variables based on a membership function. Inputs include the error signal and the change in error. The output can be using a rule base table. Defuzzification converts the output into numerical values using the same function to convert the numerical values to linguistic variables. Neural Networks uses three different layers: input, hidden and output. The number of nodes in each layer varies depending on the user. Inputs include the array parameters and atmospheric variables. Output normally controls the reference signals such as duty cycle control, voltage and current control. The hidden layer contains the algorithms and math to calculate the MPP and forces the panel to operate at the calculated point. Ripple Correlation Control Utilizes the face the panel faces ripple since the output voltage will have some ripple. It correlates the derivative of the array power and voltage/current to drive the power gradient to zero [9].

Table 2 - 1: MPPT Algorithm Characteristics

Method	**PV Dependent**	**True MPPT**	**Analog or Digital**	**Periodic Tuning**	**Convergence Speed**	**Complexity**	**Sensed Parameters**
Hill-Climbing	No	Yes	Both	No	Varies	Low	Voltage, Current
Perturb & Observe	No	Yes	Both	No	Varies	Low	Voltage, Current
Incremental Conductance	Yes	Yes	Digital	No	Varies	Medium	Voltage, Current
Fractional OC Voltage	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional SC Current	Yes	No	Both	Yes	Medium	Medium	Current
Fuzzy Logic Control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural Networks	Yes	Yes	Digital	Yes	Fast	High	Varies
Ripple Correlation Control	No	Yes	Analog	No	Fast	Low	Voltage, Current
Current Control	Yes	Yes	Digital	Yes	Slow	High	Voltage, Current
DC Link Capacitor Droop	No	No	Both	No	Medium	Low	Voltage

Control							
Load Current Load Voltage Maximization	No	No	Analog	No	Fast	Low	Voltage, Current
Feedback Control	No	Yes	Digital	No	Fast	Medium	Voltage, Current

DC-DC Converters

Power electronics play a vital role in most electronics today including photovoltaic systems. They are required for stepping up or down the DC voltage from the panel as well as inverter the DC voltage into AC for use with appliances or connected with the grid. Different converters can be used depending the panel’s operating voltages and the desired power output. With higher voltages and power outputs, flyback, two-switch forward and full-bridge converters are typically used.

DC-AC Converters

Typically, after the DC-DC converters, there are DC-AC converters. They operate at a specified operating voltage high enough the generate three-phase 60 Hz AC signals. They are mostly used for grid-tie applications while still applicable for off-grid applications. For grid-tie applications, the converter allows the users to generate power and sell excess power while the off-grid applications can operate different appliances that require AC input.

Grid-Tie System

Additionally, inverters allow solar panels to supply power to both the utilities company and the house attached. Inverters are single units that integrate the MPPT, DC-DC, and DC-AC functions. Since most appliances and the grid works with AC voltages, the micro inverters must invert the DC input it receives. The micro inverter’s output must match the grid voltages and frequency to avoid disrupting the system. The inverter performs a simple DC-to-AC conversion [10]. However, for tandem solar cells, the micro inverter cannot perform a simple DC-to-AC conversion. Since the inverter takes two DC voltages, it performs a more complex conversion.

String Inverters

Solar arrays configuration creates “strings” of solar panels, connecting a row of panels in series. For example, a 25-panel array can have 5 rows of 5 panels, creating 5 different strings. Each string connects to a string inverter. However, any shading or sub-optimal roofing drastically lowers the efficiency of the string. With only a string inverter, the highest efficiency achieved equals the lower solar efficiency since each string connects the panels in series. Power optimizers help mitigate these problems. However, string inverters do not have internal optimizers. Power Optimizers connect to each solar panel individually so each panel outputs optimal voltages and currents [11].

Micro Inverters

Most residential and commercial utilize micro inverters. Like power optimizers, micro inverters connect to each panel directly. However, they also convert power from DC to AC. Micro inverters do not induce losses when one panel is shaded like with string inverters since each panel has an inverter. These also monitor the panel’s performances individually while string inverters can only monitor the entire string. Micro inverters allow higher achievable efficiencies, but cost more than string inverters [12].

Our Project

The objective of this project is to accomplish the following two goals.

1. Design a critical stage of a dual input microinverter for a perovskite-Si four terminal tandem module: the dual input DC-DC conversion stage that follows the individual maximum power point trackers for each absorber layer and combines the output of each into a single DC voltage ready for DC-AC conversion. This design will be validated with LTSpice.

2. Design, construct, and assess the capabilities of a laboratory testbed for evaluating the performance of a complete dual input microinverter. A YC500 dual input microinverter manufactured by APSystems is used at the DUT in the testbed assessment.

Chapter 3. Design Constraints

This project has two different sections which have different constraints to each part of the project. In this section, we will explain the differences and the constraints of each part of the project.

DC-DC Conversion Design

The first objective of the project is to design a DC-DC conversion stage that can combine two DC voltages together. The block diagram is the conversion stage is depicted in **Figure 3 – 1**.

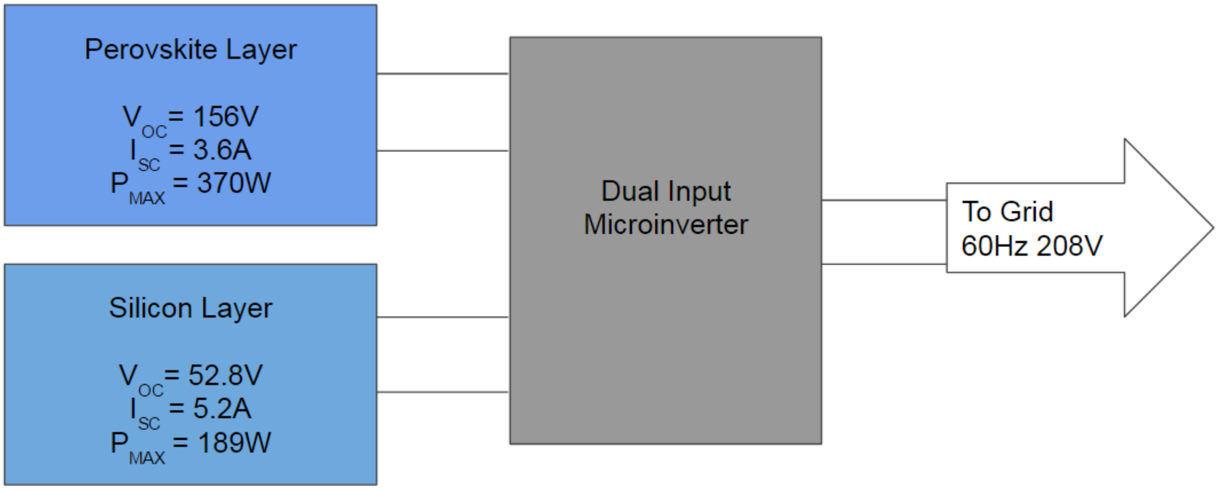

Figure 3 - 1: Level Zero Block Diagram

Figure 3 – 1 shows the most basic idea of our project. We are attempting to create parts for a dual input microinverter that can handle both a silicon module and a perovskite module. **Figure 3 – 2** shows the actual block diagram we are trying to design and simulate.

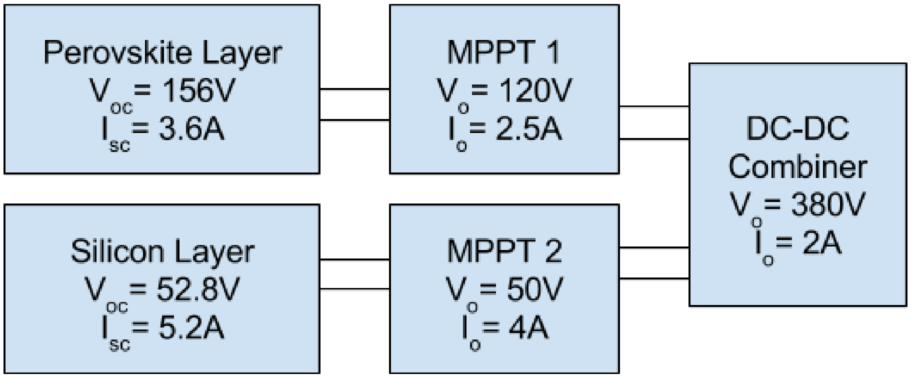

Figure 3 - 2: Level One Block Diagram

For our project, we are only designing the DC-DC converter stage. For this, we are assuming the inputs to the DC-DC converter are constants and come directly from the MPPT of each layer which output 120 V and 50 V respectively for the perovskite and silicon modules.

Designing this stage requires meeting different specifications. First, the overall efficiency of the stage must be at least 90%. Most DC-DC converters today can achieve efficiencies of 95%, but for our design we chose 90% just as proof on concept for the stage. We can monitor the efficiency by measuring the input power from the solar panel and measuring the output power with a resistive load. Second, the output of the DC-DC converter must be 380 V because inverters typically require roughly 380 V at the input.

Because we are only attempting to design the converter stage, the only constraint we have would be the program we use. The program must be able to handle all the components and model them accurately. We plan on using LTSpice to investigate component sizing and circuit performance. This program allows us to create our own components as well as visually see the circuit. It should not have many problems with handling the number of components we plan on using.

Table 3 - 1: MPPT and DC-DC Converter Parameters

	Output Voltage (V)	**Output Current (A)**	**Output Power (W)**
Perovskite	156	3.6	370
Silicon	52.8	5.2	189
DC-DC Converter	380	2	559 (Maximum)

Microinverter Testbed

For this part of the project, we are using the APsystems YC500 dual input microinverter to test its capabilities and analyze how it reacts under different conditions. The YC500 is originally designed for two similar silicon modules so we are attempting to test the microinverter with dissimilar modules to see how it reacts.

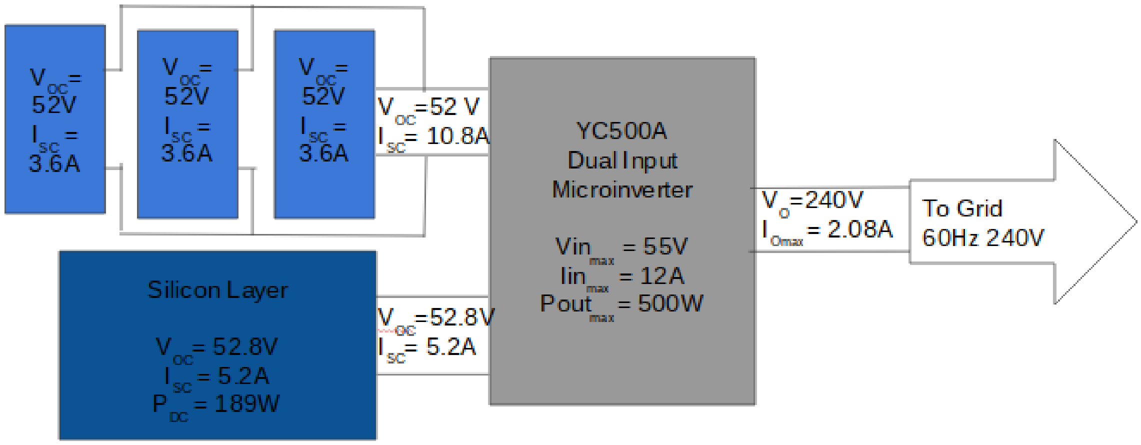

Figure 3 - 3: Microinverter Testbed

Because we are testing for perovskite layer with a V_{oc} of 156 V, we plan on designing for a module that has split the module into three different voltages of approximately 52 V and an output current of approximately 12 A.

To achieve the proper test set-up, we need a power supply that provides enough wattage to module the perovskite module. However, we currently do not have the correct power supply, we are planning on using two different solar panels with different V_{oc} to recreate different modules as close as possible to our tandem module.

The first requirement revolves around the stability of the system. The system must always be outputting between 208 - 240 VAC at 2.08 - 2.4 A to match the grid ratings. Not matching the grid voltages and current may cause disruption to the whole system and may cause damage to any of the components which include the solar panel, the microinverter or the grid itself.

The second requirement revolves around the operation of the system. Because we will be operating the microinverter close to its maximum parameters, we must ensure there is no overheating issue with the module. Additionally, we need to ensure the heating does not drastically affect the output of the output.

Upon testing the system, we want to be able to measure the voltages and currents at various locations. We want to be able to measure the input to the microinverter from both the perovskite and the silicon cells. This will allow us to calculate roughly the power into the system. We then want to be able to measure the voltage and current out of the microinverter to see how much power is being outputted. With these two measured quantities, we can check the efficiency of the microinverter to see if it matches the datasheets 95% efficiency.

