Project Helios for South Africa

Cory Bianchi, Esteban Ossa, Patrick O’Connor
and Pablo Pozo

Department of Electrical Engineering and
Computer, Science, University of Central
Florida, Orlando, Florida, 32816-2450

***Abstract* — Many locations around the world do not have reliable energy sources. A lack of reliable energy in these remote locations stunts growth and development in the population. Ramifications from a lack of energy can be as elementary as milk spoiling due to lack of refrigeration or as complex as illness due to the absence of health care. Fortunately, there are several reliable and self-sustainable energy sources. Photovoltaic power generation is an abundant source of clean energy and low maintenance.**

Index terms — Batteries, DC-DC Power Converter, Inverter, Solar Energy, Solar Power Generation, Transformer.

I. INTRODUCTION

Photovoltaic energy is a natural source that does not affect the environment. This ecofriendly solution provides flexibility in the design. It is a compact and portable system that can easily be added to any structure. It is important to have adaptability in the system to allow expansion. The system can be conveniently moved if the exposure to the sun is obstructed by a new structure. A solar system captures energy from the sun, which is abundant in South Africa. The solar panel is the first subsystem that converts the sun’s rays into electrical energy. Once the energy is converted it must be regulated and distributed. When the power is generated if the voltage is high enough, the charge controller will step up the voltage to the regulated specifications to charge the battery. If the voltage is not high enough, the charge controller will disconnect the solar panels from the battery bank. If the battery bank is full the charge controller will change to float mode. An inverter is needed to convert the energy into usable power for consumption.

II. OVERVIEW

In order to implement a self-sustaining and renewable energy system, which will not have an impact on the environment, photovoltaic panels will be implemented to gather energy. There are four parts to our project; the power supply, the charge controller, the battery bank, and the inverter. The power supply will consist of four photovoltaic panels each capable of outputting 235 watts of power during peak conditions. The power supply will feed DC power to the charge controller to charge the battery bank.

A microcontroller was installed to monitor the system in the charge controller. A feed forward circuit was installed in order to monitor the output power of the power supply. A feedback circuit was also incorporated to measure the output voltage of the charge controller to make sure it is regulated appropriately.

The battery bank will have three 6 volt deep-cycle batteries in series to create an 18 volt battery bank that goes into the inverter. The goal of the battery bank is to find an economic source of storage or get the most amp hours per battery that fits within our budget.

Lastly, the inverter, its job is to take the power from the battery bank and convert the DC power to AC power at 220VAC and 50Hz. This module will consist of multiple parts. First, the inverter module will need to have an inverter component to convert the power from DC to AC. Then, a perfect sine wave generator will be used to optimize the power. A third component to the inverter module is the voltage step up stage which will take the voltage to 220VAC.

III. DESIGN

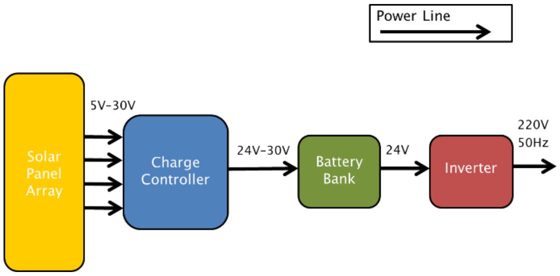
Table 1. System Specification and Requirements

SPECIFICATIONS AND REQUIREMENTS	
Input Voltage	5-30V
Input Current	Up to 32A
Output Voltage	220VAC
Output Current	4.4A
Battery Storage Capacity	100AH at 50%
System Operating Temp.	-18° - 52°C

The system design for any solar power system are all more or less the same and includes four major components that will make the system run; they are the charge controller, the inverter, the battery bank, and the power supply, look at Figure 1 below. The system components are dependent on each other based on the design, as each component is essential to the functionality. All of these pieces have intricacies within themselves to make them function and to do their task. Even though the overall design of the system is easy to grasp, designing the components themselves are more difficult.

The components are broken down to their essential parts and explained here.

