Solar Power System with Maximum Power Point Tracking

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***Abstract* — This paper presents the design and implementation of a 500W complete power system that derives its energy from solar panels, utilizes maximum power point tracking to store the energy in a battery bank, and delivers the energy in the form of a modified sine wave. The object of this project was to create a reliable source of electrical power for the community center in the Pomolong Township located in the rural area of South Africa.**

***Index Terms* — DC-DC power converters, Inverters, Maximum Power Point Tracking, Power system interconnection, Photovoltaic systems, Solar energy.**

I. Introduction

The Pomolong Township is located at 28°14'39.82"S, 29° 6'46.02"E, which is 265 kilometers southeast of Johannesburg, South Africa and 304 kilometers northwest of Durban, South Africa. The Pomolong Township is in need of resources such as running water and electricity because it is isolated from the main South African power grid. The UCF Burnett Honors College wanted to find a solution to providing power for a community center in the Pomolong Township.

The power needs were estimated to be approximately 500W per day of off-grid power. Based on the data on the irradiation levels of South Africa and the sunlight hours per day on that part of the world, it was determined that a solar-based solution would yield the most power for the least amount of monetary resources. There are many solutions to this problem. A major consideration made was that those who would need to fix or repair the power system are people with limited education and limited resources. This was an important consideration, because the Pomolong Township is in a remote area in South Africa and more complications would make the system difficult to repair or operate.

There are a lot of new and advanced technologies available for solar panels, batteries, battery charge control, and power inversion. The biggest challenge of this completely off-grid stand-alone photovoltaic power system that utilizes maximum power point tracking project is the power inversion because obtaining the pure sine wave that was in the original design proved to be very difficult.

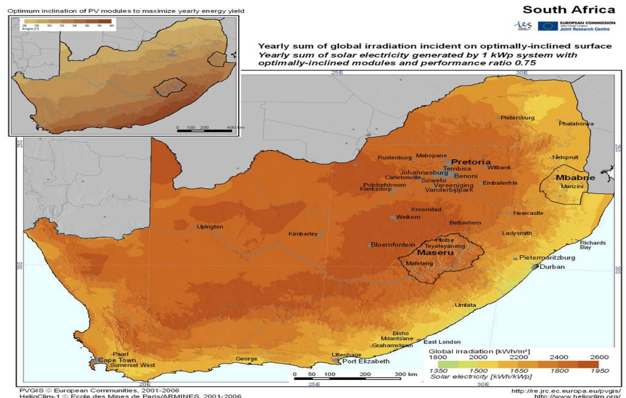


Figure 1 Irradiation Levels of South Africa

The prototype is funded by Progress Energy and was given a budget of $1995, including the materials needed to test the prototype.

II. Objectives And Goals

The main objective of this project is to design a safe and reliable source of power that can be used to turn on a projector and charge cell phones for an extended period of time each night. To do this, solar panels are used to obtain energy from the sun; a charge controller is used to maximize power from solar panels and to monitor batteries being charged to prevent battery overcharge; an inverter is used to perform the DC-AC power conversion.

A. Safety

The absolute most important objective is safety, because ensuring that the system is safe protects lives and mitigates damages.

B. Efficiency

A major objective of this project is for the power generating system to be extremely efficient, because the resources are scarce and utilizing every bit of energy gives the townspeople more time to enjoy the electricity.

C. Ease of Use

Overall design caters to being simplistic, portable, and the system is color coded to prevent and reduce user error.

III. Block Diagram and Project Components

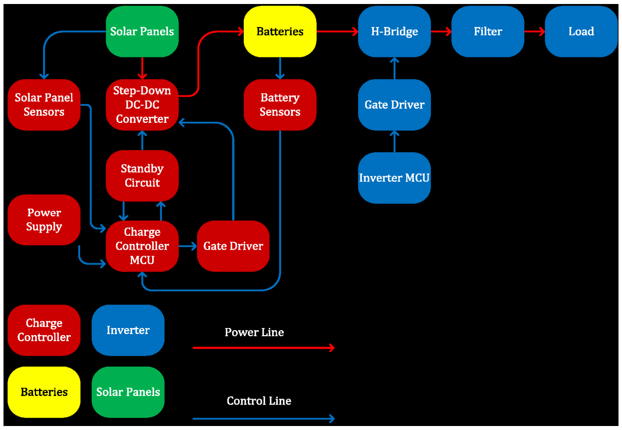


Figure 2 Block Diagram of Project

A. Charge Controller

One of the objectives is to successfully capture as much sunlight energy as possible. This is done through an MPPT charge controller system. The reason behind this controller is to vary the electrical operating point of the modules so that the modules produce the maximum power possible, regardless of the climate conditions.

