Maximum Power Point Tracker For Partially Shaded Solar Panels

Team 27 -- James Arnold, Justin Meyer, and Nate Post
ECE 445 Design Document -- Spring 2020
TA: Ruomu Hao

1 Introduction

1.1 Objective

Solar panels are a rising option for power generation due to their decreasing manufacturing cost over the last few years. A problem with solar panels is that they do not autonomously maximize the energy they transmit without a power converter or inverter that has some maximum power point tracking control system to adjust the panels output. The Electrical and Computer Engineering building utilizes solar panels on its roof as well. Power converters have already been made to accomplish such a purpose, but some solar panels in close arrangements such as the ones on top of ECEB encounter a new problem, and that is the issue of partial shading. Partial shading not only blocks the amount of sun a solar panel receives, but also limits the power a panel can output by bottlenecking power transmission from well-lit portions of the panel.

Conventional solar power converters track the maximum power point of the overall solar panel, but with our system we intend to create a converter that splits the panel into three different sections and finding the maximum operating point for each individual section. The benefit this provides is the ability to increase the efficiency and output of each panel. Our power converter also ties into a larger green energy project that this building is a part of where the power generated by the solar panel would be tracked and recorded to display them in an effort to inspire more students to join the power department. Ideally this project would be able to be scaled so every solar panel on the roof had the device attached and reporting data of the individual panels.

1.2 Background Information

1.2.1 Maximum Power Point Tracking (MPPT)

Maximum power point tracking is a technique that needs to be considered in nearly all professional applications of solar power. This is due to the non-linear nature of photovoltaic cells, which causes them to supply drastically different levels of electrical power for the same level of incident light power.

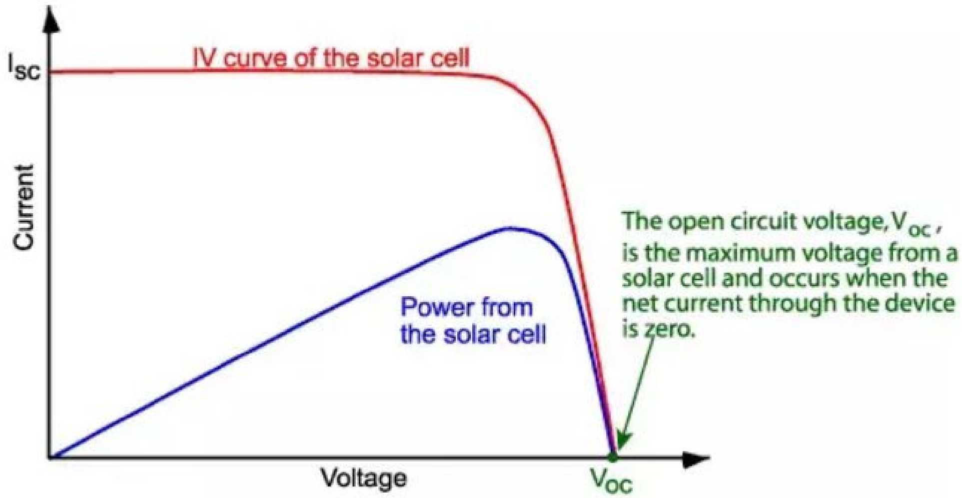

Fig 1. *Power and IV curve for a photovoltaic cell [2]*

Figure 1 shows the non-linear IV curve for a photovoltaic cell, which allows for vastly different voltages for essentially the same current. The power curve follows as per the standard equation for real power. Following these graphs, it is fairly simple to analyze whether or not a given cell is operating at the maximum power point. Specifically, we can look at either DI/DV or DP/DV. When DI/DV is at a maximum, the maximum power point has been reached. Alternatively, if DP/DV is zero, we can also say that the maximum power point has been reached. Because the duty ratio of a switching converter is related to parameters such as output power which is related to the input power, we can thus create a closed control loop that tracks the maximum power point.

MPPT is a very common addition to solar panel DC-DC converters or DC-AC inverters. The most common way that solar power is converted is with inverters that hook the solar panels directly up to the grid or the AC power supply of buildings. The largest reasons to go for DC-DC converters is for charging batteries that can store the energy for when it is needed or for creating DC microgrids. DC microgrids can work well for systems with many DC loads without having to convert power into AC and then back to DC. This ties in well with renewable energy like solar because they produce DC energy and can be converted with less losses due to large losses in transformers with AC power [3]. Competition for this kind of project comes from both companies like Bosch and other universities such as Xiamen University that are working on their own DC microgrid projects [4].

1.2.2 Partial Shading

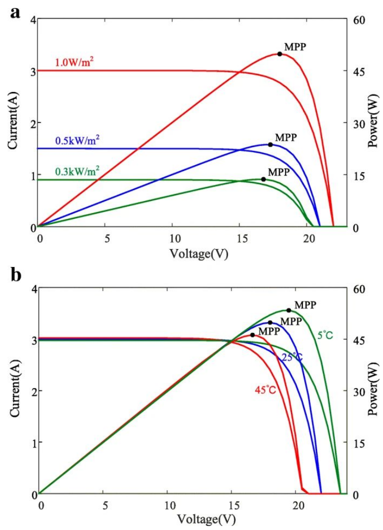

Fig 2. *Power curves of a solar panel under varying irradiance [7]*

Fig 3. *Image of a partially shaded solar panel array [8]*

Partial shading may seem like a very benign issue, however it can drastically affect the ability of a control system to perform maximum power point tracking in a manner that is actually efficient. In figure 3, we can see that some of the panels have cell blocks under high irradiance and low irradiance. This matters because each photovoltaic cell between two terminals of a solar panel are in series, therefore the current is limited to be only as high as the current in the cell providing the least power. Figure 3 demonstrates how the maximum power points of identical cells under different irradiances become unmatched, thus making it impossible to find the true maximum power point across terminals containing both cells.