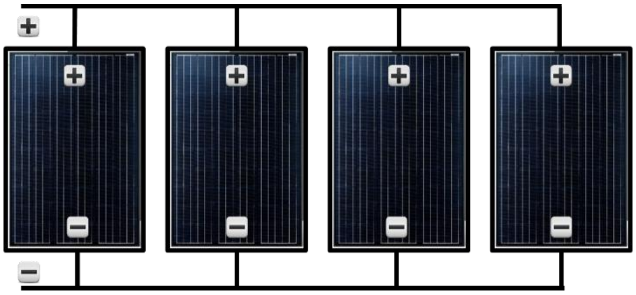
Figure 1. General Block Diagram



A. Solar Panel

Solar panels have a great life expectancy and are able to last up to 40 years. With technology nowadays, the polycrystalline photovoltaic panels lose about 1% efficiency every year. Given enough time, the panels will pay themselves back over the years.

Figure 2. Solar Panel Parallel Array



The power supply consists of four STP235 20/Wd solar panels from SUNTECH to supply the energy needs for the Pomolong Township. The panels will produce up to 235 watts of power and peak at 30.20 volts and 7.95 amps. There is a limited amount of space that will be available for the solar panels to be installed on top of the community center. Given their size, they will take up an area of about 70 square feet. The operating range for the solar panels is -40°C to 85°C and it operates best at 45°C. This range is well within the township of Pomolong in South Africa's which ranges from 27°C in the warm summer months and 2°C in the cold winter months.

The solar panels are rated for a 14.8% efficiency of converting solar radiation to electricity. The solar panels will be set up in parallel, see above in Figure 2; this configuration will regulate the output voltage of the solar panels equal to the voltage of the solar panel with the least potential, due to any shading or irregularities. Shading can be caused by weather conditions, and shadows from the surrounding environment. The panels will produce 940 watts of power at peak production time.

Four solar panels were chosen because it would occupy less space on top of the community center which has limited capacity for solar panels. Also having few solar panels makes it easier to change one out if it goes bad. Having less solar panels also makes the system more efficient because there will be less loss of power on the lines. Buying few solar panels is also more cost efficient than buying 10-100W solar panels to get the 1000W of power generation.

These panels must be able to survive the rugged conditions of South Africa.

The high quality panel is composed of polycrystalline and contains 60 cells. They weigh about 40lbs and will prevent them from being blown around in the wind. The dimensions of the solar panels are 164 x 99.2 x 3.5 cm. (length x width x height).

B. Charge Controller

The charge controller is an intricate system that will watch over the battery bank to make sure they receive charge. The charge controller's job is make sure not to overcharge the batteries and monitor the incoming and outgoing voltage to make decisions.

The PIC16F887 was used for its ease of programming and the number of pins. This PIC has an instruction set of 31.This pic has an operating voltage of 2-5.5V. It has 2 Pulse Width Modulators (PWM) to drive the Insulated Gate Bipolar Transistors (IGBT). It has 14 Analog to Digital Converters (ADC) and 14KB of programmable memory. The PIC will run on a 16 MHz oscillator.

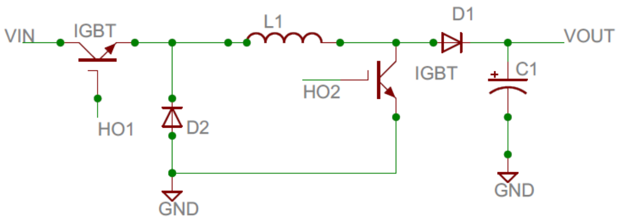
Table 2. PIC16F887

PIC16F887 SPECIFICATIONS	
Clock	8 MHz
Programmable Memory	14Kbytes
Operating Voltage	2 – 5.5V
ADC	14
PWM	4
Cost	$2.80

The voltage monitoring was done using two voltage dividers connected to two analog digital converters in the microcontroller. The charge controller will start up the DC-DC converters once the input voltage is above 5 volts; this will allow the controller to generate enough voltage output to charge the battery bank. The charge controller uses four Buck-Boost DC-DC converters in parallel that will take the unregulated incoming power and regulate the output voltage, to charge the battery bank.