Table 3 - 2: Solar Modelling Parameters

	Output Voltages (V)	**Output Current (A)**	**Output Power (W)**
First Power Supply	<50 V	<12A	370
Second Power Supply	<50V	<5.5 A	189
Microinverter	204-240 VAC	2.08-2.4 A	500W

Chapter 4. Design and Simulations

In this section, we attempted to design a feasible MISO flyback converter that can handle the different voltages coming from the tandem solar cell. After looking at different flyback controllers, we decided to use the LTC3803 for both layers.

Perovskite Layer

Using the LTC3803 spice model, we designed the flyback converter in **Figure 4 - 1** to handle the perovskite voltages. We chose a load current of 0.9 A to show a Pout = 342 W.

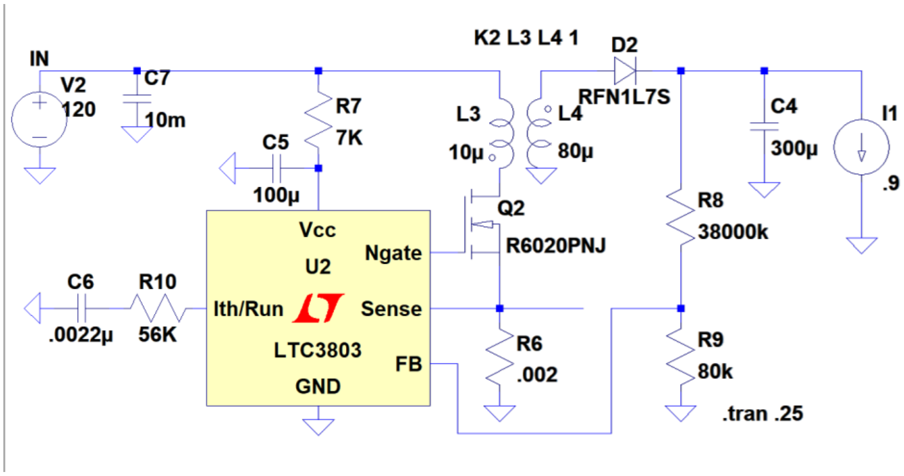

Figure 4 - 1: Perovskite Flyback Converter

We decided to want an output voltage of 380 V based different DC-AC converters. **Figure 4 – 2** shows a steady state output voltage of 380 V. To achieve the voltage, we needed to decide the feedback resistors. The datasheet recommends that R9 be less than 80K and R8 can be chosen to make the Feedback node have 0.8 V. Both C7 and C4 are used for load and line regulation.

$$R8 = \frac{Vout - 0.8}{0.8} * R9$$

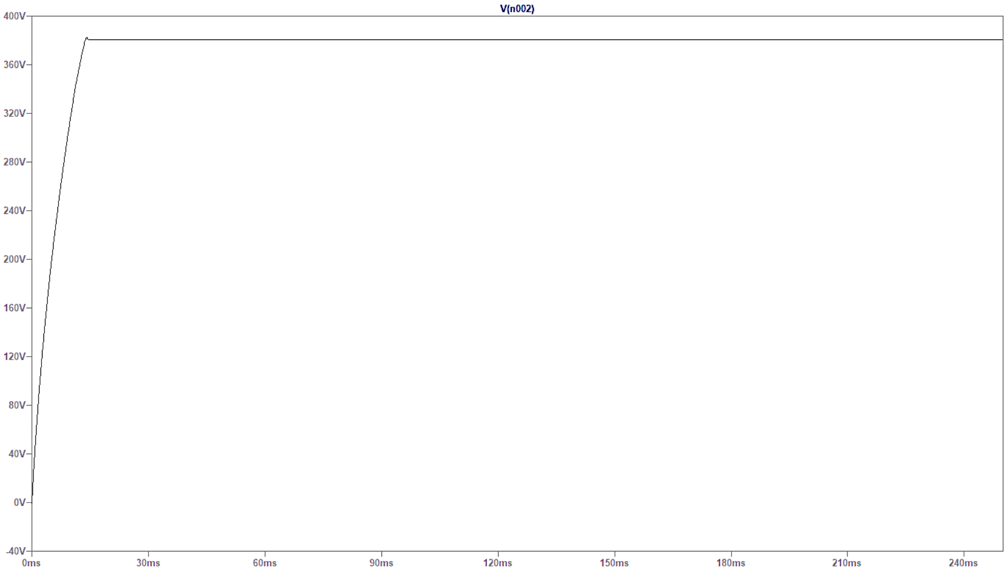

Figure 4 - 2: Perovskite Output Voltage

D2 and Q2 are chosen to meet the rated voltage and currents of the circuit. The turns ratio is selected to modify the duty cycle of the switch. Originally, we decided to use at 1:3 turns ratio, but upon inspecting the switch voltage, the duty cycle would switch between 6% and 80%. Additionally, the output voltage would peak at 370 V instead of 380 V. Note, the ratio between the inductance do not follow the turns ration linearly.

$$\frac{L1}{L2} = (\frac{N1}{N2})^2$$

Using a smaller turns ration, the switch achieves a steady 44% duty cycle instead of switching between the minimum and maximum duty cycles. **Figure 4 – 3** shows the duty cycle at the gate voltage of the switch.

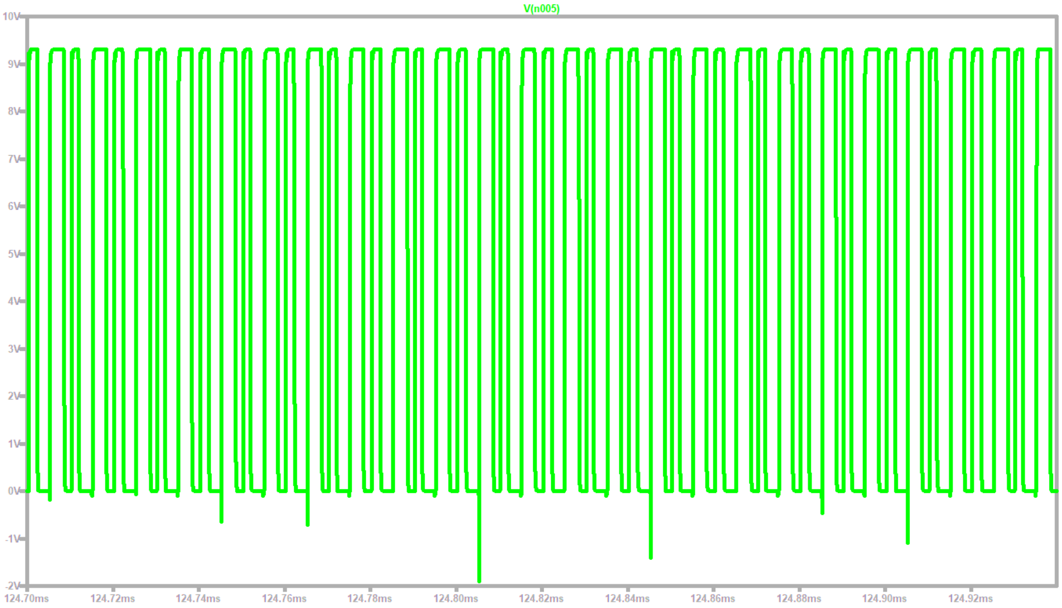

Figure 4 - 3: Vgate of the Switch

One issue that came up during the design was handling the current spikes. **Figure 4 – 4** shows current spikes reaching up to 180 A with peak currents of 210 A upon start up. We tried many different things to reduce the spike currents such as adding a snubber, but it did not reduce the current spikes. However, it did reduce the current ringing upon switching slightly as there was very minimal ringing in the first place.

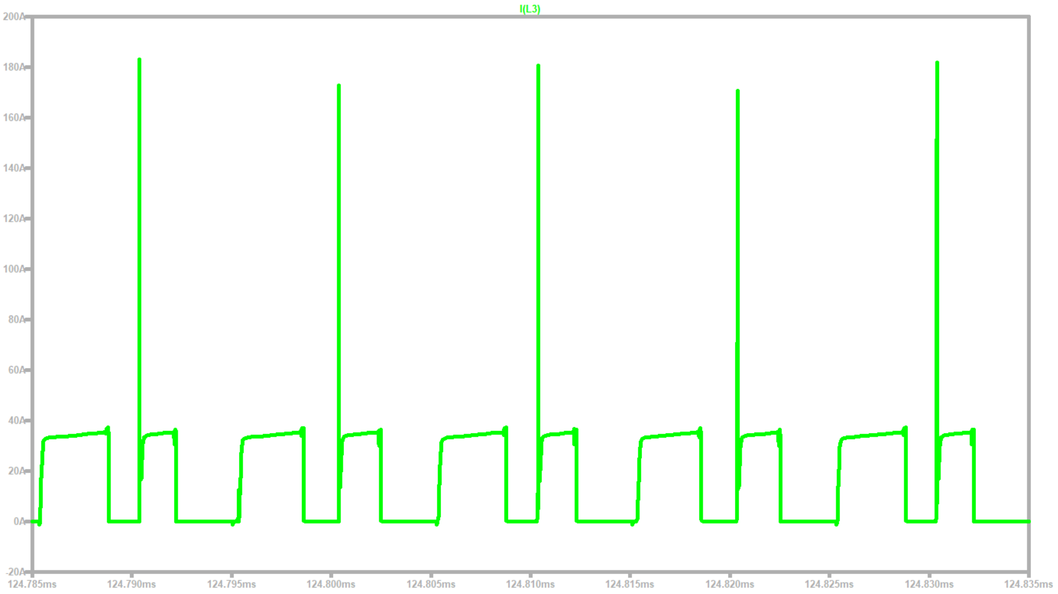

Figure 4 - 4: Current through the Primary Winding

Silicon Layer

The silicon flyback design shown in **Figure 4 – 5** follows almost the exact same design for the perovskite converter. The only difference is that the load current is only 0.4 A which results in a Pout = 152 W. The second difference is R2 which we made smaller. Keeping the same R2 value resulted in the capacitor discharging which lead the Vcc to fall below the turn on voltage for the controller causing it to have to turn on and off multiple times during usage. We chose to use similar switches and diodes to reduce costs by being able to buy multiples of the same part instead of only one of multiple different parts.

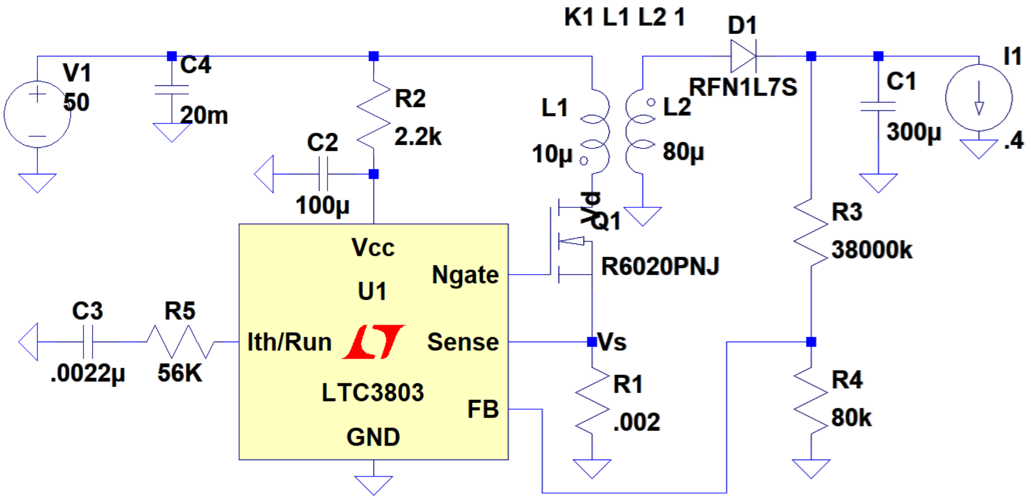

Figure 4 - 5: Silicon Flyback Converter

The output voltage should be 380 V again. Here, the inductance ratio made a significant different in the output voltage. We initially used a turns ratio of 1:6 which is a 1:36 inductance ratio. However, this resulted in a duty cycle which could not reach 380 V. It would always peak at 320 V which the feedback pin steady at 0.8 V. By decreasing, the inductance ratio, we increase the duty cycle of the switch that allows the output voltage to be reached. However, **Figure 4 – 6** shows a mostly steady output voltage with a small overshoot.