1.3 Visual Aid

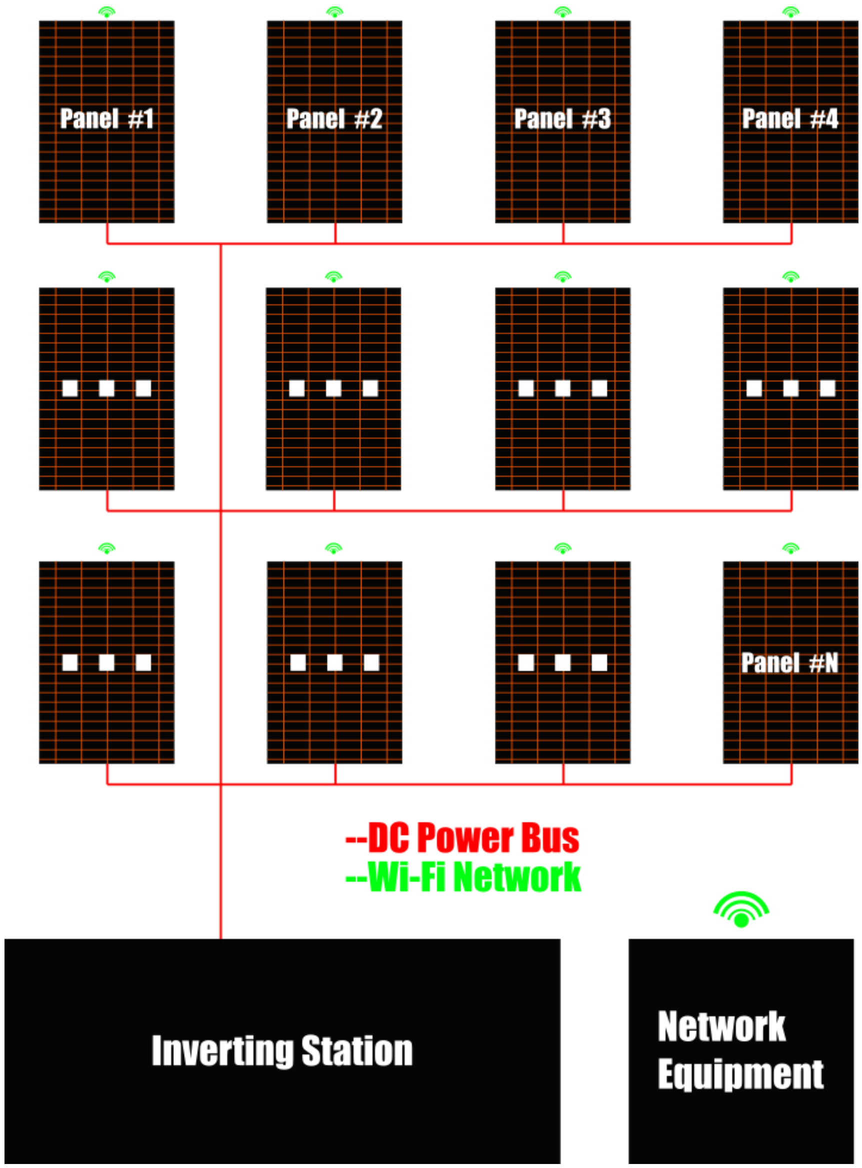

Fig 4. *Example arrangement of panels, inverter, and server used in a full deployment*

Figure 4 designates a representation of how our project could be used. A group of solar panels would each be connected with one of our converter devices, with those boards feeding the power that they convert to a central system which could invert the power and feed it back to the grid and to the ECE building itself. The power needs to be processed in such a manner because the grid must be supplied with an AC voltage at 60Hz. Each panel and board combination would also be transmitting data about each panel's power production across a wireless network to a central server to aggregate power information, potentially being used for an infographic display somewhere within the ECE building.

1.3 High-Level Requirements

- Converter must be able to take power from the panels and act as a constant current source to attach to a DC rail that will govern our output voltage at up to 425W.
- Converter must be able to find the absolute maximum power point of each of the sections of the panel and track it continuously using perturb and observe with a PID controller and convert power with an efficiency of at least 75% between the input and output.
- Converter must act as a web server so that a client device can remotely access power output data with an http request.