A Buck-Boost is comprised of two diodes, two MOSFETs, an inductor, and a capacitor. The two diodes and the two MOSFETs are used to direct the power in order to step up/down the voltage based on the input and the wanted output. The inductor takes the power and creates an electric field and based on the switching becomes a source or a load. The capacitor is used at the output to filter the DC signal and get rid of any ripple voltage, see Figure 4 below.

Figure 4. Buck Boost Converter



The duty cycle of a DC-DC Converter determines the output voltage. Duty cycle is the ratio of the amount of on time to the off time. If the Buck Boost is in Buck mode then the longer the duty cycle the higher the voltage at the output up to the input voltage. The lower the duty cycle the lower the voltage. In Boost mode, the scheme is similar, the higher the duty cycle the higher the output and the lower the duty cycle the lower the voltage down to the input voltage level. The duty cycle for the buck and boost converters are shown in equation 1 and 2, respectively.

When the Buck Boost Converter is in Buck mode then the input voltage will step down the voltage to the regulated output. In Buck mode, the HO2 pin will be low and the IGBT will act as an open and the other IGBT switches with a given duty cycle to regulate the voltage output. When HO1 is off then the inductor will send power to the output. If HO1 is on then the inductor is charging. Using the following two equations the minimum duty cycle for the buck mode and the maximum duty cycle for the boost mode can be calculated; where: Vinmax = maximum input voltage, *Vinmin* = minimum input voltage, *Vout* = desired output voltage.

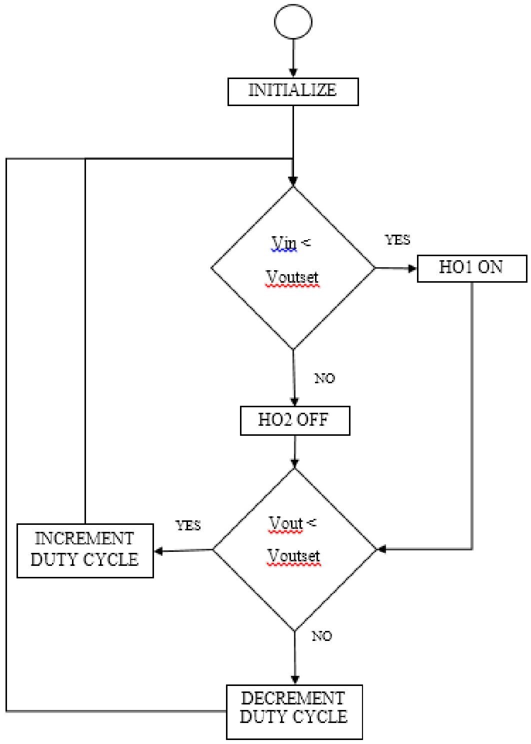
$$Dbuck = \frac{Vout}{Vinmax} \qquad (1)$$

In Boost mode the input voltage will be stepped up. To enter Boost mode HO1 will be high so the IGBT acts as a short and the other IGBT will switch. When the HO2 is low, power will be sent to the output from the inductor. In the other case the inductor will be charging and the capacitor will send power to the output.

$$Dboost = 1 - \frac{Vinmin}{Vout} \qquad (2)$$

Initially, the microcontroller calculated the duty cycle once the microcontroller knew which mode to be in, but a different method was used in our design. Two voltage dividers were used as previously stated, one on the voltage input to select the mode and the second to monitor voltage output. A feedback system was used instead to get a more accurate output and to be able to react to any voltage input changes that may occur from shading or irregularities.

Figure 3. Charge Controller Flow Chart



All of the components need to be able to withstand 8A of current and 30V. It is 8A because the DC-DC Converters are in parallel and the maximum 32A of current will split.

The following equations were used to calculate the inductance value for the Buck Boost. Where: *Iout* = desired maximum output current, *Fsw* = switching frequency of the converter, *Kind* = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current. A good estimation for the inductor ripple current is 20% to 40% of the output current, or 0.2 < *Kind* < 0.4.