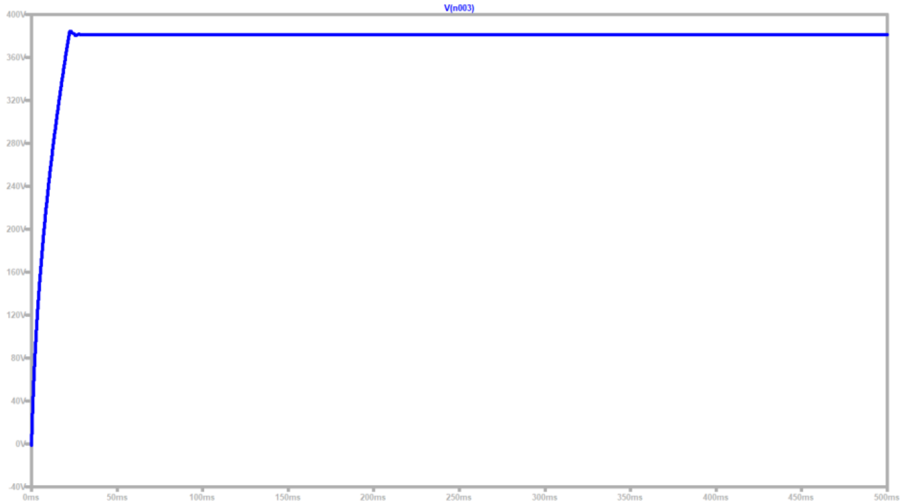

Figure 4 - 6: Silicon Layer Output Voltage

Figure 4 – 7 shows the gate voltage with a duty cycle of about 44% which remains constant throughout the switching. However, transient voltages began to appear with the smaller voltages.

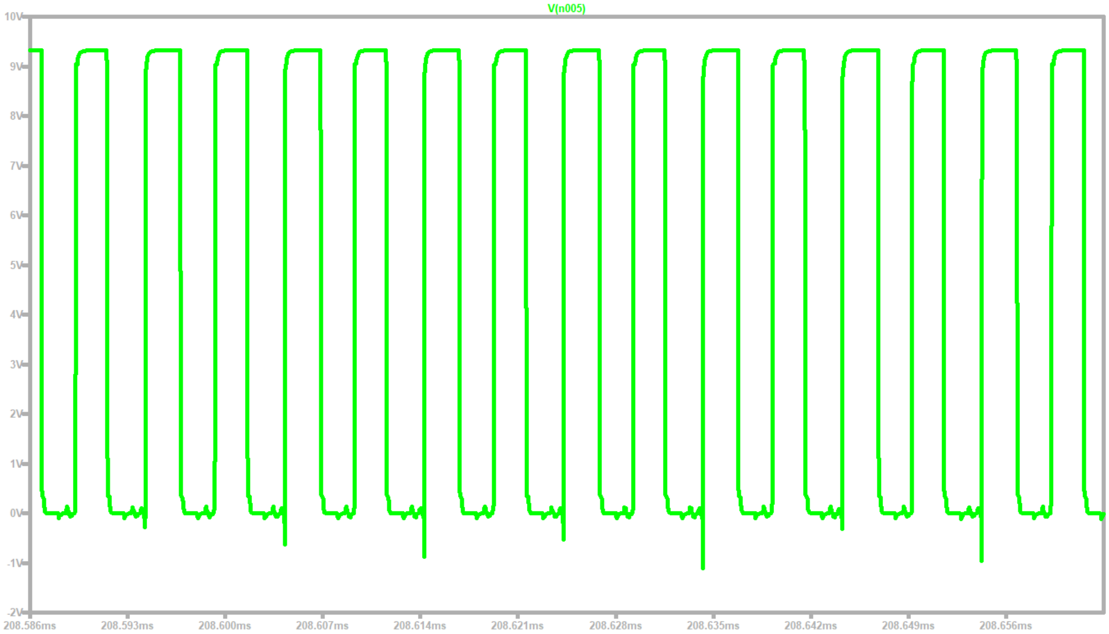

Figure 4 - 7: Vgate of Switch

The current through the inductor upon the controller startup remains an issue. The current spike maxes out at 180 A instead of 210 A. There is no current around 250 ms because the switch turns off. **Figure 4 – 8** shows the current through the primary winding. The inductor current in the primary winding follows the expected current which is triangle waveform with some transient as the switch turns on. **Figure 4 – 9** shows the inductor current a zoomed in inductor current. The average current through the primary winding is 4.5 A.

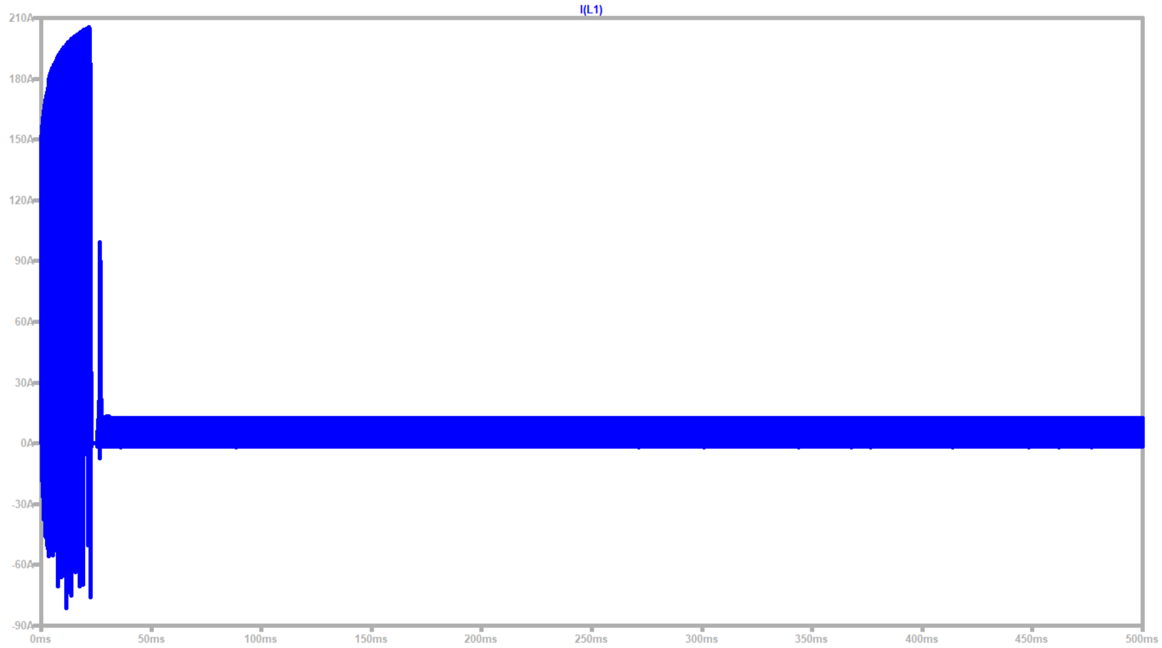

Figure 4 - 8: Current through Primary Inductor

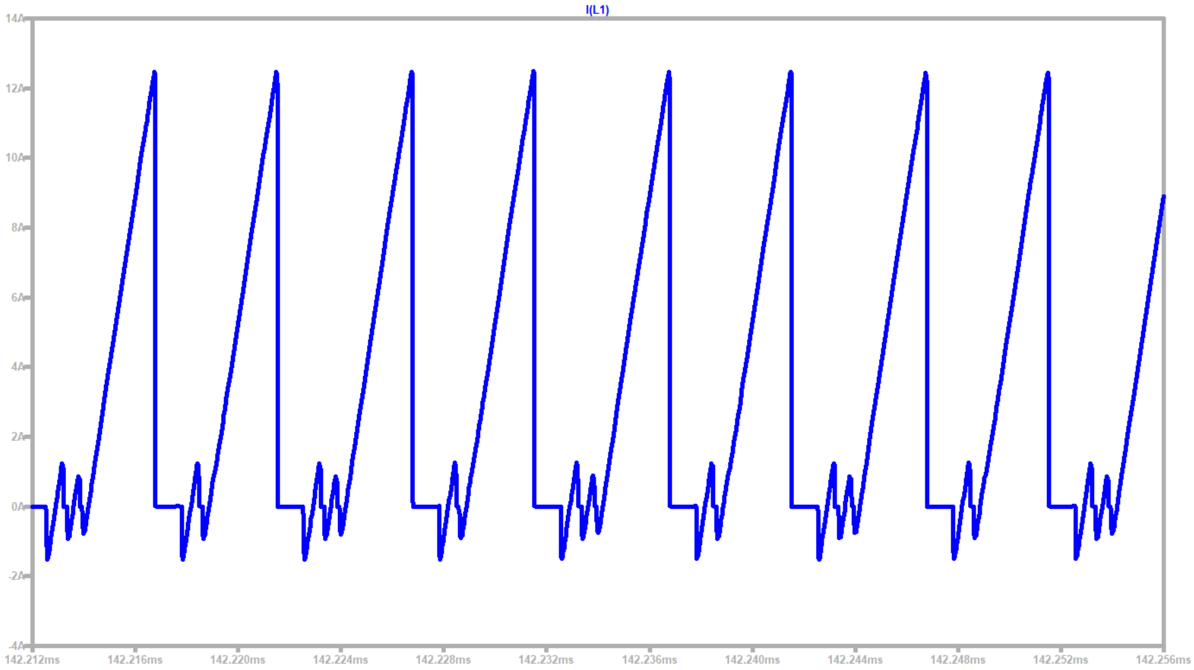

Figure 4 - 9: Zoomed in Current through Primary Inductor

To reduce the transient, we tried to add the RC snubber circuit shown in **Figure 4 - 10** across the switch.

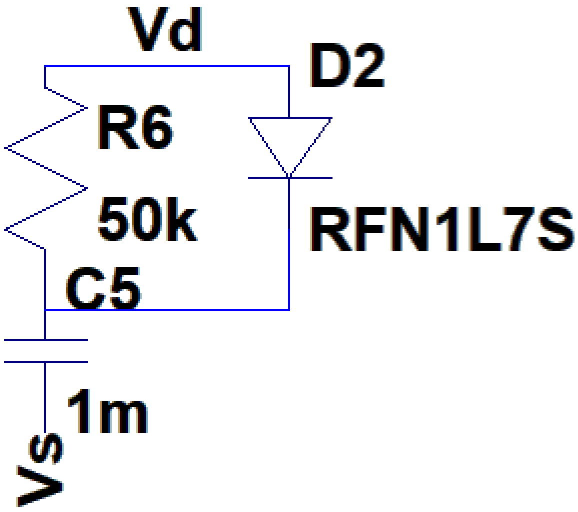

Figure 4 - 10: Snubber Circuit

However, adding the snubber circuit resulted in no change in the transients. Comparing **Figure 4 – 9** and **Figure 4 – 11** the transient voltage amplitude is approximately 2 V. Because there was no visible difference with the snubber, we decided to remove it to keep total parts at a minimum.

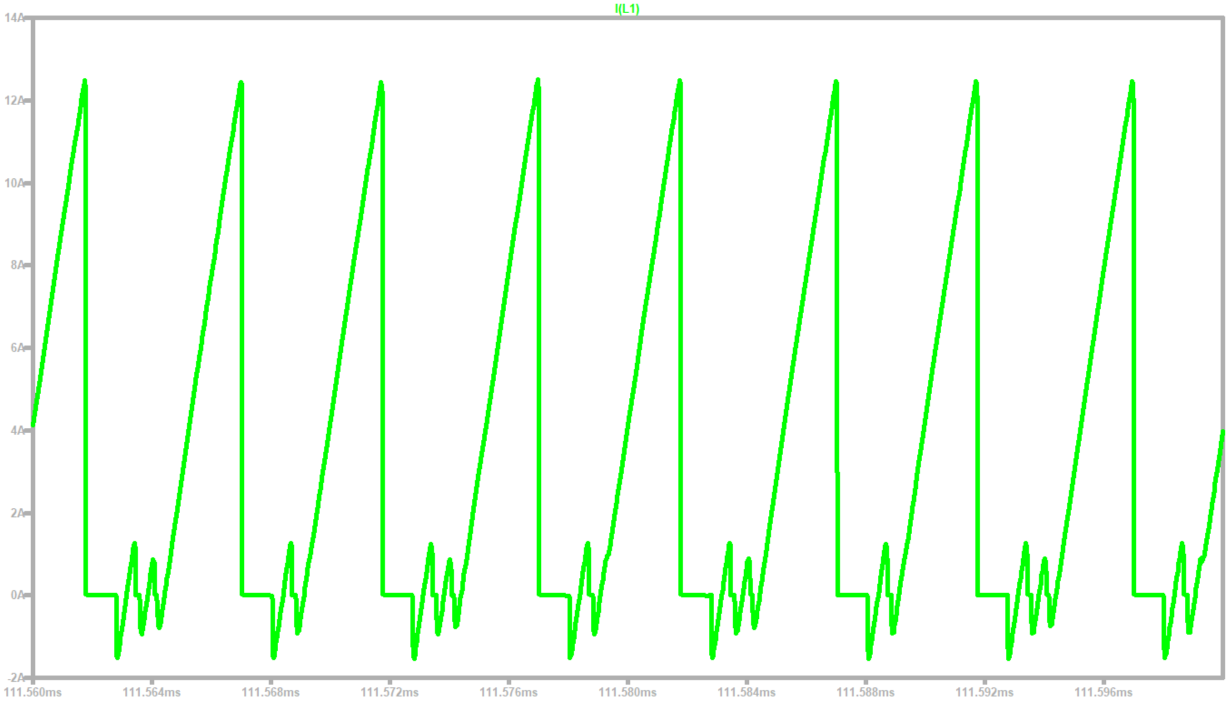

Figure 4 - 11: Current through Primary Inductor with Snubber

MISO Flyback Converter

After checking each converter individually, we connected both the layers by adding another diode and capacitor before the load. Here, the load current is 1.3 A which comes from the 0.9 A and 0.4 A from each converter respectively resulting in a Pout of 494 W. **Figure 4 – 12** shows how we connected the two converters together.