2 Design

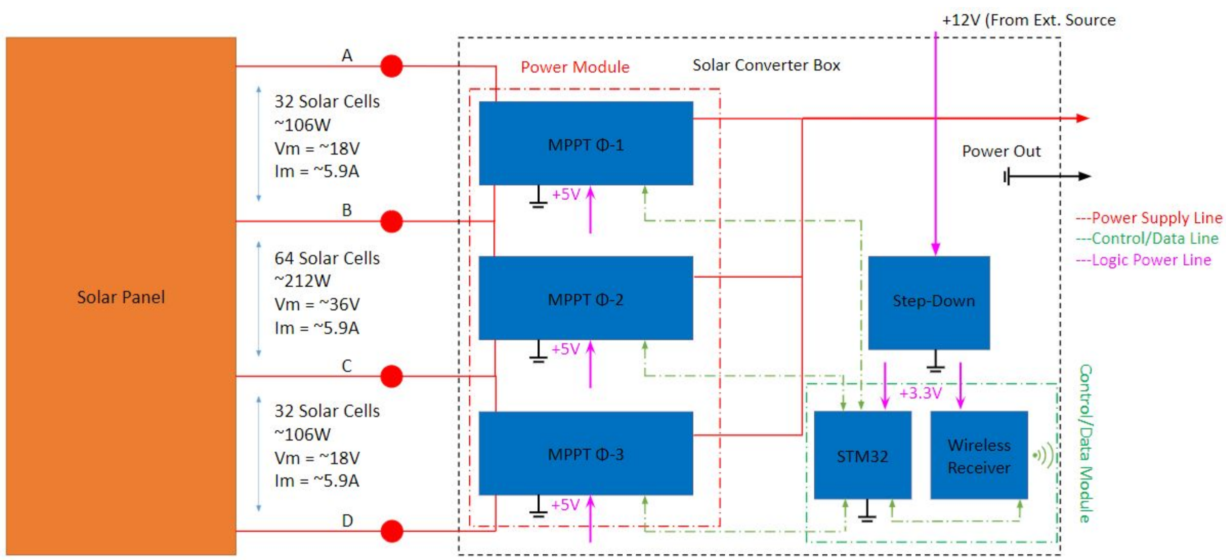

Fig 5. *Block Diagram Describing High-Level Operation of System*

2.1 Solar Panel

The panel we are working with has its specifications listed below, all measurements were taken at a STC of 1000W/m^2, an AM of 1.5, and 25 degrees Celsius.

- Peak Power of 425W (±5%) at 72.9V and 5.83A
- Open circuit voltage of 85.6V
- Short circuit current of 6.18A
- Maximum series fuse of 15A

2.2 Physical Design

While physical design is not paramount to the success of the project, a baseline level of quality is necessary to ensure that the device is safe to use, and is unlikely to break during testing and demonstration.

The enclosure can be either plastic or metal, but should be able to resist the weather present on the roof of the ECE building. A simple rectangular box will suffice, and it will need holes cut for power input, output, a programming port, a fan or air hole, and a status LED. Fig. 3 demonstrates a basic design with these requirements in mind.

Strict IPxx rating is not necessary for our prototype, but the device should be protected from accidental exposure to water and debris present in an outdoor setting. Mounting the device directly below the solar panel should accomplish most of this, but gaping holes should not be left in place.

The PCB should be electrically grounded from the outside of the enclosure, so if the enclosure is metal, non-conductive standoffs would need to be used.

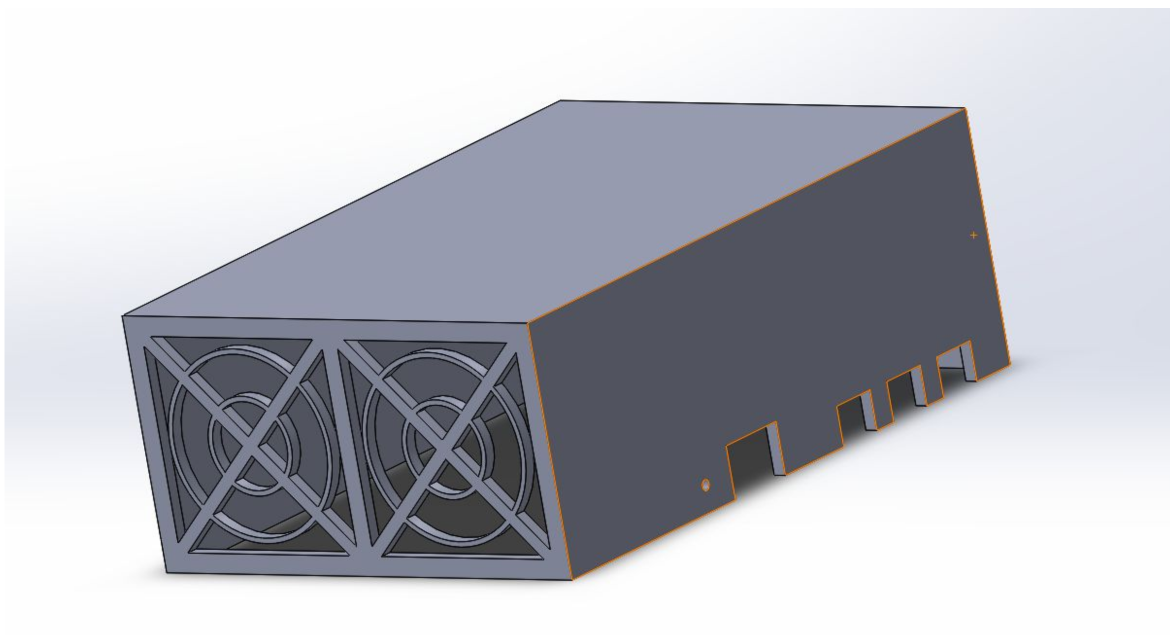

Fig. 6. *A basic enclosure sketch with fan, connecting ports, and LED*

2.3 Control Unit

2.3.1 Microprocessor

A small, cheap, and fast microcontroller is necessary to produce a highly efficient MPPT device, or the control loop cannot run fast or precisely enough. Though an Arduino UNO might work, its very low memory, and imprecise ADC and timer make it a poor choice for performing DSP and

high speed control loops. An STM32F103 was instead chosen for its ease of use, built in ADC, high operating frequency, large amounts of memory and low power consumption.
One particular issue with microcontroller programming is that their limited memory can cause instability when many function calls are made, overwriting data it was not supposed to or crashing the system. DSP can cause this when storing many previous values at once. 20 kBytes of memory should be sufficient for this application

Requirement	Verification
Be able to run a control loop across 3 different channels by reading from the ADC at at least 100Hz	1. Run designed control loop and LPF (see 2.6) on microcontroller, modified to send loop time to a serial monitor 2. Verify that the average running time for a loop cycle is less than 10 milliseconds by inspecting output times
Be able to communicate to the wireless module at 1kbits/sec or greater while not disturbing control loop speed	1. Connect wireless module to UART output of microcontroller 2. Stream dummy data over UART connection at a rate of 1Kb/sec while also running control loop 3. Ensure that the control loop still operates within 10 milliseconds using above procedure
Memory usage does not result in unpredictable behavior	Monitor behavior over 5 minutes of operation. Any unpredictable changes (eg strange input/output values) may indicate memory issues.