A switching frequency of 50KHz was chosen to calculate the inductance and capacitance that is needed to filter the DC signal. The max of the two inductance values equated to about 30uH, so a 120uH inductor was used.

$$L > \frac{Vo*(Vinmax-Vout)}{Kind*Fsw*Vinmax*Iout} \qquad (3)$$

$$L > \frac{Vinmin^2*(Vout-Vinmin)}{Kind*Fsw*Vout^2*Iout} \quad (4)$$

Table 3. Inductor Specifications

1140-121K-RC SPECIFICATIONS	
Inductance	120uH
Current Rating	14.4A
Tolerance	±10%
Operating Temperature	-55 -105°C
Cost	$7.17

To calculate the capacitance needed the following equations were used. The first two equations 5 and 6 are for the Buck and equation 7 for the Boost. Choosing a Max{*Coutmin1*,*Coutmin2*, Coutmin} will suffice for the capacitance needed to filter the DC signal. The equations below were used to calculate the necessary values; where: *Coutmin*, *Coutmin1*, *Coutmin2* = minimum output capacitance required, *ΔVout* = desired output voltage change due to the overshoot.

$$Coutmin1 = \frac{Kind*Iout}{8*Fsw*\Delta Vout} \quad (5)$$

$$Coutmin2 = \frac{(Kind*Iout)^2*L}{2*Vout*(ESR*Kind*Iout + \Delta Vout)} \quad (6)$$

$$Coutmin = \frac{Iout*Dboost}{Fsw*\Delta Vout} \quad (7)$$

The capacitance needed came to 1328uF so a 1500uF capacitor was chosen to have some extra capacitance. Choosing a higher inductance or capacitance is recommended as the equations only give the minimums.

Table 4. Output Capacitor Specifications

UHE1H152MHD SPECIFICATIONS	
Capacitance	1500uF
Voltage Rating	50V
Tolerance	±20%
Operating Temperature	-40 -105°C
Ripple Current	3.15A
Cost	$1.29

In order to handle the switching of the circuit IGBTs where chosen. They have high current capability and they drive similar to a MOSFET. The chosen IGBTs are able to handle the 50KHz switching frequency that is used in the Buck Boost circuit. They need to be able to handle the switching current, voltage, and continuous current across the collector and emitter. To figure out the switching current, the maximum of the following *Iswmax* equations were used for the design. Equations 8 and 9 are used for the Boost mode and 10 and 11 for Buck mode.

$$\Delta Imax = \frac{Vinmin*Dboost}{Fsw*L} \quad (8)$$

$$Iswmax = \frac{\Delta Imax}{2} + \frac{Iout}{1-Dboost} \quad (9)$$

$$\Delta Imax = \frac{(Vinmax-Vout)*Dbuck}{Fsw*L} \quad (10)$$

$$Iswmax = \frac{\Delta Imax}{2} + Iout \quad (11)$$

Table 5. Charge Controller UGBT Specifications

IXY6N170 SPECIFICATIONS	
Vce	1700V
Ice @ 25°C	12A
Tolerance	±20%
Operating Temperature	-55 -150°C
Power Dissipation	75W
Cost	$1.29

Lastly, to complete the circuit, diodes are needed to direct current and to protect the circuit from reverse flow. For extra protection each of the diodes for the Buck Boost were chosen to handle 10A which is 2A more than what is expected to go through the circuit. The diodes selected are Schottky rectifiers which are fast switching diodes to handle the switching frequency. Since the voltage output is up to 30V the diode needs to have a higher reverse voltage rating. The MBR1045 was chosen because it is able to handle 10A and up to 45V.

Table 6. Diode Specifications

MBR1045 SPECIFICATIONS	
Maximum Reverse Voltage	45V
Average Forward Current	10A
Operating Junction Temp.	-60 - 150°C
Power Dissipation	2W
Cost	$0.64

The battery bank has a stack of LEDs to tell the user the status of the batteries. First, the battery bank will have a stack of 10 LED lights that are colored from green to yellow to red. The top 7 will be for the operating voltage range of the batteries. The last three identify the batteries need to be charged. In the color scheme the first two LEDs will indicate the battery is fully charged 85-100%. The yellow will take the middle four LEDs to show that there is some to moderate charge 60-80%. When the last yellow LED turns off this tells the microcontroller the battery bank is at 55% charge. Lastly, when the battery falls significantly below the low voltage limit, the last red LED will show the charge is less than 50% state of charge. This will notify the users that they should refrain from using the batteries until a safe charge is reached in order to preserve the battery bank's life. A blue charging status LED will be used to show that the battery bank is in a charging state.