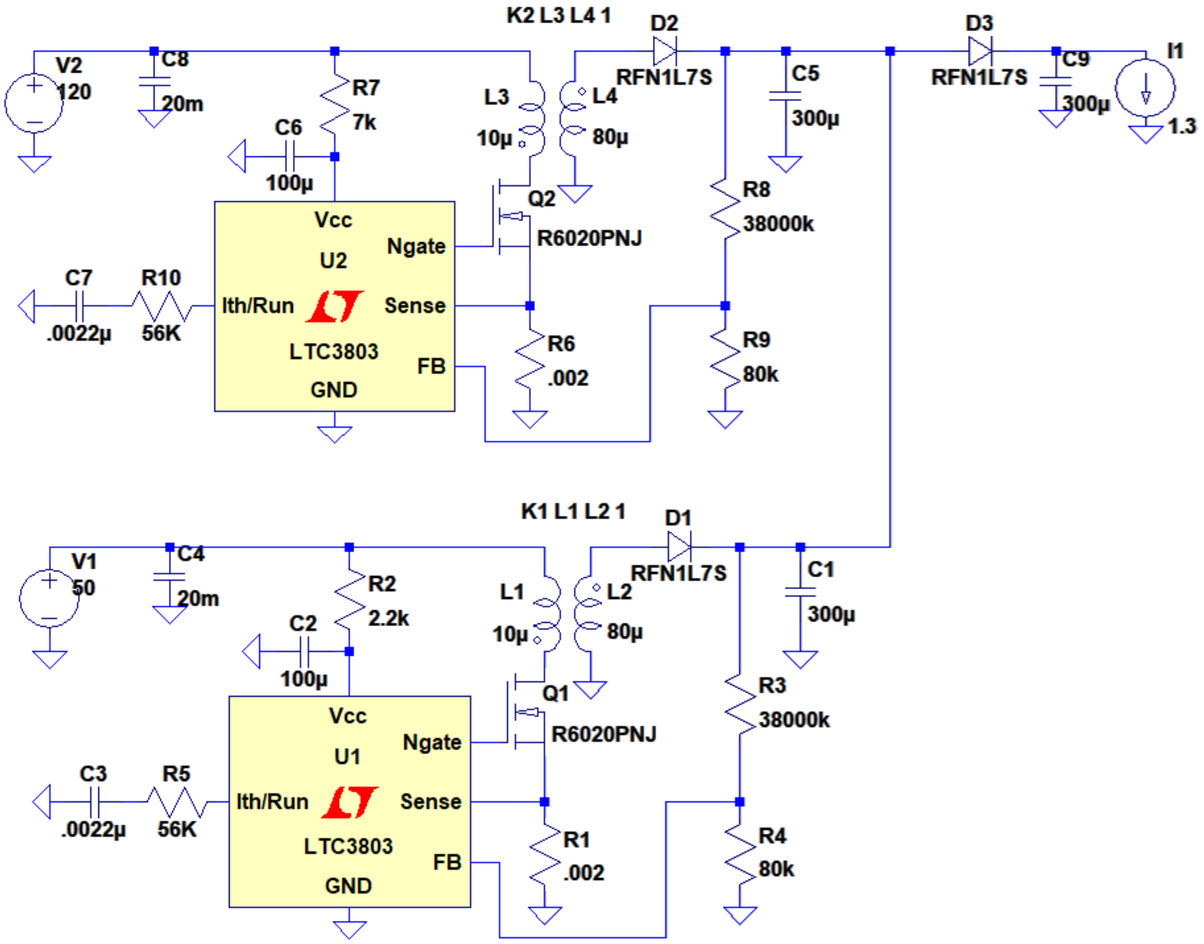

Figure 4 - 12: MISO Flyback Converter

The steady state voltage is 380 V which was expected since each converter attempts to output the same voltage. Additionally, there is very minimal voltage overshoot upon reaching the final output voltage. **Figure 4 – 13** shows the MISO converter's output.

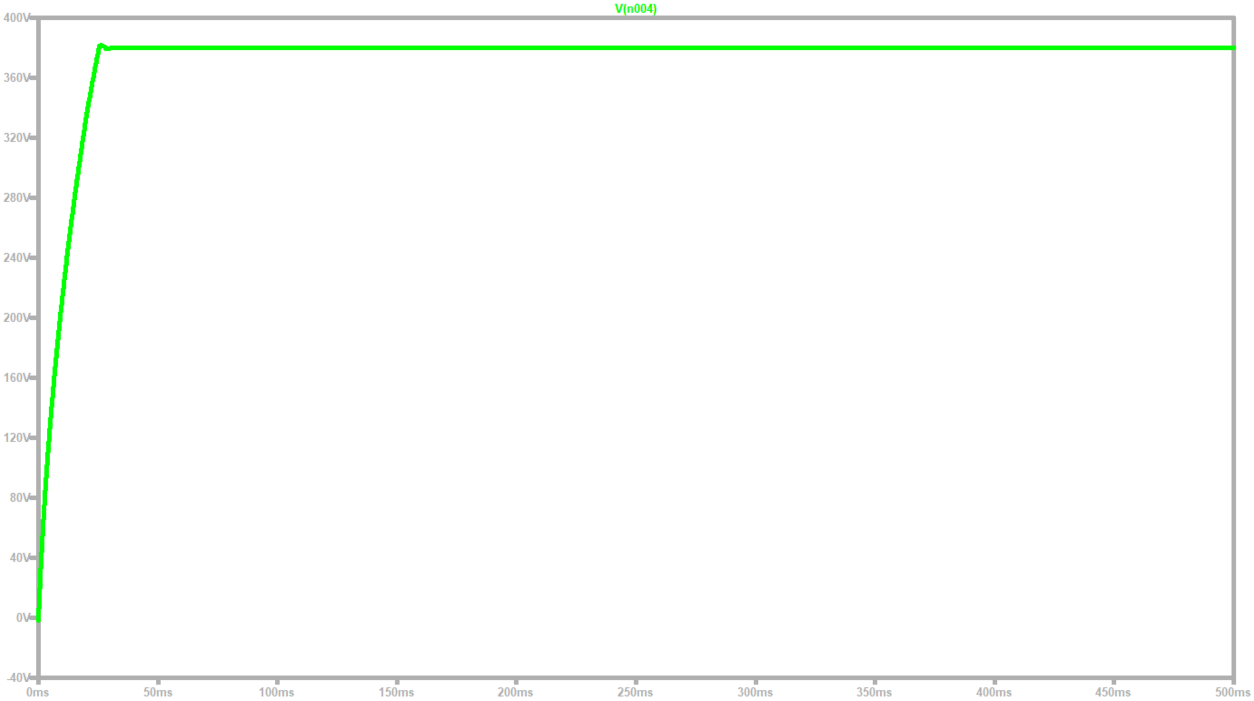

Figure 4 - 13: Output Voltage of MISO Flyback

The perovskite controller has a duty cycle of 50% shown in **Figure 4 – 14** while the silicon controller has approximately 80% duty cycle.

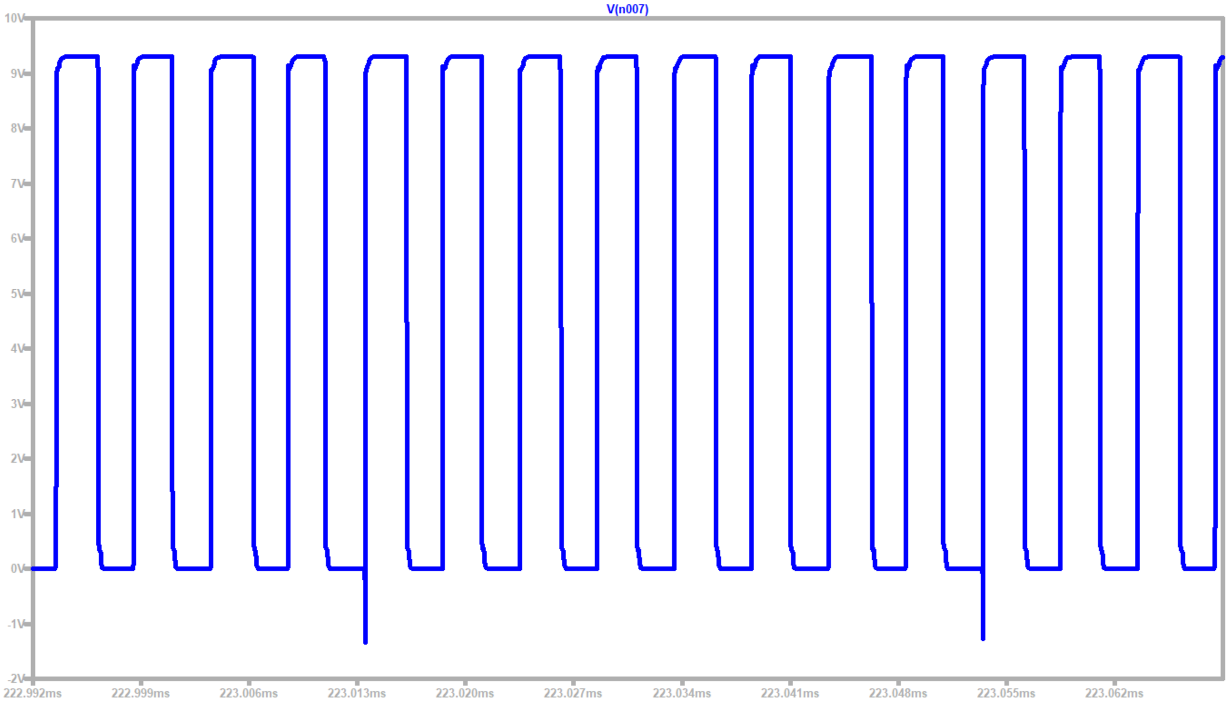

Figure 4 - 14: Perovskite Gate Voltage

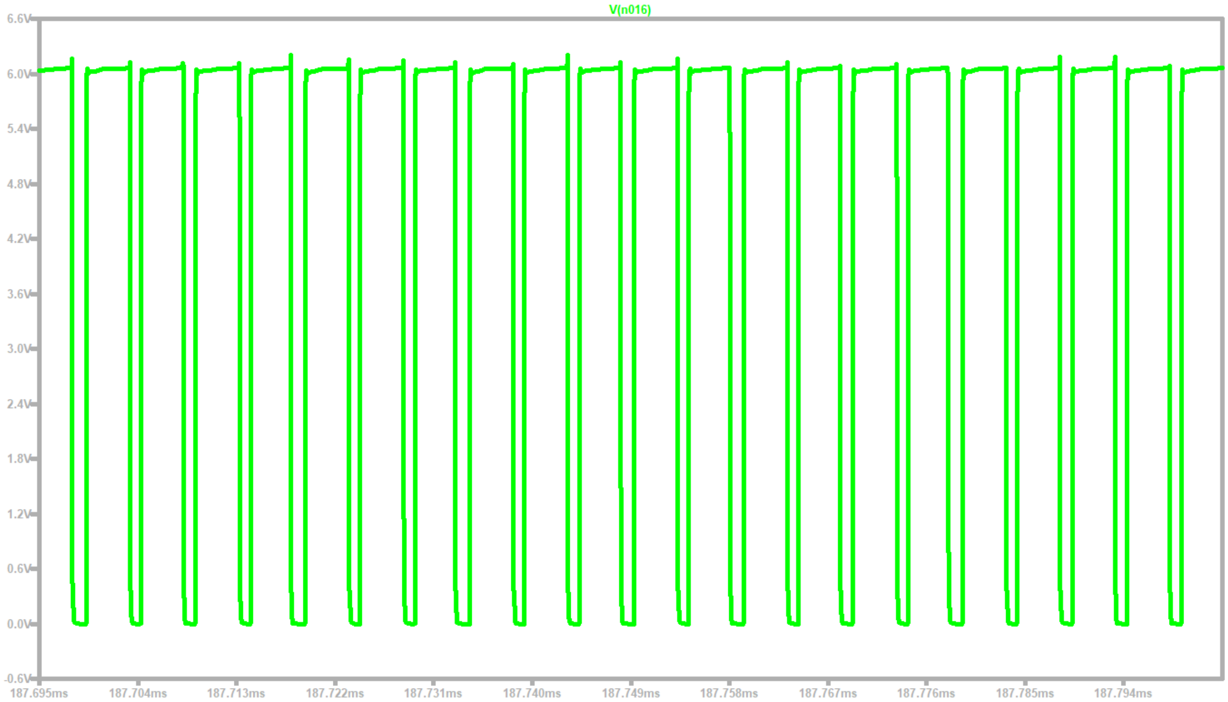

Figure 4 - 15: Silicon Gate Voltage

The perovskite primary winding has peak current spikes around 215 A during startup while during normal operation, the current spikes around 110 A. The silicon primary winding has slightly smaller peak current spikes around 209 A with spikes around 180 A during normal operations shown in **Figures 4 – 16** to **4 – 19**.