Note: Sending data to a serial monitor makes control cycles take longer to complete. However, this is the only way to monitor loop speed. This should not be a problem, as the 100Hz speed is part of design criteria, rather than reaching the limits of the hardware's capabilities.

2.3.2 Wireless module

The device will communicate wirelessly via the 802.11 Wi-Fi standard to send power data to a server. The esp8266-based ESP-01 wireless module will complete this task and can serially communicate with the STM32F103.

Requirement	Verification
The wireless device must be able to communicate at a rate of at least 1Kbits/sec to an access point at least 30 feet away while outdoors	1. Connect the device to a private wireless network while outdoors and at least 30 feet away 2. Connect a laptop to the router using a wired connecting

	3. Sample laptop-router network latency using ping <router IP>. mark average latency down 4. Now use ping <device IP>. Take that average latency and subtract laptop-router latency to find device-router latency. 5. Network speed can be taken from 256bits/(ping speed). Verify that this ping is at least 1Kbits/sec (latency is less than .25 seconds)

2.3.3 Status LED

The status LED will show if the device was able to successfully connect to the wireless network.

Requirement	Verification
Status LED should be visible from outside of the device’s enclosure.	While outdoors, power the LED using the microcontrollers GPIO. Visually ensure that the light is easily visible when not in direct sunlight.

2.4 Power Converter

2.4.1 Individual phases

The power converter will be a set of four phases that will be referenced as A, B, C, and D where the A phase refers to the phase of the top 32 cells, B is the top half of the middle 64 cells, C the bottom half of the middle section, and D the bottom 32 cells of the panel. Each section will be controlled separately by our microprocessor except phases B and C will share the same controls. The topology will be based on a forward converter design to incorporate a large amount of isolation between the solar panel and our output. This also helps to avoid ground loops that would introduce significant noise into our voltage and current sensors. Using differential voltage measurements also helps to keep our logic and power ground separate from each other. The logic will be powered by a separate isolated 12V supply that will be stepped down for the devices that need a lower 5V voltage, that voltage will also go through a linear regulator to feed 3.3V to our STM32. Each phase would then handle a max of about 106W of power if each part of the panel is outputting its maximum power.

Requirement	Verification
The voltage output ripple should be smaller than ±1.25%.for each phase, this gives a maximum total ripple of ±5%	We will use an oscilloscope to measure the ripples of individual phases and of the entire output and use cursors to evaluate the ripple

2.4.1.1 Diodes

The diode for the forward converter should have multiple qualities. It should be able to take the rated reverse voltage, and be able to conduct the desired current continuously. To be safe, the voltage ratings of the diode are set at least twice as high as expected, the continuous current through the diode should be at least 1.5 times higher. Because of this the **VBT1045BP-E3/8W** schottky diode is picked. Other desirable aspects of this diode are a fast recovery time, slightly lower forward voltage and low leakage current.

https://www.digikey.com/product-detail/en/VBT1045BP-E3%2f8W/VBT1045BP-E3%2f8WCT-ND/3102982/?itemSeq=318706840

2.4.1.2 Transformers

The transformer for the forward converter also needs to meet several specifications. The first specification is that the saturation current must exceed our peak current by a significant margin. The maximum current that the panels can supply no matter what is 6.18A which we can say because the properties of the cells make them effectively a current limited voltage source. Additionally, we need to select a turns ratio. Our output voltage is largely arbitrary as it is ultimately meant to be governed by external means, however if we select a turns ratio of 2 certain calculations for power become easier. Finally, it should not store much energy during each cycle. We can model the transformer as its leakage inductance for this purpose and use the equation E = .5*L*I^2 to calculate the energy held each cycle. The 750313441 transformer from Wurth Elektronik satisfies all of these requirements with a turns ratio of 2:1, a saturation current of 8.0A, and a leakage inductance of 600nH.

]https://www.digikey.com/product-detail/en/w-rth-elektronik/750313441/1297-1132-1-ND/4959521

2.4.1.3 RCD Snubber

In a forward converter, we use a transformer to achieve isolation and/or a specific desired step-up from the turns ratio. In this case, we don't seek to utilize the inductance of the transformer for any purpose unlike other converter topologies which utilize the stored energy in the transformer. So, we select a transformer that has very low inductance with the caveat that we still need to decide what to do with the excess energy stored in the transformer. In certain situations, like when a battery powers the circuit, it is appropriate to inject the excess energy back into the source as a form of regeneration. However, it is not useful to do so to a solar panel so we must dissipate the energy which is ideally quite minimal.

There are multiple angles from which to approach this task, but we have opted for an RCD snubber or resistor-capacitor-diode snubber. In this case, the diode prevents us from having constant dissipation, the resistor dissipates the energy, and the capacitor provides voltage regulation. The full calculations and design process for the snubber can be found in section 2.9 Tolerance Analysis.