C. Batteries

The power storage is just as expensive if not more so in some cases as the solar panels that supply the power. Most batteries for this type of system range from $100 to $450 and more. The battery bank has a storage of 215AH, which if the community center drew 10 amps per hour they will be able to have power for 20 hours and the battery bank would be fully discharged. The system however will only allow itself to get 50% discharged, so they will have about 10 hours of power at 10 amps per hour. The system has only 50% discharge to maximize the life of the batteries.

There are many different battery chemistries that are used for solar power applications. The most popular for solar is the AGM batteries. They are like a Lead Acid battery that is fused with a gel. These batteries are low maintenance and are sealed. When charging these batteries gassing is not as much of a problem. The major downfall of AGM batteries is that they are expensive.

The Lead Acid batteries are a better choice for the design for several reasons. Lead Acid are a much cheaper source of storage of energy and they are a common battery type for many other applications. They are fairly durable with some maintenance. When charging at a high enough voltage the cells will start to gas and distilled water should be added to the cells to maximize the energy that the battery can store. Lead Acid batteries are able to handle a fast or slow charge. When charged slowly the battery accepts more of the charge. An added benefit is that these batteries are hard to overcharge.

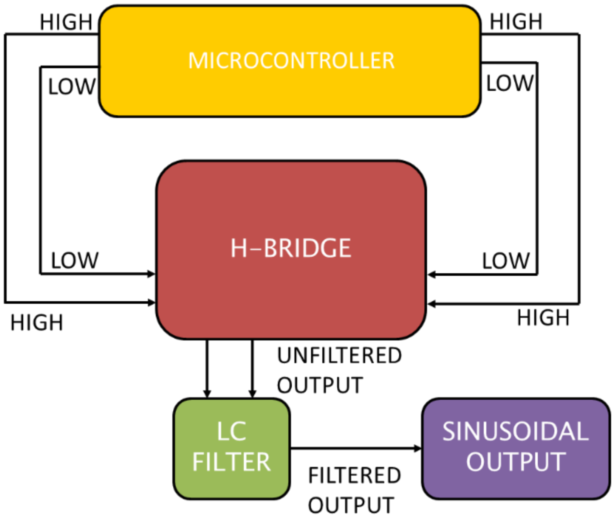
One of the differences between Lead Acid and the most common battery types that everyone uses, is a limit of discharge. Lead Acid batteries should not discharge more than 50% to maximize its longevity. Lead Acid batteries go through cycles and the bigger the discharge the less cycles a battery is able to perform due to the larger recovery to get charged. In the best case a shallower discharge/charge area will increase the longevity of the battery. Lead Acid batteries are able to last up to about 5 years but they are unpredictable and anything can go wrong after 2 years. Within the Lead Acid realm there are two kinds of batteries deep cycle and starter batteries. The starter batteries usually have a shallow cycle of 5%. The difference between the two are that the starter batteries are good for a large short power burst while the deep cycle is better for a slower steady power use. The design called for a deep cycle Lead Acid and up to a 50% discharge.

The batteries will be placed in a series combination to increase the battery bank voltage to 18 volts. Using three 6-volt batteries in series will allow the battery bank to output 18 volts. The 6-volt batteries were chosen because they are more cost effective as to how much power they are able to store. The design called for the SLIGC110, which costs a mere $0.13/Wh to store the power. The SLIGC110 is a golf cart sized battery that is able to hold 215AH. In this configuration if one of the batteries goes bad the whole battery bank needs to be replaced otherwise the new battery would lose a lot of its longevity due to the other older batteries. The batteries will also have to be the same type, so the internal chemistries match. This is important so that all of the batteries will charge at the same rate; otherwise, one battery will be charged and the others not, which will greatly decrease the life expectancy of these batteries.