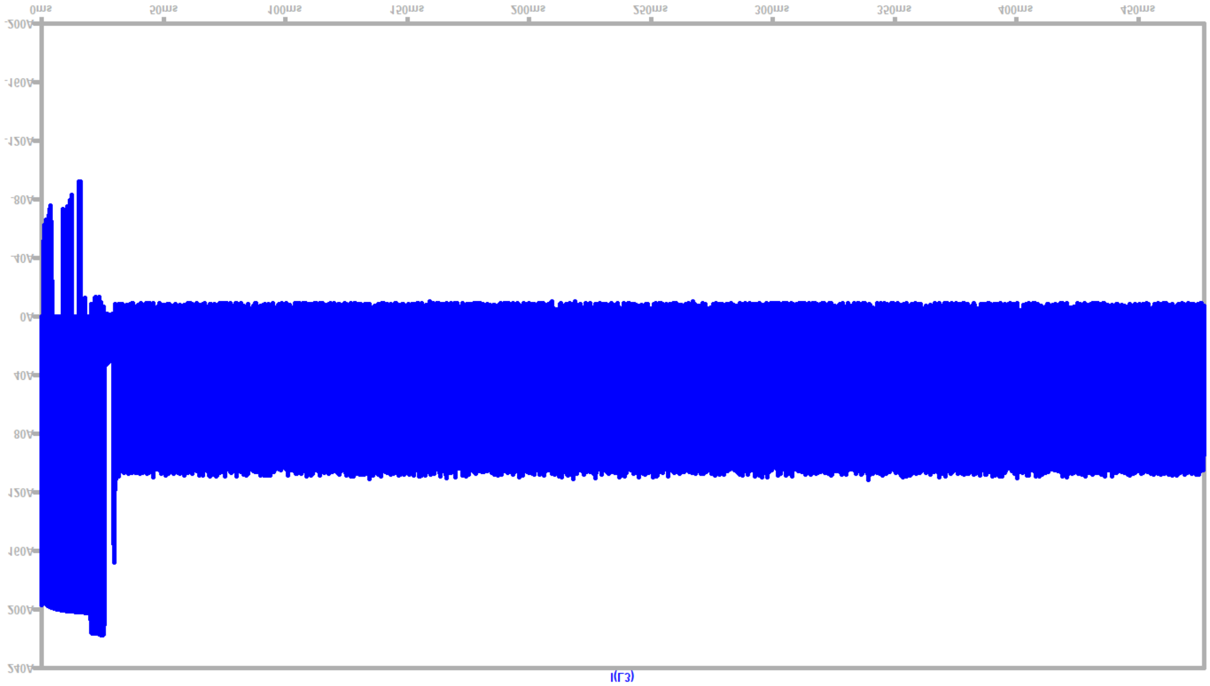

Figure 4 - 16: Perovskite Primary Winding Current

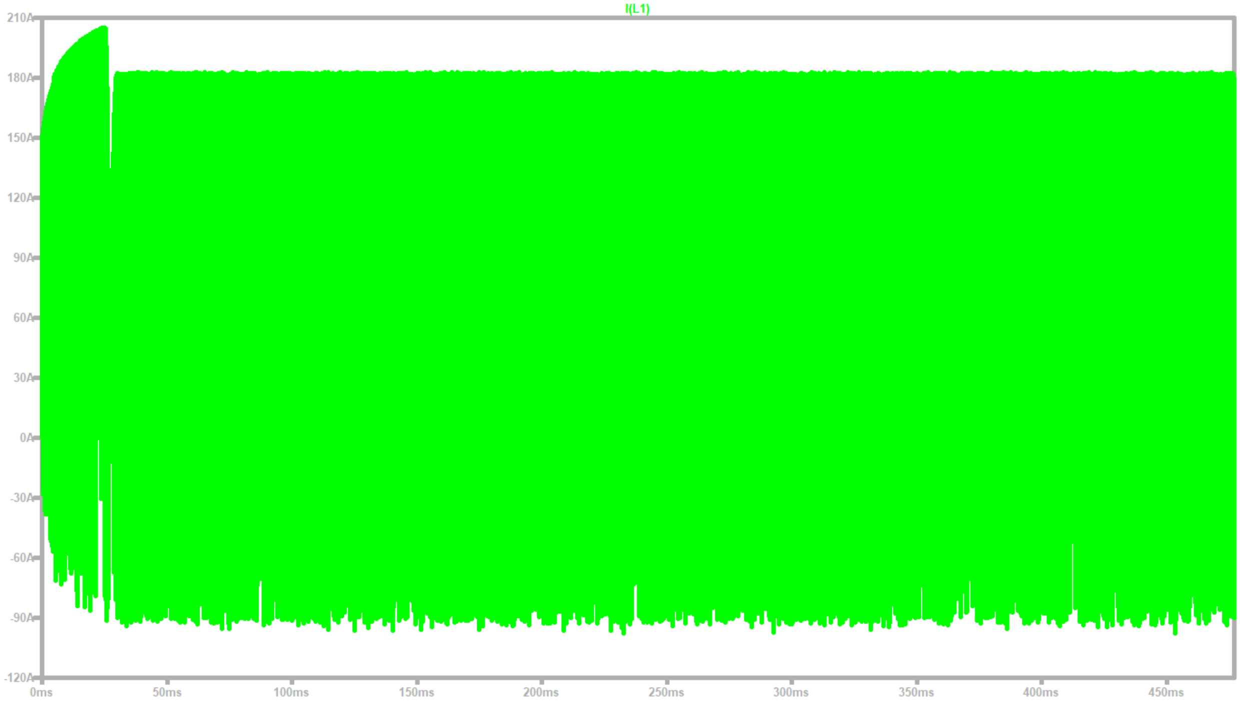

Figure 4 - 17: Silicon Primary Winding Current

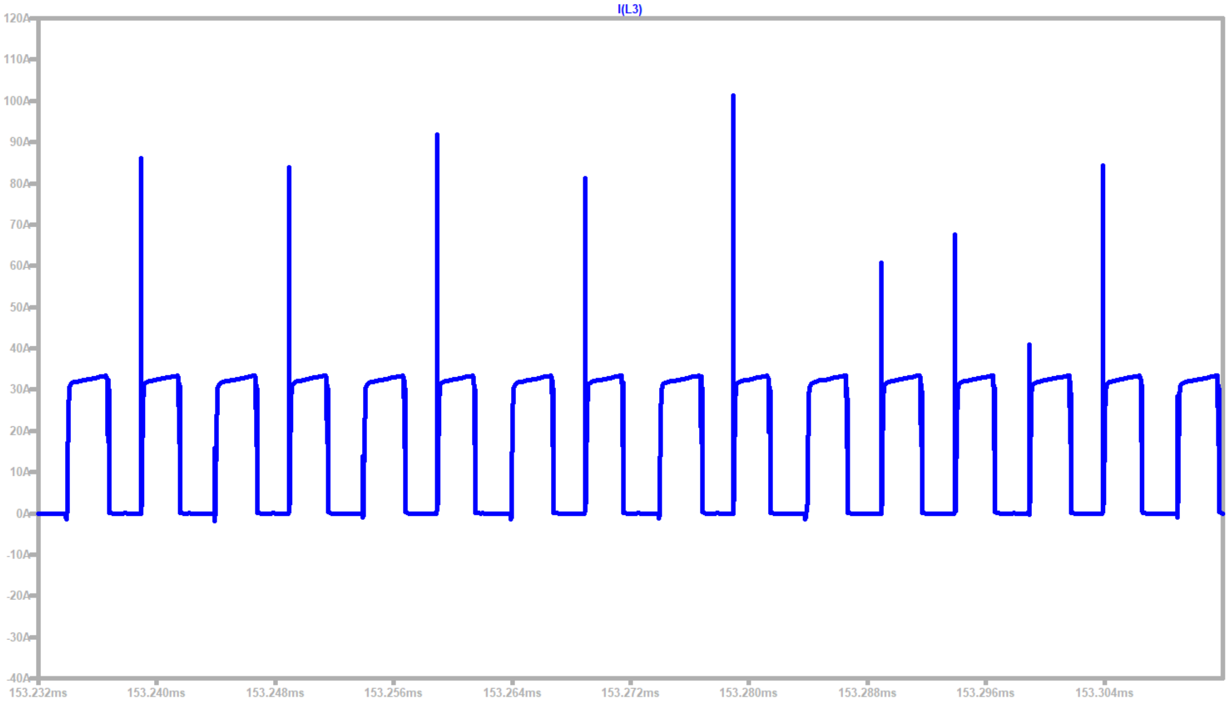

Figure 4 - 18: Perovskite Zoomed in Current

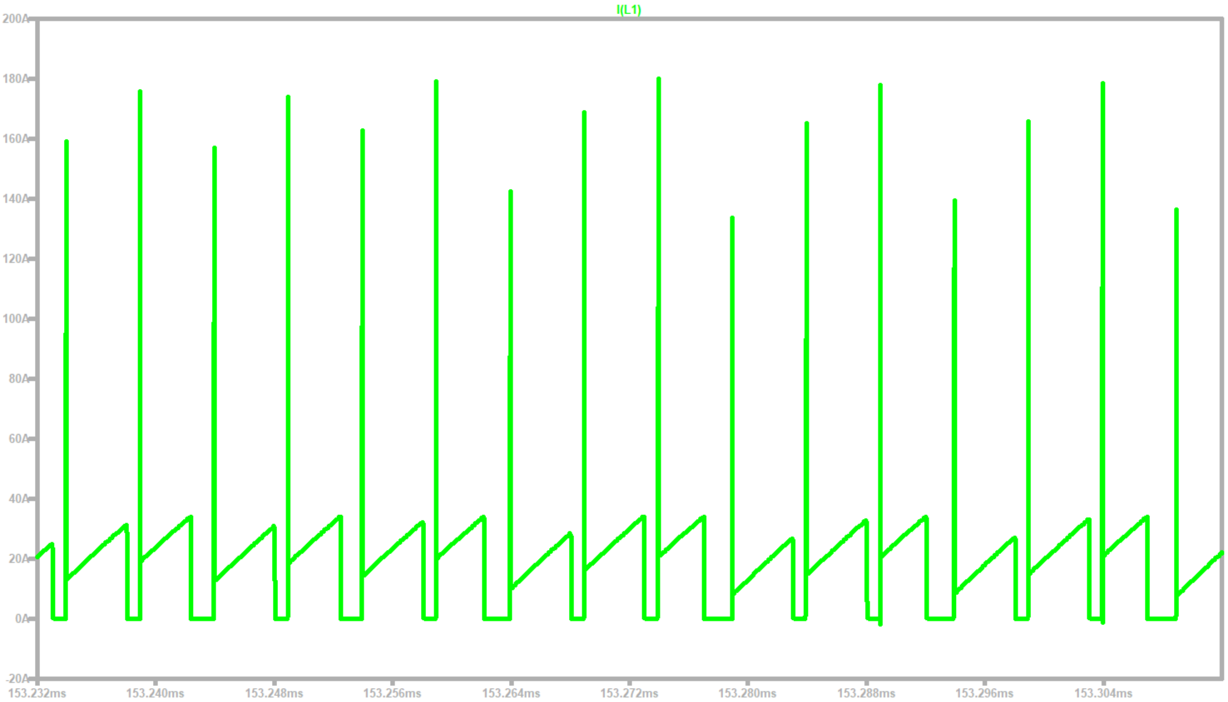

Figure 4 - 19: Silicon Zoomed in Current

Overall, the design worked as expected. The main cause for concern would be the currents flowing through the circuit. With current spikes over 200 A during start up and spikes around 180 A, the design is not entirely feasible. To make the design usable, the current must be reduced in some way throughout the circuit.