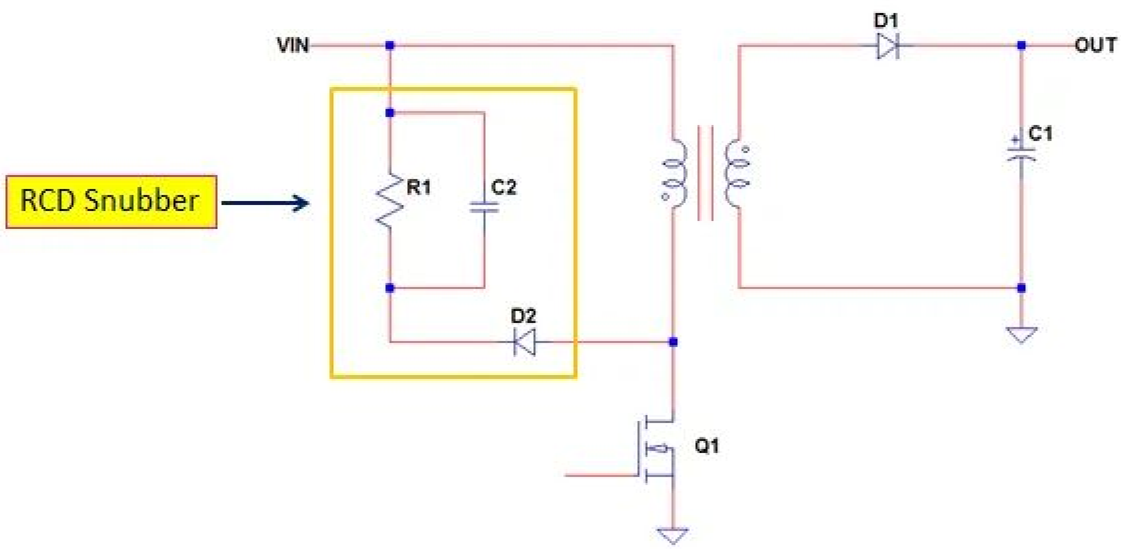

Fig 7. *Circuit diagram of a flyback converter with RCD Snubber [1]*

Requirement	*Verification*
The snubber should have a clamp voltage such that the maximum ringing across our MOSFET is no larger than 80V	We will use an oscilloscope probe to measure the voltages across the FETs in each converter to determine what the ringing voltage is.

2.4.1.4 MOSFETs

There is only one MOSFET per converter and it has two major specifications to meet. The first is that it needs to be able to pass up to our maximum current of 5.9A. Furthermore, it needs to be able to block the ringing voltage that we have set. With the clamp as it is, a MOSFET rated for a 100V drop will be safe and sufficient. Additionally, we would like for the FET to have the lowest possible gate charge to allow for faster and more efficient switching. Thus we select TK7S10N1Z,LQ which meets our specifications having a 100V, 7A rating as well as a gate charge of 7.1nC which is low considering competitors offered gate charges upward of 40nC for similar price.

https://www.digikey.com/product-detail/en/toshiba-semiconductor-and-storage/TK7S10N1ZLQ/TK7S10N1ZLQCT-ND/4815244

2.4.1.5 Capacitors

The output capacitor was chosen such that the ripple voltage at the output stayed at 1.25% of the maximum average output voltage of 25V. This maximum voltage plus the voltage ripple of .3125V is equal to 25.3125V. To achieve this ripple, a minimum of 56uF are needed, the capacitor also needs to have a ripple current rating of 2.125A at 15kHz. The capacitor chosen has a capacitance of 470uF and a voltage rating of 50V.

https://www.digikey.com/product-detail/en/panasonic-electronic-components/EEU-FM1H471/P12400-ND/613761

2.4.1.6 Output Inductors

To stay within reasonable size and cost, the ripple current experienced at the output will be 2% of the maximum possible average current of 8.5A which gives a ripple current of 2.125A, so the maximum current at the peak will be 9.56A. At this ripple current, at minimum voltage output and maximum voltage input, a minimum inductance of .76mH is required. The inductor chosen has an inductance of 1mH and a current rating of 10A.

https://www.digikey.com/product-detail/en/hammond-manufacturing/157D/HM1524-ND/455024

2.4.2 Constant current conversion

To act as a constant current source, no new circuit elements need to be introduced to meet this requirement. However, this will require an adjustment to the control loop to control for current instead of voltage at the output.

Requirement	Verification
The power output of the device should appear as a current source with a variation of current below 2%.	We will attach a current probe to the output and use an oscilloscope to verify that the waveform shape

2.5 Network

2.5.1 Server

The server would consist of a PC connected to the wireless network containing multiple MPPT devices, which will run software to gather data from each converter to obtain a total network output. This is outside the scope of this class, but is integral to educating people about the energy usage of the ECE building.

2.5.2 Wireless Access Point

A compatible wireless access point with a matching protocol is necessary for the devices to communicate with the server.

Requirement	Verification
Communicate at a rate of at least 1kbits/sec to the MPPT device at least 30 feet away while outdoors	1. Connect the device to a private wireless network while outdoors and at least 30 feet away 2. Connect a laptop to the router using a wired connecting 3. Sample laptop-router network latency using `ping <router IP>`. mark average latency down 4. Now use `ping <device IP>`. Take that average latency and subtract laptop-router latency to find device-router latency. 5. Network speed can be taken from 256bits/(ping speed). Verify that this ping is at least 1kbits/sec (latency is less than .25 seconds)

2.6 Software

2.6.1 Digital Signal Processing

Like any power application, the output of the forward converters is subject to noise, particularly ringing from switching. A finite impulse response low pass filter will be applied before the control loop performs calculations on the data. This can be accomplished by using a “rolling average” with optional weighting so that the data has less “inertia”, meaning it will respond more quickly to change in voltage outputs.