D. Inverter

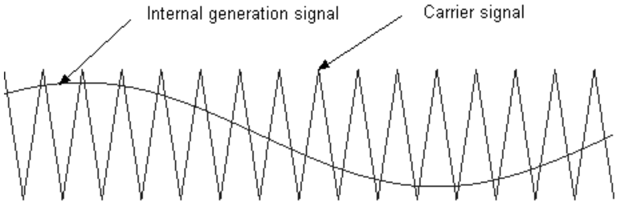
The inverter is the most important component of the system. This is the final stage of the solar system before the power is delivered to the load. At this stage the output should be a clean 50Hz sinusoidal wave with 220VAC capable of delivering around 1kW.

Figure 5. Inverter General Block Diagram



A microcontroller will be used to generate the sinusoidal waveform and the triangular waveform. The sinusoidal signal will be used as a reference signal and the triangular waveform will be used are the carrier signal. These two signals will be compared to obtain the intersection of the signals. The intersection of these two signals will create data points that will be used to control the gate drive. There are going to be two switching frequencies that will be used to control the gate drives. A high frequency of 16kHz and a low frequency of 50Hz will be used.

Figure 6. High Frequency (Triangular), Low Frequency (Sinusoidal)



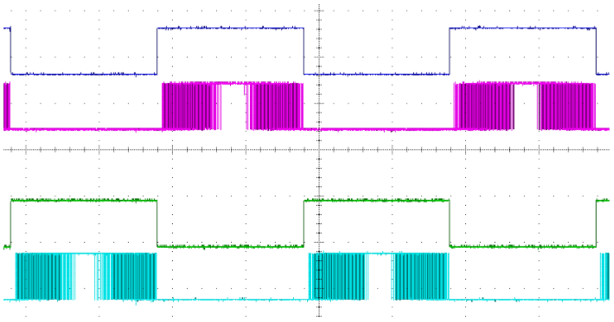
To be able to generate these two frequency signals we used the PIC16F684 microcontroller. This component was used in order to digitally create a sine wave.

Table 7. Microcontroller Specifications

PIC16F684 SPECIFICATIONS	
Clock	20 MHz
Programmable Memory	3.5Kbytes
Operating Voltage	2 – 5.5V
Comparator	2
PWM Ports	1
Cost	$1.96

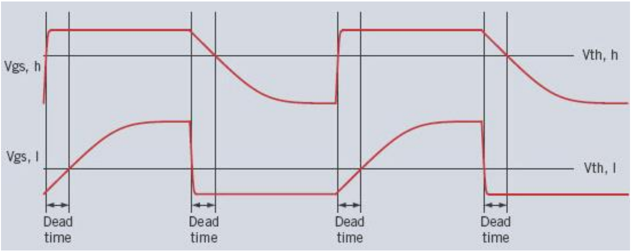
To do so, a fixed number of square wave impulses were required, the larger this number the cleaner the generated sine wave. A good number of samples that was used to generate a digital sine wave was 32. These were used in a half cycle (from 0° to 180°) and then reversed to be used on the other negative half cycle (from 180° to 360°). These four signals will be combined in an organized way in order to acquire the desired output. As seen in Figure 8 the four signals have been generated as desired.

Figure 8. 1st (Top): Positive Low Frequency Signal 2nd:Positive High Frequency Signal 3rd: Negative Low Frequency Signal 4th (Bottom): Negative High Frequency Signal



After these four signals are generated, they will now go into another component of the inverter called the gate drive. This component is in charge of controlling the MOSFETs in a synchronized manner. This stage is important because there is a level of risk involved to ensure that the switches are always on the on stage across the load. This means that the MOSFETs should never close on the same side of the load as illustrated in the following figure.

Figure 7. Dead Time Switching Graph



That is why it is important to select a reliable gate drive that offers additional features to protect the circuit and ensure minimal error. The driver that was selected for such an important task was the IR2110. When compared to other drivers in the market, this component outperforms its competitors with a larger short circuit protection capability and a faster dead time. At this point the low voltage side of the circuit has completed its duty of controlling the circuit.