B. Batteries

The goal for batteries was to find the right number of batteries with the right amount of charge capacity and power dissipation to include in our system, because it would be detrimental to the system if the batteries could never be charged or if the batteries became completely charged too quickly.

C. Inverter

The inverter takes the power from the charged batteries in the form of a DC input. The inverter then outputs AC which can be used by instruments such as laptops, TVs, and cell phone chargers. The goal is to do this as efficiently as possible.

D. Solar Panels

Solar panels are the part of the system which captures solar energy and converts it into usable power. Simply put, if the solar panels stop working then the rest of the system is useless because there is no input energy. No expense was spared on the solar panels. The best quality solar panels made with grade A Mono-crystalline silicon solar cells were obtained.

E. Enclosure

A robust, weather resistant, and safe enclosure to keep all of the entire system secure and ventilated is a crucial part of the project. A modified computer chassis was used to encase the inverter and the charge controller.

F. Wiring

Wiring can be dangerous, and if the incorrect wire gauge is used for anything other than its intended purpose, the results would be disastrous and potentially fatal, so strict adherence to the NEC was made when choosing wiring.

III. Components

A. Solar Panels

When it comes to the overall performance of solar panels, the ideal conditions of a lab are not present in the real world, and the efficiency of any given panel could be affected by an array of possibilities. Factors that could change performance are important, because solar panels are the largest investment in the project, and performance is one of the major considerations when implementing a photovoltaic in a design.

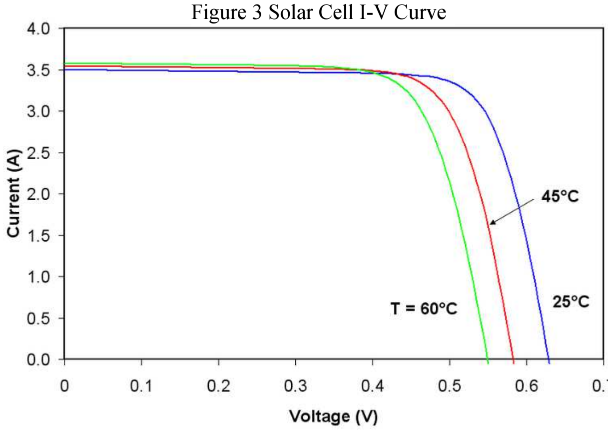
The photovoltaic cell is usually constructed of some light absorbing semiconductor material like silicon. All semiconductors are associated with a specific energy band gap. [1] With this in mind, when designing a solar cell, choosing a semiconductor material with an energy bang gap as close to the center of the solar radiation spectrum would yield optimal results. The full solar radiation spectrum ranges from infrared to ultraviolet. Unfortunately, there is no semiconductor found to date that responds to the full solar radiation spectrum.

Solar panels in all sorts of various makes and models are not very efficient at converting solar energy, noting that the highest efficiency made is 30%, which is not even available for general consumer use. The rates of electron-hole recombination for Mono-crystalline photovoltaic cells are the main reason why they perform better than Poly-crystalline cells. In Poly-crystalline photovoltaic cells, the impurity concentration and the structure abnormality associated with multiple crystals of silicon increases the electron-hole recombination rate. If the electron-hole recombination rate is increased, then the efficiency of the panel decreases.

Temperature is another negative factor that affects solar panel performance. Crystalline silicon panels suffer the most when their cell temperature rises. When the temperature of the semiconductor rises, the conductivity also rises. If there is an increase in conductivity, the electric field of the p-n junction decreases. If the electric field decreases, then the voltage across the photovoltaic cell decreases. Less voltage across the solar cell results in a smaller power output and lower efficiency. [2]

Every Solar panel has a temperature coefficient and an I-V curve that describes its I-V characteristics. The temperature coefficient is the rate of power reduction for every degree above the operating temperature. The standard operating temperature is 25 degrees Celsius.