Noise is short, undesirable output changes based on surrounding environment or physical properties of electronic devices. A high spike in voltage due to switching would be considered noise, but a person accidentally covering a portion of the solar panel for more than a brief moment would not be, as it changes the steady state output of the system. The radiance on the solar panel may change quickly due to obstructions, so the device must both account for noise and changes in maximum power

Requirement	Verification
Low amplitude noise (<1V deviations from mean) are reduced by at least 90%	1. Set up a waveform generator to produce a sine wave of magnitude 1V (offset 1.5v) with a frequency of 10 kHz (high-Z mode) Attach this to an ADC input on the microcontroller 2. Run ADC code on microcontroller, connect serial interface to laptop for debugging 3. Serially print the voltage level read on the ADC, and the new output voltage to a debug console to save as file 4. Plot these points (Volts vs. Time), verifying that the change in output is never more than ±.05V
High amplitude noise (>1V deviations from mean) are reduced by at least 75%	Same procedure, except the experimental input will be a sine wave of magnitude 2V (offset 1.5v) with a frequency of 1 kHz (high-Z mode)
Large voltage level changes (a rate of more than 0.5V/sec) are accounted for at DSP output within 0.25 seconds	Same procedure, except the experimental input will be a square wave of magnitude 3V (offset 1.5v) with a frequency of .5 Hz (high-Z mode). DSP output should reach 3V within .25 seconds of rising edge, and 0V within .25 seconds of falling edge

Note: A sharp voltage increase of over 100 V/sec is extremely unlikely at the ADC input. Using a square wave make it easier to verify that the DSP is working as intended

2.6.2 Control Loop

The method for finding the maximum power point of the solar panel will be the perturb and observe (P&O) method. This method adjusts the duty ratio of the converter while observing the input voltage and power. It then adjusts the duty ratio in the direction of increasing power until it starts to decrease and then reverses, keeping the converter very close to the maximum power point at all times.

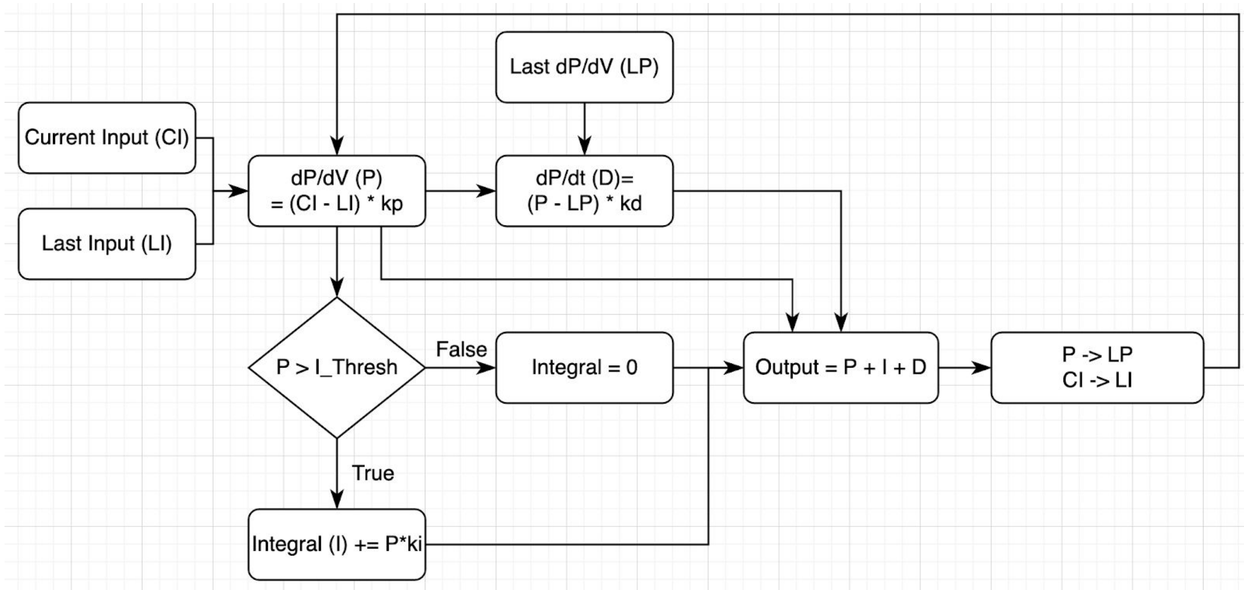

Fig. 8: PID control loop designed for MPPT, using integral thresholding to reduce overshoot

The value to be optimized by the control loop is dP/dV(The change in power with respect to voltage), where the optimum value is 0. A Proportional-Integral-Derivative (PID) loop can accomplish this by using a combination of current state, sum of previous states, and rate of change in state to produce a control scheme that is accurate and very fast at reaching the desired value.[10] It is particularly useful in that it can be designed to reduce oscillation, decreasing noise at the output.

Figure 8 shows an example control loop, which calculates dP/dV based on the change in instantaneous power from the last 2 inputs, to find the P gain. It then calculates dP/dt, the change in power with respect to time, to calculate the D gain. Finally, if dP/dV is small enough, the integral will begin to sum values to find the I gain. All of the gains are then summed to find the final change to be made to the output.

2.8.3 Wireless communication

The ESP-01 communicates with the STM32 over UART, allowing for serial data to be converted to a wireless transmission to be sent over the Wi-Fi 802.11 transmission protocol. Once assigned an IP, the converter can communicate over Wi-Fi by hosting an HTTP server that another device can access through a variety of means, including a web browser or more complex data collection program. The converter will respond to HTTP GET requests and return the current power output of the device, and possibly additional debug information.