Figure 9. Driver Specifications

IR2110 SPECIFICATIONS	
V_{OFFSET}	500V max
$I_{O+/-}$	2A/2A
V_{OUT}	10-20V
t_{on} / t_{off}	160ns / 150 ns
Delay Matching	10ns
Cost	$1.88

There is also a section of the circuit, where the 18V coming from the battery or the charge controller will be the input to the inverter.

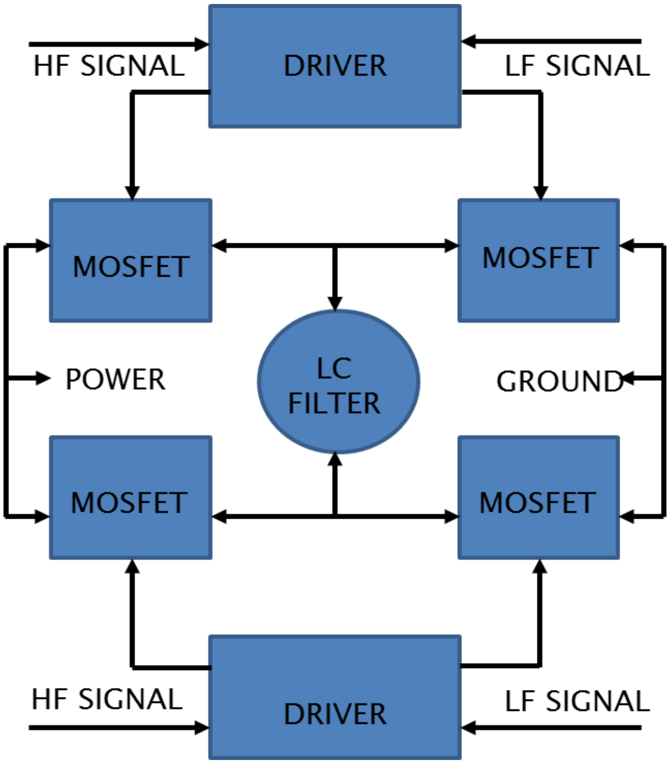
In order to feed the low side of the inverter circuit a power supply will be required to limit the current to the IC components. This power supply has an output of up to 1A to feed the inverter and protect the low power circuit from inrush currents coming from the battery bank. This power supply will also be in charge of regulating and producing a constant output. This power supply will allow us from isolate the high power side from the low power side.

After this level has been reached, the circuit will output this voltage to the H-bridge in order to put the signal through the switching process. The voltage is fed into the MOSFETs and with the MOSFET's switching sequence a pulse signal is generated. It must be noted that the MOSFETs should be chosen carefully depending on the task they will accomplish in the circuit. The following table illustrates the MOSFET's chosen for the H-bridge created.

Table 8. MOSFET Component Specifications

IRFPS3810 MOSFET SPECIFICATIONS	
Power Dissipation	12W
Operation Freq.	1MHz
Turn ON Voltage	3.0V
Speed	Ultrafast
Cost	FREE

Figure 10. H-Bridge Block Diagram



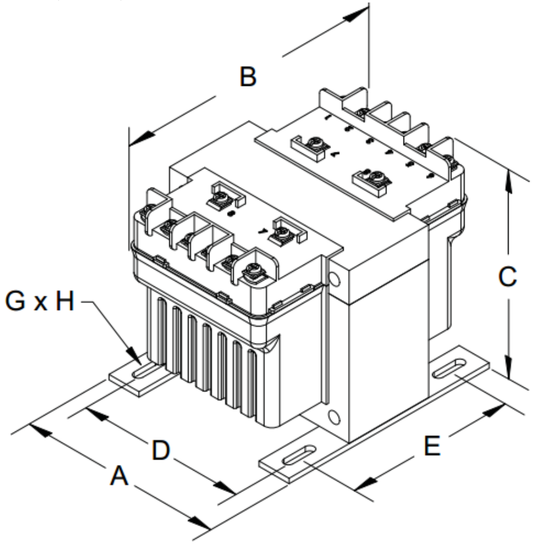
This pulse signal created by the intersections of the sinusoidal reference signal and the triangular carrier signal, created an unfiltered AC signal. This unfiltered AC signal was then filtered through a LC filter. While this section of the inverter looked very simplistic in design, it was in reality one of the most time consuming sections of this project. These two components needed to handle high currents and voltage ratings, and at the same time have a considerable high inductance and high capacitance value. These three factors greatly increased the price of the components, reduced the amount of choices available, and increased their physical size

Table 10. Transformer Specifications.