Figure 3 Solar Cell I-V Curve



The I-V curve that describes the photovoltaic's I-V characteristics shows the relationship of current and voltage for different degrees of temperatures. The area under the I-V curve is an approximation of the maximum power that the photovoltaic would produce if operating at both open-circuit voltage and closed-circuit current. From figure 4, it is shown that total photovoltaic cell power diminishes as the temperature of the panel increases.

Photo current is maximized when the amount of photons of light from the solar radiation spectrum captured are maximized. This can be improved by using better solar cells, by using MPPT techniques, or by using a combination of the two.

Figure 4 Helios 6T250

Two 250W 30V Photovoltaic Solar panel have been chosen for this project. There dimensions are 1,680 mm x 990 mm x 40 mm. The PV Panel is of Mono-crystalline composition, which makes it more efficient and lighter than its poly-crystalline competitor, while still being competitively priced. Each panel has a max power of 250W, a max operating voltage of 30.3V, and a max current of 8.22 Amps. The PV panels are manufactured by Helios, and were purchased on eBay.

B. Charge Controller

The MPT612 has an embedded RISC processor with a current sweep MPPT algorithm included. It also supports overvoltage and overcurrent protection, thermal protection, has programmable libraries for different charge profiles, alarm conditions, and vast documentation and flexibility for use in any environment and with any size panel and battery bank.

The core of the charge controller is the buck-boost DC-DC converter which transfers energy from the PV panels to the battery in short pulses via a switching MOSFET which is controlled by the MPT612. The duty cycle of the MOSFET is varied by the MPT612 based on the demands of the MPPT algorithm. The other elements of the charge controller include the voltage and current sensors, a power supply and clock generator, gate driver, and serial/UART communications.

The IC handles the sensor inputs, temperature inputs, UART and JTAG communication, as well as outputting PWM gate drive signals to operate the DC-DC converter, and digital outputs for sending charge information to a logging or monitoring interface.

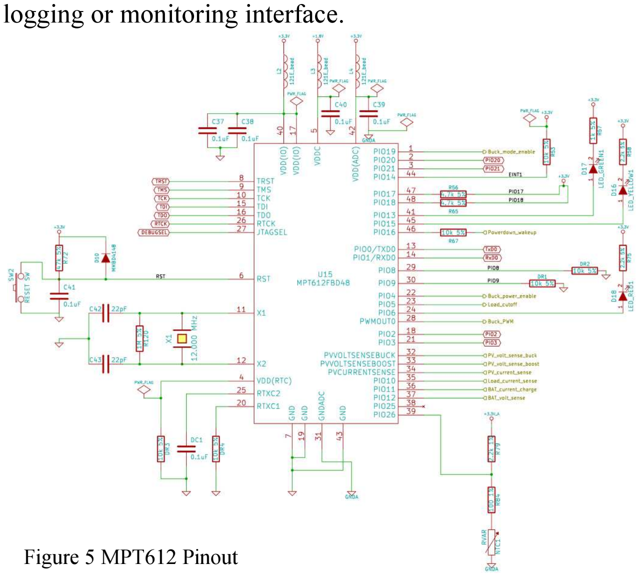
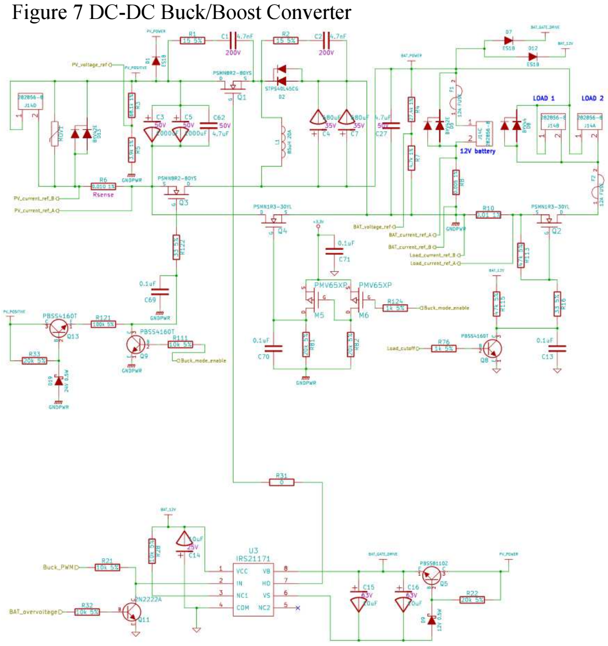


Figure 5 MPT612 Pinout

Architecturally, the MPT612 features an ARM 32 bit processor and 32kB on-chip flash memory and 8kB static RAM. Pins that are not connected to a specific peripheral function are controlled by GPIO registers. They can be dynamically configured as inputs or outputs.