Requirement	Verification
The HTTP server on the converter responds	1. Set up an HTTP endpoint, `<Device`

to GET requests	IP>:80/hello, as a GET request that returns "Hello, World!" 2. Connect the device to a private wireless network 3. Connect any device with a web browser to the same network 4. Visit the website <Device IP>:80/hello and verify that the message "Hello, World! Has been successfully returned (will be displayed in the browsers content window)

2.9 Tolerance Analysis

Our evaluations have revealed that the most complex and difficult to implement component is the switching converter. Especially with continued use, many parts are prone to heating up. Proper thermal management and device choices need to be made to account for this constant use. The part most likely to fail in the converter is the switching MOSFET, this is due to the high ringing of the voltage across the drain and source of the MOSFET during switching times which might go over the rated blocking voltage of the MOSFET. We have opted to use an RCD clamp, covered in section 2.4.1.3. The algorithm for designing an RCD clamp is as follows

- Acquire from the manufacturer or in a lab the leakage inductance of the transformer
  - For the 750313441 transformer, this is typically 600nH
- Determine the power which the inductance stores
  - E = .5*L*I^2 is the energy per cycle
  - P = .5*L*I^2*fsw is the power
  - P = .5*600nH*(5.9)^2 * 15000 =156.65mW
    - We select 5.9A as this is the theoretical maximum current through the inductor
- Determine the theoretical power dissipated in our clamp resistor
  - Figure 9 shows how over time we should see a linear decrease in current through the clamp resistor which is based on the inductor equation V = L*dI/dt
  - We take the integral of this dissipation and multiply by the switching frequency in order to find the power-- P = .5*fsw*I*Tsn*Vclamp
  - Convert the time term into a function of constants and other design parameters such as Vclamp-- Tdis = I*L/(Vclamp - Vsec *n) where Vclamp is the clamp voltage (i.e. what do we clamp the ringing to) and Vsec is the voltage across the secondary terminal of the transformer.
  - We make this substitution and then also substitute the power through the resistor with the expression P = Vclamp^2/R

    - The resulting equation allowing us to solve for R based upon design parameters is R = (2*Vclamp*(Vclamp - n*Vsec)/(fsw*Ipeak^2*L)
- Select a clamp voltage
    - The clamp voltage affects the FET, which will see a maximum of Vin + Vclamp at its terminals during ringing. The maximum Vin per phase is only 16V, which allows us to select a relatively high Vclamp. A high clamp voltage reduces the time required to dissipate the additional energy but we will see later that this increases the required capacitance. Thus, we can select a middling value like 50V for the clamp. This way, we can select a FET with a 100V rating that will operate very comfortably and be incredibly unlikely to fail.
        - From here, we check Rcalc which comes out to be (2*50*(50-16*.5)/(15000*5.9^2*600e-9) where we have picked 16V as the secondary voltage, i.e. the maximum secondary voltage. N = .5 because we intend to step up our input voltage with the 2:1 transformer. Rcalc = 13.4k Ohm
        - The power dissipated in the resistor is just 186.5mW based on the calculation from earlier
        - The time to discharge is 84.286nsec according to the equation for Tdis which fits very comfortably within our switching period of 66.67usec
- Calculate the necessary capacitance
    - The capacitance mostly depends upon the ripple that we would like to see in our clamp network. Using the standard decay equation for a charged capacitor, we get Vmin = Vclamp* exp(-Tsw/(R*C)) which converts to be C = -Tsw/(R*ln(Vmin/Vclamp)) where Vmin is the minimum voltage we would like to charge the capacitor to. We would like our ripple to be very small and Tsw is very small so we can select a 200mv ripple and use a capacitor of .6194uF and achieve our desired effect.
- Select a diode-- All of the diodes in our system need approximately the same current and fast switching ratings, so we can opt to use the same schottky diode we use elsewhere.

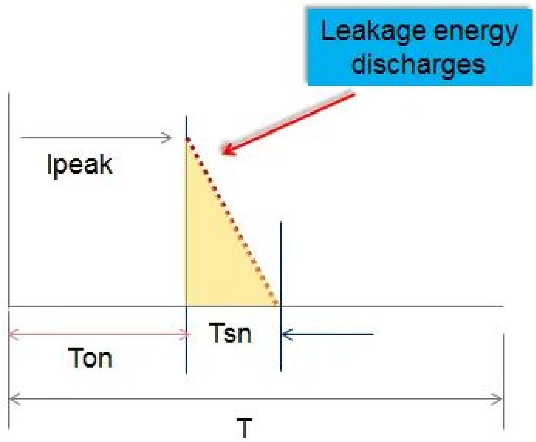

Fig 9. *Diagram of power dissipation in clamp resistor*

3. Cost and Schedule

3.1 Schedule

TASK NAME	START DATE	END DATE	START ON DAY*	DURATION* (WORK DAYS)	TEAM MEMBER	PERCENT COMPLETE
Design Document						
Cost Analysis	2/18	2/26	0	9	Justin	0%
Visual Aid	2/18	2/26	0	9	James	0%
Transformer Losses	2/18	2/26	0	9	James	0%
Network Mapping	2/18	2/26	0	9	Nate	0%
Control Loop Diagram	2/18	2/26	0	9	Justin	0%
Control Loop						
Transfer Function of Converter	2/18	2/26	0	9	Justin	0%
MPPT	2/26	3/15	8	19	James	0%
Unit test	3/15	3/29	26	15	All	0%
Integration	3/29	4/6	40	9	All	0%
Power Converter						
Components Calculation	2/18	2/26	0	9	J&J	0%
PCB Design	2/26	3/3	8	7	J&J	0%
Soldering	3/3	3/6	14	4	J&J	0%
Unit Test	3/6	3/29	17	24	All	0%
Integration	3/29	4/6	40	9	All	0%
Microcontroller & Wifi-Module						
Coding of Control Loop	2/26	3/8	8	12	Nate	0%
Coding of wireless	2/26	3/8	8	12	Nate	0%
Unit Test	3/8	3/29	19	22	All	0%
Integration	3/29	4/6	40	9	All	0%

Fig10. : Schedule overview

This is a general overview of the schedule of the project. Dates are subject to change, this schedule allows for extra days as needed as it only schedules until April 6th.