PH1000MLI TRANSFORMER	
Output (VA)	1K Volt-Amps
Primary Volts AC	240/460 Volts AC
Secondary Volts AC	25/120 Volts AC
Weight	31 Lbs.
H X W X D (in)	4.94 x 5.25 x 8.19

Finally, to be able to step up this voltage from 12.7VAC to 220VAC it is required to use a transformer. In order to obtain this output, the corresponding ratio of the transformer will be used to obtain the 220VAC. This output voltage should also have an output frequency of 50Hz and a power rating of 1kW.

Table 9. Transformer Dimensions. C (4.94in), A (5.25in) and B (8.19in)



The step up ratio required for this transformer made its configuration, and market availability rare. Due to this transformer specifications, it was a challenge to find it on the market, and its price was of high value compared to other transformers with a more common step up ratio. Another aspect to have into account is the amount of space this component took on the design, about 30% of the total design dimensions.

Now that the voltage has finally been stepped up and is sinusoidal, it can be used in most of the electronics that require this kind of output. To do so, a BS-546 AC power socket will be installed in the output terminal. This terminal socket is essential for use in South Africa allowing the use of regular electronics used in this region. In the case of using the default American socket, it will be required to connect an adapter plug in order to solve any compatibility issues.

IV. CONCLUSION

Photovoltaic energy is an abundant source of energy and more research and development is being done in the market. It is becoming a more viable source of energy as technology gets better and cheaper to be able to compete with coal or nuclear power. Many rural areas are investing solar for its cheaper cost.

The design as a whole has four major components to make it work the solar panels, the charge controller, the battery bank, and the inverter. Choosing the right solar panels for their physical size and power transformation is important to the cost of the rest of the system and the solar panels themselves are the most expensive part of the system.

The charge controller design was based on a 1000W system to help give the township of Pomolong free energy that they were unable to harness before. A constant voltage charge is the simplest way to charge a battery and using the DC-DC converter made it feasible.

The battery bank was based on the needs of the inverter. Having a higher voltage on the battery bank makes the inverter's job easier to convert the power from DC to AC.

Lastly, the inverter needs to be able to handle the current from the batteries as the voltage is stepped up from 18V to 220V and converted from DC power at the input to AC power at the output.

ACKNOWLEDGEMENT

The authors wish to acknowledge Dr. Richie for finding funding for the trip to South Africa and being a mentor through the semester. Mr. Mahbub for all the knowledge shared specifically designing the inverter. Mr. Tullbane helped with the testing and prototyping of the inverter. Monetary donations and sponsors include Progress Energy, CECS, EECS, and Dr. Wang.

BIOGRAPHY

Cory Bianchi will graduate from University of Central Florida with a B.S. in Computer Engineering. He plans on pursuing a career as a computer engineer in the communications field.

Patrick O'Connor will graduate from University of Central Florida with a B.S. in Electrical Engineering and a minor in Computer Science. He plans on pursuing a career as an Electrical engineer in the simulation field.

Pablo Pozo plans to graduate with his Bachelor's in Electrical Engineering May 2013. He plans on pursuing a career as an Electrical Engineer in the aviation and aerospace industry.

Esteban Ossa will graduate from University of Central Florida with a B.S. in Electrical Engineering. He plans on pursuing a career as an Electrical Engineer in the music industry or power systems industry.

REFERENCES

Microchip. (2007). PIC16F684 Datasheet. Retrieved from Microchip: http://ww1.microchip.com/downloads/en/devicedoc/41202f-print.pdf

Microchip. (2007). PIC16F887 Datasheet. Retrieved from Microchip: http://ww1.microchip.com/downloads/en/DeviceDoc/41291D.pdf

Rectifier, I. (2005). IR2110 Datasheet. Retrieved from IRF: http://www.irf.com/product-info/datasheets/data/ir2110.pdf