The MPT612 also contains one 10-bit Analog-to-Digital Converter (ADC), capable of performing more than 400,000 samples per second. The chip also has two UARTs, two I2C bus controllers and two serial I/O controllers.

Figure 7 DC-DC Buck/Boost Converter



The DC-DC converter is the muscle behind the charge controller. It is responsible for taking energy from the PV panels and via PWM pulsing it through the inductor which allows the energy to be converted to a different voltage and current in a theoretically lossless manner. The converter is using a buck-boost topology, and can operate in buck-boost mode or buck-only mode. In buck-only mode, the PV voltage must always be higher than the battery voltage. In buck-boost mode, both the PV voltage and battery voltage can be variable values with the system switching between buck and boost based on the relative voltages. The power electronics circuit is shown in Figure 6.

The switching frequency of the converter is fixed at 20kHz to optimize both the switching loss and the inductor size. The inductor equation is given by:

$$I_{L(AV)} = I_O/(1-\delta) \qquad (1)$$

I_O is the output current and δ is the duty cycle. In buck-boost mode, the maximum duty cycle is 60%. The input bulk capacitor calculation is equation 2. The parameter to keep in mind for this application is the Effective Series Resistance or ESR and RMS current rating. Low ESR is desired to minimize input voltage ripple and high current changes on the output. Placing two capacitors in parallel also further reduce the ESR.

$$C_{I(min)} = (I_I \times t_{on})/\Delta V_I \qquad (2)$$

$$ESR = \Delta V_I/(I_I/\delta) \qquad (3)$$

The efficiency of the converter in buck-boost mode depends on the diode forward voltage drop V_f, so a diode with low V_f is desired. Schottky diode STPS40L45CG has a forward voltage drop $V_f = 0.45V$. With the V_f parameter calculated, the output filter capacitors can now also be calculated:

$$\frac{C_O \geq I_{O(max)} \times \left((V_O+V_f)/\left((V_{I(min)}-V_{sw})+(V_O+V_f)\right)\right)}{f_{osc} \times \Delta V_{OC}} \qquad (4)$$

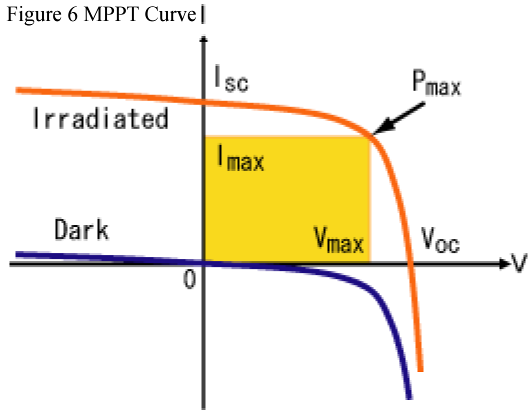
Where f_{osc} is the switching frequency (20kHz), $\Delta V_{OC} = 200mV$, and $V_{sw} = 0.4V$.

C. Batteries

Maximum Power Point Tracking (MPPT) is utilized by the MPT612 to get the maximum power of the solar panels. When the batteries are fully charged and the solar panel production exceeds the maximum load, the MPPT can no longer operate the solar array at its maximum power point because the excess power cannot be stored. The MPPT must then either shift the array operating point away from the peak power point solar power until the battery charge is dissipated or divert surplus PV power into a resistive load, allowing the array to operate continuously at its peak power point. The electrical output of a solar plotted can be seen on an I-V curve like Figure 4.

MPPT technique changes the voltage of the panels to keep at its maximum potential. For example, to charge a 12V battery approximately 13.5V would be needed to charge. However, most solar panels work at a higher voltage of about 20V and the Amps (current) stay the same. Since power is equal to current multiplied by voltage, it is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. [3] In figure 7, the yellow rectangle gives the output power. The top right is the maximum power point, which is the target desired.

Figure 6 MPPT Curve



In order to maximize efficiency gained from using the MPPT algorithm, choosing the right batteries to store the generated power becomes crucial to the design.

For our project the batteries are required to store and smooth out the electricity from the renewable source. The five factors that were considered beyond the design criteria while choosing the batteries are: (1) Cost, (2) performance, (3) safety, (4) size and (5) availability.