3.2 Cost Analysis

3.2.1 Labor

Additional labor outside the members of the group should not be necessary, apart from that factored into the cost of parts. Estimate 150 hours of work per person, at $40 an hour, for 3 people. Total labor comes to be:
60 * 3 * 40 = $7,200

3.2.2 Non-Standard Parts

Description	Manufacturer/Part No.	Quantity	Cost	Total
STM32F103 Daughterboard		1	$5.00	$5.00
ESP-01 Wifi board	MakerFocus #SE154	4	$3.50	$13.98
ST-Link v2	DAOKI #BG-US-973898	1	$6.29	$6.29
Schottky Diode	VBT1045BP-E3/8W	12	$0.88	$10.56
Output Capacitor	EEU-FM1H471	4	$0.24	$0.96
Output Inductor	157D	4	$17.34	$69.36
Transformer	753013441	4	$3.88	$19.52
MOSFET	TK7S10N1Z,LQ	4	$1.33	$5.32
Snubber Resistor	30k SMD 1210 RES	8	$.12	$.96
Snubber Capacitor	1uF ALUM ELEC CAP	4	$.25	$1.00
Total				$132.95

4. Ethics and Safety

4.1 Ethics

This project is in full compliance with the IEEE code of ethics [6], provided that the design accounts for all necessary safety precautions. All members of the team working on this project will perform work diligently, with attention to personal and public safety, and will report honestly to their peers and mentors on the results of the project. Furthermore, any information acquired from external sources for use in the development of this project will be used with permission of whosoever owns that intellectual property in which case credit will also be given. The software used and developed for this project will similarly be developed adhering to the ACM code of ethics by using the same metrics as above [11].

Due to the location of the panels, the personnel developing this project must take into account the safety of any person who would be in close proximity to a panel utilizing the system and in general the safety of the people in a building with a panel utilizing the system.

Finally, the panels are already installed, therefore we shall assume that the various building codes for an initial installation have been met. With the addition of our board, most regulations will have been met already, but if there is an intent to sell the electricity it would require an Ameren employee to perform installation [12].

4.2 Safety

The primary concern in this project is that of electrical fires. The system will be enclosed with no leads exposed so the probability of electrical shock to a passerby or person transporting the system is low. Following this concern, we will implement several safety features that constitute a failsafe system.

Electrical fires can be caused in several ways:

- Accumulated dust ignites due to extended contact with hot components
- A power line fails and ignites a flammable material in close proximity to the system and/or panel

The proposed solutions to these issues are addressed as follows in order:

- A ventilation system for the purpose of cooling components will be fitted to the system housing. In addition, this ventilation system will filter any air entering or exiting the enclosure such that a minimal quantity of dust accumulated within the enclosure. In the event of a ventilation system failure, one or multiple thermistors will trigger a shutdown of the system.

- The STM32 microcontroller and software control loop will maintain bounds on the operation of the system such that the power flowing through a module at any given point in time will be within the specifications of all components used. In addition, a fuse will be placed in series with the power distribution lines in order to prevent surges and sustained over-currents

5. Citations

[1] “Snubber Circuit Design Analysis”, *electronicsbeliever.com*, 2020. [Online] Available: http://electronicsbeliever.com/snubber-circuit-design-analysis/ (accessed 24 Feb 2020).

[2] Detjen, Bradley. “How does maximum power point tracking (MPPT) work?” *solarchoice.net*, 2020 [Online] Available: https://www.solarchoice.net.au/blog/how-does-maximum-power-tracking-work (accessed 24 Feb 2020)

[3] Burger, Andrew. “Shouldn’t We Have More DC Microgrids?” *microgridknowledge.com*, 2020. [Online] Available: https://microgridknowledge.com/dc-microgrids/ (accessed 25 Feb 2020)

[4] “DC Microgrids.” *microgridprojects.com,* 2020. [Online] Available: http://microgridprojects.com/dc-microgrids/ (accessed 25 Feb 2020)

[5] “AN-776 20 Watt Simple Switcher Forward Converter.” *ti.com*, 2020. [Online] Available: . http://www.ti.com/lit/an/snva027a/snva027a.pdf (accessed 22 Feb 2020)

[6] “7.8 IEEE Code of Ethics” *ieee.org*, 2020. [Online] Available: https://www.ieee.org/about/corporate/governance/p7-8.html (accessed 27 Feb 2020)

[7] Shang, Liqun. “Maximum power point tracking of PV system under partial shading conditions through flower pollination algorithm” *pcmp.springeropen.com,* 2020. [Online] Available: https://pcmp.springeropen.com/articles/10.1186/s41601-018-0111-3 (accessed 27 Feb 2020)

[8] “Shade Losses in PV Systems, and Techniques to Mitigate Them” *blog.aurorasolar.com*, 2020. [Online] Available: https://blog.aurorasolar.com/shading-losses-for-pv-systems-and-techniques-to-mitigate-them/ (accessed 27 Feb 2020)

[9] [5]J. Nedumgatt, K. Jayakrishnan, S. Umashankar, D. Vijayakumar and D. Kothari, "Perturb and observe MPPT algorithm for solar PV systems-modeling and simulation", *IEEE*, 2020. Available: https://ieeexplore.ieee.org/document/6139513/authors#authors. [Accessed 27 February 2020].

[10]"PID controller", *En.wikipedia.org*, 2020. [Online]. Available: https://en.wikipedia.org/wiki/PID_controller. [Accessed: 27- Feb- 2020].

[11]"ACM Code Of Ethics", *Acm.org*, 2020. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: 27- Feb- 2020].

[12"Renewables", *Ameren.com*, 2020. [Online]. Available: https://www.ameren.com/illinois/residential/supply-choice/renewables. [Accessed: 27- Feb- 2020].