Chapter 5. Hardware Test and Results

We constructed our test bed setup using a YC500A dual input microinverter from APSystems, along with a 40V solar panel, and a 35V solar panel, shown in Figure 5-1. The YC500A microinverter is equipped to handle two solar panels with a maximum input voltage of 55V and a maximum input current of 12A, so the two panels we selected fit within the limits of the microinverter. We tried three methods of connecting the microinverter output to the grid; connecting one line to a single 120V wall outlet, connecting both lines to two 120V wall outlets, and connecting both lines to a single 240V wall outlet.

Figure 5 - 1: Solar panels connected to microinverter with MC4 plugs

We used the MC4 connectors from the solar panels to plug into the microinverter, and bought an extension cord to convert the microinverters output cable into bare wires. The microinverter produces an output of 240VAC between two lines, the red and black wires, and each of those lines has 120VAC with respect to the neutral white wire. For our first test, we tried using the hot black wire from the microinverter and the neutral white wire to connect to a single 120V wall outlet, as shown in Figure 5-2.

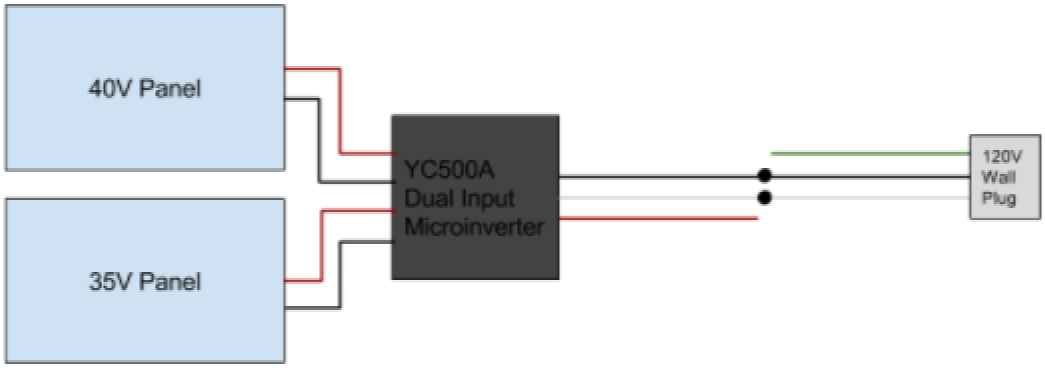

Figure 5 - 2: Test 1 Wiring Diagram

When we connected the system for test 1, the LED on the microinverter blinked red, indicating no power flow. We thought maybe it was a balance issue, so for our second test we tried connecting another wall plug to the other side of the split 240, equaling to 120VAC on each wall plug shown in Figure 5-3 and Figure 5-4.

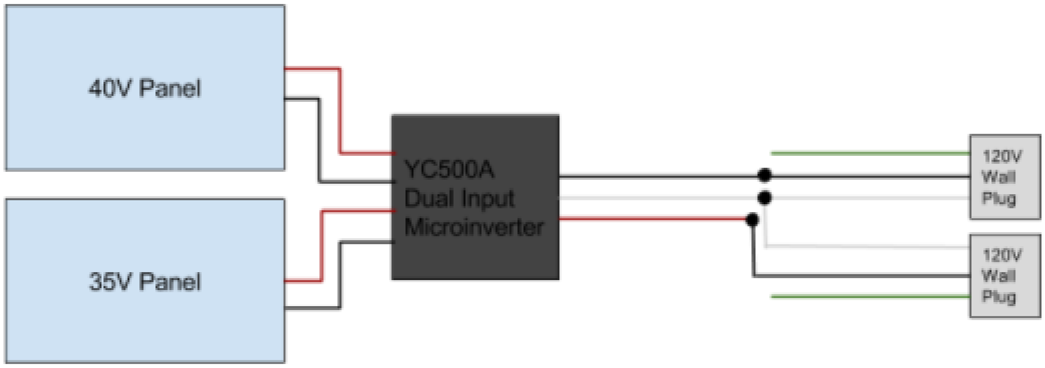

Figure 5 - 3: Test 2 Wiring Diagram

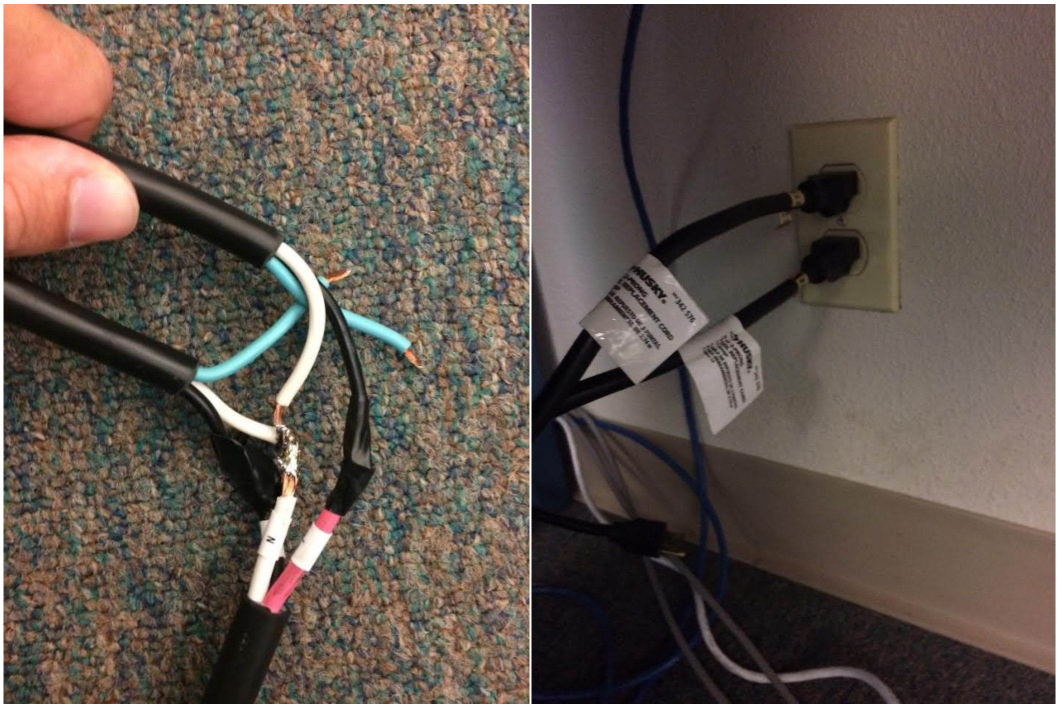

Figure 5 - 4: Microinverter to wall bare wires and plug connection

We measured the voltage on the wire connections with a multimeter and confirmed that the wall outlet was connected and providing 120V AC on each line, however we also observed the blinking red LED on the microinverter, indicating no power flow. We considered that there could be a problem with the two 120V AC signals from the microinverter being out of phase, and that we might need to connect directly to a 240V outlet. Our results from the first two tests are summarized in Table 5-1.

Table 5 - 1: Microinverter connected to 120VAC wall outlet

First panel Voltage	Second panel Voltage	Voltage measured between black and white wires	LED indicator
40VDC	35.8VDC	120VAC	RED: no power flow

For our final test, we decided to use the 240V outlet in room 104, connecting the solar panels to the microinverter as shown in Figure 5-6, and connecting the microinverter to the 240V outlet as shown in Figure 5-7 and Figure 5-8.

Figure 5 - 5: Microinverter and solar panel setup for 240V outlet

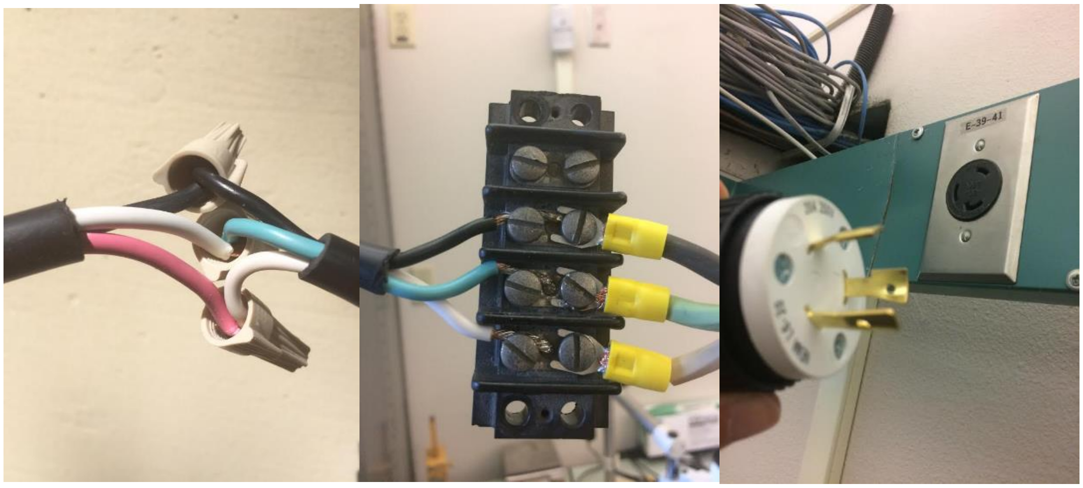

Figure 5 - 6: Microinverter Connections to 240V Wall Outlet

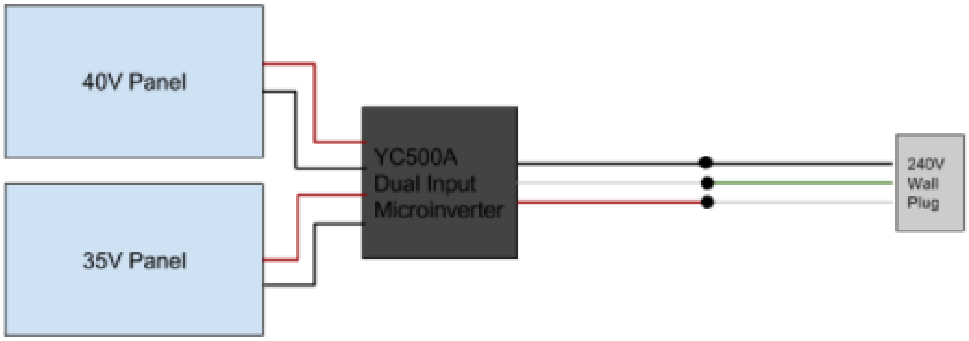

Figure 5 - 7: Test 3 Wiring Diagram

For each test, we began by connecting the solar panels to the microinverter using the MC4 connectors, then connecting the microinverter into the wall outlet using a plug. We then monitored the LED on the microinverter to determine if power was being produced and measured the voltage on the wires and the solar panels using a multimeter. For the final test, the LED indicator on the microinverter still blinked red, which meant no power was flowing. We weren't able to retrieve any useful data for efficiency or power production besides seeing the expected voltages of 40V and 35V from the solar panels, 240VAC between the black and white wires, as well as 120VAC between the black and green and white and green wires from the wall outlet. These findings are summarized in Table 5-2.

Table 5 - 2: Microinverter connected to 240VAC wall outlet

First panel Voltage	Second panel Voltage	Voltage measured between white and black wires	Voltage measured between black/white and green wires	LED indicator
40VDC	35VDC	240VAC	120VAC	RED: no power flow

This power flow problem with the microinverter may be due to the type of connection it requires to produce power. The wires of the microinverter are red, black, and white, indicating 120V split, with 240V between red and black, 120V between red and white, 120V between black and white, and white as neutral. Although the wall outlet was 240VAC, it had a black, white, and green wire, which doesn't match up exactly to the wires coming out of the microinverter. We connected the red to white, black to black, and white to green, so it might not be the 120V split connection we needed. If we were to repeat this experiment another time it would be useful to have a standard meter and an AC junction box to connect to, like the ones in a normal household. That way, the microinverter would connect to the grid as it was meant to, and we could easily measure power production. It would also be useful to purchase an ECU, or an energy communications unit which connects to the microinverter and gives more detailed information about the performance of the microinverter. This would allow us to better diagnose problems when the LED indicates "no power flow", however purchasing the ECU would have exceeded our budget for the project.

Chapter 6. Conclusions

From this project, we learned a lot about solar panels, maximum power point tracking, microinverters, and power electronics. We started out with an ambitious goal to design and build a dual input microinverter specialized for a tandem perovskite photovoltaic, but after some reverse engineering and research, we realized that we wouldn't be able to complete such a sophisticated project within our time and budget constraints. We decided to instead learn about and test an existing dual input microinverter, while designing and simulating a dual input microinverter specialized for the tandem photovoltaic panel. In the end, we were not able to build a working prototype, but we learned throughout the process.