The battery chosen must be a secondary battery, so that it can be charged and discharged completely. The two competing chemicals are lead-acid and lithium-ion.

As one of the most popular secondary batteries for portable electronics, lithium-ion batteries have “one of the best energy densities, no memory effect, and only a slow loss of charge when not in use”. [4] Weight wise, they are much lighter than other secondary batteries and come with a wide variety of shapes and sizes. However, one disadvantage of Lithium-ion batteries disqualifies them to be a part of the power generation system: high cost.

Lead-acid batteries, have the lowest cost and highest price-to-power ratio among the four secondary battery types. They are the oldest secondary battery technology, and they are the most widely available in the world. Performance speaking, lead-acid batteries have low internal resistance and can deliver very high currents. They are also tolerant to abuse and overcharging. Lead-acid batteries are currently the best option due to cost, availability, and functionality.

Lead-acid batteries are divided into three categories: starting, deep-cycle, and marine.

Starting lead-acid batteries are designed for starting automotive engines. Obviously, their most significant specialty is the ability to output a high current with almost no delay. In order to achieve this ability, starting lead-acid batteries have many thin plates designed to maximize surface area, which allows for maximum current output. However, they are also vulnerable to deep discharge and “repeated deep discharges result in capacity loss and ultimately premature failure”.

Deep-cycle lead-acid batteries, on the other hand, have thicker plates. Although they do not output as high current as starting batteries do, they can endure frequent discharging and recharging without degradation.

Marine batteries have thicker plates than starting batteries, but thinner plates than deep cycle batteries. They are designed to serve as a compromise between the two lead-acid batteries above, and therefore have a current output and life time lying between starting batteries and deep-cycle batteries. Since the goal of the Pomolong Township project is to construct a power generation system, high endurance in frequent discharging and recharging are more important than high current output. Therefore, deep-cycle lead-acid batteries were chosen for the design.

The internal resistance of a battery affects its performance. The higher the internal resistance, the higher the losses of energy is while charging or discharging the battery. In other words, the batteries with a lower AH discharges very fast while the one with the higher AH discharges really slowly. That is why batteries with high amp-hour are served as an optimal choice for the Pomolong Township project.

Peukert's Law were used to determine the parameters.

$$t = H(C\ /\ IH)^k \qquad (5)$$

Peukert's Law expresses the capacity of a battery in terms of discharge rate, where t is the total time to discharge the battery, k is the Peukert constant, I is the discharge current, C is the rated capacity at the discharge rate, and H is the rated discharge time.

There are three types of deep-cycle lead-acid batteries: flooded, gel, and absorbed glass mat (AGM).

Flooded batteries are the most inexpensive deep-cycled batteries and work well under extremely hot conditions. Performance speaking, they have a low amount of discharge rate due to their low internal resistance; they can keep the charge even after being placed in the storage for months without usage. Their low internal resistance also enables them to handle shock and vibration very well. Flooded batteries are very reliable and work well with all types of design. Their life expectancy is between 5 and 15 years, depending on the battery. For maintenance purpose, flooded batteries are required to be watered and ventilated in order to expel the gas that they produce.

The AGM batteries cost more than flooded batteries, but are maintenance free. The AGM batteries are sealed and have a low internal resistance.

For the Pomolong Township Project, flooded batteries were chosen for their low cost and their ability to endure volatile climate conditions.

The two batteries that were purchased were 12V 75Ah 280W batteries. The name of the model is HRL12280WFR manufactured by CSB and purchased from TNR. They each weigh 47.2 lb with dimensions of 216.00mm x 168.50mm x 209.70mm.

Figure 8 Battery

D. Inverter

The inverter enables the system to deliver power stored in the batteries to the users efficiently and safely. This is the final part of the project and is the final major section of the system. The main function of the inverter is to convert direct current to alternating current. Inverters are not only used in off grid power systems but also inside electronic devices such as computers and small switching power supplies.

Low pass filters are applied to allow the important parts of the waveform but not allowing distortion to go through the signal. Feedback is required around each semiconductor switch because a path is needed for loads that contain inductance. When the switch is turned off there exists a path for the peak inductive load current. The feedback is implemented through rectifiers or anti-parallel diodes.

To create the AC signal output the Pulse Width Modulation (PWM) technique is used, in which a signal is produced by a switch that quickly turns on and off. To expand on that, all the electric components of the inverter are turned on and off to generate proper RMS voltage levels. A triangle wave generator and a modulation sine wave generator go into an Op-amp to produce the PWM. The triangle generator is the carrier signal and it controls the frequency of the switching. The modulation generator produces the signal that determines the width of each pulse hence the RMS voltage level of the signal. Next, the output of the PWM Generator can be seen.

In most uses, making the waveform is adequate, but for higher power, power amplification is needed. After the signal is generated, a switching boost converter is used to amplify the signal. The most common types of Boost converters are half bridge, fly-back, and push-pull conversion. The topology that was used for this project was the push-pull conversion because it requires the least amount of parts, resulting in the lowest cost and the most manageable amount of trouble shooting.

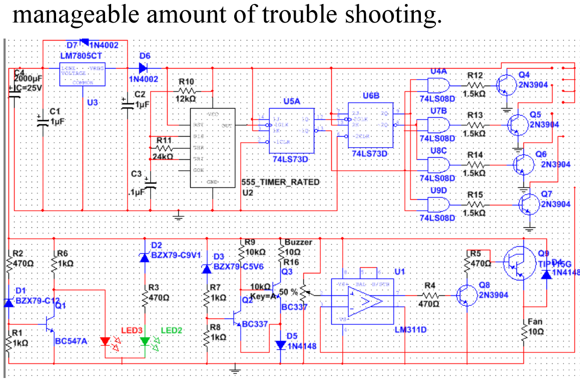


Figure 9 Inverter Signal Generation

In the implementation of the modified sine wave inverter, the design can be broken down into a signal generator and a DC to DC converter. The signal generator is what creates the waveform, and it is further broken down into a 5V voltage regulator power supply to power the chips and a 555 timer that was set to 60 clock cycles by using a 12kΩ and a 24kΩ resistor with 240Hz multivibrator. To convert the signals we used 2 JK Flip-Flops (74LS73D) and 4 AND gates(74LS08D). 2N3904 Bridge Drivers give the final output.

To make the converter four three hundred watt IRFP260N power MOSFETs were used. The 12-0-12 transformer is driven by the inverter signal generation circuit. The circuit is finally filtered by a CD295 200V 1800uf electrolytic capacitor and a M106102125-524 2u2 K250 WN Metallized Polypropylene Film Capacitor.

E. Sensors

Sensors are a very important part of this project. Without sensors, the charge controller would not be able determine voltage levels of the battery, making an entire system pointless. Sensors give data on the status of the system, and without them, vital information about the system would not be known. This would be a problem, because without knowing vital information of the system, identifying when the system is malfunctioning would be almost impossible.

Part of the design for the project is to continuously monitor the amount of voltage and current that is being outputted by the solar panel. This information is sent to the microcontroller and displayed on the monitoring system. The data which is sent from the voltage divider circuit is then sent to the microcontroller. Before this is done, Operational Amplifier are used. The use of Op-Amps are important to the design because they help ensure that the data being sent to the microcontroller are accurate by decreasing the noise. The op-amps that were used for the voltage sensors were MCP6004 because there operating voltage was similar to the MPT612, whereas other op-amps needed higher voltages, which would require another voltage regulator circuit.

When traveling long distances in cable, voltage signals tend to develop noise. This unnecessary noise can affect the data being outputted. This can lead to misleading results which is why the use of Op-Amps in this circuit is very important. There are many kinds of Operational Amplifiers, but Unity Gain Op-Amps have characteristics which fit the design requirements for this project because the overall gain of the circuit is in unity. It is important to minimize external influences to the output. The reason for this is that added gain to the output generates incorrect values and extra circuitry would be needed to step the voltage down before the signal can be received by the microcontroller.

The voltage of the solar panel can range from around 0 to 33 volts. This voltage range must match the maximum input voltage range of the microprocessor chip which is between zero and five volts. To measure the voltage coming from the panels, a sensor is not needed, but a voltage sensing circuit is implemented. By connecting a voltage divider in parallel with the solar panel the maximum output from the solar panel can be dropped to match the maximum voltage of the microprocessor.

A current sensor is utilized to monitor the DC current which is being outputted from the solar panels and batteries. There are several different technologies which can serve the purpose of a current sensor. The ones available are surface mount Hall Effect sensors, Hall effect current clamp sensors, the Hall effect open loop current sensor, the Hall Effect current sensor, and the Inductive current sensor.