From the beginning, we started by researching solar panels and the tandem perovskite cell being developed by Iris Photovoltaics, a startup company from Stanford. We learned how the solar cell operates, how the different materials absorb different wavelengths of light, and how it gets converted into electrical current at different voltage values. The perovskite layer of their tandem solar cell absorbs high frequency photons, and converts them into photocurrent at a higher voltage, letting lower frequency photons pass through and be absorbed by the silicon layer below and converted into photocurrent at a slightly lower voltage. This results in each layer of the photovoltaic having its own power curve, within which it could provide a given voltage at a specific current defined by the curve. There is always a point on the curve which provides the maximum power, and when operating at that point you can provide the maximum efficiency.

We learned about maximum power point trackers, or MPPTs which are designed to connect to the solar panel and transfer power at its maximum power point, following the point when it changes due to sunlight or shading. We explored several maximum power point tracking techniques, and found the simplest and most practical method to be the "perturb and observe" method, where the MPPT constantly adjusts its position on the power curve, measures the power, then adjusts again depending on whether the new power value was higher or lower than the last measurement. We considered implementing this into our microinverter design, however after reverse engineering an Enphase microinverter, we realized it would be too complex to design an entire system. We decided to focus onto the DC-DC combination part of a dual input microinverter because it is what makes it unique. After examining our available options, we settled on designing a DC-DC combiner using a flyback converter as the main method of power transfer. We researched some methods, such as interleaving, which would allow us to use multiple smaller flyback transformers to share a large amount of power. Eventually we discovered that we would need to wrap our own transformers, which we didn't have the experience or time for, or buy specially made transformers which were out of our budget. We decided to instead design a simulation for the DC-DC combiner, and test an already built dual input microinverter.

For our simulation, we decided to create a DC-DC combiner using flyback transformers which would take the estimated outputs from two individual MPPTs, one for each layer of the tandem module, and convert them into 380V output at the DC bus into the inverter. For this design, we used LTSpice to build and simulate it. After considering a few options, we decided on the LTC3803 as our flyback controller, and utilized two of them in our DC-DC combiner, with diodes to pair them to a common coupling point. By looking at the datasheet provided by Linear Technology, we were able to come up with a circuit design. Then, through research and multiple simulations and revisions we reached a final design which combines the two inputs into a single voltage output at 380V.

For the hardware and testing portion of our project, we decided to purchase a dual input microinverter. We settled on the YC500A dual input microinverter because it could handle two inputs each with a maximum of 55V and 12A. We planned to use a PV simulator to simulate the photocurrent from the tandem solar panel, however the equipment was broken so we had to find another way to test it. We considered using a normal DC power supply with power resistors to make a crude PV simulation, however we weren't able to find any DC power supplies with enough power to simulate the tandem solar panel. We finally decided to use solar panels to test our microinverter, and obtained a 40V and a 35V solar panel. We first tried this setup with the microinverter connected to a single 120 wall outlet, but although the voltage on the wires was reading correctly, the microinverter indicated that power wasn’t flowing. We tried connecting the other line of the microinverter into a second wall outlet, but that yielded the same result. For our final test, we found a 240V wall outlet and connected the microinverters 240V output directly to it but again it had the correct voltages but no power flow. Our results were inconclusive, but if we had more time and a larger budget for this project it would be beneficial to connect the microinverter into an AC combiner box with a meter how it is described in the user’s manual. With a larger budget, I would also consider purchasing an Energy Communications Unit made by APSystems which can monitor and track the status of the microinverter, reporting efficiency data as well as diagnosing power flow issues, which we ran into during our experimentation.

Overall, we were not able to design a full working dual input microinverter, however we did create a design for the DC-DC combiner specialized for the tandem perovskite panel. In the end our dual input microinverter test setup did not operate as intended, but we learned a wide variety of material through problem solving and troubleshooting. This was an ambitious senior project, and we came to realize that when we ran into many barriers that forced us to change the scope of our senior project. Throughout the process, we learned all about solar panels, tandem photovoltaics, maximum power point tracking, microinverters, and various power electronics topics. Dual input microinverters are an interesting technology, and by going through the design process we gained knowledge about everything that goes into making one, and the various pieces and parts that allow it to function.

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Appendix A: ABET Senior Project Analysis

Project Name: Dual Input Microinverter for Tandem Cells
Student's Names: Daniel Dich-Dang Signature: ______________________________
Forrest Lipske Signature: ______________________________
Advisor Name: Taufik Initials: ___________________ Date: ________

Functional Requirements

Our project serves two functions: a proof on concept and creating testbed. Half of our project was designated to designing a MISO flyback converter that can handle voltages higher than standard silicon photovoltaic cells. The second half of our project was used to testing existing dual input microinverter and testing its functionality and ability to handle differing voltages.

See Chapter 3 for more information.

Primary Constraints

Designing the system for future market poses significant concerns. Currently, some microinverters are being integrated with the solar cell themselves without any extra connections or external components, making replacements difficult if the inverter fails. Since our system is relatively new without other precedents, it is unclear whether to design for an external connection or an internal connection.

Another concern for the system involves the different DC inputs. The two layers of the solar cell outputs different voltage levels causing extra circuitry for an DC to AC inverter. Current solar cells have Maximum Power Point Tracking (MPPT) which records the voltage readings over time and optimizes the connection between the solar array and the grid or battery. However, for the system, MPPT cannot be designed the same as inverters for standard arrays because of the different voltage levels. Not only are the voltage inputs different, the two different layers follow different I-V curves making optimization different. With a different I-V curve, a simple DC-to-DC conversion may not suffice for power optimization.

One final concern involves the actual solar cells in question. The start-up company requested the micro inverter without having the tandem solar cell finished. They are currently still developing and testing different solar cells for maximum efficiency which makes specifying our system more difficult.

Some issues that arose during our project included various changes to our project scope. Originally, we planned on designing and constructing an entire dual input microinverter, however as time passed and we talked to different professors, we realized our scope of the project was to large. We then scaled it down to only designing and building the DC-DC converter. Again, however the scope was still larger than expected so we finally decided on just designing the DC-DC converter and physical testing an existing dual input microinverter.

See Chapter 3 for the system requirements.

Economic Impact

Our project requires significant human capital. A significant portion involves testing and developing both the microinverter and the tandem solar cell. Additionally, installing and implementing the system in solar farms requires more human capital. Finally, maintaining and repairing the system requires even more human labor.

After completion, the microinverter creates significant financial capital. If the project meets specifications, solar farms can produce more energy efficiently which allows home owners to spend less on energy and save more if they also own solar cells as well. Additionally, Iris PV will be able to sell both their tandem solar cells along with our dual input microinverters for more profit as they will have a small monopoly since they will be the first to enter the market.

Our project creates real capital when it enters mass production for tandem solar cells as the microinverter will be almost required for the tandem solar cells to operate optimally.

To perform optimally, companies need to have access to significant amounts of natural capital, especially land and water. For solar farms, available land is a limiting factor while water will be used for cleaning purposes.

Most of the costs of the system accrue during design and testing because of labor and the different testing phases. However, the benefits start building after the first design test. With one design completed, tandem solar cells can be implemented using our project. After production beings, Iris PV will be the company profiting from our design.

To emerge in the market, several benchmarks need to be met first. The first would be that Iris PV has developed an efficient, working tandem solar cell. The second would be packing our design along with other components into a tandem solar cell. Finally, production must be worked out to meet demand of the market. We expect it would take at least five to ten years before our product enters the market.

If Manufactured on a Commercial Basis

Entering mass production, the inverter sells as much as tandem solar cells sell. Following today’s trends, the estimated number of devices sold per year equals 20,000 units [13]. Since the APSystems dual input microinverter costs about $200, we estimate our product to sell for $250 at a minimum. We expect our design will cost about $150 which includes parts and labor. This totals to a profit of $200,000 profit yearly from just the product. In addition to sales profit, installation and maintenance adds additional costs. Installation costs $20 per device with a yearly fee of $50 for maintenance.

Environmental

The project greatly impacts the environment after completion. The main impact involves making solar energy more abundant and affordable. With our project, tandem solar cells become more profitable and efficient for production. Solar and land are the main resource that the project utilizes. The environmental effects mirror the environmental effects of the current solar arrays since tandem solar cells may replace the solar arrays. Theoretically, the tandem solar cells will provide more power than currently existing solar panels which will allow society to decrease power usage from non-renewable sources. Using less of these non-renewable sources will decrease the CO_2 emissions from the power generation facilities.

The main environmental issues include land usage, water usage, hazardous materials and emissions [14]. Solar farms take acres of land depending on the size of them. Small arrays, such as those installed on homes and businesses, take much less land than industry solar farms which use land ranging from 4 to 16.5 acres per megawatt. Water usage comes from manufacturing of both the solar cell and the microinverters as well as cleaning panels.

Manufacturability

If our design incorporates an internal connection with the solar cells, manufacturability becomes an issue. To produce the microinverter, we must work in conjunction with the solar companies developing the panels to produce the entire system. We would work alongside the tandem solar cell designers to produce a single, interconnected product instead of two externally connected products. Automation of this process would prove beneficial depending on how accurate connections can be made.

Sustainability

The main issue for maintaining the completed system depends on whether the microinverter connects to the solar panel internally or externally. If connected internally, system failure requires complete tear down while external connection only requires replacing the failed components. This project increases the sustainable use of solar energy by increasing solar output capabilities. Improving the project depends on improving the solar panel efficiencies as well as improving the power conversion efficiency. However, improving efficiency becomes increasingly difficult the higher it becomes.

Ethical

Viewing the project as a Utilitarian, the project has the potential to provide benefits for everyone, even those without solar. By utilizing more solar energy, everybody can have access to power. With more solar energy, prices may lower from abundance of energy. By providing power to everyone, society can improve. Additionally, more power means people can focus on improving other aspects of their lives which can continually improve society.

From John Rawl’s Contractarianism, the microinverter attempts to provide everyone the equal access to power. By increasing solar output, power becomes more available to those who cannot afford it. Additionally, all those who understand the device and system can work with the system and continually improve and work with the project. However, those who can afford their own solar panels benefit the most from the project. Those who cannot still receive some benefits from the project, mainly from cheaper energy costs and a possibly a better environment.

Using the IEEE Code of Ethics [14], this project accepts the responsibility that it comes with. The project publicly explains the reasoning behind each decision that may endanger the public. The project attempts improve the solar industry by improving the current solar cell design.

Health and Safety

One safety concern of the project involves the inverter’s voltage output. If someone touches bare metal or ungrounded wires, they can be electrocuted. However, this can be mitigated by properly designing the system and extensively testing the system. Extensive testing allows the designers find possible faults that may occur and provide a design change to prevent such faults from occurring. The more testing performed, the less likely for the design to fail.

Social and Political

Customers who use solar panels and utility companies embody the main stakeholders of this project while everyone else embodies the indirect stakeholders. With the microinverter, customers may desire to upgrade their existing solar cells while utility companies may need to upgrade their solar farms.

The major political issue involves deciding who gets the extra power generated by the new solar cells and micro inverters. The project impacts almost everyone that uses power. Indirectly, the project affects everyone. However, the rich may benefit more because they can afford their own panels which in turn can make more money for them while the poor must rely on buying power from the utilities companies. Despite this inequity, everyone still benefits from the project. Our project harms the companies dealing with standard solar cells however. As tandem solar cells become more efficient and viable, companies selling standard micro inverters must develop new inverters for the new solar cells.

Another political issue involves creating more solar farms or replacing preexisting farms. In either case, large amounts of human and financial capital are required to be completed. If more solar farms are created, more land will be used. Additionally, the increased power output creates another issue involving whether to stop some non-renewable power generation or to keep the same facilities.

Development

Reverse engineering helped the project. We reversed engineered the SolarEdge Power Optimizer and the Enphase M250 Microinverter to see how they work and which components used which in turn helped design our own inverter. However, we tried analyzing the components of each device, but realized the complexity of analyzing the designs. The main benefit we received from the reverse analysis was from seeing some of the parts they used. In our design, we compared our component values to some of their component values to check the viability of different components.

Literature Search

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This reference gives some references for designing the micro inverter. Knowing the output of Tandem Solar Cells, the design of the micro inverter can be tailored more specifically for the cells instead of a general range of inputs. The source is credible because it was published in IEEE conferences and peer reviewed.

[2] Y. Levron and R. W. Erickson, "High Weighted Efficiency in Single-Phase Solar Inverters by a Variable-Frequency Peak Current Controller," in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 248-257, Jan. 2016.

This gives references of a micro inverter topology. Micro inverters have a multitude of topologies and reading about different topologies will give me insight on which one would work best in this design. This was published in a peer reviewed IEEE journal.

[3] R. W. Erickson and Maksimović Dragan, *Fundamentals of power electronics*. Norwell, MA: Kluwer Academic, 2001.

This book will be used for understanding how each component of the micro inverter works and explain different topologies as well. This book has been cited 7031 times.

[4] Texas Instruments, “Highly stable 555 timers for generating accurate time delays and oscillation” LM555 Datasheet, Feb. 2000, [Revised January 2015].