The IC that is used for current sensing is the INA194a because it performs a difference amplification with a gain of 50, giving the MPT612 very precise changes in current.

Temperature is also a very important consideration. This is because temperature affects the efficiency in both the batteries and the solar panels. To circumvent this, methods have been made to keep these components at idea temperature. The problem is that you can't moderate temperature without knowledge of the temperature. The logical conclusion is that it would be beneficial to know the temperature. To gain knowledge of the temperature, the addition of a temperature sensor is needed.

To implement a temperature sensor, the sensor needs to have direct physical contact with the components that need it most. Namely, the batteries, the solar panels, and the inverter. The optimal sensor would be reliable, inexpensive and easy to replace.

The first method that can be used to measure temperature is with the thermocouple. This temperature sensor is a junction of two different metals. When the temperature is different between them, there is a potential difference between the two metals. One of the two metals is treated as a reference temperature. The other metal is at the location where the temperature is to be measured.

Thermocouples are cheap, tough and reliable over a wide temperature range. One thing to remember when using thermocouples is that it each of the metals are connected to copper wires to integrate them in a circuit or into instrumentation. This connection will create two extra junctions. These two junctions will have a voltage difference that is temperature dependent.

E. Encasing and Wiring

The encasing is made of aluminum to provide a lightweight yet sturdy frame to protect the electrical components. Plexiglass is used as a cover for our metal frame. It has a double purpose as it provides additional protection of our project but also as a window to check for any malfunctions of fans, wiring, chips, or electrical components. Also, the switches, LEDs, and power outlets are attached to the Plexiglass cover. The fans are attached to the metal frame and adequate ventilation holes are provided on the cover.

The electrical components rest on wood to provide insulation of the electrical components from the metal frame.

Figure 10 Enclosure

Additionally, since the solar panels are large in size and heavy, a wooden frame was constructed to support the panels. The frame supports the panels at an angle of 60 degrees to provide a reception of solar energy for April in Florida. The panel frames also hold our batteries underneath the panel and are wired with 10 AWG wire. The panel frames are also mobile which provide an easy way to move them and the batteries around since they are by far the heaviest parts of the project.

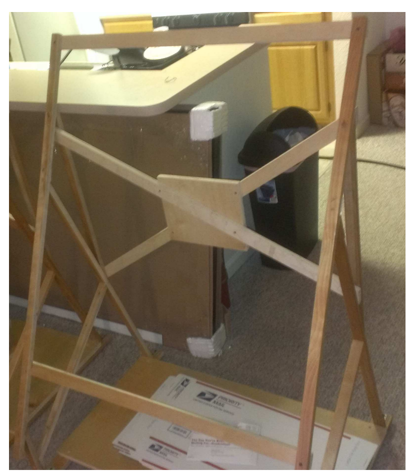


Figure 11 Solar Panel Frame

As for the wiring in the electrical components, we used 20-18 AWG wire for the control signals and 12 AWG for the power lines.

IV. Conclusion

In order to fully satisfy our initial pure sine wave inverter specifications, a stable and safe half-bridge DC-DC boost converter was needed. It was found through research that the cost of parts for the DC-DC boost converter was going to be too expensive.

Another minor problem that was encountered in inverter design was the ability to properly test the output signal at high power levels due to large voltage swings and high levels of current. Several improvisations had to be made and many components were destroyed in testing the high powered DC to DC boost converter.

Due to these problem and time constraints, we decided to implement a modified sine wave inverter. However, besides this minor setback our solar power generator system meets our initial specifications.

The encasing provides adequate protection and cooling for the electrical components. The charge controller operates at MPPT and the inverter provides high power to operate non-sensitive equipment such as mobile phone chargers. In reflection, we found that with high capacity microcontrollers available today, a single system with a charge controller and inverter can be achieved. This method would be more efficient and reduce space and costs.

Finally, we hope that the project our group designed will be a long term asset to the Pomolong Township.

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Engineers

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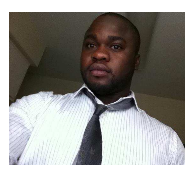
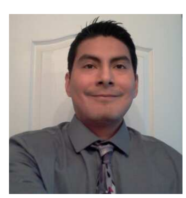


Armel Nidjeu is graduating with a degree in Electrical Engineering. He is planning on pursuing a career in Power Systems in Virginia. Furthermore, he plans to obtain a master's degree in Power Electronics.



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