The LM555 datasheet will allow give insight on using the chip and designing an oscillator. It is a credible datasheet because Texas Instruments is a very well-known company within the industry.

[5] Fornage, Martin, “Method and apparatus for improved burst mode during power conversion,” US Patent 9,461,56, 4 October 2016.

The patent gives some information about improving micro inverters which may be applied on my designed micro inverter. The patent holder has many other patents as well.

[6] S. Krauter and J. Bendfeld, "Cost, performance, and yield comparison of eight different micro-inverters," *Photovoltaic Specialist Conference (PVSC), 2015 IEEE 42nd*, New Orleans, LA, 2015, pp. 1-4.

This article also gives insight how well different topologies perform and how much they cost. This will have set a baseline of costs and efficiencies of my design. This was a peer-reviewed IEEE conference publication.

[7] A. M. Sadati, S. Krauter and J. Bendfeld, "Comparison of micro inverters based on practical analysis," *Energy (IYCE), 2015 5th International Youth Conference on*, Pisa, 2015, pp. 1-6.

This article also gives insight on different micro inverters in use which can help decide which design will be best. This was also in an IEEE conference that is also peer-reviewed.

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This article explains a different micro inverter topology that utilizes a flyback transformer. This is a peer-reviewed IEEE journal article.

[9] M. E. S. Ahmed, M. Orabi and O. M. Abdelrahim, "Two-stage micro-grid inverter with high-voltage gain for photovoltaic applications," in *IET Power Electronics*, vol. 6, no. 9, pp. 1812-1821, November 2013.

This article explains a different micro inverter topology that utilizes two stages of inversion for high-voltage gain. This is a peer-reviewed IEEE journal article.

[10] A. Abramovitz, B. Zhao and K. M. Smedley, "High-Gain Single-Stage Boosting Inverter for Photovoltaic Applications," in *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3550-3558, May 2016.

This article explains a different micro inverter topology that utilizes a single stage inverter for high-voltage gain. This is a peer-reviewed IEEE journal article.

Appendix B: Project Timeline

From our initial project scope, we created three different Gantt charts to plan and track our project timeline and milestones with each chart outlining fall, winter and spring quarter of the year. **Figure B – 1** shows our planned Fall quarter. This quarter was mainly used for planning our project and doing the appropriate research necessary to complete the project efficiently and effectively.

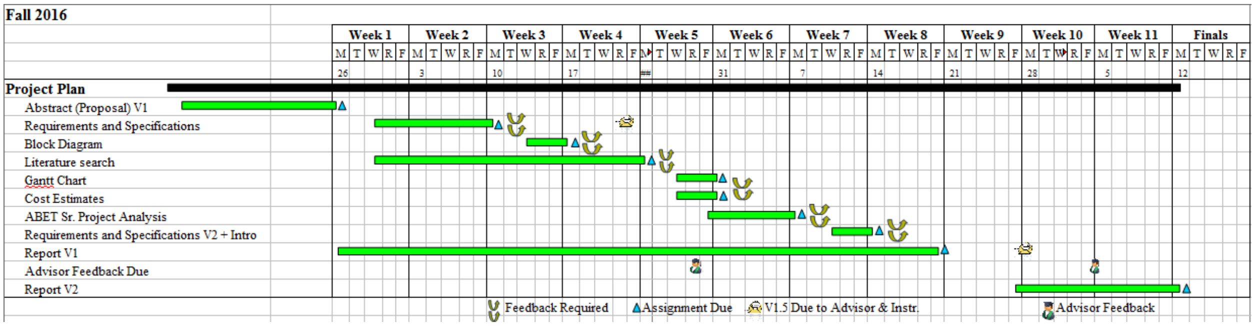

Figure B - 1: Fall Gantt Chart

Figure B – 2 outlines Winter quarter. For this quarter, we planned on continuing research on MPPT and DC-DC converter designs and finalize a topology we wanted to use. Additionally, we reversed engineered the M250 Enphase Microinverter and the SolarEdge Power Optimizer. For the rest of the quarter we wanted to start doing the design work and begin prototyping our design.

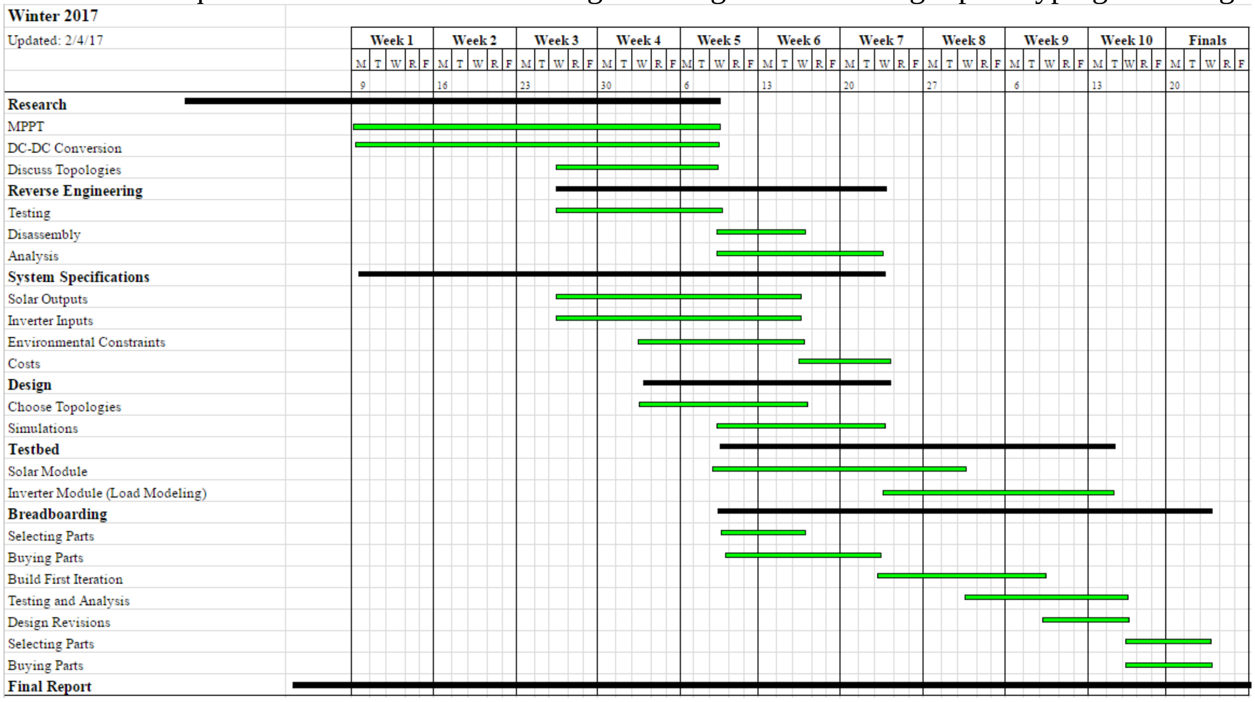

Figure B - 2: Winter Gantt Chart

Figure B – 3 shows our planned Spring quarter. We wanted to continue our testing and then finally create a final product that is fully packaged and viable to use.

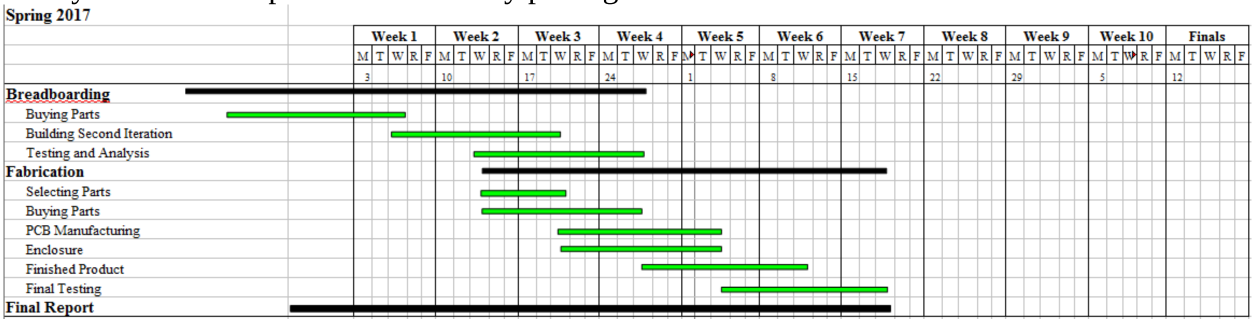

Figure B - 3: Spring Gantt Chart

Due to unexpected barriers having to do with equipment costs and time constraints, we were forced to change the scope of our senior project, which also changed our tasks and milestones for the project. The revised Gantt charts shown in **Figure B-4** and **Figure B-5** more accurately represent the design process we followed in the Winter and Spring quarters.

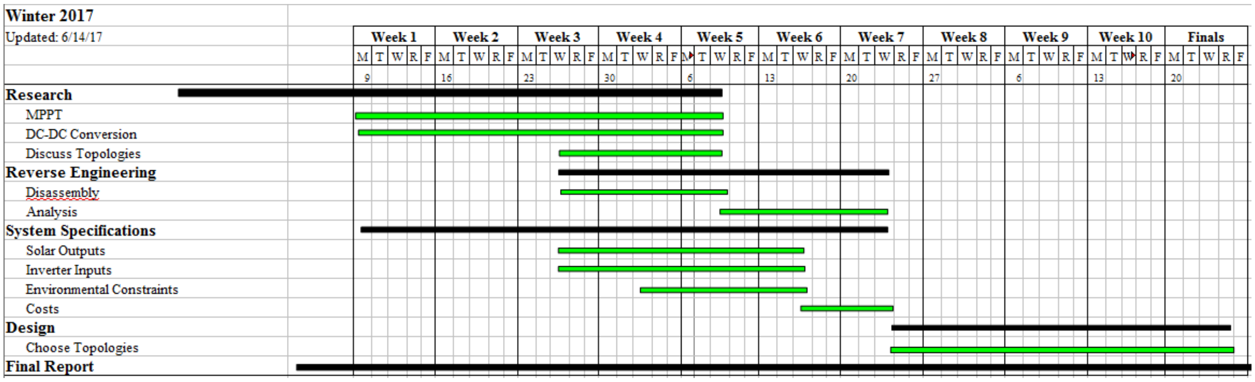

Figure B - 4: Revised Winter Gantt Chart

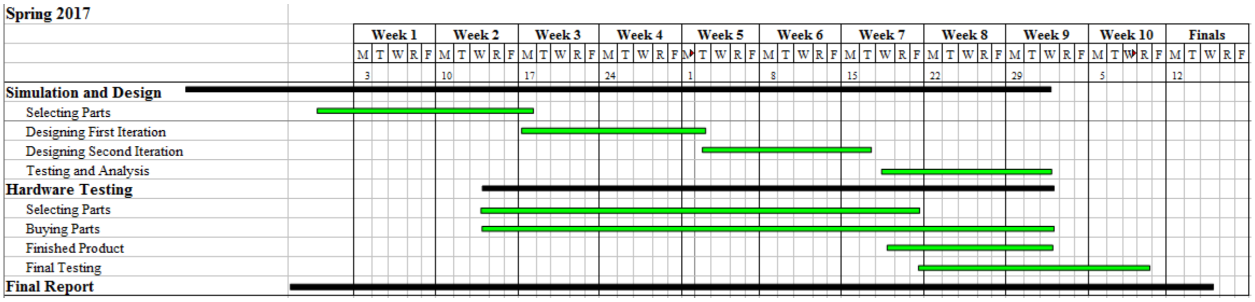

Figure B - 5: Revised Spring Gantt Chart

Appendix C: Bill of Materials

This bill of materials includes all the equipment we purchased for the hardware and testing portion of the project, shown in **Table C-1**. These were used to construct our test bed setup discussed in Chapter 5.

Table C-1: Bill of Materials

Equipment	**Description**	**Vendor**	**Quantity**	**Price**
APsystems YC500A 500W Dual Input Microinverter	Microinverter with dual inputs for two solar panels	The Power Store Inc.	1	$192.94
Trina TSM-PA05-235, 235W Solar Panel	First solar panel, loaned by the Cal Poly EE Department	Cal Poly	1	$0.00
BP SX 150S 150W Solar Panel	Second solar panel, loaned by the Cal Poly EE Department	Cal Poly	1	$0.00
APsystems AC Female Termination Cable	Microinverter to bare wire used to connect to the grid	The Power Store Inc.	1	$45.48
APsystems AC 25A Female Cap	End cap for the microinverter	The Power Store Inc.	1	$12.91
Husky 9 ft. 14/3 Power Tool Replacement Cord	Wall plug to bare wire connection to connect to microinverter in test 1 and 3	Home Depot	2	$27.94
			Total Cost	$279.27